GEOLOGICAL AND GEOCHEMICAL CONTROLS ON THE CHEMICAL EVOLUTION OF SUBSURFACE WATER IN UNDISTURBED AND SURFACE-MINED LANDSCAPES IN WESTERN NORTH DAKOTA

by

G. H. Groenewold, R. D. Koob, G. J. McCarthy,
B. W. Rehm, and W. M. Peterson

REPORT OF INVESTIGATION NO. 79
NORTH DAKOTA GEOLOGICAL SURVEY
Don L. Halvorson, State Geologist
1983

GEOLOGICAL AND GEOCHEMICAL CONTROLS ON THE CHEMICAL EVOLUTION OF SUBSURFACE WATER IN UNDISTURBED AND SURFACE-MINED LANDSCAPES IN WESTERN NORTH DAKOTA

by

G. H. Groenewold, R. D. Koob, G. J. McCarthy,
B. W. Rehm, and W. M. Peterson

REPORT OF INVESTIGATION NO. 79

NORTH DAKOTA GEOLOGICAL SURVEY

Don L. Halvorson, State Geologist

1983

FOREWORD

This report was prepared by the North Dakota Geological Survey, Grand Forks, North Dakota under United States Bureau of Mines (USBM) Contract number J0275010. The contract was initiated under the Advanced Mining Technology Program, subsequently the Minerals Environmental Technology Program. It was administered under the technical direction of Denver Mining Research Center with Michael J. Bailey, W. W. Watts, Jr., and Tim Hackett acting as Technical Project Officers. Darlene Wilson was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period October 1, 1979 to June, 1982. This report was submitted by the authors on July 2, 1982.

CONTENTS

Page

APPENDICES

ILLUSTRATIONS

Tables Page

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Baukol-Noonan Inc., The North American Coal Corporation, and Consolidation Coal Company for so generously allowing access to their properties. We would also like to thank Constance Triplett for her considerable efforts in the preparation of this report. This research was supported by U.S. Bureau of Mines Contract J0275010 and, in part, by U.S. Environmental Protection Agency Grants R-803727 and R-805939, and Department of Energy Contract No. AB18-80FC10120.

ABSTRACT

Previous studies of several surface coal-mining sites in western North Dakota have resulted in the development of a hydrogeochemical model which accounts for the observed chemical characteristics of subsurface water in undisturbed settings. Critical hydrogeochemical processes include sulfide oxidation, gypsum precipitation and dissolution, carbonate mineral dissolution and cation exchange. In western North Dakota the near-surface several metres of the landscape is constantly subjected to alternate wetting-drying which is a key mechanism in hydrogeochemical evolution.

The major purposes of this study were to refine the hydrogeochemical model, with particular emphasis on the sulfur cycle, and to determine the applicability of the model to postmining (spoils) landscapes. Field activities of the project included detailed groundwater instrumentation of undisturbed and spoils areas at two geologically distinctive mine sites in western North Dakota. Refinement of the model included detailed analyses of the texture, bulk mineralogy, clay mineralogy, sulfide abundance, and sulfur concentrations in overburden core samples. Laboratory experiments were designed to determine the source and mechanisms of sulfate salt production from overburden samples.

From the study we conclude that the hydrogeochemical model is equally applicable to undisturbed and spoils landscapes and that the major species of concern in this region are sodium and sulfate. We also conclude that the major source of sulfate is sulfides in the overburden and that the solubility of sulfate in groundwater in these settings is largely controlled by the sodium/calcium ratio. Although sufficient sulfides are present in the overburden to account for the observable sulfate concentrations in groundwater, much of the sulfate presently found in overburden sediments in these settings probably arose from sulfides in near-surface sediments that have been slowly eroding through time, resulting in a constantly replenished sulfate source.

We conclude that negative hydrogeochemical impacts resulting from surface mining in the Northern Great Plains will include increased mineralization of groundwater, sodic and salt effects on plants and increased mineralization of surface waters. The degree of these impacts will be dependent upon site specific hydrogeologic, geochemical, and mineralogical variables.

EXECUTIVE SUMMARY

Surface coal mining in the Northern Great Plains has generated concern and considerable debate regarding impacts on subsurface water. Hydrogeochemical studies have been ongoing since 1974 at several active and proposed surface coal-mining sites in western North Dakota. These studies have resulted in the development of a conceptual hydrogeochemical model which accounts for observed subsurface water chemical characteristics and chemical evolution in undisturbed settings.

In the semi-arid climate of western North Dakota, the near-surface several metres of the landscape is constantly subjected to alternate wetting-drying. This mechanism is the key to hydrogeochemical evolution in this region. Qualitatively the hydrogeochemical model assumes that oxygen, along with other atmospheric gases, are brought into the solum along with water during precipitation events. The oxygen initiates the oxidation of reduced carbon and sulfur materials in the solum. The products of these oxidation reactions are SO_4^{2-}, CO_2, and H^+. The H^+ production allows the dissolution of calcite and dolomite, which produces Ca^{2+}, Mg^{2+}, and HCO_3^- accompanied by a reduction in the concentration of the H^+ produced in the oxidation reactions. If the water is now evaporated or transpired, the ions are left behind in the upper few metres of the landscape as calcium and/or magnesium sulfates and bicarbonates. On the infrequent occasion that sufficient water is present to carry the ions below the root zone, infiltration leading to recharge of groundwater, some of the divalent ions exchange on the sodium-montmorillonitic clays which predominate throughout the area releasing Na^+. This combination of processes is sufficient to account for the alkaline, sodium sulfate groundwaters common in the Northern Great Plains.

The major purposes of this study were to refine the hydrogeochemical model and to determine the applicability of the model to spoils settings. Specific attention was directed toward clarification of the sulfur cycle.

This study included both field and laboratory experimentation. Field activities involved detailed instrumentation of undisturbed and spoils settings at two mines. Instrumentation, consisting of piezometers and pressure-vacuum lysimeters, was designed to evaluate subsurface water quality in both the unsaturated and saturated portions of the field study areas. Laboratory activities included detailed analyses of overburden core samples representative of all the types of overburden sediments present in western North Dakota. These analyses included texture, bulk mineralogy, clay mineralogy, and determination of sulfide and sulfur concentrations. Laboratory experiments focused on the source and mechanisms of sulfate salt production from overburden samples. Laboratory experiments included exhaustive leaching, accelerated weathering, pan experiments, and acid/base neutralization experiments.

From this study we have concluded that two sources of sulfate exist which may supply sulfate to the groundwater via recharge from the surface. These are presently existing soluble sulfate salts such as gypsum and reduced sulfur. Previous work suggested that presently available soluble sulfate salts derive ultimately from the oxidation of reduced sulfur. This study has found no evidence to the contrary.

Limited extractable sulfate exists throughout the overburden at all the study sites. The data from leaching and weathering experiments indicate that the sulfate is either in a readily extractable form, or is readily converted to such a form.

The fact that the amount of sulfate is finite suggests that the available sulfur may not be adequate to account for the high sulfate concentrations found in native groundwater in these settings. From this study we have concluded that in these settings reduced sulfur exceeds oxidized sulfur by factors of two to ten. This seems an inadequate excess if a static landscape were assumed. However, the landscape is not static; slow erosion is occurring which is continually exposing reduced sediments to air. Thus, a constantly replenished reservoir of reduced sulfur is available as a source for sulfate in the groundwater.

From this study we have concluded that the processes and mechanisms described in the hydrogeochemical model are equally applicable to undisturbed and spoils settings. Disruption of the landscape by surface mining typically results in changes which are particularly significant with respect to hydrogeochemical impacts. These changes include redistribution of the overburden materials and increased availability of oxygen in the spoils relative to premining conditions.

Redistribution of overburden sediments potentially results in significant changes in the chemical reactivity of the landscape. Emplacement of unoxidized sediments in the oxidizing near-surface environment increases the potential for sulfide oxidation, sulfate dissolution/precipitation, and cation exchange on clays. Air, and thus oxygen, entrapped in spoils during mining will promote oxidation of sulfides present in the unsaturated portion of the spoils. This can result in the generation of highly mineralized pore water and groundwater.

Mineralization of subsurface water in spoils in this region is typically two to three times as great as premining conditions. Species of particular concern in subsurface water in spoils are sodium and sulfate. Although available sulfides in overburden in the Northern Great Plains are sufficient to cause acid conditions, it was found that the natural buffering capacity of the overburden in this region will eliminate, except in occasional highly localized settings, acid drainage to water courses and groundwater.

The generation of highly mineralized subsurface water in spoils not only impacts groundwater quality but also has the potential to cause sodic and salt effects on plants. In addition, the generation of highly mineralized water in spoils has the potential to significantly impact surface-water bodies which are discharge points for local flow systems. Of particular concern in western North Dakota are closed depressions (sloughs) which are common in certain mining areas.

The degree of short-term impacts of surface mining on subsurface water quality in this region has been clearly documented by this study. Long-term trends are more difficult to evaluate. Without selective handling of highly reactive overburden, the key factor determining long-term impacts will be the degree of vertical infiltration (recharge) through the spoils. If recharge is essentially eliminated, soluble salts present in the base of the spoils will likely cause an initial flush of groundwater high in sodium and sulfate due to lateral inflow and flushing in the base of the spoils. This, however, will result in a short-term peak in the generation of highly mineralized groundwater in the base of the spoils. Under such conditions, sodium and salt effects on plants could be a severe and long-term problem. If, as is required by present laws, recharge in the spoils is similar to that of the premining landscape and selective handling of chemically reactive overburden is not considered, then the generation of highly mineralized subsurface water in spoils due to vertical infiltration and the generation and flushing of salts from the upper portions of the spoils can be anticipated. Under these conditions, the generation of highly mineralized subsurface water in spoils will likely continue for a considerable period of time and will have a potentially severe impact on both plant growth and groundwater and surface water quality.

Thus, long-term plant growth success and groundwater and surface water quality in postmining settings in western North Dakota is dependent largely upon site specific geologic and geochemical characteristics of the original overburden, how those materials are redistributed by mining, and the groundwater recharge characteristics of the postmining landscape. Particularly critical is the chemical characteristics of the spoils which are emplaced immediately below the soil zone. Thus, the simple replacement of topsoil and subsoil materials without regard for the physical and chemical characteristics of materials below the soil zone is, at best, a temporary and elementary approach to reclamation and only by chance can such an approach result in long-term success with respect to groundwater and surface water quality and plant growth. Without selective replacement of overburden, minimizing recharge in spoils would appear to be the optimum method for minimizing impacts on groundwater. This approach, however, would likely maximize salt and sodic effects on plant growth.

INTRODUCTION

History and Perspective

Surface coal mining in the states of North Dakota, Wyoming, and Montana and the Canadian provinces of Alberta and Saskatchewan has increased significantly in recent years. These activities have generated concern and considerable debate regarding the impact of surface coal mining on the quality of subsurface water both in the rooting zone and below the water table. The majority of active and proposed mining areas in this region is in agricultural lands. Throughout many of these coal mining areas groundwater from shallow wells (less than 100 m in depth) constitutes the major water source for domestic and stock purposes, and, occasionally, for municipal supplies. Throughout this region, fractured coals are a major source of shallow groundwater. Thus, the long-term quality of subsurface water in postmining settings is of particular concern.

Hydrogeochemical research activities at several proposed and active mining sites in western North Dakota have allowed the development of a conceptual model for the chemical evolution of groundwater in undisturbed landscapes (Moran et al., 1978; Groenewold et al., 1979, 1981). This model, which is summarized in a later section of this report, focuses on several key geochemical processes which are responsible for groundwater chemical characteristics in these settings. Critical variables in this model are gross textural and mineralogical characteristics of the near-surface materials of the landscape. The same geochemical processes which are operating in undisturbed landscapes are also operating in disturbed (postmining) landscapes. Thus, evaluation of the long-term effects of surface coal mining upon groundwater quality requires verification and refinement of the geochemical model in disturbed landscapes and determination of critical geochemical conditions or variables which are related to surface coal-mining activities.

The concepts presented in this report are largely the result of research at sites in western North Dakota. However, because of regional geologic, climatic, and mineralogical similarities, it is felt that these concepts have wide applications to groundwater quality concerns associated with surface coal mining throughout the arid to semiarid regions of western North America.

Objectives

Previous work in disturbed landscapes has largely been restricted to a limited amount of chemical characterization of spoil waters. Considerable textural and mineralogical variability exists in the overburden at various mines. Thus, a wide range of groundwater chemistries can be anticipated in the various postmining landscapes. Verification and refinement of the geochemical model and application to disturbed landscapes requires detailed characterization of water quality and mineralogy in various disturbed and undisturbed settings and an evaluation of the significance of key mineralogical variables and chemical reactions to groundwater quality. Specific objectives of this study are:

1. To characterize the quality of groundwater in geologically and geochemically distinct postmining landscapes.
2. To determine the mineralogy of the material matrix through which groundwater flows in those landscapes.
3. To relate this mineralogy to the chemistry of the groundwater in those landscapes.
4. To define the minerals and chemical reactions that control the chemical evolution of groundwater in postmining landscapes and thereby gain the capability to design postmining landscapes in which groundwater quality can be predicted and guaranteed.

Conceptual Hydrogeochemical Model

The conceptual model which has been developed to account for the observed chemical characteristics of subsurface water in western North Dakota has been discussed in several recent publications (Moran et al., 1978; Groenewold et al., 1979; Groenewold, Rehm, and Cherry, 1981; Groenewold et al., 1981). The following discussion is summarized from those publications.

Key Processes

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. We have proceeded 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 of salt generation and accumulation in reclaimed land. The framework used in this report follows closely that originally proposed by Moran et al., 1978.

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 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 (discharge).

Figure 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 produced from oxidation of organic materials

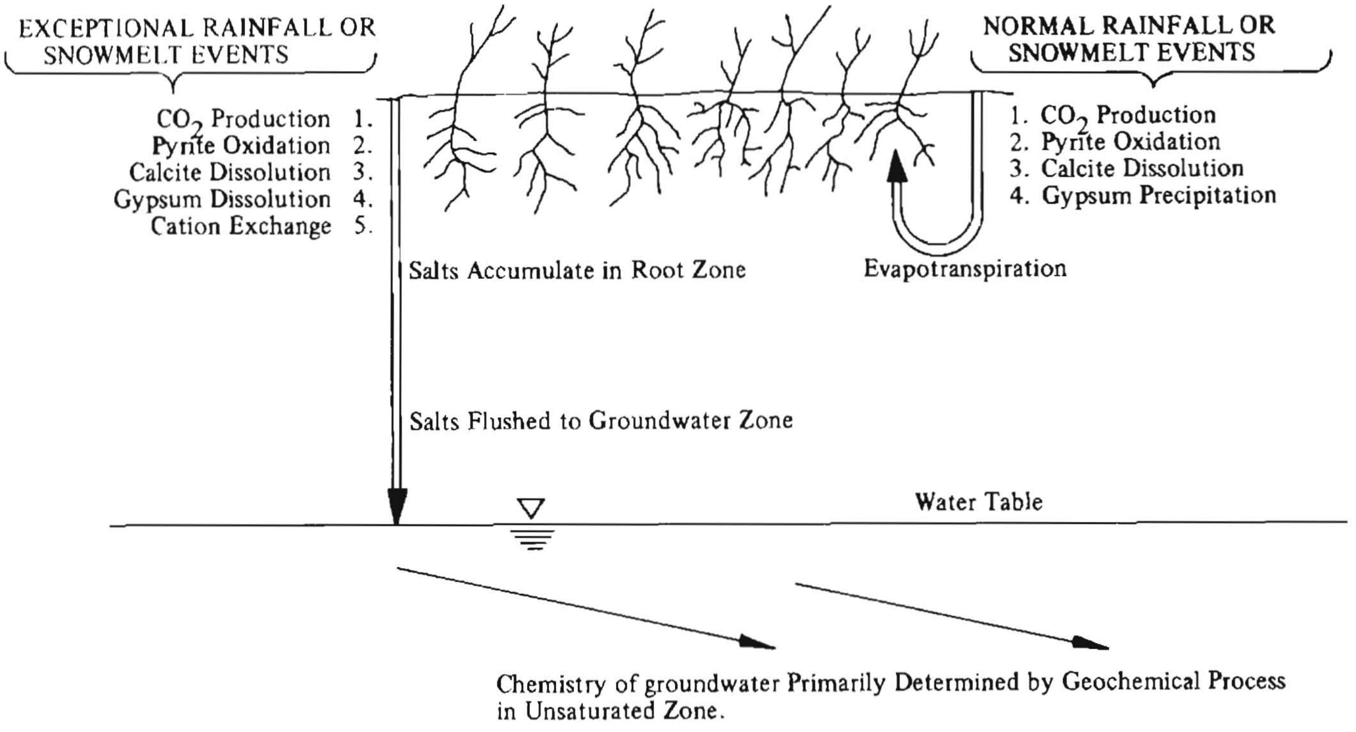


Figure 1. Schematic diagram of chemical processes and salt movement in much of the plains region (from Moran et al., 1978).

and pyrite oxidation. Evaporation and transpiration cause concentration of salts in the soil water and, as a consequence, calcite and gypsum precipitate 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 individual components of the geochemical framework summarized in figure 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 of 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. However, in western North Dakota, and, therefore, presumably in the entire Fort Union region, this H^+ source plays a key role in the geochemical evolution of soil water and groundwater. As will be shown in a later section, iron sulfide minerals are finely but widely dispersed throughout the landscape.

Numerous studies have shown that the partial pressure of CO_2 (P_{CO2}) in the organic-rich horizons of solum is typically much above the P_{CO2} in the earth's atmosphere, which is approximately $10^{-3.5}$ atmospheres. The P_{CO2} in soil horizons in the study area has not been measured. The occurrence of elevated CO_2 pressures in solum 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. Deionized water in contact with the earth's atmosphere ($P_{CO_2} = 10^{-3.5}$ atm) will have an equilibrium pH of approximately 5.7. If this water is brought into 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 solum 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 infiltrate into solum, 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 solum 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 solum.

As the infiltrating water passes through the organic-rich soil horizons into the mineral-rich horizons lower in the soil profile and below the solum, it comes into contact with minerals, with which it reacts. The most important types of reactions that occur are: oxidation of sulfide minerals, precipitation and dissolution of carbonate minerals, precipitation of gypsum, and cation exchange. These four chemical processes exert a dominant control on the chemistry of subsurface water that infiltrates through the solum. 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.

The soil horizons below the uppermost organic-rich layer and the parent geologic materials below the solum are composed of a wide variety of mineralogical constituents. Of these, only a very small number exert a significant influence on the development of a 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 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 constituents in the overburden of western North Dakota that undergo significant oxidation are iron sulfide minerals. 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:

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

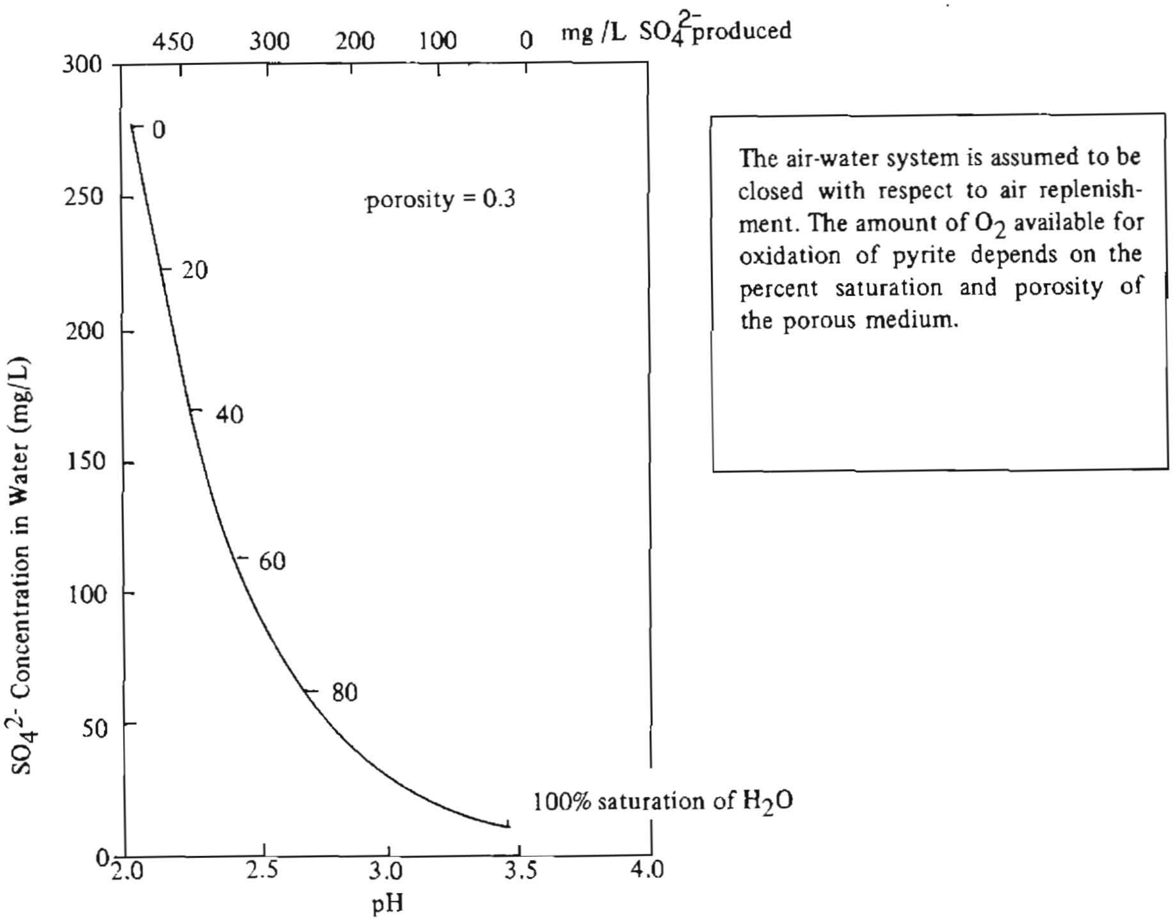
This relation indicates that reaction of oxygen, water, and pyrite produces iron hydroxide, sulfate ions, and hydrogen ions. This reaction is one of the strongest acid-producing reactions known to occur in natural geological systems. It is the cause of the acid mine-drainage problem that has been so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

If water with dissolved oxygen 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/litre (16 mg/L) of SO_4^{2-} and 3.3×10^{-4} moles/litre 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 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 effects of buffering reactions are considered in a later discussion.

Figure 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.

Another major geochemical process is 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 (Rauch and White, 1977). The dissolution reaction for calcite and dolomite can be expressed as follows:



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.

RESULTS OF REACTION $4FeS_2+14H_2O \rightleftharpoons 4Fe(OH)_3+16H^++8SO_4^{2-}$

Figure 2. pH and SO_4^{2-} concentrations in water as a result of pyrite (from Moran et al., 1978).

$$CaCO_3 + H^+ \rightleftharpoons HCO_3^- + Ca^{2+} \quad (1)$$

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

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^{2-} ions from the carbonate minerals to form HCO_3^-. As a result of carbonate mineral dissolution, the pH and HCO_3^- concentration in the water increase. The pH and HCO_3^- concentration will rise until the water is saturated, with respect to the carbonate minerals present. Saturation will occur when the following equilibrium relations are attained:

$$\frac{[Ca^{2+}][HCO_3^-]}{[H^+]} = K_{eq.cal} = 10^{2.15} \quad (3)$$

$$\frac{[Ca^{2+}][Mg^{2+}][HCO_3^-]^2}{[H^+]^2} = K_{eq.dol} = 10^{-6.14} \quad (4)$$

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 1 and 2 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 relations between activities and concentrations, the reader is referred to Garrels and Christ (1965). Saturation levels 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 bracketed 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 typical 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 1,500 mg/L. The unusually high HCO_3^- concentration is one of the main distinguishing features of this water.

It is evident that a high HCO_3^- concentration 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^- water of 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 3 and 4. Results of these computations are shown graphically in figure 3. This graph indicates 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 1,500 mg/L can occur if the pH values are in the range of 7.8 to 6.3. 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

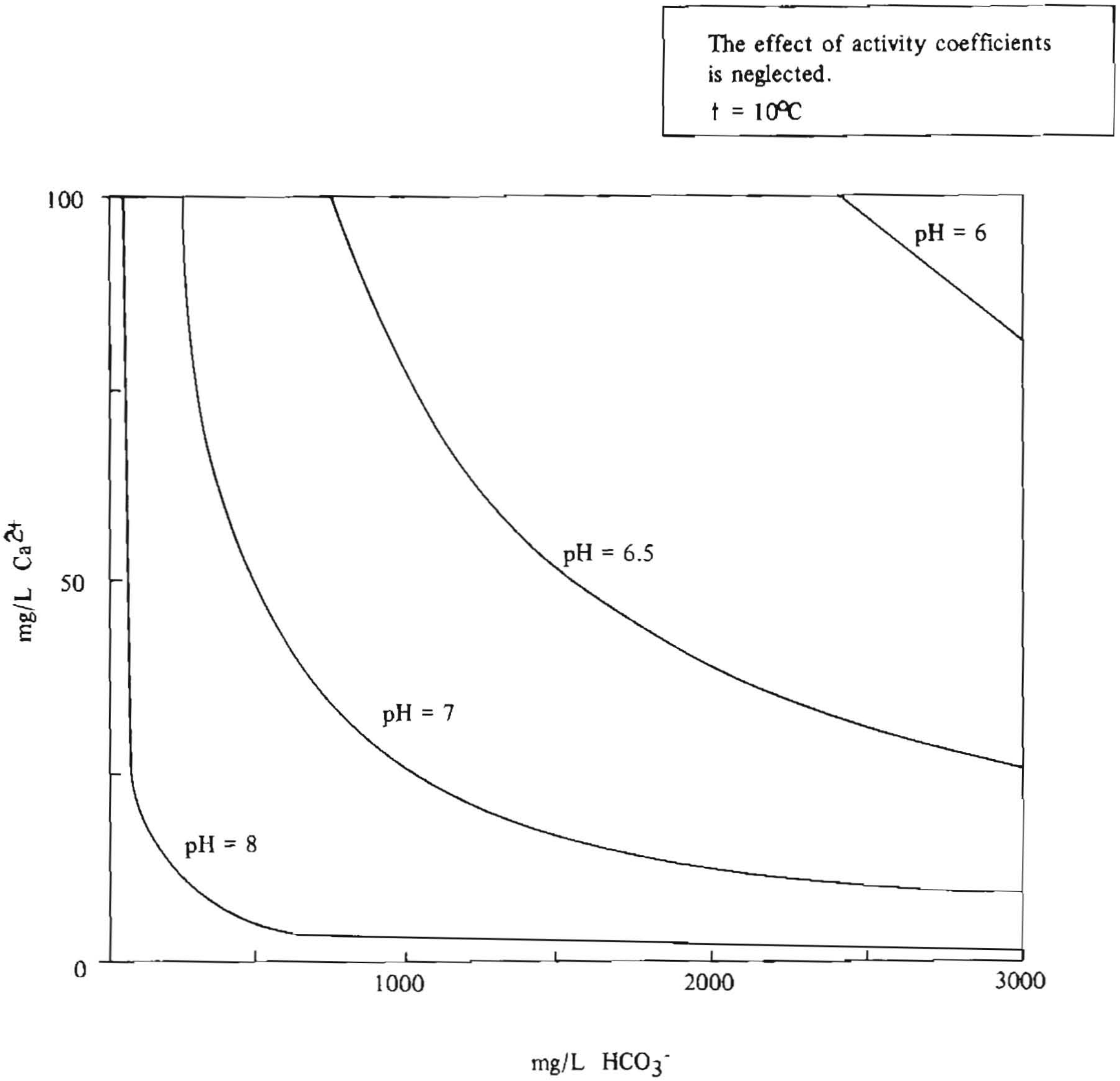


Figure 3. Relations between pH, HCO_3^-, and Ca^{2+} in water at equilibrium, with respect to calcite with specified Ca^{2+} concentrations (from Moran et al., 1978).

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 solum. If the dissolution occurs in partially saturated (i.e., pores contain both air and water) solum in which CO_2 in the soil air replenished 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:

$$CaCO_3 + H_2CO_3 \longrightarrow Ca^{2+} + 2HCO_3^- \qquad (5)$$

$$CaMg(CO_3)_2 + 2H_2CO_3 \longrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^- \qquad (6)$$

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:

$$CO_2\,(gas) + H_2O \rightleftharpoons H_2CO_3 \qquad (7)$$

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

$$K_{CO_2} = \frac{[H_2CO_3]}{P_{CO_2}} \qquad (8)$$

$$K_{H_2CO_3} = \frac{[H^+][HCO_3^-]}{[H_2CO_3]} \qquad (9)$$

$$K_{HCO_3^-} = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]} \qquad (10)$$

$$K_{H_2O} = [H^+][OH^-] \qquad (11)$$

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 the concentration of H_2CO_3 is constant. As dissolution of calcite or dolomite occurs, H^+ decreases and HCO_3^- increases, as can be surmised from equation 9. The solubility of calcite in water as a function of fixed P_{CO_2} and Ca^{2+} concentration is shown in figure 4. The initial pH and pH of the water after dissolution to equilibrium are also indicated on this

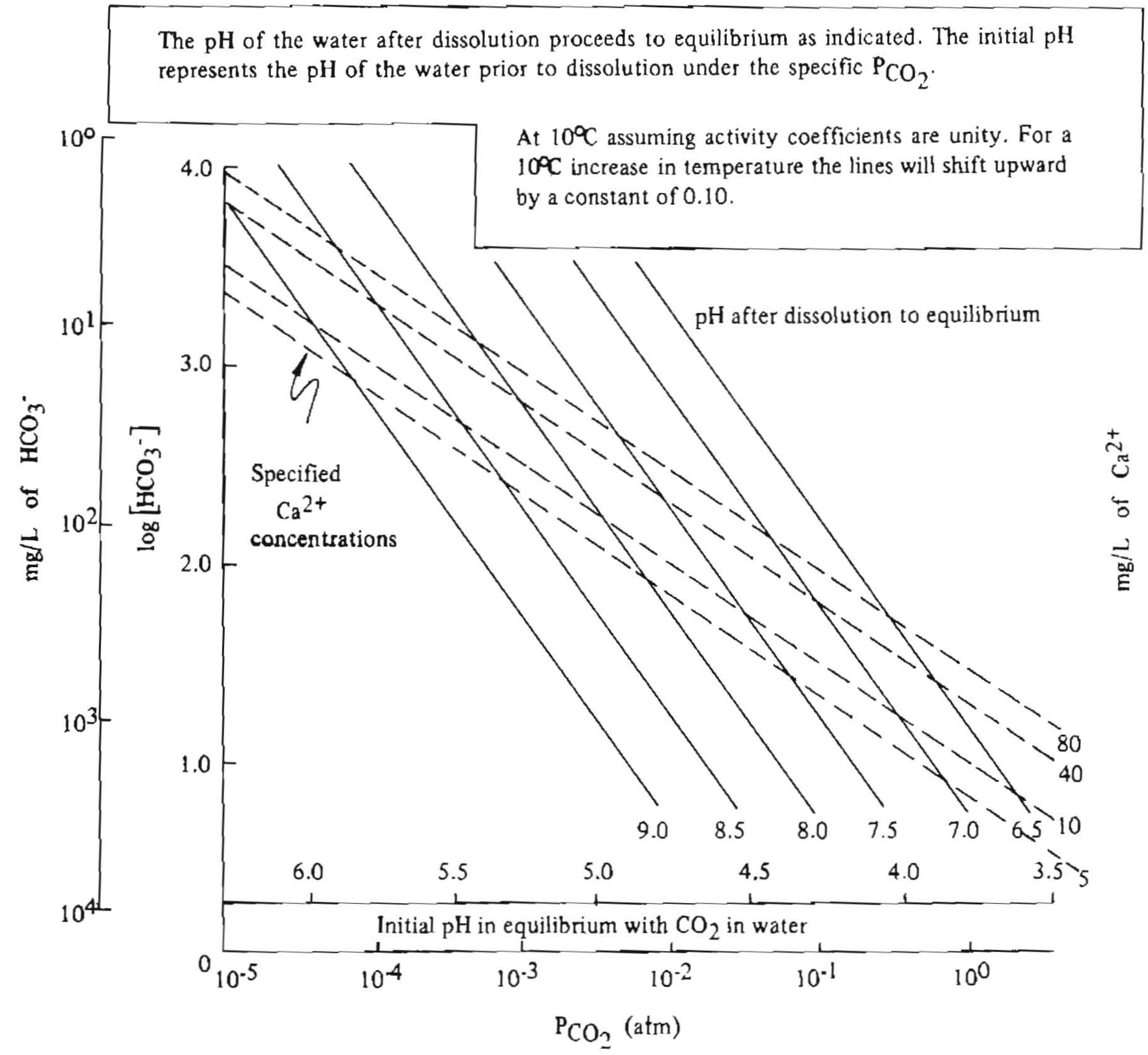


Figure 4. Relations between pH, P_{CO_2}, HCO_3^-, and Ca^{2+} for open-system dissolution of calcite at specified Ca^{2+} values.

diagram. It is assumed that prior to dissolution H^+ is the cation species in the water. Specification of the P_{CO2} 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^- groundwater of western North Dakota.

Figure 4 indicates that under open-system dissolution conditions P_{CO2} of 6×10^{-1} to 3×10^{-3} atm would be necessary to produce the HCO_3^- values in the range of 500 to 1,500 mg/L in water with Ca^{2+} concentrations in the range specified above. Soil zone CO2 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 indicates that if open-system dissolution is a common occurrence in solum of western North Dakota, the partial pressure of CO_2 in the solum would be anomalously high in at least some areas. This figure indicates that P_{CO2} 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 litre. For example, figure 4 indicates that water with a HCO_3^- concentration of 1,000 mg/L and Ca^{2+} concentration of 40 mg/L, values commonly observed in the study area, would require initial P_{CO2} of 10^2 in order to originate from open-system dissolution of calcite with Ca^{2+} content controlled by ion exchange. Exceptionally high P_{CO2} 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 8, the equilibrium P_{CO2} would be higher than would be the case if CO_2 generation were the only control on H^+.

Partial pressures of CO_2 have never been measured in solum 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_{CO2} 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 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} can be computed. Figure 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 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 indicates that H^+ production 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. There is no way of knowing, based on existing data, the extent of open-system versus closed-system dissolution that occurs in the solum of western North Dakota. However, the above conceptual analysis is strong evidence in support of the hypothesis that the anomalously high HCO_3^- values in groundwater of the region occur 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.

$$CaSO_4 + 2H_2O \longrightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad (12)$$

If gypsum is dissolved in deionized water at 8°C, the equilibrium concentrations of Ca^{2+} and SO_4^{2-} will be 520 and 1,240 mg/L, respectively (Cherry, 1968). It is evident, therefore, that if water traveling through subsurface systems encounters gypsum, it can acquire relatively high

Closed System Dissolution at 20°C with Ca-Na exchange as Ca sink. A decrease of 10°C will increase all final pH values by 0.14. Closed-system dissolution is assumed.

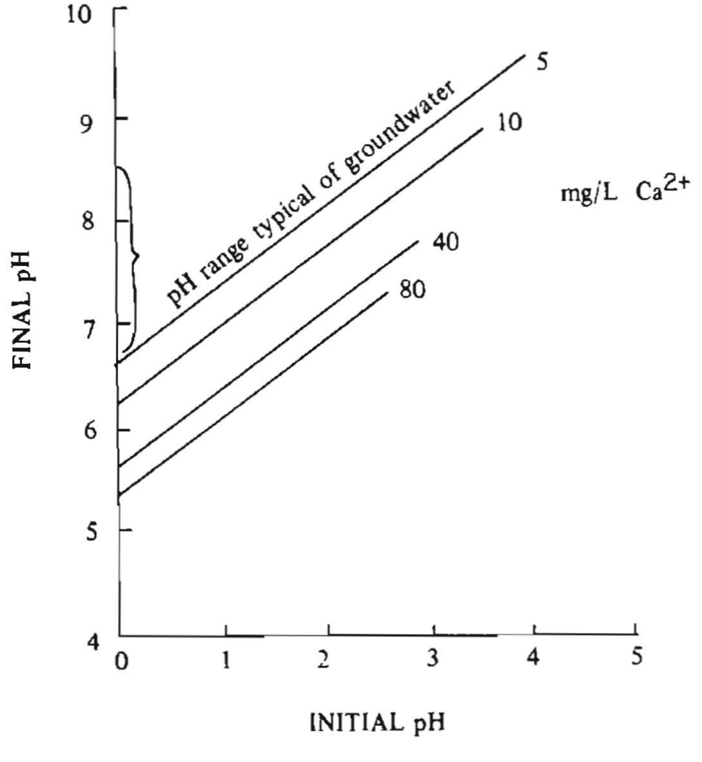


Figure 5. Relations between initial pH, final pH, and HCO_3^- for calcite dissolution to equilibrium with Ca^{2+} at specified Ca^{2+} contents.

concentrations of Ca^{2+} and SO_4^{2-}. 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 graph in figure 6 which was computed using the equilibrium relation.

$$\left[Ca^{2+}\right]\left[SO_4^{2-}\right] = K_{eq.\,gyp} \tag{13}$$

where $K_{eq.gyp} = 2.17 \times 10^{-5}$ at 10°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 of figure 6 that has Ca^{2+} values specified at levels below the free 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 12 proceeds to the left, precipitation occurs. If the products $\left[Ca^{2+}\right]$ and $\left[SO_4^{2-}\right]$ exceed 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.

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 overburden zones 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 surface. 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

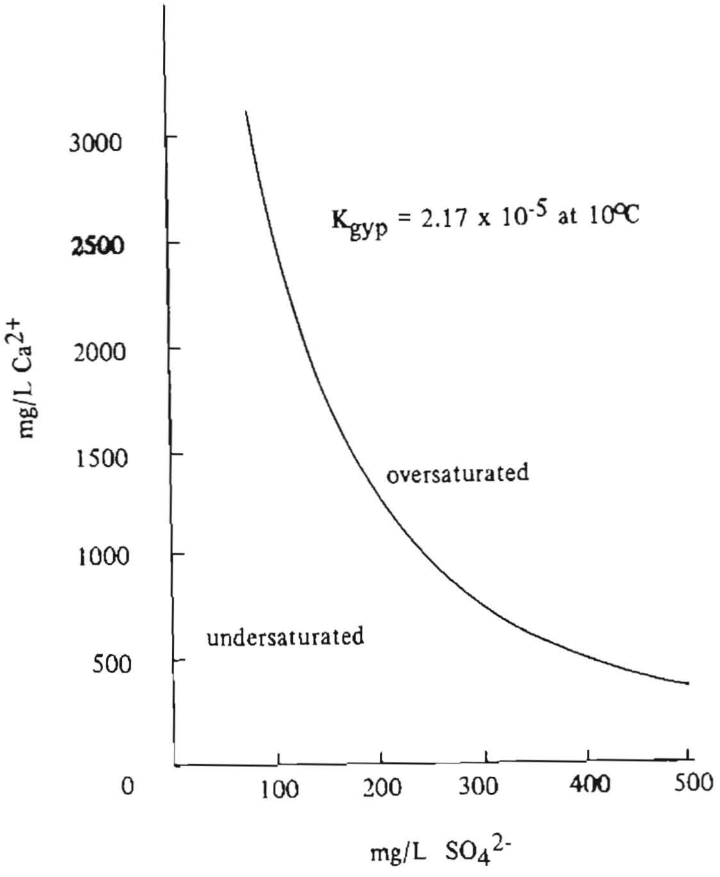


Figure 6. Relations between Ca^{2+} and SO_4^{2-} under conditions of gypsum saturation at 10°C.

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:

$$Ca^{2+} + 2NaX \rightleftharpoons 2Na^{+} + CaX_2 \qquad (14)$$

$$Ca^{2+} + MgX \rightleftharpoons Mg^{2+} + CaX \qquad (15)$$

$$Mg^{2+} + 2NaX \rightleftharpoons 2Na^{+} + MgX_2 \qquad (16)$$

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

$$K'_{Na-Ca} = \frac{[Na^{+}]^{2}\, N_{Ca}}{[Ca^{2+}]\, N^{2}_{Na}} \qquad (17)$$

$$K'_{Mg-Ca} = \frac{[Mg^{2+}]\, N_{Ca}}{[Ca^{2+}]\, N_{Mg}} \qquad (18)$$

$$K_{Na-Mg} = \frac{[Na^{+}]^{2} N_{Mg}}{[Mg^{2+}]\, N^{2}_{Na}} \qquad (19)$$

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 14, 15, and 16 proceed to the right in order to achieve equilibrium in situations where the concentrations of cations in solution 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^{2+}-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 equilibrium 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 suggested by previous studies of Jacob (1973), Royse (1967), and Sandoval and others (1973) and established by this study. Montmorillonitic clays have relatively large cation exchange capacities. Values in the range of 20 to 80 milliequivalents per 100 g of dry weight solum 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 of Ca^{2+}, 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, as discussed later. 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.

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 solum and comes in 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 solum, the HCO_3^- concentration will rise to several hundred milligrams per litre and the Ca^{2+} concentration will rise as high as 200 to 300 milligrams per litre. 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 litre. 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 solum 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 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 litre 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 if the solum 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 litre), 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, it is unlikely 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. This supposition is borne out by mineralogical data from the Gascoyne area in southwestern North Dakota that show abundant gypsum in the oxidized zone, above about 6 m, but none deeper in the section (Croft; personal commun., 1977). 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 production of 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 solum 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 7.

If water acquires SO_4^{2-} by pyrite oxidation and acquires Ca^{2+} by calcite dissolution prior to evaporation or evapotranspiration, a small

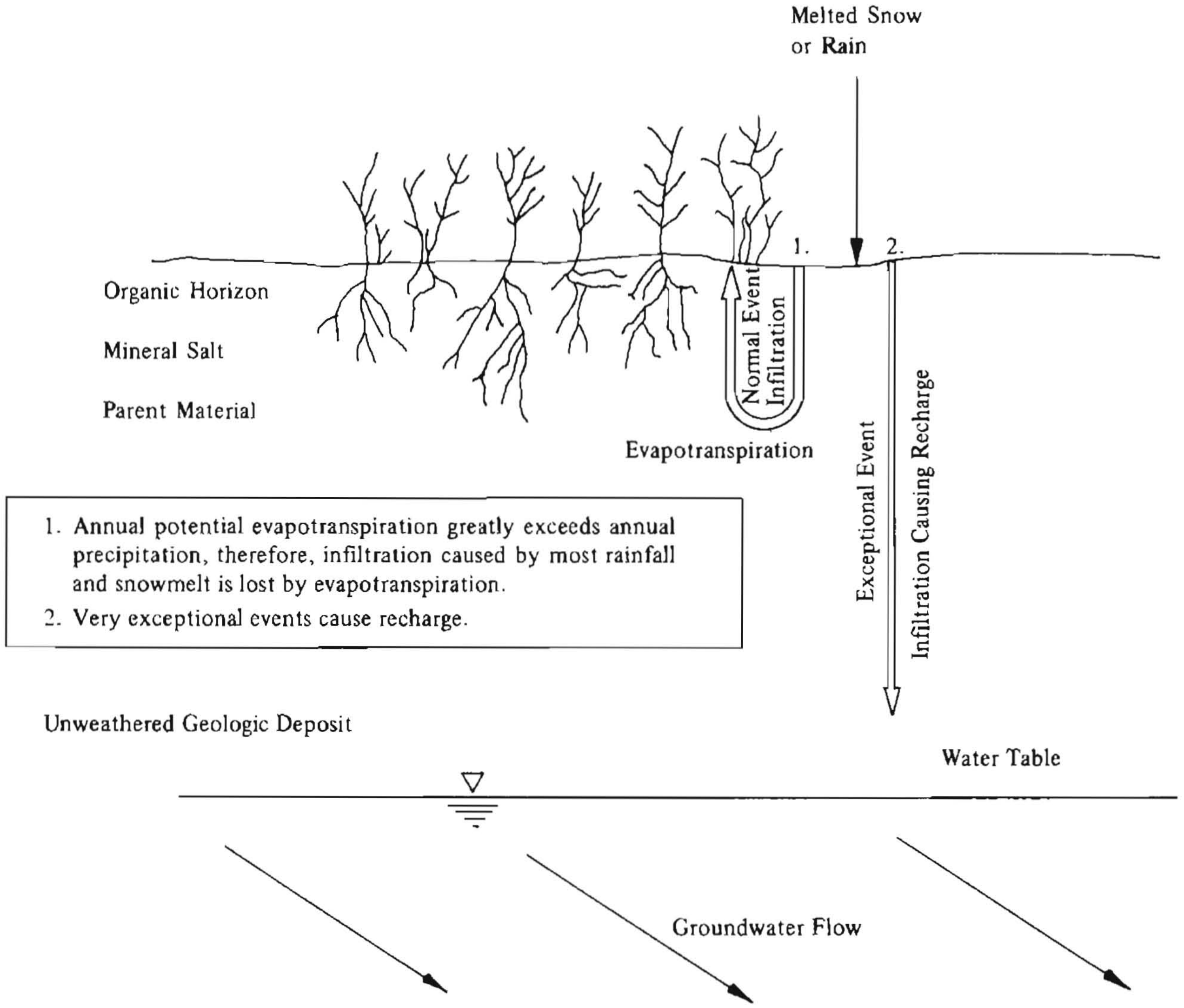


Figure 7. Relations between major geochemical processes and water chemistry resulting from infiltration that does not pass below the root zone (from Moran et al., 1978).

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 solum and by pyrite oxidation in the solum or subsolum; (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 have the potential to dissolve calcite and dolomite. This tendency 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 deposition in western North Dakota (water with dominant concentrations of Na^+, HCO_3^-, and SO_4^{2-}) can be generated by various seqences 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 solum 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 litre 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 acquire only 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 litre 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 runoff and erosion. The surface environment is the most highly oxidizing when water is present. After rainfall or snowmelt runoff, 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 as was discussed above. 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 8 and 9 summarize the geochemical processes and their role in the genesis of subsurface water chemistry. Figure 8 represents conditions associated with infiltration events that do not cause flow below the root zone. In figure 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 pyrite oxidation is an active process. If any of the other geochemical processes illustrated in the hydrogeochemical evolution sequences (figs. 8 and 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 in-

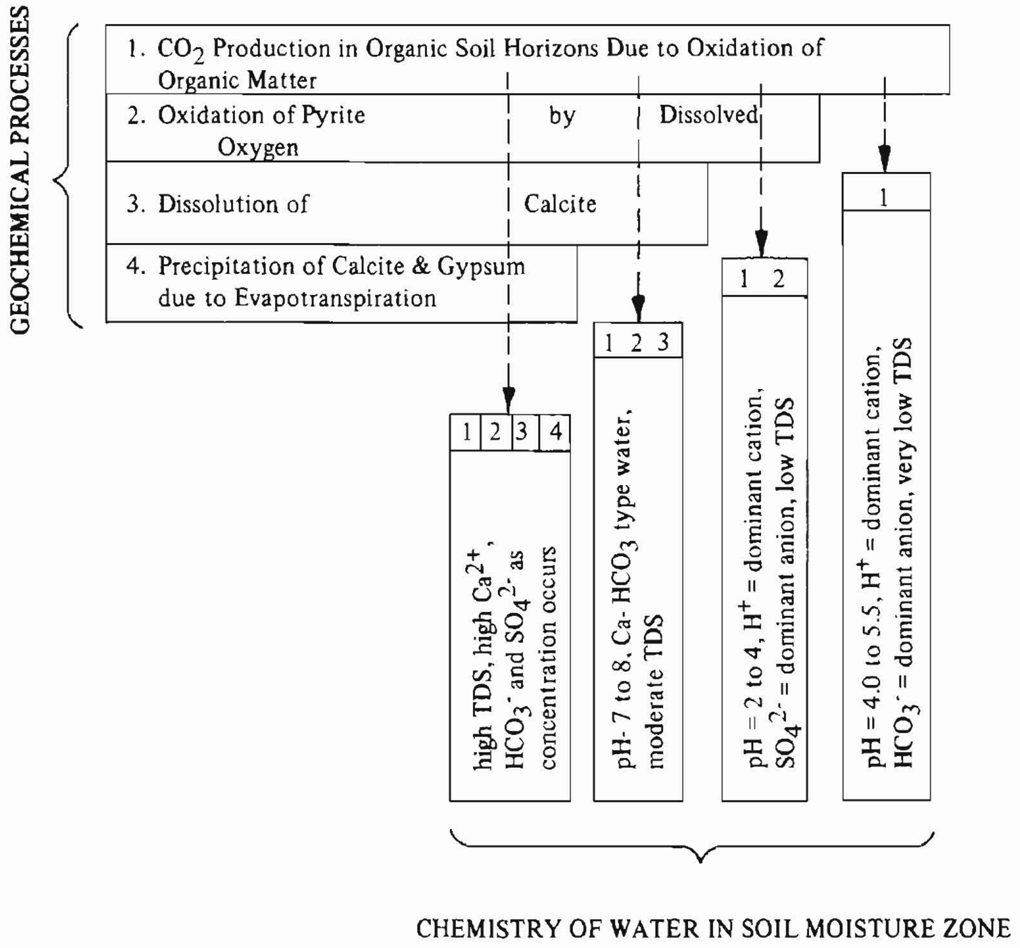


Figure 8. Relations between major geochemical processes and water chemistry resulting from infiltration that does not pass below the root zone (from Moran et al., 1978).

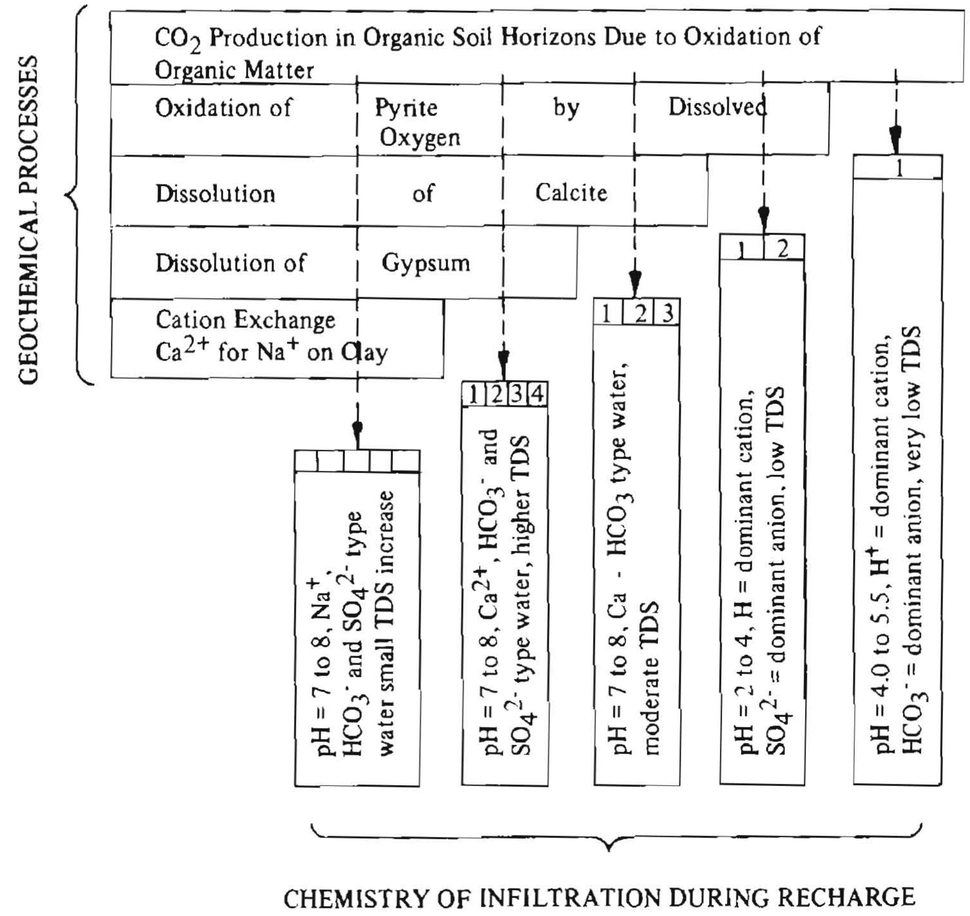


Figure 9. Relations between major geochemical processes and water chemistry resulting from infiltration that penetrates below the root zone (from Moran et al., 1978).

dicate the interpretive framework summarized in figures 8 and 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 flow systems acquires its characteristic features (i.e., salinity, alkalinity, and pH) in shallow zones above the water table. The chemistry of the water, regardless of its age or the distance that it 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.

Need for Refinement

In the previous section we have discussed the state of our understanding of the geochemical processes governing groundwater evolution in western North Dakota prior to the beginning of the study covered by this report. There is little controversy about the assertions of the model concerning the role of carbonate minerals. The reduced sulfur-sulfate interaction is another matter, however. We stated above that there is little evidence of gypsum mineralization at the end of the period of glaciation, and suggest that the gypsum now found arose from the oxidation of native pyrite. The evidence for extensive pyrite concentration in the sediments is not overwhelming. The most critical need in refining the conceptual model at the onset of the study period was clarification of the sulfur cycle. Specifically, these questions had to be answered:

*What is the total sulfur concentration in any given overburden volume?

*How is that sulfur distributed between oxidized and reduced forms of sulfur?

*What is the ease of interconversion between the two forms?

In the work reported below we answer the first two questions, and provide a partial answer to the third.

Total Landscape Perspective

It is important to consider the impact of surface coal mining on groundwater from the perspective of the total impact of surface mining on a landscape. Each landscape consists of complexly interrelated components. These components include the morphology of the surface, the physical and chemical characteristics of the surface and subsurface materials, and the hydrologic regime that is operating upon and within the sequence of materials. Prior to mining, in the time scale of normal observations, these landscape components are largely in a steady state with each other and with the forces acting upon them.

The disturbance of a landscape by surface coal mining typically results in severe disequilibrium within that landscape. Disequilibrium in postmining settings may take various forms. The most obvious indications of disequilibrium in postmining settings, when contrasted with premining conditions, are:

1. Significant degradation of plant growth potential.
2. Significant degradation of groundwater quality.
3. Instability of the surface.

Design of disturbed landscapes based upon reestablishment of the premining equilibrium should be the objective of reclamation activities. This necessitates an integrated evaluation and redesign of all components of the landscape. As discussed in the previous section, the chemical evolution of subsurface water in most settings in the plains region of North America is largely determined by geochemical processes active in the upper two to five metres of the landscape. These processes determine not only the quality of water which reaches the water table, but also the quality of pore water in the rooting zone. In addition, various forms of instability in postmining landscapes, particularly piping, are largely a function of the mineralogy of the upper few metres of spoils (Groenewold and Rehm, 1980). Thus, long-term biological productivity, groundwater quality, and stability in postmining settings are all largely dependent upon the same near-surface geochemical processes.

Unfortunately, "reclamation," as commonly defined, typically refers only to the plant growth potential of the disturbed landscape. Even more unfortunate, the vast majority of "reclamation" research has focused only on the soil component of the landscape. The other components of the landscape and associated concerns have been largely ignored by this body of research. The result has been a plethora of recommendations focused only on the soil zone, many of which are in direct conflict with other concerns such as restoration of recharge capacity, groundwater and surface water quality, and stability in the postmining setting.

It is hoped that the results of this study will promote a better understanding of the need for site-specific geologic, hydrogeologic, and geochemical data as input to reclamation design.

Study Sites

Overview

As previously discussed, extensive geologic, hydrogeologic, and hydrogeochemical studies have been ongoing at several active and proposed surface coal-mining sites in western North Dakota since 1974. North Dakota study sites include the Falkirk, Indian Head, Beulah-Hazen, Dunn Center, and Center study areas (fig. 10). Various aspects of these studies have been summarized by Moran et al., 1975, 1976, 1978, and 1979; Winczewski, 1977; Groenewold, 1979; Groenewold et al., 1979, 1980, and 1981; Groenewold and Bailey, 1979; Groenewold and Rehm, 1980; and Rehm et al., 1982. These studies, in conjunction with similar studies in Montana and Wyoming (Williams et al., 1978) and Alberta (Alberta Environment, 1980), have resulted in the development of the conceptual hydrogeochemical model as previously discussed. These studies, in turn, form the foundation for the present study.

Location

Four sites were used for this study. These were the Center, Indian Head, Falkirk, and Glenharold Mines in west-central North Dakota (fig. 11). Detailed premining geologic, hydrogeologic, and groundwater chemical data were available for the Center, Indian Head, and Falkirk Mines. In addition, considerable data regarding postmining hydrogeologic and groundwater chemical characteristics as well as mining and reclamation

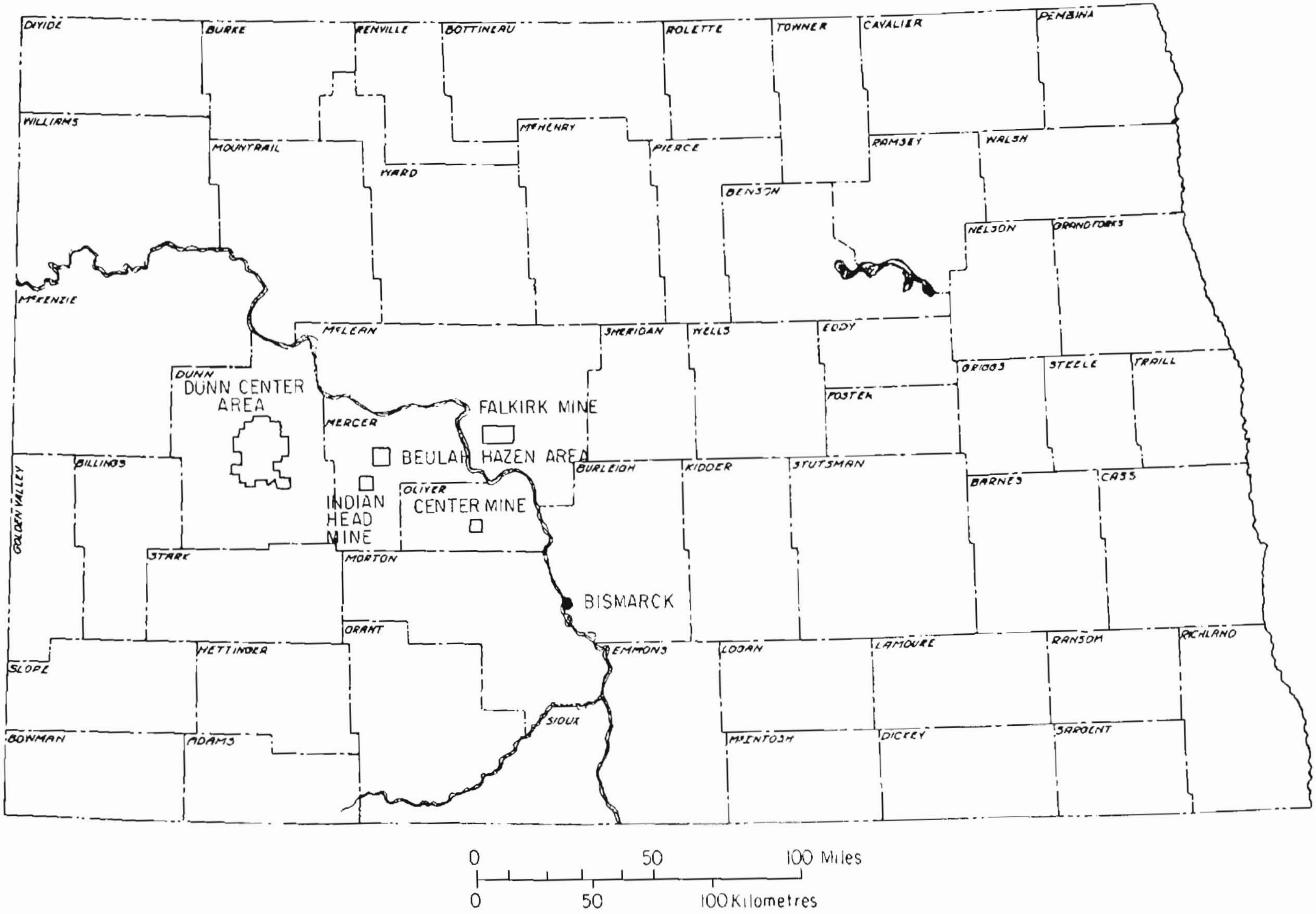


Figure 10. Location of the hydrogeologic study sites in western North Dakota.

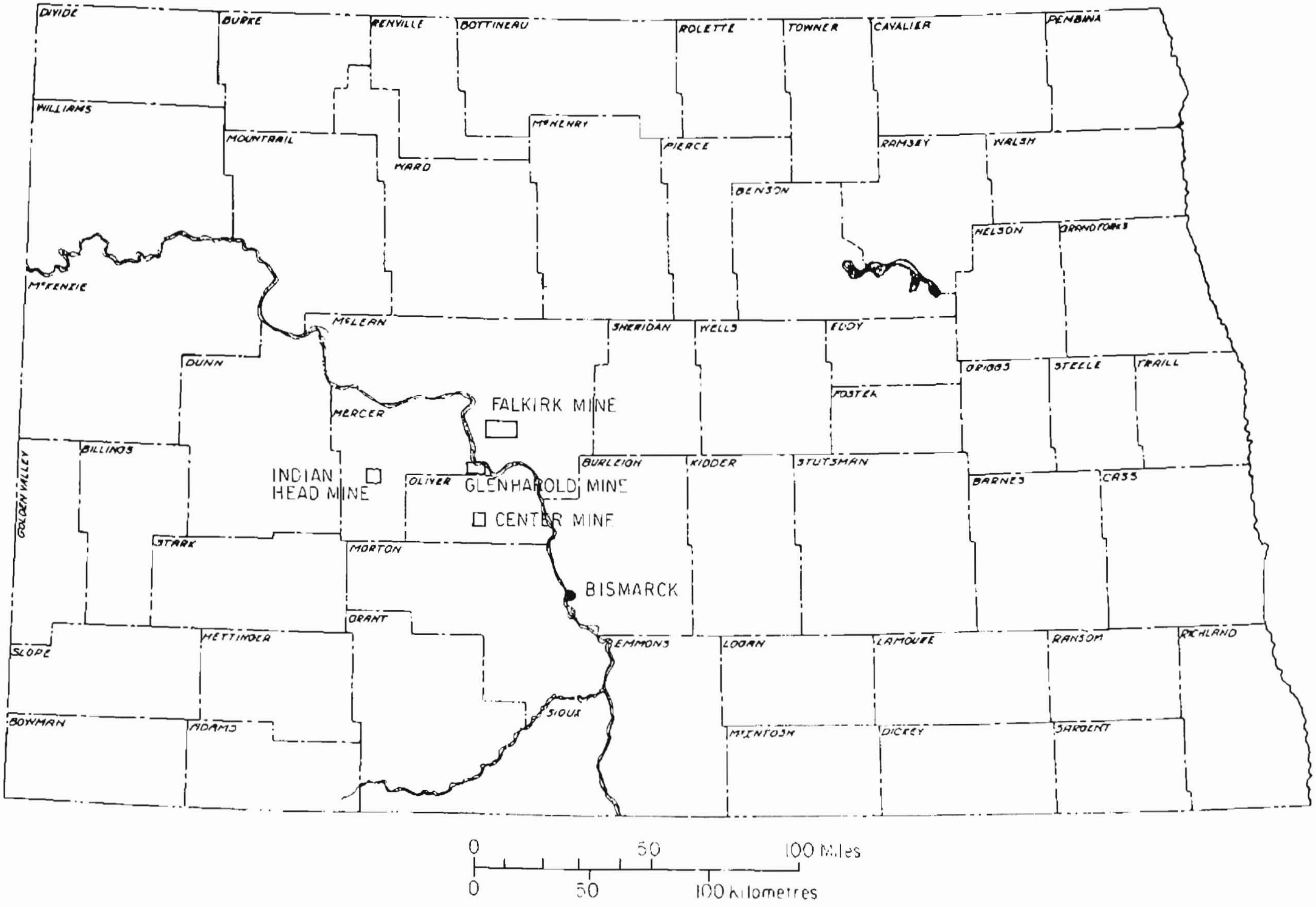


Figure 11. Location of the four western North Dakota sites used in this study.

techniques were available for spoils areas at the Center and Indian Head Mines. These data had been generated as part of a USBM-funded project, initiated in 1977, designed to evaluate the causes of instability in surface mining settings at these two mines (see Groenewold and Rehm, 1980). The Center and Indian Head Mines were thus chosen as the key study sites for the project.

Mining at both sites utilizes a walking dragline to remove overburden and dozers and pan scrapers to recontour spoils. Previous research at the Center and Indian Head Mines had indicated apparent significant and consistent differences in both the character of the overburden and groundwater quality in both undisturbed and spoils settings at these mines (Groenewold et al., 1979, 1981). Considerable variability in overburden characteristics is present at both mines. However, the overburden in the area of the Indian Head Mine was predominantly silty and clayey sediment; the overburden in the area of the Center Mine was predominantly silty sand to sandy silt. Groundwater in undisturbed settings and spoils at Indian Head was typically much more highly mineralized than in similar settings at Center Mine. Since all other significant variables such as mining and reclamation methods and climate were the same at these sites, the Center and Indian Head Mines offered an essentially unique opportunity to compare overburden textural and mineralogical characteristics with groundwater quality and chemical evolution in undisturbed and spoils settings.

Overburden samples for mineralogical and textural characterization and laboratory experimentation were obtained from various settings at the Center and Indian Head Mines. In addition, the Glenharold and Falkirk Mines were utilized as sites for overburden sampling. Expansion of the overburden sampling activities to these additional mines allowed for a more representative evaluation of stratigraphic and areal textural and mineralogical variation in the coal-bearing sediments than if sampling were restricted to the Center and Indian Head Mines.

Geology

The North Dakota study sites are representative of the geologic conditions found in most surface coal-mining areas in the plains areas of western North America. Glacial sediments (tills) veneer portions of the Center and Falkirk sites but are absent at the Indian Head and Glenharold sites. The potentially mineable coal at all the sites occurs in the Tertiary Sentinel Butte Formation of the Fort Union Group. Although the thicknesses of the coal beds are less than in some other areas, the coal and associated sediments which underlie the North Dakota sites are typical of the Cretaceous and Tertiary coal deposits found throughout the plains region of western North America.

About 60 to 80 percent of the sediment making up the coal-bearing Sentinel Butte Formation in North Dakota consists of interbedded silt and clay that occurs in beds ranging from a few millimetres to tens of metres in thickness. From 15 to 35 percent of the sediment making up these formations consists of silty, fine-grained to medium-grained sand in beds that range in thickness from 0.3 to 35 m. Lignite is a minor constituent occurring in beds that range in thickness from 1 cm to about 12 m locally. The lignite generally comprises less than 5 percent of the total thickness of these units in North Dakota.

The sediments of which the rocks are composed were derived from tectonically active areas to the west. The sediments were transported via low-gradient streams which terminated at the shorelines of inland seas. The coal-bearing sediments were deposited in various subenvironments within an alluvial flood-plain environment. Sand and silt were deposited in predominantly oxidizing environments on point bars and natural levees. Clayey sediments were deposited farther from the channels in largely reducing flood-basin settings (Jacob, 1972, 1973; Hemish, 1975; Cherven, 1978).

These differences in the original depositional settings of the sediments are reflected in the mineralogy of the sediments. Carbonate minerals are most abundant in the sand and silts. Clay minerals and pyrite are more abundant in the fine-textured sediments deposited in reducing environments. Thus, the original depositional setting of the near-surface sediments in an area has particular significance with respect to hydrogeochemical evolution in that setting, both prior to and after disturbance by mining. Detailed discussion of the geology of the coal-bearing sediments of western North Dakota and, in particular, Center, Indian Head, and Falkirk study sites can be found in Moran et al., 1978; Groenewold et al., 1979; and Groenewold et al., 1981.

Geohydrology

As is common throughout the plains region of North America, the hydrologic regime at any site is primarily a function of the climate and stratigraphy, as well as the configuration of the landscape. Most precipitation at the study sites is scattered both temporally and spatially. Most precipitation is lost through evapotranspiration.

All the study sites are within groundwater recharge areas. Nearly all recharge to the groundwater system occurs during spring runoff and occasionally during periods of relatively heavy precipitation in the fall of the year (Rehm et al., 1982). The upper portion of the landscape is constantly subjected to alternating wet and dry cycles. Recharge occurs, to some degree, over most of the landscape but is concentrated in restricted positions. These include areas of standing surface water (closed depressions) and ephemeral stream bottoms. In most other landscape positions, the majority of the precipitation is lost through either runoff or evapotranspiration.

Subsurface water movement is largely controlled by the lithologic characteristics of the sediments. Movement of water through sand and lignite aquifers is generally lateral, whereas movement through fine-textured Tertiary sediment is generally vertical and downward. The hydraulic conductivity of sediments at the North Dakota sites varies considerably, ranging from 10^{-5} to 10^{-6} m/s in sandy Tertiary sediments, from 10^{-5} to 10^{-7} m/s in the lignite, and from 10^{-8} to 10^{-10} m/s in the fine-textured Tertiary and glacial sediments (Groenewold et al., 1979; Rehm et al., 1980). The hydrogeologic characteristics of the North Dakota study sites have been discussed in detail by Moran et al., 1978; Groenewold et al., 1979, and Rehm et al., 1980.

Climate, Topography, and Physiography

The climate in the vicinity of all the study sites is classified as semiarid-continental. The summers are generally cool with only a few hot, humid days. The winters are typically quite cold and long. The mean annual temperature for Bismarck, North Dakota, which is located approximately 50 kilometres southeast of the Center Mine (fig. 11) is 5.7°C, varying from -12.3°C in January to 22.1°C in July. Precipitation at Beulah, North Dakota, approximately six kilometres east of the Indian Head Mine averages 43.7 centimetres annually.

All four of the study sites are located in the Missouri Plateau of the Great Plains Physiographic Province. The Indian Head site is situated on an upland area between Spring Creek and the Knife River. Although the area has been glaciated, essentially all glacial sediment has been eroded. The topography is generally rolling to very steep with occasional small areas of "badlands" topography along surface drainages. The site is predominantly pastureland.

The Center site is situated on an upland area between Square Butte Creek and Hagel Creek. Glacial sediment underlies the surface in most of the western half of the site. Postglacial erosion has removed most of the glacial sediment in the remainder of the study site. The topography is generally rolling with occasional small areas of steep slopes. The site is predominantly cropland. Pastureland is generally limited to steep slopes along drainages.

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 a 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. The surface in the Falkirk area is generally undulating to rolling. The northern part of the Falkirk area is characterized by numerous prairie-pothole sloughs. The remainder of the area is characterized by longer slopes and the better integrated drainage of the underlying bedrock topography. Most of the area is cropland. Pastureland is generally limited to steep slopes along the valley sides.

The Glenharold site is situated between a broad, gently rolling upland plateau on the southwest and low-lying, flat Missouri River flood plain on the northeast. The mine occupies an area of dissected plateau ("breaks") adjacent to the Missouri River flood plain. This dissected plateau rises rather abruptly 100 to 150 metres above the Missouri River flood plain. A maximum of about 100 metres of local relief separates the gently rolling upland surfaces of the dissected plateau from the relatively steep-walled, narrow drainages that dissect the area and form a dendritic pattern. The predominant direction of drainage in the mine area is north-northeast to the Missouri River. The site is predominantly pastureland.

METHODOLOGY

Overburden Sampling

Philosophy of Sampling

Representative samples of overburden were collected from various locations at the Center, Indian Head, Falkirk, and Glenharold Mines. Sampling locations were commonly immediately adjacent to previous test-hole or piezometer locations. A detailed descriptive log and geophysical logs (gamma, density, spontaneous potential (SP), and resistivity) were available for most potential sites. Information gained from the logs was used as a guide for sampling site selection.

The major objective of the overburden sampling activities was to collect samples that would be representative of all the major variables found in overburden in mining areas in western North Dakota. Variables that were considered significant included texture, position relative to water table (oxidized or unoxidized), glacial or Tertiary sediment, and stratigraphic position within the Sentinel Butte Formation. An attempt was also made to sample at locations in various landscape positions (upland, hillslope, surface depression, etc.).

Techniques

Continuous cores of overburden were obtained with a truck-mounted hollow-stem auger utilizing 7.6 x 76.2 cm Shelby tubes. Immediately after withdrawal of the Shelby tube, the ends were sealed with heavy tape to avoid contact with air. The Shelby tubes were then sent to the laboratory for sample extrusion. If the sample could not be extruded, a portion of the tube was sawed off to obtain a sample for laboratory characterization and experimentation. Unused portions of the samples were stored in the tubes with the ends resealed.

Locations

A total of nine locations were selected for overburden sampling. One hundred twenty-three Shelby tube samples were obtained from those locations. Logs of each sampling test hole as well as site information and other descriptive data are included in appendix A.

Three sampling locations were selected at the Center Mine (Center 361, 366, and 380). Samples from the Center sites represent a textural range of Tertiary sediments and include both oxidized and unoxidized sediments. The Center samples were stratigraphically from the middle to lower part of the Sentinel Butte Formation.

Overburden samples from the Indian Head Mine were obtained from one location (Indian Head X-2). Samples from this location were predominantly fine-textured Tertiary sediment, both oxidized and unoxidized. Stratigraphically, the Indian Head samples were from the upper portion of the Sentinel Butte Formation.

Four overburden sampling sites were selected at the Falkirk Mine (Falkirk 514, 526, 561, and 576). The Falkirk samples represent a complete spectrum of Tertiary textural types, both oxidized and unoxidized. In addition, several tills were sampled at Falkirk site 576. The Tertiary sediments sampled at Falkirk were from the lower part of the Sentinel Butte Formation.

One sampling location was selected at the Glenharold Mine (Consol 31). Overburden samples from the Glenharold site represent a complete range of Tertiary textural types, both oxidized and unoxidized. Samples from this location were obtained from the lower middle part of the Sentinel Butte Formation.

Textural Analysis

Two portions of the Shelby core specimens were selected for textural analyses in order to provide more information on their lithology. Determinations were made at either the University of North Dakota (UND) or North Dakota State University's (NDSU) Soils Department over several periods of time to make optimum use of available personnel. Samples used for textural analyses performed at UND were obtained from the middle of the Shelby tubes. Samples used for textural analyses at NDSU were obtained from the bottom of each Shelby tube. One group of duplicate specimens was examined at both sites and a systematic difference in results was noted. The following are the methods used by each laboratory.

North Dakota State University (NDSU)

The hydrometer method of Bouyoucos as described by Day (1965) was the basis for the routine analysis of approximately 120 Shelby tube specimens. Forty grams of each specimen were ground with mortar and pestle sufficiently to break up the coarser agglomerates and placed in a glass jar. A 50 ml volume of dispersing solution (4 percent sodium hexametaphosphate $(NaPO_3)_6$, plus 1 percent Na_2CO_3) was added along with enough distilled water to nearly fill the jar. A group of jars was placed on a shaker overnight and was typically agitated for 12 hours. In the morning, the suspension was placed in a dispensing cup and treated with a mechanical analysis stirrer (milkshake mixer) for five minutes. The suspension was quantitatively transferred to a one litre graduated cylinder in a constant temperature room (25°C) where all hydrometer measurements were made. After stirring the suspension, the first hydrometer reading was taken at 40 seconds, the point at which the sand fraction had settled out. The second reading was taken two hours later after settling of the silt.

In calculating the silt and clay fractions, corrections are first made for the actual density of the solution with the added dispersing agent and for the temperature of the solution. The basic assumption is that sand and silt have settled after two hours and only clay remains in suspension. Silt is determined as the fraction remaining in suspension between the 40-second and 2-hour hydrometer reading. Sand is assumed to have settled out after

40 seconds and is determined by difference once the silt and clay are known.

University of North Dakota (UND)

The sample was air-dried and placed on a thin cardboard box lid on a wooden surface. The blunt end of a rock chisel was dropped on the sample with just enough force to disaggregate the sample. This was done until the pieces were approximately 15 mm or smaller. The day before analyses were run, a batch of 4 percent Calgon solution was mixed and placed in a carboy. At the same time, two distilled water carboys were filled and all three were left overnight to attain room temperature. Approximately 45 grams of a sample were weighed and put in a beaker (pint jar). The sample was soaked overnight in 125 ml of 4 percent Calgon solution. A test cylinder of 125 ml 4 percent Calgon solution was prepared to determine the hydrometer weight of the Calgon. After soaking, the sample was put in the mechanical analysis stirrer with some distilled water and agitated for one to two minutes. It was then decanted into a settling cylinder. If any clay balls coated with sand grains were present, they were gently flattened with a glass stirring rod and agitated in the stirrer with additional distilled water until completely dispersed before being added to the settling cylinder. The cylinder was topped off with distilled water and agitated for about 45 seconds with a rubber stopper full of holes attached to an iron rod. Any sand or gravel clinging to the stopper was washed off with distilled water into the soaking beaker and added to the sample during wet-sieving. The sample was left to settle for approximately two and one-half hours depending on the water (room) temperature (two hours thirty-three minutes for 22°C). The hydrometer reading was recorded and the test Calgon reading subtracted from it to obtain the clay weight. The sample was then wet-sieved and the sand and gravel was returned to the soaking beaker. The sample was dried overnight in an oven at 100°C. The sample was then put on the Ro-Tap mechanical shaker for ten minutes with No. 10 (2 mm), No. 18 (1 mm), and No. 230 (63 μm) sieves. The sand envelopes were weighed during sieving then filled with the sand and gravel fraction and weighed again subtracting the envelope weight to obtain the sand and gravel weight. The gravel was subtracted from the original sample weight and the corrected weight was used to calculate the sand, silt, and clay percentages. All weight not accounted for by the gravel, sand, and clay was considered silt.

Mineralogical Analyses

Previous Work

Previous studies of the mineralogy of the Tertiary coal-bearing sediments in western North Dakota concentrated on the clay-size fraction (Brekke, 1977; Emanuel et al., 1976; Kulland, 1973; and Clark, 1966) and on the heavy minerals of the fine to very fine sand fraction (Chisholm, 1965; Crawford, 1967; Jacob, 1975; and Steiner, 1979). In addition, Royce (1970) presented limited data on the carbonate-mineral content of the coal-bearing sediments. Most of these studies involved either a limited number of samples or limited geographic and stratigraphic distribution of samples.

Bulk mineralogical analytical data for these sediments are extremely sparse in previous studies. This study proceeded with the assumption that the most critical mineralogical data needs with respect to hydrogeochemical concern were in the areas of bulk mineralogy, clay mineralogy, and sulfide determinations. The bulk mineralogy, the clay mineralogy, and sulfide mineralogy of the overburden samples obtained from the four study sites were evaluated using X-ray diffraction (XRD).

Bulk Mineralogy

Portions of all 123 Shelby tube samples were studied by X-ray diffraction (table 1). A Philips diffractometer equipped with a proportional counter, diffracted beam graphite monochromator, theta compensating slit and strip chart recorder was used. The X-radiation was CuKα (λ = 1.54178 Å) and the instrument was operated at 37 kV and 17-18 mA with the goniometer and recorder set for a scan rate of 2°2θ per minute, time constant of two seconds and scale factor of 500 counts per second (cps).

Two sets of samples were collected from the Shelby tubes for bulk mineralogical analysis. Three-inch (7.6 cm) sections were cut from all 123 tubes and split into thirds for the bulk mineralogy, for the clay mineralogy

TABLE 1.--Overburden Shelby tube samples utilized in this study indicating textural, bulk analyses, clay mineralogical analyses, laboratory experimentation, and sulfur analyses performed on each sample.

Location	Depth (ft)*	Test
CENTER 361	0 - 2.5	a
	3 - 4	ba
	7 - 9.5	ba
	12 -14.5	a
	17 -19.5	cba
	22 -24.5	ba
	27 -29.5	ca
	32 -34.5	a
	37 -39.5	ba
	39.5-41.5	ba
	42 -44.5	cba
	44.5-46.5	baa
	47.5-49.5	ba
	49.5-52	cbaa
	54.4-57	baa
	54.5-57	baa
	57 -59	a
CENTER 366	5.5- 7	ba
	9.5-12	cba
	19.5-22	ca
	22 -24.5	ba
	27 -29.5	ba
	29.5-31.5	cba
	34.5-37	ba
	39.5-42	ba
	45 -47	ba
	50 -52.5	caa
	54.5-57	baa
CENTER 380	2 - 4.5	cba
	4.5- 7	cba
	7 - 9.5	a
	9.5-12	cba
	12 -14.5	ba
	14.5-17	cba
	17 -19.5	bad
	19.5-22	cba
	22 -24.5	baa
	24.5-27	cbad
	27 -29.5	bad
	29.5-32	ca
	32 -34.5	ba
	34.5-37	cbaad
	37 -38	bad
	42 -44.5	cbad
	44.5-47	ba
	47 -48.5	bad
	48.5-49.5	a
	49.5-50.5	cad
CONSOL 31	2 - 4.5	cba
	4.5- 7	ba
	7 - 9.5	cba
	12 -14.5	cba
	14.5-17	cba
	17 -19.5	cba
	19.5-22	cba
	22 -24.5	cbad
	24.5-27	cba
	27 -29.5	ba
	29.5-32	ba
	32 -34.5	cba
	34.5-37	cbad
	37 -39.5	bad
	39.5-42	cbad
	44.5-46.5	bad
	46.5-47.5	ca
	47.5-49.5	cba
	49.5-52	ba
	52 -54.5	cbad
	54.5-56	bad
	56 -57.5	ba
INDIAN HEAD X-2	2 - 4.5	cba
	4.5- 7	cba
	7 - 9.5	ba
	9.5-12	ba
	12 -14.5	cba
	14.5-17	ba
	17 -19.5	cba
	19.5-22	ba
	22 -24.5	ba
	24.5-27	cba
	27 -29.5	ba
	29.5-30.5	cba
	34 -36.5	ba
	36.5-38	ca
FALKIRK 514	7 - 9.5	ba
	9.5-12	ba
	12 -14.5	cba
	14.5-16	a
	19.5-22	ba
	22 -24.5	ba
	24.5-27	a
	27 -29.5	ca
	34.5-37	ba
	37 -39.5	a
	47 -49.5	a

TABLE 1.--Continued

Overburden Shelby tube samples utilized in this study indicating textural, bulk analyses, clay mineralogical analyses, laboratory experimentation, and sulfur analyses performed on each sample.

Location	Depth (ft)*	Test	Location	Depth (ft)*	Test
FALKIRK 526	27 -28.5	cbaad	FALKIRK 576	2.5- 3.5	ba
	29.5-30.5	ca		7.5-10	cba
	32 -34.5	ba		12.5-15	ba
	37 -39.5	bad		17.5-20	cba
	39.5-42	bad		22.5-25	cba
	42 -44.5	bad		27.5-30	ba
	44.5-47	bad		32.5-35	cba
	47 -49.5	bad		37.5-38.5	a
	49.5-52	cad		40 -42.5	ba
				47.5-50	cba
FALKIRK 561	27 -29.5	cba		52.5-55	cba
	29.5-30.5	a		57.5-59.5	ba
	32 -34	a		62.5-65	cba
	34 -35	a		67.5-70	ba
	37 -38	a		72.5-75	cba

---

[a] Analyzed by X-ray diffraction for bulk mineralogy and clay mineralogy; also textural analysis.

[b] Analyzed by X-ray diffraction for bulk mineralogy; also textural analyses.

[c] Laboratory experimentation (exhaustive leaching, accelerated weathering, and pan experiments).

[d] Sulfur determination

*Multiply by 0.3048 to convert to metres.

TABLE 2.--X-ray reflections used in mineral analyses.

Mineral	2θ (CuKα)	d (Å)
Quartz	20.9	4.26
Plagioclase	27.9-28.1	3.20-3.18
Alkali Feldspar	27.4-27.6	3.25-3.23
Dolomite	30.9	2.89
Calcite	29.4	3.04
Gypsum	11.6	7.63
Pyrite	33.1	2.71
Siderite	31.7	2.82
Mica-Illite	8.8	10.0
Smectite	6.3- 7.2	14.0-12.5
Chlorite & Kaolinite	12.3-12.4	7.2- 7.1

and texture analysis, and for the leaching tests. Another sampling was made of the center of 97 of the Shelby tubes for bulk mineralogical and additional textural analyses (table 1). The textural data are discussed in a later section of this report. The samples for X-ray analysis were air-dried. An approximately 300 g sample was ball milled for grinding and homogenization. One or more portions were packed into an aluminum specimen holder. As a test of reproducibility and sample homogeneity, several cores were put through the sampling and X-ray analysis eight times.

A data analysis scheme recommended by Griffin (1971) was adopted at the start of the study for comparisons of the mineralogies in the samples. The heights of characteristic strong reflections of each mineral were measured. Table 2 contains the 2θ and d values for each of the minerals observed in at least one of the samples.

The typical sample contained approximately eight minerals detectable by the X-ray technique and some had as many as twelve. Overlaps of weak reflections from other minerals with the characteristic reflections listed in table 2 are unavoidable, and it was anticipated that this would present difficulties in efforts to use the results quantitatively. Two other factors militate against quantitative mineralogical analysis in such samples. Certain minerals (especially clays and gypsum) will have varying degrees of preferred orientation from sample to sample so that the reflection chosen for the analysis will be unpredictably enhanced or suppressed from sample to sample. The most severe factor is the great difficulty in insuring that the very small area sampled by the X-ray beam contains all minerals in proportions representative of a bulk sample where the constituent minerals differ so much in hardness, size, and habit. It was hoped that at least the results for minerals as similar as calcite and dolomite might be used quantitatively so particular attention was given to these. For the rest of the minerals, examination of the peak height trends and the reproducibility tests indicated that the bulk mineralogical results could only be used qualitatively.

Clay Mineralogy

Further study of the clay mineralogy in 112 of the 7.6 cm bottom section samples was carried out. The $< 2\,\mu\text{m}$ fraction of each sample was separated and oriented clay specimens were prepared for X-ray diffraction study. The procedures used were adapted from those in use by the NDSU Soils Department.

A representative sample of each core was ground with a mortar and pestle sufficiently to break up larger agglomerations and 10 g of this ground sample was used to prepare a 7 weight percent (wt %) aqueous suspension. Next, 24 ml of 50 g/L solution of sodium hexametaphosphate was added to the suspension to serve as a dispersing agent and to make the smectite clays homoionic. The suspension was mixed for five to six minutes with an electric mixer and subjected to ultrasound for five minutes to insure good disaggregation of the particles.

The $> 50\,\mu\text{m}$ sand fraction was removed by passing the suspension through a 300-mesh sieve. The silts and clays were washed free from the sand into a clean glass bottle. The sand was then transferred to a 50 ml beaker, dried in an oven at 110°C, and retained for XRF analysis.

The bottle containing the silt and clays was filled to the 900 ml mark with deionized water. This suspension was mixed for two to three minutes with a rubber-bladed mixer and the bottle was inverted 20 times immediately before being placed in a 30°C constant temperature bath. Stokes law was used to compute the time required for the $2\,\mu\text{m}$ size particles to settle to a depth of 10 cm (6 hours, 7 minutes at 30°C). The $< 2\,\mu\text{m}$ clay fraction was then removed by inserting a pipette and drawing off the clay particles with suction. The pipetting apparatus was set up to allow one to just make contact between the pipette tip and surface of the suspension, and then to lower the pipette exactly 10 cm before suction was applied in an effort to disturb the suspension as little as possible during the suction period.

The remaining silt and clay suspension was allowed to stand overnight to insure that all of the silt-sized particles had settled to the bottom of the bottle. The excess liquid was then decanted from the settled silt and the silt collected and dried. The clay suspension drawn off with the pipetting apparatus was transferred to 300 ml beakers. A hollow ceramic "candle" was then placed in the beaker and suction applied to collect the clay particles. After a layer of clay particles had accumulated on the candle, back pressure was used to "sheet" off the clay which was then stirred into a thick paste with a rubber spatula. The paste was transferred to a glass slide with a smear-type technique and allowed to air-dry. Two slides of each sample were prepared. This method of X-ray diffraction slide preparation was chosen because the short drying time and settling interference minimizes particle segregation such as that which typically occurs with larger illite and chlorite and typically much smaller smectite clay particles. Because smectite settles out last from a water slurry, its reflections would be stronger in the X-ray diffractograms. This problem was minimized with the method adopted in this study.

The oriented slides were scanned from 2-30° at $2°2\theta$/minute with the scale factor adjusted to place all reflections on the strip chart. Room humidity was not controlled and varied between 30 and 60 percent during the summer months of 1981 when the work was done.

Initial interpretation suggested that the clay fractions consisted only of a smectite, mica-illite, chlorite, and minor kaolinite. To confirm this, several dozen specimens were treated with ethylene glycol at 60°C overnight. This expanded the smectite (001) spacing from 12-15Å to about 17Å and confirmed the presence of non-expanding chlorite. These specimens were then fired at 550°C for one hour. This treatment destroyed the crystallinity of kaolinite and eliminated the (003) of chlorite while leaving the (001) and (002), thereby confirming their preliminary identification.

Thus, with a few exceptions, the clay minerals proved to consist only of a smectite, mica-illite, chlorite, and kaolinite. The exceptions were the occasional appearance of a mixed layer smectite-illite.

To enable ranking of the clay minerals in order of relative abundance, four standard API clays (Na-montmorillonite in Wyoming bentonite, Fithian illite, Georgia kaolinite, and a chlorite) were mixed in various proportions and run through the same treatment and specimen preparation as the core specimens. Their diffractograms were used as comparison standards in determinations of relative abundance. Because it was realized that these standards were likely to differ in chemistry and crystallinity from the clay minerals in the cores, no attempt was made to interpret the results more quantitatively.

It was anticipated from previous work (Emanuel et al., 1976; Brekke, 1977) that the smectite clay was Na-montmorillonite. In order to confirm this, ten randomly selected cores were run through the separation treatment using deionized water instead of the sodium hexametaphosphate solution as the dispersal medium, thereby retaining the exchange cation(s). When the resulting X-ray specimens were scanned with a room humidity near 40 percent, the (001) spacing of the smectite was found to be in the range 12.5-13Å, which indicated that the smectite was chiefly Na-montmorillonite. A spacing of approximately 15Å would have indicated Ca-montmorillonite.

Sulfide Mineralogy

The presence of FeS_2 as pyrite and/or its polymorph marcasite figures in the geochemical modeling described elsewhere in this report. Pyrite was observed in only five of the bulk X-ray diffractograms. To learn whether pyrite was more widespread, but present below the detection limit of the bulk X-ray measurements, a systematic examination of the sand and silt fractions from the separations described above was made.

First, X-ray fluorescence with a KEVEX energy dispersive unit was used to screen all sand and silt fractions. Specimens with a sulfur $K\alpha,\beta$ signal (detection limit about 1 wt % pyrite) were next examined by X-ray diffraction to determine whether the sulfur was due to pyrite (rather than sulfates such as gypsum). All sand fractions with sulfur signals were put through a heavy mineral separation using bromoform, and the heavy portions were also examined with an optical microscope at 60X and by X-ray diffraction. The instrument was run with relatively high sensitivity settings (40 kV 20 mA, 100 cps scale factor) and it was established that pyrite could be observed at the 2 weight percent level in a matrix of the typical minerals observed in the core specimens. The technique readily distinguishes the pyrite and marcasite forms of FeS_2 and in several cases a mixture of both forms was observed.

Sulfur Analyses

Sulfur analyses were performed on selected samples from one test hole at each of the four mine sites. Samples from each test hole were selected (table 1) which represented as wide a range as possible of textural types as well as oxidized and unoxidized sediments (table 3).

The procedure for sulfur analyses of overburden samples involved mixing one part solum (about 4 g) with five parts (20 ml) of pH 4.5 acetate buffer (Chesnin and Yien, 1950) and mixed intermittently with a vortex mixer over a three-hour period (Hesse, 1971). The sample was centrifuged, drained, and washed four times with distilled water. Centrifugation was used between each washing to separate sample from wash solution. After drying for approximately six hours at 95-100°C, the samples were ground and analyzed for total sulfur. The separation scheme was as follows:

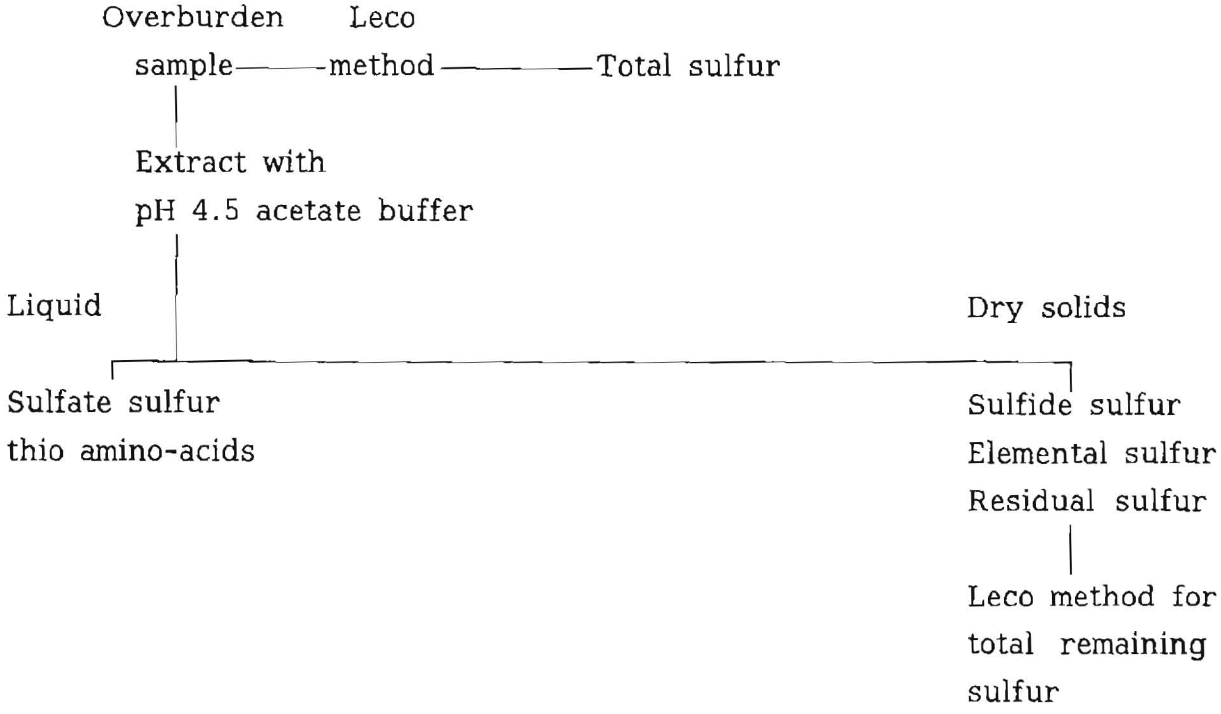


TABLE 3.--Samples used for sulfur analyses.

Location	Depth (ft)*	Lithology
CENTER 380	17 -19.5	clay, silty, oxidized
	24.5-27	silt, clayey, sandy, oxidized
	27 -29.5	clay, sandy, unoxidized
	34.5-37	clay, carbonaceous, unoxidized
	37 -38	silt, carbonaceous, unoxidized
	42 -44.5	clay, carbonaceous, unoxidized
	47 -48.5	clay, unoxidized
	49.5-50.5	clay, unoxidized
CONSOL 31	22 -24.5	silt, unoxidized
	34.5-37	silt, clayey, unoxidized
	37 -39.5	clay, silty, unoxidized
	39.5-42	silt, sandy, unoxidized
	44.5-46.5	clay, unoxidized
	52 -54.5	clay, unoxidized
	54.5-56	clay, unoxidized
INDIAN HEAD X-2	17 -19.5	clay, oxidized
	19.5-22	clay, oxidized
	22 -24.5	clay, slightly oxidized
	24.5-27	clay, silty, slightly oxidized
	27 -29.5	silt, sandy, carbonaceous, slightly oxidized
FALKIRK 526	27 -28.5	clay, oxidized
	37 -39.5	sand, silty, unoxidized
	39.5-42	silt, sandy, unoxidized
	42 -44.5	sand, silty, unoxidized
	44.5-47	silt and sand, unoxidized
	47 -49.5	silt, sandy, unoxidized
	49.5-52	silt, sandy, unoxidized

*Multiply by 0.3048 to convert to metres.

The detection limit was 0.003 percent. By this scheme the polysulfide and monosulfide constituents were not separated (Karchmer, 1970). The final weight of dry solids was corrected to weight before extraction when calculating S content.

Saturated-Paste Extract Data

The saturated-paste 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. When the sample is dried, ions in the pore water are precipitated in the pore space.

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 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. Regardless of these limitations, this procedure is the most reliable test of pore water chemistry presently available.

Saturated-paste extract tests were performed on 44 samples of spoils which were obtained from the Center and Indian Head Mines (app. C). The samples were obtained from either immediately below the topsoil or within several inches of the spoils surface in areas that had not been topsoiled. The samples were obtained for purposes of comparing pore water chemistry in the spoils at these two mines with spoils groundwater chemistry.

Subsurface Water Instrumentation

Piezometers

Approximately two hundred seventy-five piezometers have been installed within the spoils and unmined areas at the Center and Indian Head Mines. The piezometers were screened at various stratigraphic positions at both mines. The purpose of this instrumentation was to gather base-line data on the occurrence, flow, and chemistry of groundwater in unmined and spoils settings.

At the Indian Head Mine, groundwater instrumentation was located in undisturbed areas adjacent to the mine and within two study plots in areas of reclaimed spoils (fig. 12). The spoils study plots are identified as the Montana State University (MSU) and USBM plots (fig. 12). The locations of piezometers in these two spoils test plots are shown in figures 13 and 14. Most of the instrumentation in the undisturbed settings was destroyed by mining activity during the course of the project. Therefore, most premining groundwater chemical data from the Indian Head Mine was collected during the beginning phase of the project (app. D). Groundwater instrumentation at the Indian Head Mine was designed to monitor three stratigraphic positions. These were the lignite which is being mined (the Beulah-Zap bed), the base of the spoils, and a lignite about 10 metres below the spoils (Spaer bed).

Groundwater instrumentation at the Center Mine was located in undisturbed settings adjacent to the mine (fig. 15) and in several test plots within the reclaimed spoils (figs. 16a-j). Groundwater instrumentation at the Center Mine was more extensive than at the Indian Head Mine. This was due to the fact that several other groundwater research projects were ongoing at the Center Mine during the period of this study. This resulted in the availability of considerable groundwater chemical data from Center. Although some of these data may not be essential to the present study, all have been included in appendix D.

Groundwater instrumentation at the Center Mine was designed to monitor several stratigraphic positions. These stratigraphic positions include the upper lignite (Kinneman Creek bed), the lower lignite (Hagel bed), the base of the spoils, a silty sand unit generally less than five metres

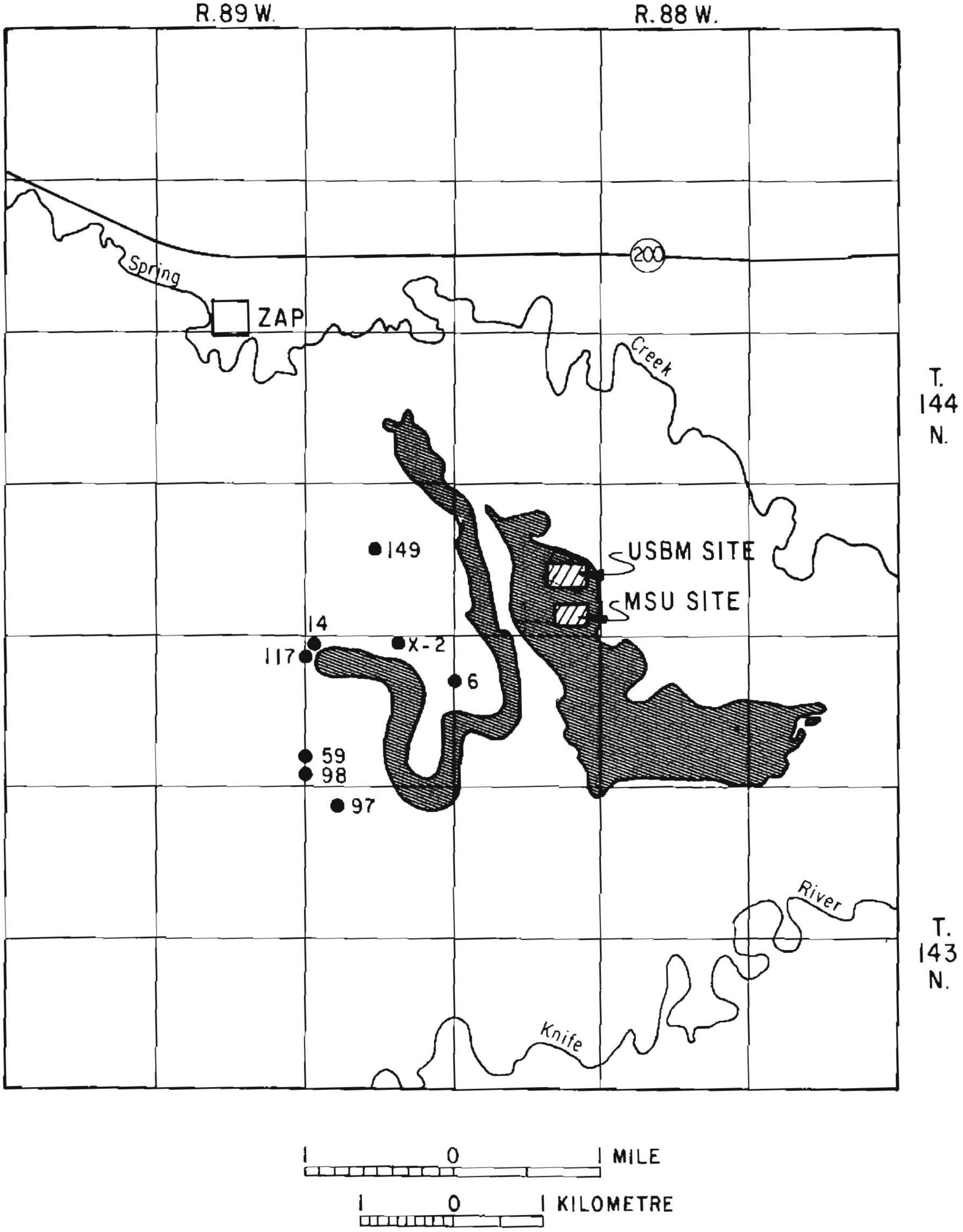


Figure 12. Location of piezometers in undisturbed settings and MSU and USBM spoil test plots at the Indian Head Mine. Location of piezometers in spoils test plots shown in figures 13 and 14. See table 5 for stratigraphic position of screened interval for each piezometer. Stippled areas represent spoils area, as of April, 1977.

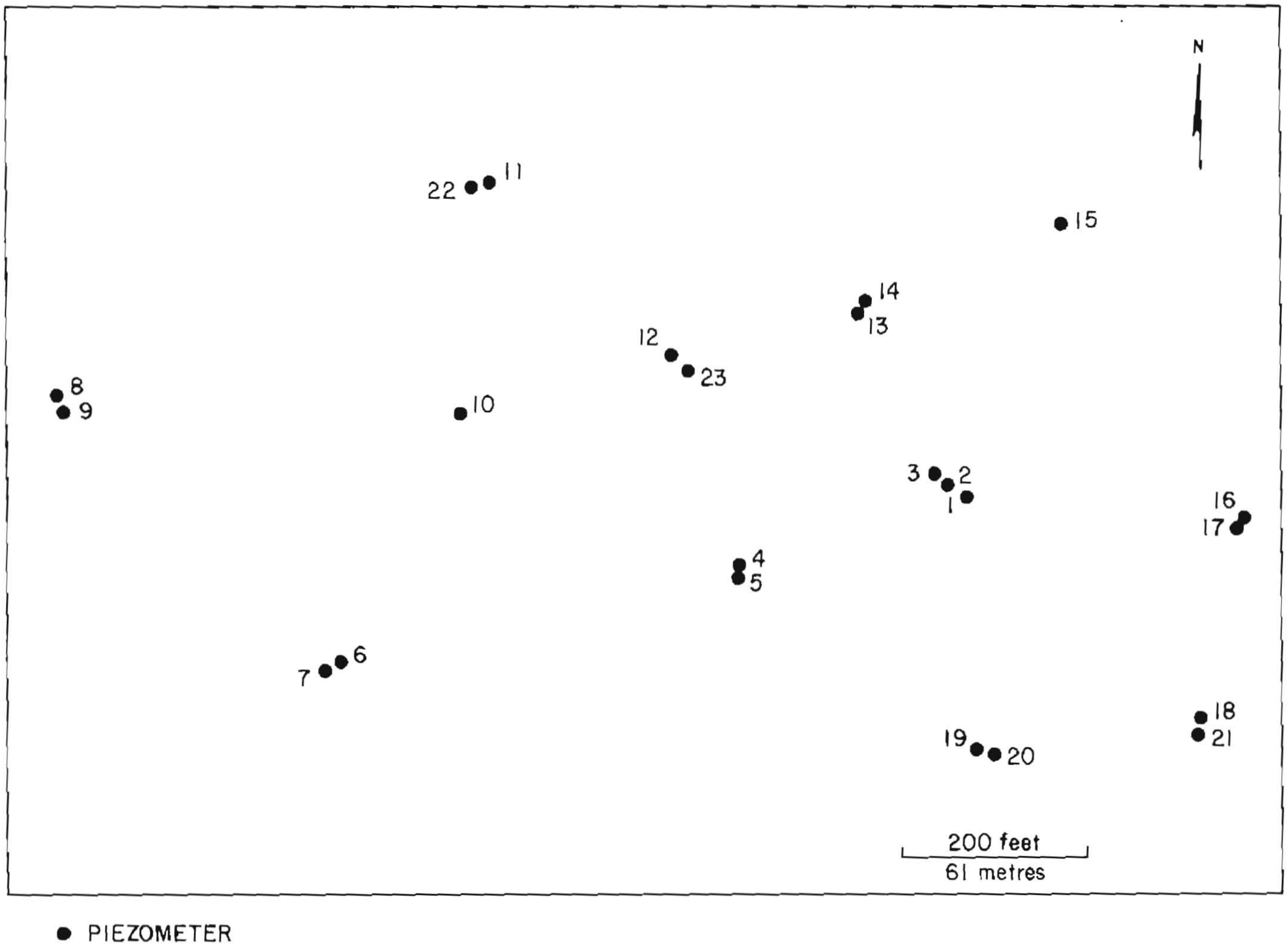


Figure 13. Location of piezometers in MSU spoils test plot at the Indian Head Mine. See table 5 for stratigraphic position of screened interval for each piezometer.

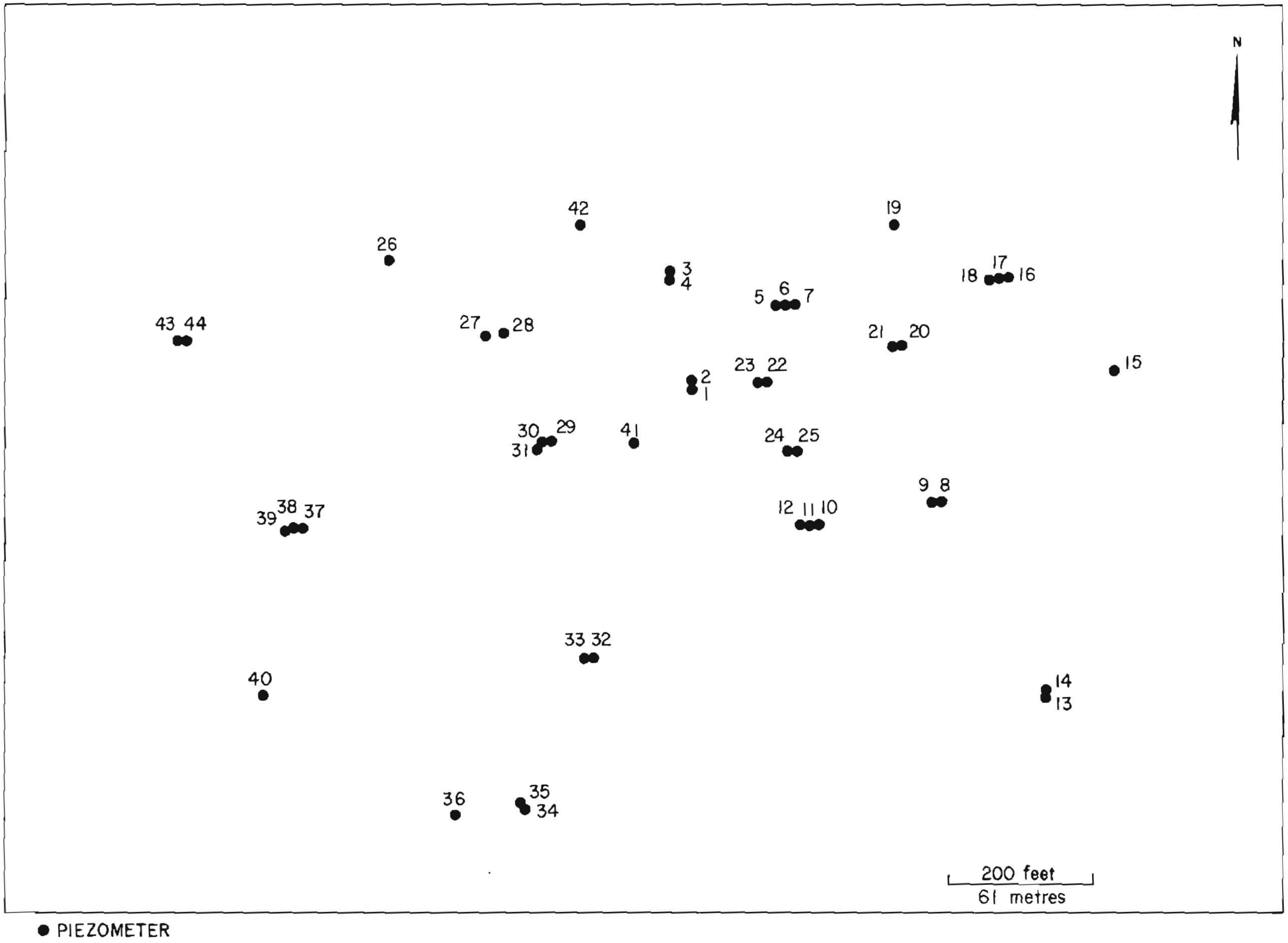


Figure 14. Location of piezometers in USBM spoils test plot at the Indian Head Mine. See table 5 for stratigraphic position of screened interval for each piezometer.

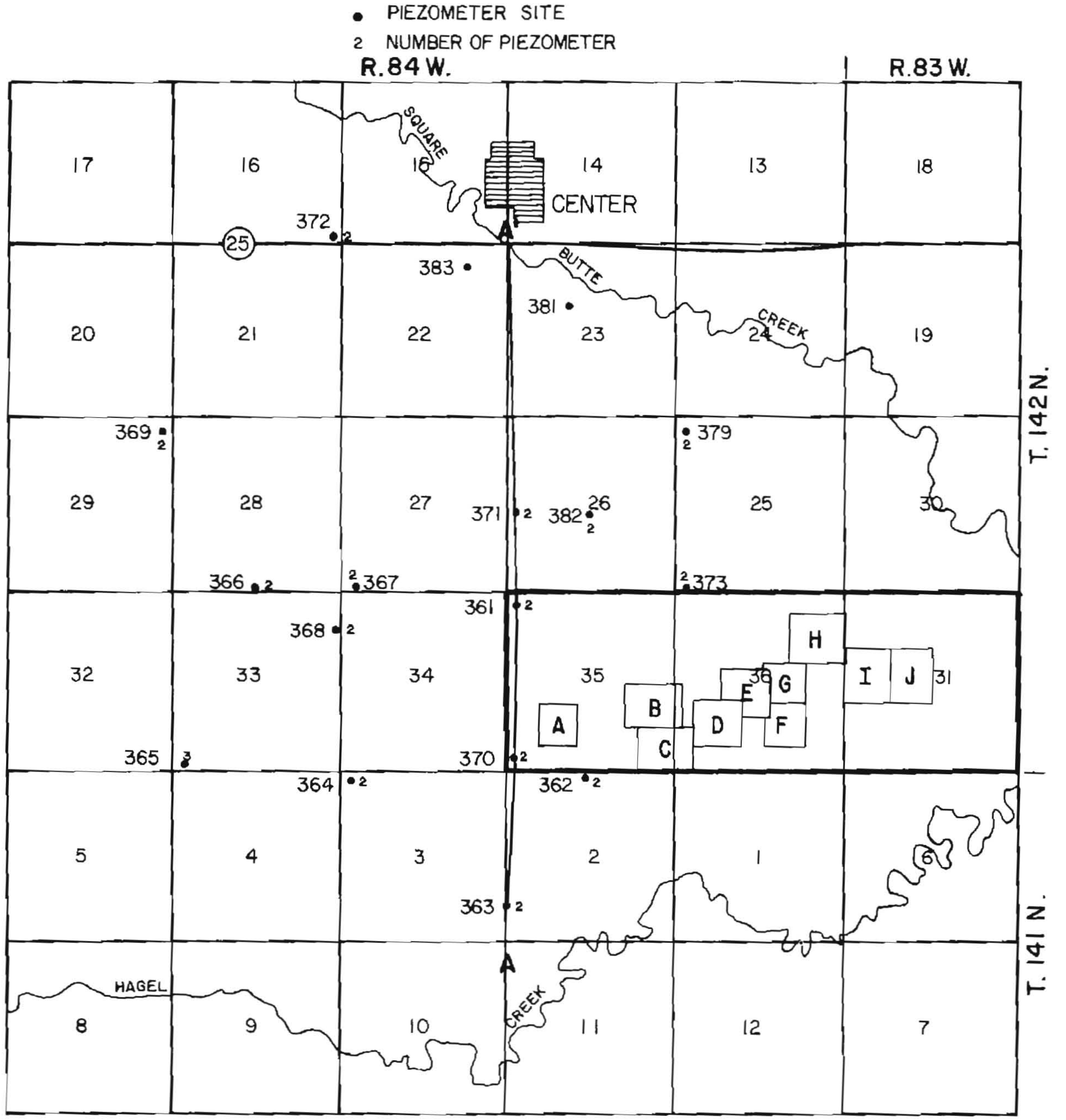


Figure 15. Location of piezometers in undisturbed areas near the Center Mine. Area of active mining and spoils indicated by heavy borderline. Areas labeled A-J are spoils study areas and correspond with figures 16a-j. A-A' is location of cross section shown on figure 22.

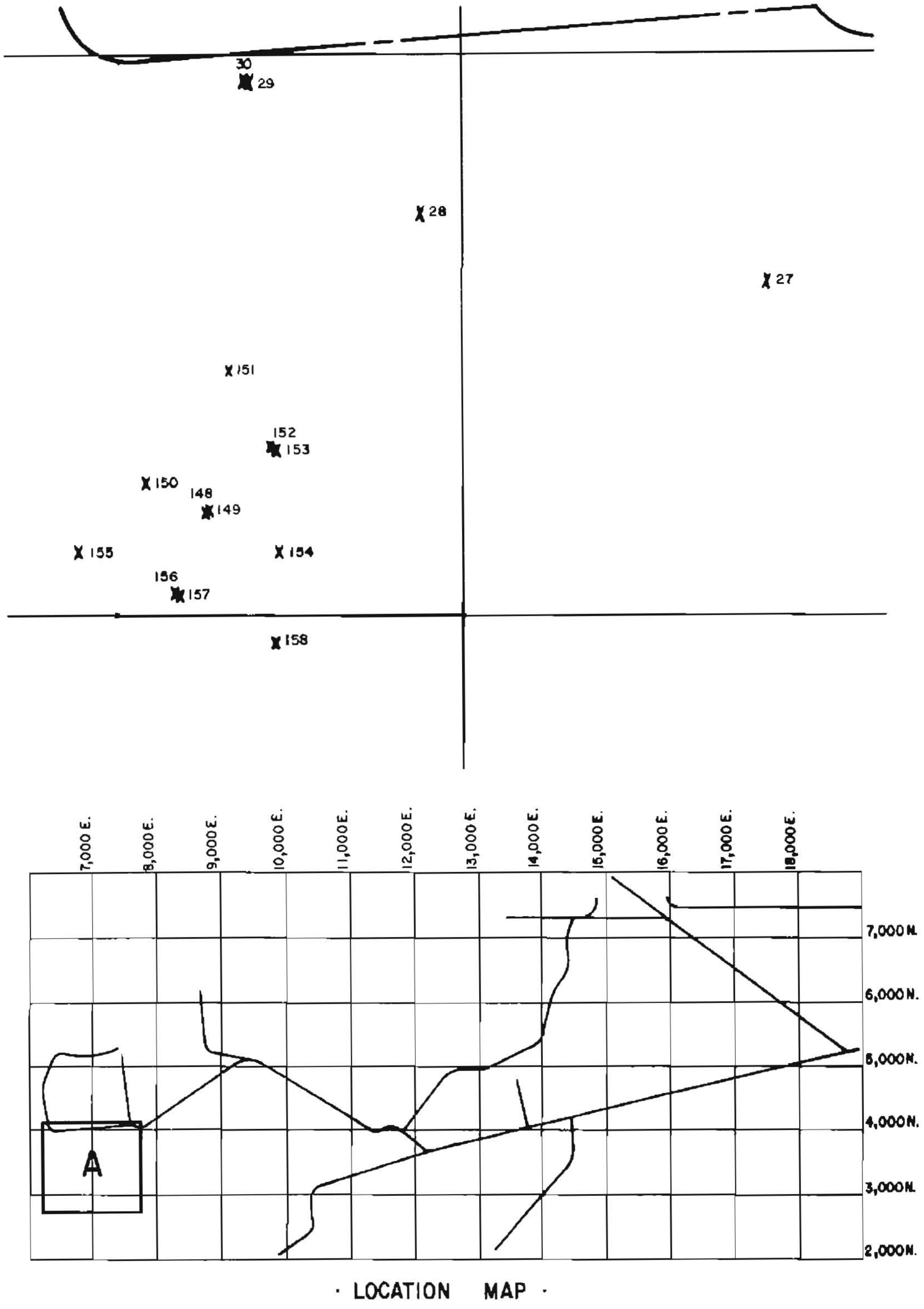


Figure 16a. Location of piezometers in spoils area A at the Center Mine. See figure 15 for location of area A.

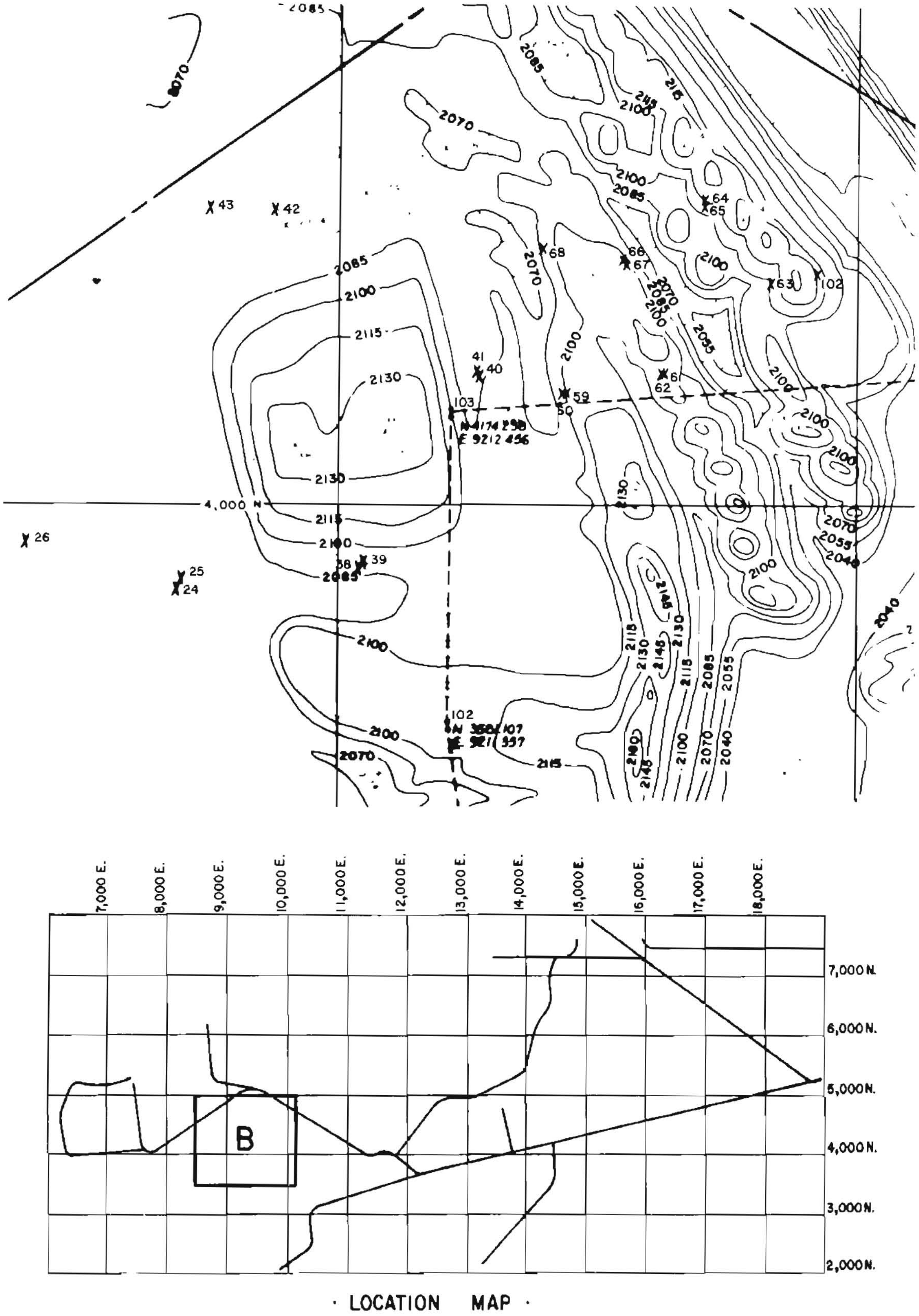


Figure 16b. Location of piezometers in spoils area B at the Center Mine. See figure 15 for location of area B.

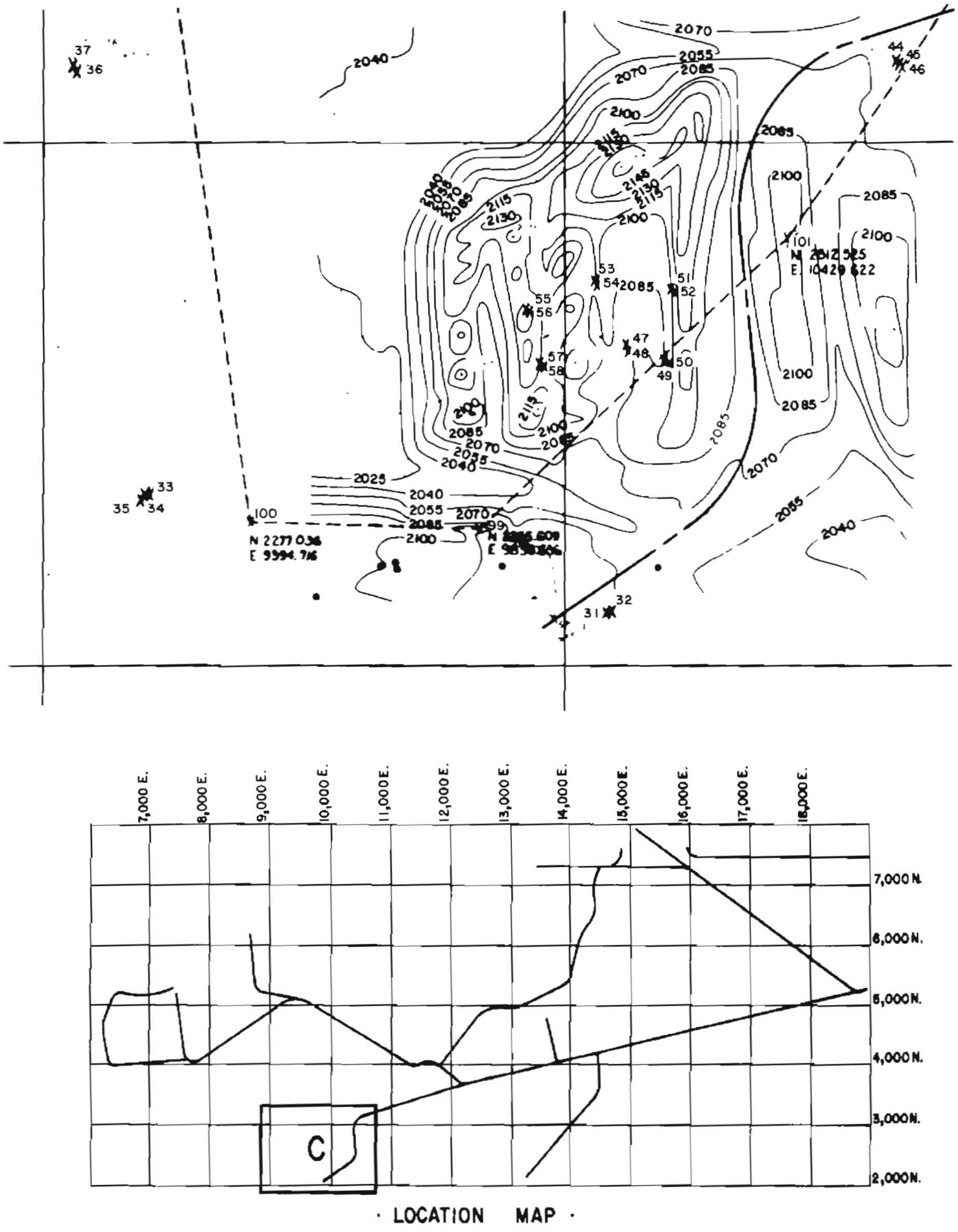


Figure 16c. Location of piezometers in spoils area C at the Center Mine. See figure 15 for location of area C.

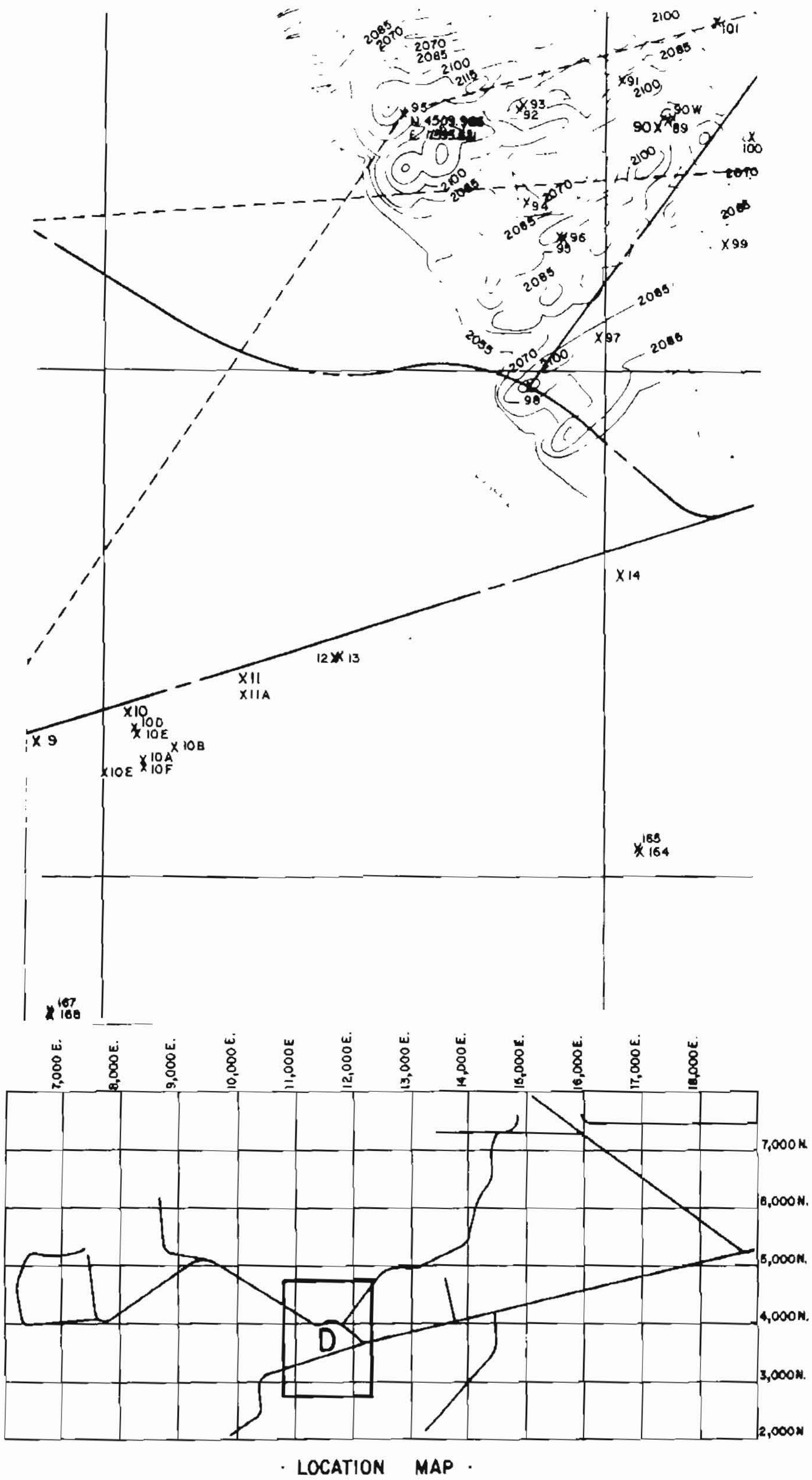
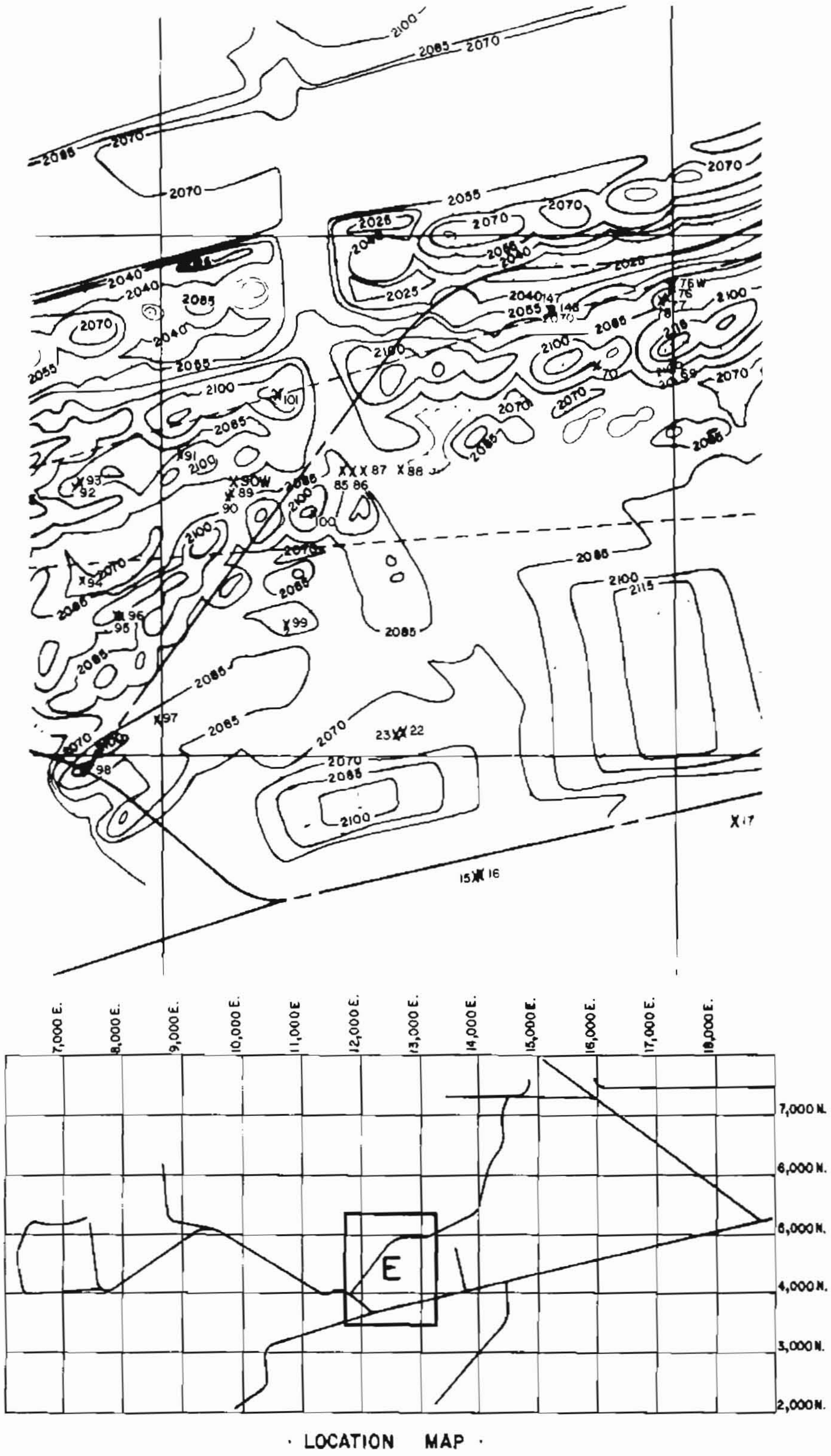


Figure 16d. Location of piezometers in spoils area D at the Center Mine. See figure 15 for location of area D.



· LOCATION MAP ·

Figure 16e. Location of piezometers in spoils area E at the Center Mine. See figure 15 for location of area E.

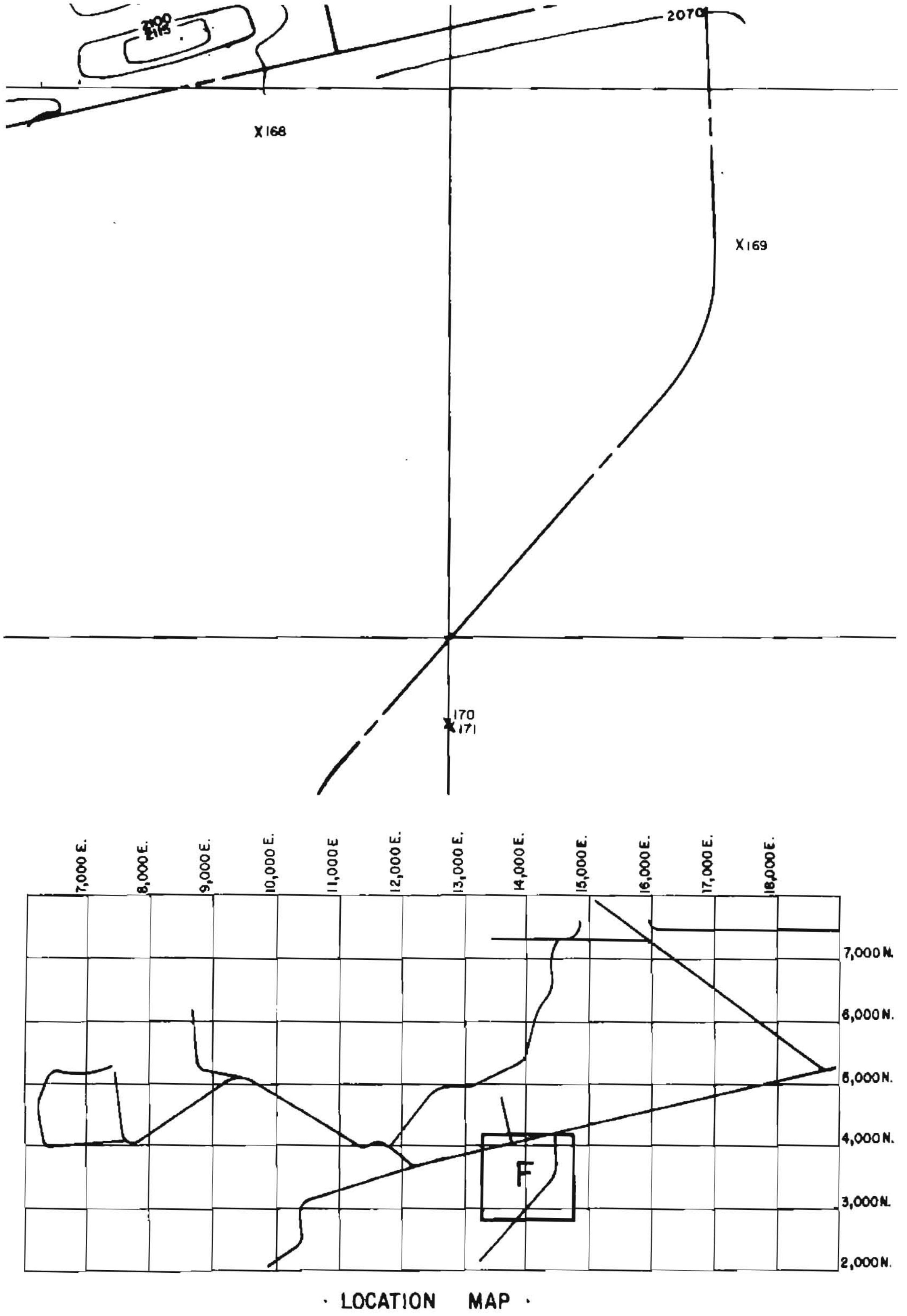


Figure 16f. Location of piezometers in spoils area F at the Center Mine. See figure 15 for location of area F.

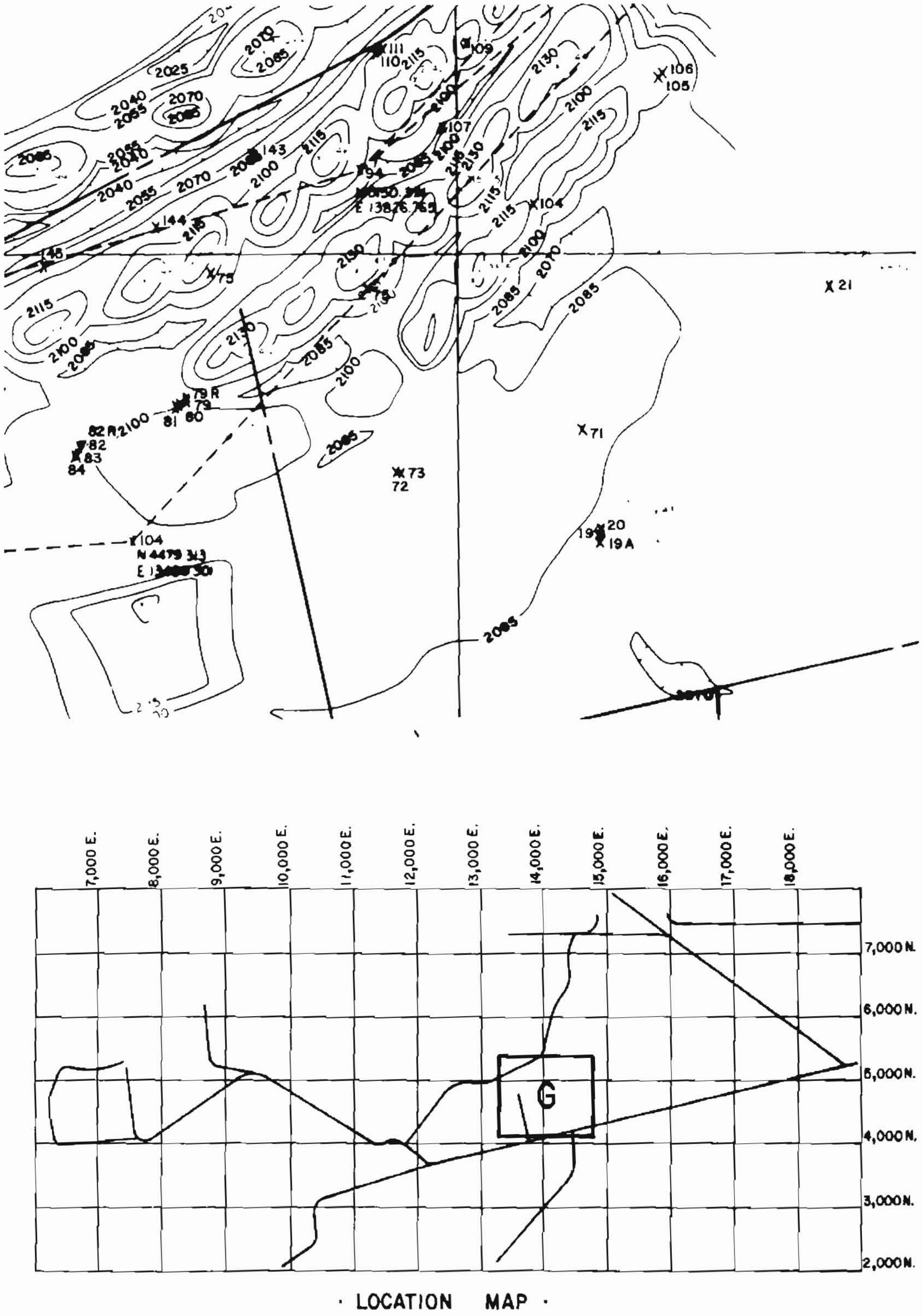
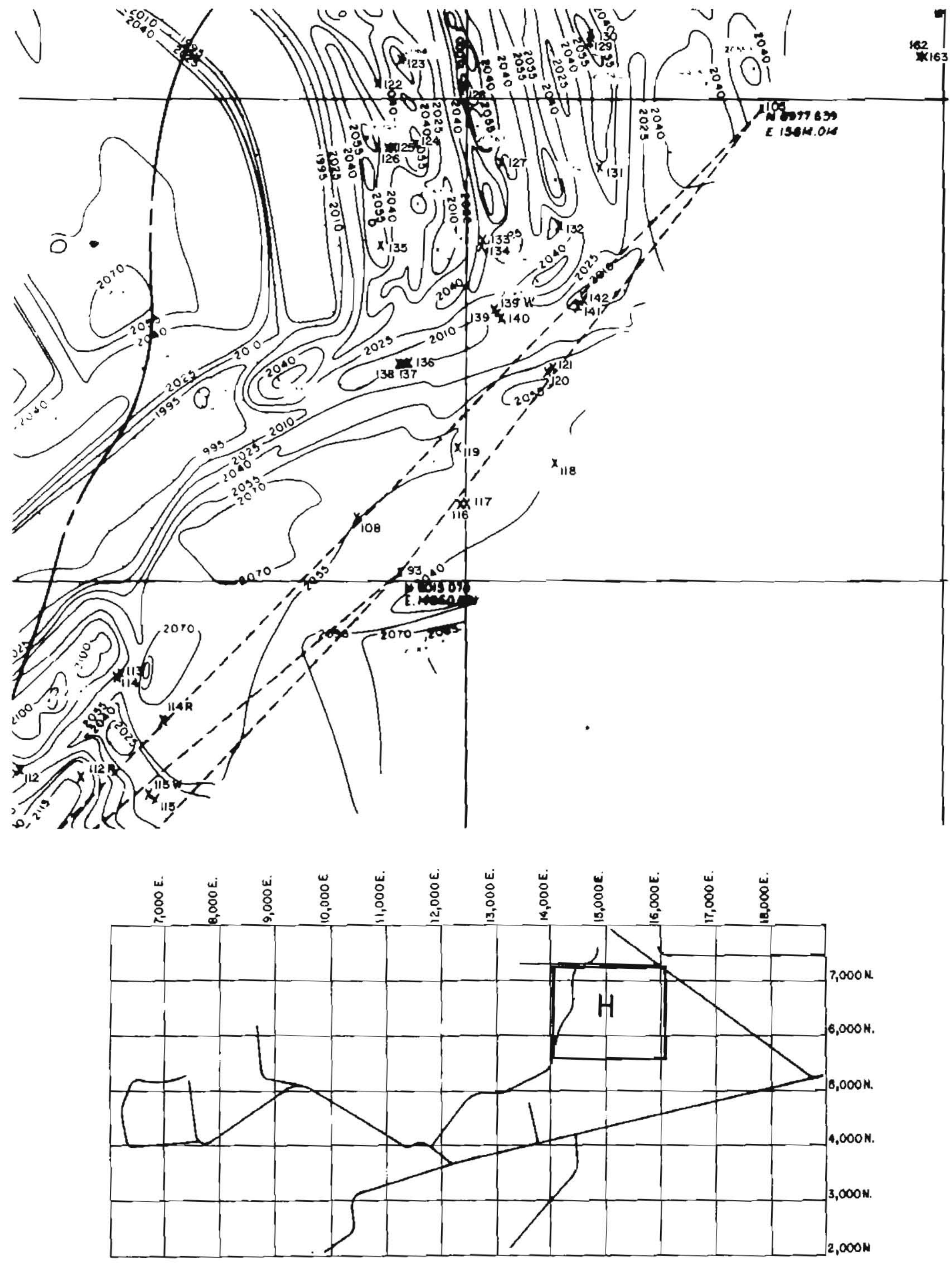


Figure 16g. Location of piezometers in spoils area G at the Center Mine. See figure 15 for location of area G.



· LOCATION MAP ·

Figure 16h. Location of piezometers in spoils area H at the Center Mine. See figure 15 for location of area H.

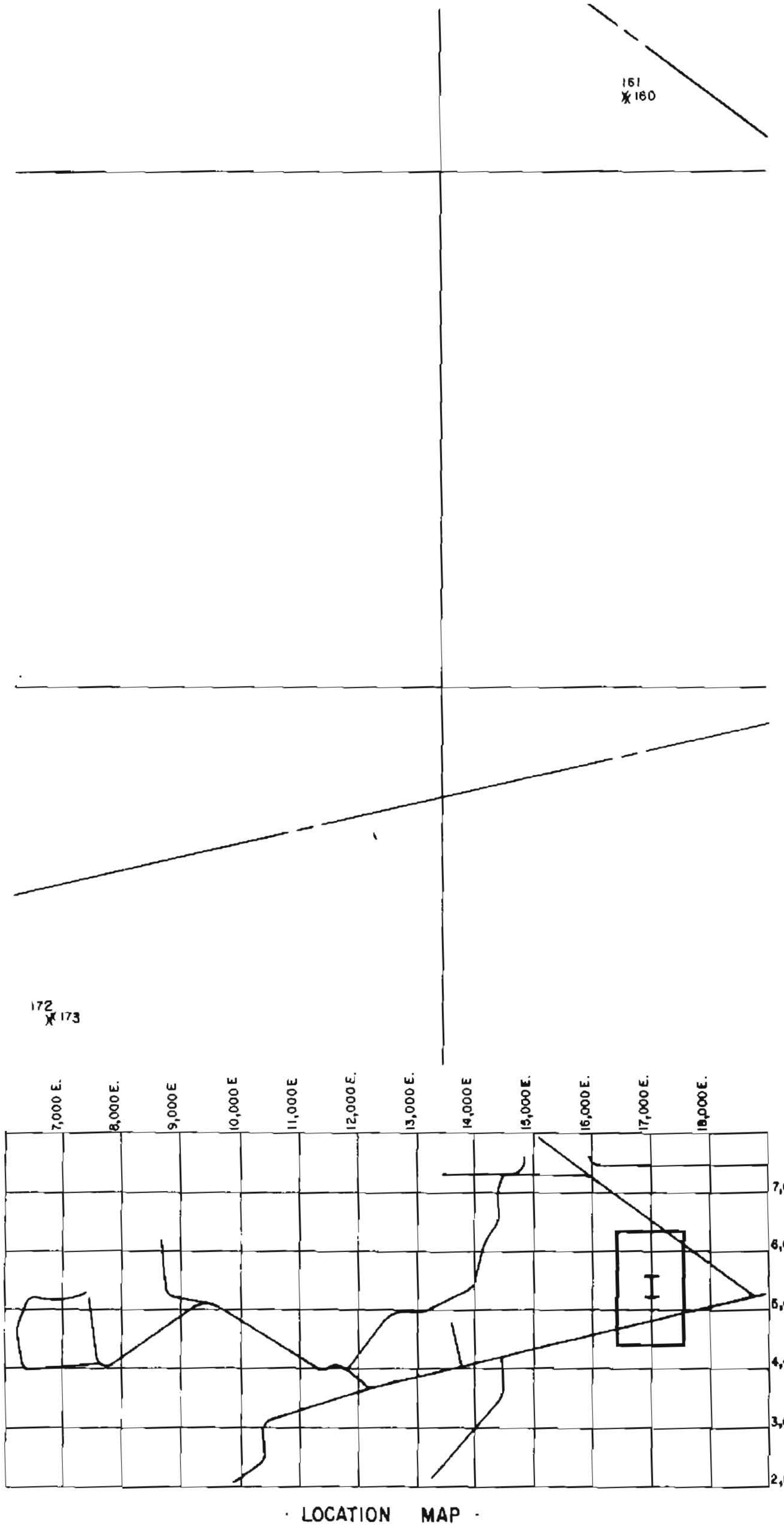


Figure 16i. Location of piezometers in spoils area I at the Center Mine. See figure 15 for location of area I.

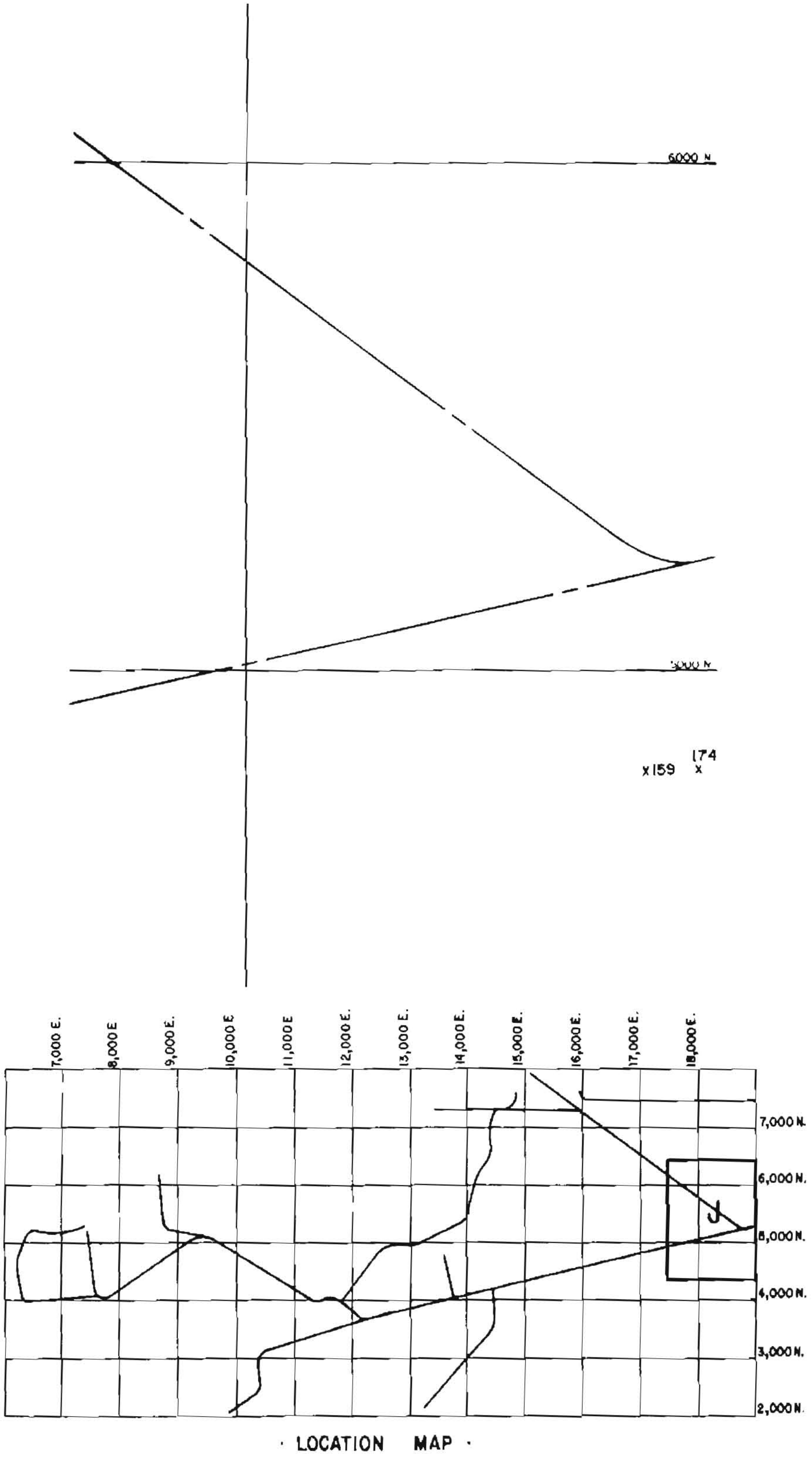


Figure 16j. Location of piezometers in spoils area J at the Center Mine. See figure 15 for location of area J.

below the Hagel bed or base of spoils, and a silty sand to silt unit typically between 10 and 15 metres below the Hagel bed or base of spoils.

Tables 4 and 5 list the piezometers and stratigraphic positions of the screened intervals for each installation at the two mines. All groundwater chemical data from piezometers are included in appendix D. As is evident from table 4, certain piezometers in spoils at the Center Mine are screened near buried thermoelectric wastes (fly ash and FGD waste). Groundwater chemical data from any piezometer showing impacts of dissolution of these wastes were not used in this study and are not included in appendix D.

All piezometer test holes were drilled utilizing a rotary drilling rig. With few exceptions, the piezometer test holes were drilled using only air for circulation, thereby eliminating potential chemical contamination associated with the injection of fluids during drilling operations.

The majority of the piezometers consist of 5-cm-diameter PVC pipe with a 1.5 metre preslotted PVC screen (slot size 0.5 mm). Several of the piezometers consist of 10-cm-diameter PVC pipe. Washed sand was packed around the screened interval. Grout was then emplaced from the top of the sand pack to the surface. A more detailed discussion of well installation and sampling procedures can be found in Groenewold et al., 1979. Water levels in all the piezometers were monitored on a monthly basis. These data were used to develop an interpretation of groundwater flow in the study areas. In addition, single-well-response tests of selected piezometers were conducted to determine the hydraulic conductivities of the spoils and various undisturbed units.

Pressure-Vacuum Lysimeters (Soil Water Samplers)

Pressure-vacuum lysimeters were installed in nests in several locations in both spoils and undisturbed materials at the Center and Indian Head Mines. A more complete description of pressure-vacuum lysimeters can be found in Parizek and Lane (1970) and Wood (1973).

The pressure-vacuum lysimeters were utilized to obtain samples of pore water from various positions in the unsaturated zone in both undisturbed and spoils settings. The nests of pressure-vacuum lysimeters were installed adjacent to piezometer nests and were identified accordingly. (See figs. 13, 14, 15, and 16a-j.) Table 6 lists all the pressure-vacuum lysimeters at

TABLE 4.--Stratigraphic position of screened interval of piezometers in undisturbed and spoils areas at the Center Mine.

Piezometer Number	Depth (m)	Stratigraphic Position
1	41.5	Hagel bed
2	55.0	Silt 15 m below Hagel
3	39.4	Hagel bed
5	35.6	Hagel bed
6	41.5	Hagel bed
9	15.1	Base of spoils
10	16.3	Base of spoils, fly ash
10A	15.2	Base of spoils
10B	14.4	Base of spoils
10C	15.3	Base of spoils
10D	16.6	Base of spoils
10E	18.6	Silt 5 m below spoils
10F	17.8	Silt 3 m below spoils
11	15.8	Base of spoils
11A	14.3	Base of spoils
12	28.8	Silt 12 m below spoils
13	12.8	Base of spoils
14	14.5	Base of spoils
15	27.2	Silt 12 m below spoils
16	15.5	Base of spoils
19	28.3	Silt 12 m below spoils
19A	22.7	Silt 12 m below spoils
20	20.2	Base of spoils
22	29.0	Silt 12 m below spoils
23	17.6	Base of spoils
24	30.7	Silt 12 m below spoils
26	20.4	Base of spoils
27	16.8	Base of spoils
29	37.1	Silt 12 m below spoils
30	24.7	Hagel bed below spoils
31	30.6	Silt 15 m below Hagel
32	16.3	Hagel bed
33	35.5	Silt 18 m below Hagel
34	23.1	Sand 5 m below Hagel
36	18.7	Sand 3 m below spoils
37	9.8	Base of spoils
38	22.7	Sand 8 m below spoils
39	17.4	Base of spoils
40	23.6	Sand 5 m below spoils
42	24.0	Sand 3 m below spoils
44	21.8	Silt 8 m below spoils
45	15.8	Base of spoils
46	13.4	Base of spoils
47	23.6	Silt 2 m below spoils
48	21.7	Base of spoils
49	21.5	Base of spoils

TABLE 4.--Continued
Stratigraphic position of screened interval of piezometers in undisturbed and spoils areas at the Center Mine.

Piezometer Number	Depth (m)	Stratigraphic Position
50	17.4	5 m above base of spoils
51	27.4	Silt 5 m below spoils
52	23.1	Base of spoils
53	24.2	Base of spoils
54	19.4	5 m above base of spoils
55	28.0	Silt 3 m below spoils
56	24.2	Base of spoils
57	21.4	3 m above base of spoils
58	24.0	Base of spoils
59	21.8	Base of spoils
60	16.9	5 m above base of spoils
61	24.0	Silt 2 m below spoils
62	22.2	Base of spoils
63	24.1	Base of spoils
64	27.8	Silt 3 m below spoils
65	24.7	Base of spoils
66	22.4	Base of spoils
67	17.0	5 m above base of spoils
68	18.3	Base of spoils
69	27.8	Base of spoils
70	25.0	Base of spoils
71	22.1	Base of spoils
72	27.9	Silt 3 m below spoils
73	25.4	Base of spoils
74	29.3	Base of spoils
75	27.9	Base of spoils
76	27.0	Base of spoils, 18 m below FGD waste
76W	24.8	Base of spoils
77	6.4	Below FGD waste
78	4.3	FGD waste
79	27.2	Base of spoils, 19 m below FGD waste
79R	25.4	Base of spoils, 17.5 m below FGD waste
80	10.4	1.5 m below FGD waste
81	8.5	FGD waste
82	27.6	Base of spoils, 17 m below FGD waste
82R	25.7	Base of spoils, 15 m below FGD waste
83	11.9	Base of spoils, 1.5 m below FGD waste
84	10.1	FGD waste
85	27.5	Base of spoils
86	9.0	Offset from FGD waste
87	8.5	Offset from FGD waste
88	5.7	FGD waste
89	29.1	Silt 6 m below spoils

TABLE 4.--Continued
Stratigraphic position of screened interval of piezometers in undisturbed and spoils areas at the Center Mine.

Piezometer Number	Depth (m)	Stratigraphic Position
90	23.4	Base of spoils, 15.5 m below FGD waste
90W	27.0	Base of spoils, below FGD waste
91	23.2	Base of spoils
92	20.4	3 m above base of spoils
93	28.8	Silt 2 m below spoils
94	8.4	FGD waste and bottom ash
95	22.5	Base of spoils
96	27.7	Silt 5 m below spoils
97	20.7	Base of spoils
98	19.7	Base of spoils
99	21.0	Base of spoils, below FGD waste at unknown depth
100	23.2	Base of spoils
101	25.1	Base of spoils
102	26.6	Silt 2 m below spoils FGD waste (?)
104	21.5	Base of spoils
105	28.0	Silt 5 m below spoils
106	23.7	Base of spoils
107	31.1	Base of spoils
108	20.3	Base of spoils
109	31.4	Base of spoils
110	36.3	Silt 4 m below spoils
111	32.5	Base of spoils
112	29.6	Base of spoils
112R	27.9	Base of spoils
113	29.6	Silt 4 m below spoils
114	24.0	Base of spoils
114R	21.0	Base of spoils
115	23.0	Base of spoils
115W	21.0	Base of spoils
116	23.9	Silt 5 m below spoils
117	18.3	Base of spoils
118	17.4	Base of spoils
119	18.1	Base of spoils
120	15.6	Base of spoils
121	21.0	Silt 5 m below spoils
122	15.9	Base of spoils
123	16.1	Base of spoils
124	17.9	Base of spoils
125	17.9	Base of spoils
126	23.4	Silt 5 m below spoils
127	17.2	Base of spoils
128	16.9	Base of spoils
129	17.7	Sand 4 m below spoils
130	13.3	Base of spoils

TABLE 4.--Continued
Stratigraphic position of screened interval of piezometers in undisturbed and spoils areas at the Center Mine.

Piezometer Number	Depth (m)	Stratigraphic Position
131	10.7	Base of spoils, bottom ash
132	15.4	Base of spoils
133	15.7	Base of spoils, offset, 20 m from fly ash
134	20.7	Sand 5 m below spoils
135	18.0	Base of spoils
136	21.1	Sand 6 m below spoils; 5 m below fly ash
137	14.3	Base of spoils, at three positions 7.5 m below fly ash
138	7.7	Fly ash and bottom ash
139	15.6	Base of spoils, 7.5 m below fly ash
140	8.0	Fly ash and bottom ash
141	12.0	Fly ash and bottom ash
142	14.2	Sand 1 m below spoils and unmined coal; 5 m below bottom ash and fly ash (?)
143	29.3	Base of spoils, 21 m below FGD waste
144	26.5	Base of spoils, 18 m below FGD waste
145	24.9	Base of spoils, 18 m below FGD waste
146	22.4	Base of spoils, 17 m below FGD waste
147	6.2	FGD waste
148	15.2	Silt 5 m below spoils
149	10.4	Hagel bed
150	5.3	FGD waste
151	17.3	Hagel bed
152	21.5	Silt 5 m below Hagel
153	15.6	Hagel bed
154	10.6	Base of spoils
155	12.7	Hagel bed
156	17.1	Silt 5 m below Hagel
157	11.5	Hagel bed
158	9.5	Hagel bed
360AR	31.7	Silty sand 15 m below Hagel
360BR	15.3	Hagel bed
361A	19.7	Kinneman Creek bed
361R	37.1	Hagel bed
362	25.7	Silty sand 15 m below Hagel
362A	9.7	Hagel bed
363	25.6	Silty sand 15 m below Hagel
363A	12.4	Hagel bed
364	24.2	Hagel bed
364A	9.3	Kinneman Creek bed
365	43.8	Silty sand 15 m below Hagel

TABLE 4.--Continued
Stratigraphic position of screened interval of piezometers in undisturbed and spoils areas at the Center Mine.

Piezometer Number	Depth (m)	Stratigraphic Position
365A	28.6	Hagel bed
365B	13.9	Kinneman Creek bed
366	35.7	Hagel bed
366A	20.6	Kinneman Creek bed
367	56.4	Hagel bed
367A	41.8	Kinneman Creek bed
368	34.9	Hagel bed
368A	23.4	Kinneman Creek bed
369	39.5	Hagel bed
369A	33.0	Kinneman Creek bed
370A	11.8	Kinneman Creek bed
370R	31.3	Hagel bed
371	34.7	Hagel bed
371A	21.9	Kinneman Creek bed
372	14.9	Hagel bed
372A	9.8	Kinneman Creek bed
373A	25.6	Hagel bed
373B	13.1	Kinneman Creek bed
381	17.0	Sand 5 m below Hagel
382	49.9	Hagel bed
382A	30.1	Kinneman Creek bed
383	15.0	Silty sand 9 m below Hagel

TABLE 5.--Stratigraphic position of screened interval of piezometers in undisturbed and spoils areas at the Indian Head Mine.[a]

Piezometer Number	Depth (m)	Stratigraphic Position
		UNDISTURBED
X-2	25.0	Sand 21 m above Beulah-Zap bed
6	21.3	Beulah-Zap bed
14	19.9	Beulah Zap bed
97	40.8	Sand 9 m below Beulah-Zap bed
98	27.0	Beulah-Zap bed
99	36.9	Beulah-Zap bed
117	21.0	Beulah-Zap bed
127	27.7	Beulah-Zap bed
149	48.1	Sand 21 m above Beulah-Zap bed
		USBM SPOILS TEST PLOT
1	27.5	Spaer bed
2	18.6	Base of spoils
2W	19.6	Base of spoils
3	24.4	Spaer bed
4	11.7	Base of spoils
5	19.6	Spaer bed
6	11.8	Base of spoils
7	7.7	5 m above base of spoils
8	16.2	Base of spoils
9	12.5	5 m above base of spoils
10	23.6	Spaer bed
11	16.2	Base of spoils
12	11.2	5 m above base of spoils
13	11.4	Base of spoils
14	6.9	5 m above base of spoils
15	10.4	Base of spoils
16	18.7	Spaer bed
17	10.8	Base of spoils
18	7.5	5 m above base of spoils
19	7.0	Base of spoils
20	14.9	Base of spoils
21	10.9	5 m above base of spoils
22	18.0	Base of spoils
23	14.4	5 m above base of spoils
24	17.0	Base of spoils
25	12.1	5 m above base of spoils
26	16.2	Base of spoils
27	20.0	Base of spoils
28	5.4	5 m above base of spoils
29	24.6	Spaer bed
30	16.2	Base of spoils
30W	17.4	Base of spoils
31	12.3	5 m above base of spoils

TABLE 5.--Continued
Stratigraphic position of screened interval of piezometers in undisturbed and spoils areas at the Indian Head Mine.[a]

Piezometer Number	Depth (m)	Stratigraphic Position
32	9.3	Base of spoils
33	5.2	5 m above base of spoils
34	16.0	Spaer bed
35	7.8	Base of spoils
36	7.5	Base of spoils
37	21.3	Spaer bed
38	9.6	Base of spoils
39	5.8	5 m above base of spoils
40	6.8	Base of spoils
41	14.1	Base of spoils
42	14.8	Base of spoils
43	11.6	Base of spoils
43W	10.4	Base of spoils
44	6.1	5 m above base of spoils
		MSU SPOILS TEST PLOT
1	26.6	Spaer bed
2	24.4	Spaer bed
3	15.9	Base of spoils
4	26.2	Spaer bed
5	15.1	Base of spoils
6	26.5	Spaer bed
7	19.9	Base of spoils
8	26.7	Spaer bed
9	13.6	Base of spoils
10	18.5	Base of spoils
11	15.2	Base of spoils
12	16.8	Base of spoils
13	24.8	Spaer bed
14	15.7	Base of spoils
15	13.7	Base of spoils
16	21.2	Spaer bed
17	13.1	Base of spoils
18	15.3	Base of spoils
19	17.4	Base of spoils
20	28.1	Spaer bed
21	25.4	Spaer bed
22	30.0	Spaer bed
23	26.3	Spaer bed

[a] See figures 12, 13, and 14 for locations.

TABLE 6.--Depth of pressure-vacuum lysimeters installed in undisturbed settings and spoils at the Center and Indian Head Mines.[a]

Pressure-Vacuum Lysimeter	Depth (m)	Pressure-Vacuum Lysimeter	Depth (m)
CENTER MINE (SPOILS)			
15-1	11.60	90-3	4.90
15-2	8.75	90-4	2.60
15-3	5.70	99-1	10.40
15-4	2.60	99-2	9.00
69-1	11.70	99-3	7.35
69-2	8.70	99-4	5.70
69-3	5.60	99-5	3.40
69-4	2.55	136-1	14.33
74-1	11.70	136-2	12.50
74-2	8.65	136-3	10.82
74-3	5.70	136-4	3.66
74-4	2.70	139-1	12.04
80-1	12.40	139-2	10.52
80-2	10.75	139-3	9.15
80-3	9.25	139-4	7.92
80-4	8.25	139-5	3.66
80-5	6.70	143-1	6.95
90-1	9.15	143-2	5.70
90-2	7.50	146-1	4.80
CENTER MINE (UNDISTURBED)			
367-1	3.96	368-1	4.85
367-2	1.68	368-2	3.35
367-3	7.47	368-3	1.50
367-4	10.82		
INDIAN HEAD MINE (USBM SPOILS TEST PLOT)			
34-1	5.65	38-3	4.15
34-2	4.20	38-4	1.15
34-3	2.65	44-1	4.75
38-1	10.10	44-2	3.30
38-2	7.20	44-3	1.90
INDIAN HEAD MINE (UNDISTURBED)			
117-1	8.84	117-4	3.00
117-2	6.80	117-5	1.65
117-3	4.75		

---

[a] Pressure-vacuum lysimeters are identified according to adjacent piezometer numbers. See figures 12, 14, 15, and 16 for locations.

the Center and Indian Head Mines and indicates the position of the intake zone of each. Analytical data for water samples obtained from this instrumentation are included in appendix D.

Groundwater Sampling Procedure

Typically, three different samples were collected from each piezometer; these included samples for major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, NO_3^{-}, F^{-}), hardness, total alkalinity, total dissolved solids, trace metals (Fe, Mn, Ni, Cu, Cd, Se, As, and Pb), and isotopes (^{18}O, ^{3}H). Sampling of soil water samplers (pressure-vacuum lysimeters) followed procedures as discussed in the previous section and typically resulted in sufficient sample for analyses of only trace, or trace and major constituents. Before taking a sample from a piezometer, the well was bailed until at least three times the volume of water standing in the well was removed. A bailer was used to collect the sample.

The pH, electrical conductivity, and temperature of the water were recorded in the field and sent to the lab with the sample. Dissolved oxygen was also recorded at some sites before and after bailing.

Water was collected in one-quart bottles for analysis of major ions, one pint for trace metals, one-half pint for ^{3}H, and 100 ml for ^{18}O. The major ions and trace metals samples were filtered through 0.45 μm paper using a pressurized filtration unit with a nitrogen gas drive (Ghering, 1976). The organic carbon samples were filtered through a 0.45 μm silver filter.

The major ions and trace metal samples were placed in plastic bottles with screw-on caps. The ^{18}O samples were placed in 100 ml glass serum vials with rubber stoppers and the ^{3}H samples were placed in eight-ounce glass bottles with screw-on metal caps. The isotope sample containers were filled to the top to exclude air.

The trace metals samples were preserved with 5 ml of concentrated Reagent grade nitric acid. The major ions, organic carbon and the isotope samples did not require any preservatives. The samples were labeled (sample identifier, well depth, date, pH, temperature, electrical conductivity, preservatives, and whether the sample was filtered), placed in styrofoam coolers packed with ice, and shipped by bus to the lab.

Groundwater Analyses

Major/Trace

The following methods of analysis were used on western North Dakota water samples since they were the most precise and the most efficient of the published procedures for the determination of large numbers of samples of western U.S. groundwaters (Williams et al., 1978).

Total hardness and alkalinity were determined volumetrically using Eriochrome Black T and a mixed bromcresol green/methyl red as the indicators. Total carbonate was determined by measuring the pH of the sample and total alkalinity.

The sulfate was determined indirectly using ion exchange and was measured spectrophotometrically at 240 nm.

The chloride was determined coulometrically using a KIM minicomputer.

The nitrates were analyzed using the brucine method and monitoring the line at 410 nm, the intensity of which is related to the concentration of the nitrate-brucine complex.

Conductivity was measured using a digital conductance meter and corrected to 25°C.

The boron was determined using the curcumin method. Boron forms a red complex with curcumin and the intensity of the complex is determined spectrophotometrically at 450 nm.

The following elements were determined by atomic absorption techniques, which have the necessary sensitivity for determination of metals in trace amounts.

Cu, Mg, Na, and K were determined by flame emission. Standard solutions were used in these determinations. Magnesium was determined by the difference between hardness and calcium determined by flame emission.

Mercury was determined by a cold vapor technique and measured by a Perkin Elmer (P.E.) 603 atomic absorption unit.

The following metals were determined by use of a P.E. 603 equipped with a graphite furnace. Arsenic was determined by reduction with $NaBH_4$. A standard prepared from As_2O_3 was used.

Selenium was determined in a similar fashion to arsenic, although the sample was first digested.

Cd, Cu, Cr, Fe, Mo, Mn, Ni, and Pb were all measured using suitable standards. These elements were determined using a P.E. 603 Atomic Absorption Spectrometer. The standards and conditions for these determinations are given in the appendix.

O-H Isotopes

Isotopic analyses were performed on suitably prepared samples with a Nuclide 3", 90° magnetic focusing mass spectrometer with dual inlet and detector systems. Procedures followed closely the techniques used in the U.S. Geological Survey Isotope Geology Laboratory, Denver, Colorado. $^{18}O/^{16}O$ ratios were measured by determining the CO_2 (46/44 amu) relative peak intensities. CO_2 was equilibrated with the water sample of interest for 24 hours at 25°C prior to the determination. D/H ratios were measured by determining the HD/H_2 relative peak intensity. Hydrogen was liberated from the water sample of interest by reduction over heated uranium turnings.

Laboratory Weathering Experiments

Choice of Technique

The focus of laboratory experimentation was on determination of the source and mechanisms of production of sulfate salts from selected overburden samples from the four mine sites. The rate of dissolution of salts is dependent on many factors in the field (precipitation, permeability, temperature, surface area of soil solids, etc.) and is very difficult to reproduce in the laboratory. We chose, therefore, to determine a more fundamental parameter than rate, the amount of available salt. This is best accomplished by exhaustive leaching. This could have been accomplished by flushing large amounts of water through soil columns, as was originally proposed for this study, but was done more efficiently by the techniques described below. The selected samples from the various sites used for laboratory experimentation are shown in table 1.

Exhaustive Leaching

Work done on western solum at Montana State University had indicated that eleven pore volumes of water extracted soluble salts either exhaustively or to a constant concentration (Williams et al., 1978). Therefore, selected soil samples were placed in excess water 8:1 to 64:1 by weight water:solum. Comparable results were obtained throughout this range for samples equilibrated at 25°C for at least two hours with continuous shaking. Extracted materials were analyzed as described in the previous section. More detail regarding the exhaustive leaching technique is given in the results section.

Accelerated Weathering Experiments

A set of accelerated weathering experiments was performed to evaluate the significance of extremes in temperature and pH, and alternate wet/dry cycles with aeration on the production of sulfate.

Weathering was simulated by subjecting 15 g samples of overburden in Erlenmeyer flasks to a variety of extremes. Each of these conditions is described on the title page to appendix F. Where drying is indicated, a vacuum oven was used.

Pan Experiments

These experiments were designed to test three aspects of overburden weathering: (1) exposure under milder conditions than tested in the accelerated weathering experiment; (2) an open system which would allow for bacterial action; (3) demonstration of the upward mobility of salts in evaporative conditions.

Selected samples of overburden from the four mine sites were placed in a mound in a small pan (evaporation dish), with a variety of waters added at the base. The upper portion of the mound was thus allowed to dry through evaporation. The pans were then observed to determine if upward movement of water and resultant precipitation of soluble salts was occurring on the surface of the mound. The different types of water used along with photographs (figs. 27-29) of the experiment are available on the explanation page.

Acid/Base Neutralization of Overburden Samples

A major concern associated with surface mining, particularly in the eastern United States, is the generation of acid drainage. Although sufficient sulfide is available in western spoils to generate conditions similar to those common in eastern areas, acid drainage is not commonly seen in this region. This suggests a natural buffering capacity within western spoils. We concluded that a set of simple experiments designed to evaluate the natural buffering capacity of selected overburden samples should prove instructive. Both the acid and base neutralization capacity were evaluated.

Small amounts (typically 2.5 g) of selected overburden material were added to the distilled water and brought to the desired pH with HCl or NaOH. The overburden samples were selected to evaluate the buffering capacity of glacial till and a complete range of textural types typical of the Tertiary sediments. The pH of the fluid was then monitored to evaluate changes with time.

Flooding Experiments

Background

For the geochemical processes discussed in the hydrogeochemical model to be relevant to groundwater chemical evolution in spoils settings, as well as in undisturbed settings, it is essential that water infiltrate below the rooting zone in the spoils to the water table. Although not originally proposed as part of this study, it was determined during the later part of the project that little if any data was available regarding the recharge potential of spoils. To address this question, at least in a preliminary sense, it was concluded that a set of conceptually simple experiments be attempted in various spoils settings.

These experiments consisted of flooding four diked areas within reclaimed spoils at the Center Mine with water. Neutron probe access tubes installed to depths of at least 3.75 m below ground surface were used to monitor water movement. Water table wells (piezometers) screened at depths of 16 to 30 metres below ground surface were present at each site. The four sites (Ctr 15, Ctr 70, Ctr 74, and Ctr 79) were identified according to the adjacent piezometers. (See figs. 16a-j.)

Site Descriptions

Sites Ctr 70, Ctr 74, and Ctr 79 were reclaimed under current reclamation practices. Site Ctr 15 is located in an area that was not reclaimed under current reclamation practices. The subsoil and topsoil at site Ctr 15 were not returned in separate lifts as at the other three sites. As observed during drilling, the soil material is a relatively homogeneous dark- to medium-gray, silty to sandy loam. The spoils at sites Ctr 70 and Ctr 79 were recontoured during the winter with scrapers. The spoils at these sites consist of dark- to medium-gray, silty clay loam to clay. The depth to the spoil is approximately 0.85 m at Ctr 70 and 0.50 m at site Ctr 79. The subsoil at sites Ctr 70 and Ctr 79 is buff to brown silty loam and occurs at depths between 0.15 to 0.25 metres below the surface. The topsoil at sites Ctr 70 and Ctr 79 is dark-brown to yellow-brown clayey silt to silty loam. The spoils at site Ctr 74 were recontoured during the spring with bulldozers. The topsoil and subsoil materials are the same at site Ctr 74 as at sites Ctr 70 and Ctr 79 with the topsoil extending to a depth of 0.30 m and the subsoil extending to 0.90 m.

Methods

Dikes were constructed around each access tube. The rectangular dikes, 0.6 m tall, were constructed of plywood sheets. The sheets were buried approximately 0.3 m below ground. The trenches in which the plywood was buried were refilled with bentonite and solum to prevent leakage around the dike. At site Ctr 74 the diked area covered 4.29 m^2. The area of the other three diked areas was 1.72 m^2. All the ponded areas were covered with plastic to limit evaporation losses during and after the flooding periods.

The neutron probe access tubes were installed with a Giddings Soil Probe over a year before the flooding experiments were started. A bentonite plug approximately 0.25 m thick was placed around the top of each tube to prevent the migration of water down the walls of the access tube.

Before any site was flooded neutron measurements were taken along the total length of the access tube. Once flooding began, probe measurements were taken several times an hour for the first one to two hours. The time interval then steadily increased to one reading every several hours and eventually reached one reading every 10 to 15 days.

The sites were all flooded as quickly as possible to a depth of approximately 0.10 m at the access tube. This depth was then maintained to within 0.01 m through the flooding period. At site Ctr 74 water was added from a tank truck. The flow rate was measured periodically with a bucket and stopwatch. When the infiltration rate into the solum became too low to maintain with the truck valves the water inflow was turned off and the water level in the diked area was allowed to fall several centimetres before more water was added to bring the level back to 0.10 m.

A different flooding procedure was used at the other three sites. These sites were flooded by hand, transferring water from barrels to the diked area with a bucket. Buckets of water were added whenever it was necessary to raise the water back to a depth of 0.10 m.

RESULTS

Textural Analyses

Results of textural analyses obtained at NDSU and at UND are given as tables 7 and 8, respectively. In the NDSU tests, the overburden materials were sampled from the bottom 7.6 cm (3 in) portion of all 123 Shelby tubes that had been used first in the bulk mineralogy, clay mineralogy, and sulfide studies. In 20 cases, there was insufficient sample for textural analyses remaining after those studies, so there are blank entries for these in table 7. The UND samples were taken near the center of the Shelby tube. As indicated in table 1, a total of 97 samples was available from this position in the tubes. Because no direct comparisons of results could be obtained with this sampling scheme, the set of fifteen samples

TABLE 7.--Texture analyses determined at the North Dakota State University (NDSU) Soils Department.

Core	Depth (m)	% Sand	% Silt	% Clay
CENTER 361	0.69- 0.76	--	--	--
	1.14- 1.22	34	24	42
	2.82- 2.40	--	--	--
	4.34- 4.42	--	--	--
	5.87- 5.94	54	17	29
	7.34- 7.47	--	--	--
	10.44-10.52	--	--	--
	11.96-12.04	--	--	--
	12.57-12.65	62	11	27
	14.10-14.17	--	--	--
	17.30-17.37	43	6	51
CENTER 366	2.06- 2.13	--	--	--
	7.39- 7.47	14	39	47
	8.92- 8.99	19	49	32
	11.20-11.28	10	58	32
	12.73-12.80	20	45	35
	14.25-14.33	0	5	95
	17.30-17.37	11	46	43
CENTER 380	1.30- 1.37	67	12	21
	2.06- 2.13	59	15	26
	2.82- 2.90	69	8	23
	3.58- 3.66	74	8	18
	4.34- 4.42	73	6	21
	5.11- 5.18	69	10	21
	5.87- 5.94	19	40	41
	6.63- 6.71	27	29	44
	7.39- 7.47	32	25	43
	8.15- 8.23	--	--	--
	9.68- 9.75	17	39	44
	10.44-10.52	24	36	40
	11.20-11.28	14	39	47
	11.51-11.58	14	39	47
	13.49-13.56	--	--	--
	14.25-14.33	34	34	32
	14.71-14.78	4	21	76
	15.01-15.09	13	46	41
	15.33-15.39	--	--	--
CONSOL 31	1.31- 1.37	0	38	62
	2.06- 2.13	0	32	68
	2.82- 2.90	0	35	65
	4.34- 4.42	32	42	26
	5.11- 5.18	--	--	--
	5.87- 5.94	14	50	36

TABLE 7.--Continued
Texture analyses determined at the North Dakota State University (NDSU) Soils Department.

Core	Depth (m)	% Sand	% Silt	% Clay
CONSOL 31, Cont.	6.63- 6.71	--	--	--
	7.39- 7.47	--	--	--
	8.15- 8.23	49	20	31
	8.92- 8.99	12	54	34
	9.68- 9.75	41	28	31
	10.44-10.52	--	--	--
	11.20-11.28	29	19	52
	11.96-12.04	7	13	80
	12.73-12.80	11	31	58
	14.10-14.17	4	12	84
	14.40-14.48	--	--	--
	15.01-15.09	0	39	61
	15.77-15.85	0	19	81
	16.54-16.61	5	16	79
	16.99-17.07	10	13	77
	17.45-17.53	--	--	--
INDIAN HEAD X-2	1.30- 1.37	--	--	--
	2.06- 2.13	35	14	51
	2.82- 2.90	57	10	33
	3.58- 3.66	0	30	70
	4.34- 4.42	0	32	68
	5.11- 5.18	0	38	62
	5.87- 5.94	0	26	74
	6.63- 6.71	0	19	81
	7.39- 7.47	0	7	93
	8.15- 8.23	0	0	100
	8.92- 8.99	17	50	33
	9.22- 9.30	7	63	30
	11.05-11.13	27	47	26
	11.51-11.58	24	55	21
FALKIRK 514	2.82- 2.90	0	28	72
	3.58- 3.66	0	32	68
	4.34- 4.42	0	5	95
	4.80- 4.88	21	21	58
	6.63- 6.71	0	42	58
	7.39- 7.47	11	50	39
	8.15- 8.23	4	48	48
	8.92- 8.99	4	27	69
	11.20-11.28	12	49	39
	11.96-12.04	6	47	47
	15.01-15.09	7	47	46

TABLE 7.--Continued
Texture analyses determined at the North Dakota State University (NDSU) Soils Department.

Core	Depth (m)	% Sand	% Silt	% Clay
FALKIRK 526	8.61- 8.69	--	--	--
	10.44-10.52	47	31	22
	11.96-12.04	27	46	27
	12.73-12.80	10	51	39
	13.49-13.56	17	55	28
	14.25-14.33	11	59	30
	15.01-15.09	6	59	35
	15.77-15.85	--	--	--
FALKIRK 561	8.92- 8.99	69	14	17
	9.22- 9.30	27	36	37
	10.29-10.36	8	58	34
	10.59-10.67	17	50	33
	11.51-11.58	6	60	34
FALKIRK 576*	0.99- 1.07	49	20	31
	2.97- 3.05	39	25	36
	4.5 - 4.57	36	26	38
	6.02- 6.10	44	22	34
	7.54- 7.62	36	23	41
	9.07- 9.14	31	23	46
	10.59-10.67	36	23	41
	11.66-11.73	36	21	43
	12.88-12.95	32	25	43
	15.16-15.24	34	25	41
	16.69-16.76	31	27	42
	18.06-18.14	34	25	41
	19.74-19.81	39	22	39
	21.26-21.34	36	27	37
	22.78-22.86	31	31	38

*Specimens also contained gravel.

TABLE 8.--Texture analyses determined at the University of North Dakota (UND).

Core	Depth (m)	% Gravel	% Sand	% Silt	% Clay
CENTER 361	0.79- 0.84	0.36	27.0	36.2	36.8
	2.48- 2.51	0.83	31.8	39.1	29.1
	5.55- 5.56	0.00	52.5	23.1	24.4
	7.09- 7.10	0.00	44.7	30.9	24.4
	12.25-12.27	0.00	65.9	16.3	17.8
	13.17-13.18		sample	destroyed	19.8
	14.07-14.09	0.00	64.0	17.1	18.9
	14.69-14.71	0.00	58.90	18.9	22.2
	15.46-15.47	0.05	64.1	19.2	16.7
	16.97-16.99	0.00	7.1	60.7	32.2
CENTER 366	0.97- 0.99	0.00	69.4	17.3	13.3
	1.73- 1.75	0.00	2.1	76.8	21.1
	3.27- 3.29	0.01	5.8	70.9	23.3
	7.10	38.40	3.3	58.9	37.8
	8.61- 8.63	0.2	18.1	63.0	18.9
	9.22- 9.23	0.00	0.8	62.9	36.3
	10.87-10.90	0.00	0.3	65.7	34.0
	12.42-12.54	0.00	12.7	66.3	21.0
	13.93-13.94	0.002	1.1	17.3	81.6
	16.99	0.00	27.5	48.1	24.4
CENTER 380	1.73- 1.75	0.01	58.4	26.1	15.5
	3.26- 3.28	0.00	26.6	54.6	18.8
	4.02- 4.04	0.5	73.7	14.0	12.3
	4.78- 4.80	0.2	74.6	14.3	11.1
	5.54- 5.56	0.00	9.5	59.4	31.1
	6.31- 6.32	0.00	6.4	54.8	38.8
	7.07- 7.09	0.2	38.8	35.6	25.6
	7.83- 7.85	0.2	9.0	42.2	48.8
	8.59- 8.61	0.00	13.3	51.2	35.5
	10.12-10.13	0.00	12.2	55.6	32.2
	10.87-10.90	0.04	21.6	52.8	25.6
	11.26-11.28	0.00	2.7	62.9	34.4
	13.16-13.18	0.4	33.4	47.6	19.0
	13.93-13.94	0.3	29.4	46.1	24.5
	14.36-14.40	1.4	35.2	46.8	18.0
CONSOL 31	0.97- 0.99	0.00	0.5	35.1	64.4
	1.73- 1.75	0.08	0.5	49.5	50.0
	2.49- 2.51	0.00	0.05	48.9	51.0
	4.03- 4.04	0.00	0.2	49.8	50.
	4.79- 4.80	0.00	2.1	66.8	31.1
	5.55- 5.56	1.7	2.8	67.9	29.3
	6.32- 6.34	0.00	9.5	68.3	22.2
	7.07- 7.09	0.00	2.7	56.2	41.1
	7.84- 7.85	0.00	56.6	24.5	18.9
	8.60- 8.61	0.00	59.4	20.6	20.0

TABLE 8.--Continued
Texture Analyses Determined at the University of North Dakota (UND).

Core	Depth (m)	% Gravel	% Sand	% Silt	% Clay
CONSOL 31, Cont.	9.36- 9.37	0.00	1.3	75.4	23.3
	10.12-10.13	0.1	3	64.0	33.0
	10.88-10.90	1.4	7.0	63.7	29.30
	11.64-11.66	0.00	0.2	45.4	54.40
	12.40-12.42	0.00	0.1	40.0	59.90
	13.78-13.79	0.00	0.2	19.9	79.9
	14.68-14.71	0.00	1.0	41.3	57.7
	15.45-15.47	0.00	0.4	41.8	57.8
	16.21-16.23	0.2	0.6	29.3	70.1
	16.67-16.69	0.0	0.2	29.8	70.0
	17.13-17.15	0.00	0.1	22.1	77.8
INDIAN HEAD X-2	0.98- 0.99	0.02	51.3	23.2	25.5
	1.74- 1.75	0.01	60.2	20.9	18.9
	2.49-2.51	0.00	62.3	19.9	17.8
	3.26- 3.28	0.4	66.1	17.2	16.7
	4.02- 4.04	0.06	0.9	15.8	83.3
	4.79- 4.80	0.00	0.2	63.2	36.6
	5.55- 5.56	0.00	0.02	42.3	57.7
	6.31- 6.32	0.00	0.2	34.3	65.5
	7.07- 7.09	0.1	0.6	23.8	75.6
	7.96- 7.97	0.1	0.6	43.8	55.6
	8.59- 8.61	0.03	0.5	9.5	90.0
	8.99- 9.30	0.00	2.2	72.3	25.5
	10.73-10.74	0.00	1.8	74.9	23.3
FALKIRK 514	2.51- 2.53	2.2	5.5	32.1	62.4
	3.26- 3.28	0.0	0.7	17.2	82.1
	4.02- 4.04	0.0	0.3	42.0	57.0
	6.32- 6.35	0.00	0.5	93.9	5.6
	7.09- 7.10	0.00	0.1	56.6	43.3
	10.88-10.90	0.00	2.5	65.3	32.2
FALKIRK 526	8.28- 8.31	0.2	1.1	40.0	58.9
	10.11-10.13	0.1	5.9	59.7	34.4
	11.63-11.66	0.00	28.7	55.8	15.5
	12.40-12.42	0.00	4.3	74.6	21.1
	13.16-13.18	0.00	0.9	68.0	31.1
	13.93-13.94	0.1	1.6	75.1	23.3
	14.69-14.71	0.00	1.4	74.2	24.1
FALKIRK 561	8.60- 8.61	0.02	68.5	18.2	13.3
FALKIRK 576	0.67- 0.69	0.00	10.8	48.1	41.1
	2.65- 2.67	8.3	36.8	31.7	31.5
	4.17- 4.19	5.9	33.8	35.5	30.7
	5.70- 5.72	9.7	36.1	33.2	30.7

TABLE 8.--Continued
Texture Analyses Determined at the University
of North Dakota (UND).

Core	Depth (m)	% Gravel	% Sand	% Silt	% Clay
FALKIRK 576, Cont.	7.23- 7.24	5.5	33.6	34.7	31.7
	8.74- 8.76	2.9	20.8	42.6	36.6
	10.27-10.29	3.4	40.7	32.7	26.4
	12.53-12.57	3.2	30.3	36.5	33.2
	14.84-14.86	3.9	33.2	34.4	32.4
	16.36-16.38	3.7	26.6	39.9	33.5
	17.73-17.75	1	26.7	39.7	33.6
	19.41-19.43	3.3	29.4	37.3	33.3
	20.93-20.96	1.8	31.0	37.3	31.7
	22.48-22.50	2.3	30.3	37.9	31.8

from Falkirk 576 from the bottom of the tubes was run at both laboratories. The results of this comparison are shown in table 9.

Before interpreting the results of the textural analyses it is instructive to examine the comparison in table 9. The 22.9 m of samples from Falkirk 576 are dominantly till and contain approximately equal proportions of sand, silt, and clay along with some gravel. If the determinations of sand, silt, and clay are simply averaged across the 15 specimens, the following is observed:

	Average of		
	% sand	% silt	% clay
NDSU	36.3	24.3	39.4
UND	30.8	36.1	33.0

The NDSU measurements are about 18 percent greater in sand, 33 percent lower in silt, and 19 percent greater in clay than the UND measurements. Greater attention was given to sand (and gravel) determinations in the UND measurements, while the NDSU technique determined sand by subtraction of the silt and clay result from 100 percent, assuming that all sand has settled at the time before the first hydrometer measurement is made (after 40 seconds). Thus, the UND data are believed to be more accurate for sand. The only substantial difference in silt and clay measure-

TABLE 9.--Comparison of texture analyses
on Falkirk 576 specimens.

Depth (m)	% Sand*	% Silt*	% Clay*
0.99- 1.07	49	20	31
	43.8	31.5	24.7
2.97- 3.05	39	25	36
	33.1	37.2	29.7
4.50- 4.57	36	26	38
	33.3	34.7	32.0
6.02- 6.10	44	22	34
	36.3	33.5	30.2
7.54- 7.62	36	23	41
	31.0	34.3	34.5
9.07- 9.14	31	23	46
	25.2	37.2	37.6
10.59-10.67	36	23	41
	30.3	33.6	36.1
11.66-11.73	36	21	43
	29.8	35.4	34.8
12.88-12.95	32	25	43
	28.1	37.1	34.8
15.16-15.24	34	25	41
	29.6	37.1	33.3
16.69-16.76	31	27	42
	25.5	39.3	34.2
18.06-18.14	34	25	41
	29.4	36.8	33.8
19.74-19.81	39	22	39
	26.7	39.6	33.7
21.26-21.34	36	27	37
	30.0	37.5	32.5
22.78-22.86	31	31	38
	30.0	36.8	33.2

*Wt %; NDSU data have 2 significant figures, UND data have 3.

ment techniques is in the extent of dispersion treatment. The overnight treatment with rigorous agitation at NDSU compared to an overnight soak at UND is likely to have disagglomerated silt-sized particles made up of clay minerals more effectively. It is possible that the addition of the one percent Na_2CO_3 to the dispersion liquid at NDSU also contributed to more effective dispersion. Thus, the NDSU results are expected to be a more accurate representation of the silt and clay fractions. It should be noted that the two-hour hydrometer reading used at both laboratories places the clay-silt boundary at about 4 μm instead of the more conventional 2 μm. These comparison tests have shown that in any future studies where precise texture analysis is crucial, interlaboratory comparison and calibration with more time consuming but accurate procedures will be necessary.

For the purposes of this study, the analyses as performed by the two laboratories fulfill the intended purpose of demonstrating the wide range of textural types found in Tertiary coal-bearing sediment in western North Dakota. The data suggest a predominance of silt- and clay-rich sediment in the Tertiary units. Predominantly clayey sediments are common in samples obtained from Indian Head X-2, Consol 31, and Falkirk 514 (tables 7 and 8). In addition, clay-rich Tertiary sediments are found in scattered positions at most of the sample locations. Tertiary sediments consisting predominantly of sand are less common than fine-textured sediments. Sandy sediments are common at Center sites 361 and 380 and are present in samples from the upper two to three metres at Indian Head X-2. As previously discussed, the glacial tills at Falkirk site 576 consist of essentially equal percentages of sand, silt, and clay.

Mineralogical Analyses

Bulk Mineralogy

As previously discussed, 123 samples from the bottom 7.6 cm of each Shelby tube were analyzed by XRD to determine the bulk mineralogy of each sample. In addition, samples from the middle of 97 of the Shelby tubes were analyzed to determine bulk mineralogical characteristics. (See table 1.) These data are summarized by sampling location in appendix B. Since XRD analyses can only be considered as semi-quantitative, these data have been presented according to the height of the major peak for each mineral. The general lithology and dolomite/calcite ratio for each sample is also included in appendix B.

Each sample from the bottom 7.6 cm of the 123 Shelby tubes is identified according to the total depth interval represented by that tube (typically 0.762 m). Each sample from the center of a tube is identified according to the actual interval represented by that sample (app. B).

The bulk mineralogical data can be summarized as follows:

1. Quartz and plagioclase are present in all the Tertiary Sentinel Butte sediments and all glacial till samples.
2. Alkali feldspar is present in 91 percent of the Sentinel Butte samples and 74 percent of the glacial till samples.
3. Dolomite is present in all the glacial till samples. Dolomite is present in 89 percent of the Sentinel Butte samples.
4. Calcite is present in all the glacial till samples. Calcite is present in 67 percent of the Sentinel Butte samples. If calcite is present, dolomite is also present. Calcite is more abundant than dolomite in only 16 percent of the samples containing both calcite and dolomite.
5. In general, the dolomite/calcite ratios for Sentinel Butte sand are larger than 1.80; for fine-textured Sentinel Butte sediments the ratios are generally smaller than 1.80.
6. Montmorillonite is present in all the glacial till samples and at least 98 percent of the Sentinel Butte samples. (A few samples were run with the shield in such a position as to obliterate the 14Å peak). The detailed clay mineralogy data discussed later in this section indicate the presence of montmorillonite in all the samples.
7. Illite-mica is present in all the samples.
8. Chlorite is identifiable in all but two of the glacial till samples and is present in all the Sentinel Butte samples.
9. Kaolinite is a minor constituent in some of the Sentinel Butte samples. (The clay mineralogy studies indicated some kaolinite in nearly all samples.)
10. Gypsum is present in 27 percent of the glacial till samples and probably present (near detection limit) in another 27 percent. Gypsum is present in 7 percent of the Sentinel Butte samples,

particularly in those samples from the upper 4 metres of the landscape.

11. Pyrite, although commonly seen in nodular form in outcrops of the Sentinel Butte Formation, was seldom detected in the samples by XRD. This observation is attributed to the fact that the pyrite, as discussed later in this section, is very finely disseminated in the sample matrix and typically below the XRD detection limit (less than one percent).

Clay Mineralogy

Table 10 lists the relative abundances of the four clay mineral groups determined in the X-ray studies. Not included in the table is the fact that some quartz was usually observed in the $< 2 \mu m$ clay fraction. These data clearly indicate that smectite and illite-mica are the predominant clay minerals in all the samples. As noted earlier, the smectite (S) is dominantly Na-montmorillonite. The illite-mica (I) reflections were sharp and indicated good crystallinity, better in fact than the Fithian, IL, illite used as a standard. The chlorite reflections were likewise comparatively sharp. A number of entries have "K?", indicating uncertainty in the presence of even small amounts of kaolinite. The strong (001) reflections of kaolinite occur close to those of chlorite and can overlap them when the chlorite is much more abundant. In most cases, however, there was sufficient resolution to unambiguously identify the presence of kaolinite.

An interesting correlation can be made between the sediment textures (table 7) and these relative clay mineral abundances. High clay content correlates strongly to greater illite-mica abundance. In 33 of the 35 specimens that had "I > S" or "I >> S" in table 10 and for which textural analyses were available, the clay content was > 40 wt %. Statistical textural data for these 33 specimens (using the NDSU results) are:

	% sand	% silt	% clay
$\bar{x}$	9	27	64
s	-	±14	±18

also, the greater relative smectite (Na-montmorillonite) abundances correlate with the more sandy, less clayey sediments. For 18 of the specimens

TABLE 10.--Relative proportions of clay minerals in 123 Shelby tube samples determined by X-ray diffraction.

Core	Depth (m)	Relative Proportion
CENTER 361	0.69- 0.76	S > I > K ≈ C*
	1.14- 1.22	S > I > K ≈ C
	2.82- 2.90	S > I > K > C
	4.34- 4.42	S > I ≫ K ≈ C
	5.87- 5.94	S ≫ I > C(>K?)
	7.39- 7.47	S ≫ I > C ≫ K
	10.44-10.52	S ≫ I > C(>K?)
	11.96-12.04	S ≫ I > C > K
	12.57-12.65	S ≫ I > C > K
	14.10-14.17	S ≫ I > C > K
	17.30-17.37	I > S > C > K
CENTER 366	2.06- 2.13	I ≫ S ≈ C(>K?)
	7.39- 7.47	I > S > C ≈ K
	8.92- 8.99	S > I > C > K
	11.20-11.28	S ≫ I > C > K
	12.73-12.80	S ≫ I > C > K
	14.25-14.33	I ≫ S ≈ C > K
	17.30-17.37	S > I > C > K
CENTER 380	1.30- 1.37	S ≫ I > C > K
	2.06- 2.13	S > I > C > K
	2.82- 2.90	S > I > C ≈ K
	3.58- 3.66	S ≫ I > C > K
	4.34- 4.42	S ≫ I > C(>K?)
	5.11- 5.18	S ≫ I > C(>K?)
	5.87- 5.94	I > S > C > K
	6.63- 6.71	I > S > C > K
	7.39- 7.47	I > S > C(>K?)
	8.15- 8.23	I ≫ S ≈ C(>K?)
	9.68- 9.75	I ≫ S ≈ C ≫ K
	10.44-10.52	I ≫ S ≈ C ≫ K
	11.20-11.28	I ≫ S ≈ C ≫ K
	11.51-11.58	I ≫ C > S ≫ K
	13.49-13.56	I ≫ S ≈ C ≫ K
	14.25-14.33	S > I ≈ K ≈ C
	14.71-14.78	I > S > C > K
	15.01-15.09	S > I > C > K
	15.32-15.39	S ≫ I > C > K

TABLE 10.--Continued
Relative proportions of clay minerals in 123 Shelby tube samples determined by X-ray diffraction.

Core	Depth (m)	Relative Proportion
CONSOL 31	1.30- 1.37	I > S > C > K
	2.06- 2.13	I > S > C > K
	2.82- 2.90	I > S > C > K
	4.34- 4.42	S >> I >> C > K
	5.11- 5.18	S >> I >> C > K
	5.87- 5.94	S >> I >> C > K
	6.63- 6.71	S >> I >> C > K
	7.39- 7.47	S >> I > C > K
	8.15- 8.23	S >> I >> C >> K
	8.92- 8.99	S >> I > C > K
	9.68- 9.75	S >> I >> C > K
	10.44-10.52	S >> I > C > K
	11.20-11.28	I ≈ S > K ≈ C
	11.96-12.04	I > S ≈ C > K
	12.73-12.80	I > S > C > K
	14.10-14.17	I >> S ≈ C > K
	14.40-14.48	I >> S ≈ C > K
	15.01-15.09	I >> S ≈ C >> K
	15.77-15.85	I >> S > C > K
	16.54-16.61	I >> S > C >> K
	16.99-17.07	I >> S ≈ C > K
	17.45-17.53	I >> S > C > K
INDIAN HEAD X-2	1.30- 1.37	S >> I > C > K
	2.06- 2.13	S >> I > C > K
	2.82- 2.90	S >> I > C > K
	3.58- 3.66	I > S > C >> K
	4.34- 4.42	I >> S > C > K
	5.11- 5.18	I ≈ S > C >> K
	5.87- 5.94	I > S > C > K
	6.63- 6.71	I >> S > C > K
	7.39- 7.47	I >> S > C >> K
	8.15- 8.23	I >> S ≈ C > K
	8.92- 8.99	I > S > C ≈ K
	9.22- 9.30	I > S > C >> K
	11.05-11.13	S >> I > C > K
	11.51-11.58	S > I > C > K
FALKIRK 514	2.82- 2.90	I > S > K > C
	3.58- 3.66	S > I > K(>C?)
	4.34- 4.42	I > S > K(>C?)
	4.80- 4.88	I > S > K(>C?)
	6.63- 6.71	I > S > C > K
	7.39- 7.47	S > I > C > K
	8.15- 8.23	S > I > C > K

TABLE 10.--Continued
Relative proportions of clay minerals in 123 Shelby tube samples determined by X-ray diffraction.

Core	Depth (m)	Relative Proportion
FALKIRK 514, Cont.	8.92- 8.99	S > I > C > K
	11.20-11.28	S > I > C > K
	11.96-12.04	S > I > C >> K
	15.01-15.09	S > I > C > K
FALKIRK 526	8.61- 8.69	I > S > C > K
	10.44-10.52	S >> I > C ≈ K
	11.96-12.04	S >> I > C > K
	12.73-12.80	S > I > C > K
	13.49-13.56	S >> I > C > K
	14.25-14.33	S > I > C > K
	15.01-15.09	S > I > C > K
	15.77-15.85	S ≈ I > C >> K
FALKIRK 561	8.92- 8.99	S > I >> C ≈ K
	9.22- 9.30	S > I >> C(>K?)
	10.29-10.36	S > I > C > K
	10.59-10.67	S > I > C > K
	11.51-11.58	S > I > C > K
FALKIRK 576	0.99- 1.07	S ≈ I > K > C
	2.97- 3.05	S ≈ I > K > C
	4.5 - 4.57	S ≈ I > K > C
	6.02- 6.10	S ≈ I > K > C
	7.54- 7.62	S > I > K > C
	9.07- 9.14	S > I > K > C
	10.59-10.67	S > I > K > C
	11.66-11.73	S > I > K > C
	12.88-12.95	S > I > K > C
	15.16-15.24	S > I > K > C
	16.69-16.76	S > I > K ≈ C
	18.06-18.14	S > I > K ≈ C
	19.74-19.81	S > I > K > C
	21.26-21.34	S ≈ I > K > C
	22.78-22.86	S ≈ I > K > C

*S = Smectite
K = Kaolinite
I = Illite-mica
C = Chlorite

where the relative clay abundance was S >> I, the statistical textural data are:

	% sand	% silt	% clay
$\bar{x}$	42	27	29
s	±22	±18	± 8

Pyrite Studies

All sand, silt, and clay separates from the clay mineralogy study were screened by X-ray fluorescence for a sulfur signal. None of the clay fractions, relatively few of the silt fractions, but more than half of the sand fractions had a sulfur signal. Those silts and sands with substantial sulfur contents were studied directly by XRD. Pyrite could be detected only in two sand fractions:

Center 366	14.25-14.33 m
Consol 31	14.40-14.48 m

The former had pyrite at the 10-20 weight percent level in a matrix of quartz, feldspar, calcite, and dolomite. Pyrite was less abundant in the latter.

When heavy mineral separations were carried out on all of the sand fractions having a sulfur signal, nearly one-quarter of the specimens were found to contain pyrite and, in the case of two sands from Center 361, the marcasite polymorph also. Table 11 lists the pyrite occurrences and whether the pyrite constituted a "major" or "minor" portion of the sink fraction. These designations are strictly subjective and are based on the intensity of the pyrite reflections in X-ray diffractograms. Figures 17 through 21 show typical habits of pyrite, marcasite, and gypsum on pyrite picked from these sands, in SEM photomicrographs.

Sulfur Analyses

The results of sulfur analyses of selected samples from the four study sites are presented in table 12. These data indicate that total sulfur concentrations in the overburden at the North Dakota sites are relatively low and range over three orders of magnitude. Conversion to μg/g indicates a

TABLE 11.--Pyrite occurrences in sand fraction.

Core	Depth (m)	Lithology[a]	Texture[b]			Pyrite in Sand[c]
			Sand	Silt	Clay	
CENTER 361	4.34- 4.42	Sand	--	--	--	Minor
	11.96-12.04	Sand	--	--	--	Major pyrite and marcasite
	12.57-12.65	Sand	62	11	27	Major
	14.10-14.17	Sand	--	--	--	Major pyrite and marcasite
	17.30-17.37	Silt/Clay	43	6	51	Minor
CENTER 366	2.06- 2.13	Sand	--	--	--	Minor
	7.39- 7.47	Clay	14	39	47	Minor
	12.73-12.80	Silt/Sand	20	45	35	Minor
	17.30-17.37	Clay	11	46	43	Minor
CENTER 380	7.39- 7.47	Sand	32	25	43	Major
	13.49-13.56	Clay	--	--	--	Minor
	14.25-14.33	Sand	34	34	32	Major
	15.01-15.09	Silt	13	46	41	Minor
	15.32-15.39	Sand	--	--	--	Major
CONSOL 31	9.68- 9.75	Sand	41	28	31	Major
	10.44-10.52	Sand	--	--	--	Major
	14.40-14.48	Clay	--	--	--	Major
	15.01-15.09	Clay	--	--	--	Major
INDIAN HEAD X-2	8.92- 8.99	Sand/Silt	17	50	33	Major
	11.05-11.13	Sand	27	47	26	Minor
	11.51-11.58	Silt	24	55	21	Major
FALKIRK 514	7.39- 7.47	Clay	11	50	39	Major
	8.92- 8.99	Silt	4	27	69	Major

TABLE 11.--Continued
Pyrite occurrences in sand fraction.

Core	Depth (m)	Lithology[a]	Texture[b]			Pyrite in Sand[c]
			Sand	Silt	Clay	
FALKIRK 526	11.96-12.04	Sand	24	46	27	Minor
FALKIRK 576	18.06-18.14	Till[d]	34	25	41	Minor
	19.74-19.81	Till	39	22	39	Major[e]
	21.26-21.34	Till	36	27	37	Minor
	22.78-22.86	Till	31	31	38	Minor

---

[a] Determined by visual examination of samples when removed from Shelby tube.

[b] Texture Analyses at NDSU--see text for discussion.

[c] "Major" means that more than 10% of the original sand was in the sink fraction and more than 25% of the sink fraction consisted of pyrite (or marcasite) grains, crystals, or nodules. "Minor" means that at least a few pyrite grains, crystals, or nodules were observed in a sink fraction.

[d] Gravel was noted in all Falkirk 576 specimens.

[e] Pyrite was observed in the bulk mineralogical analysis.

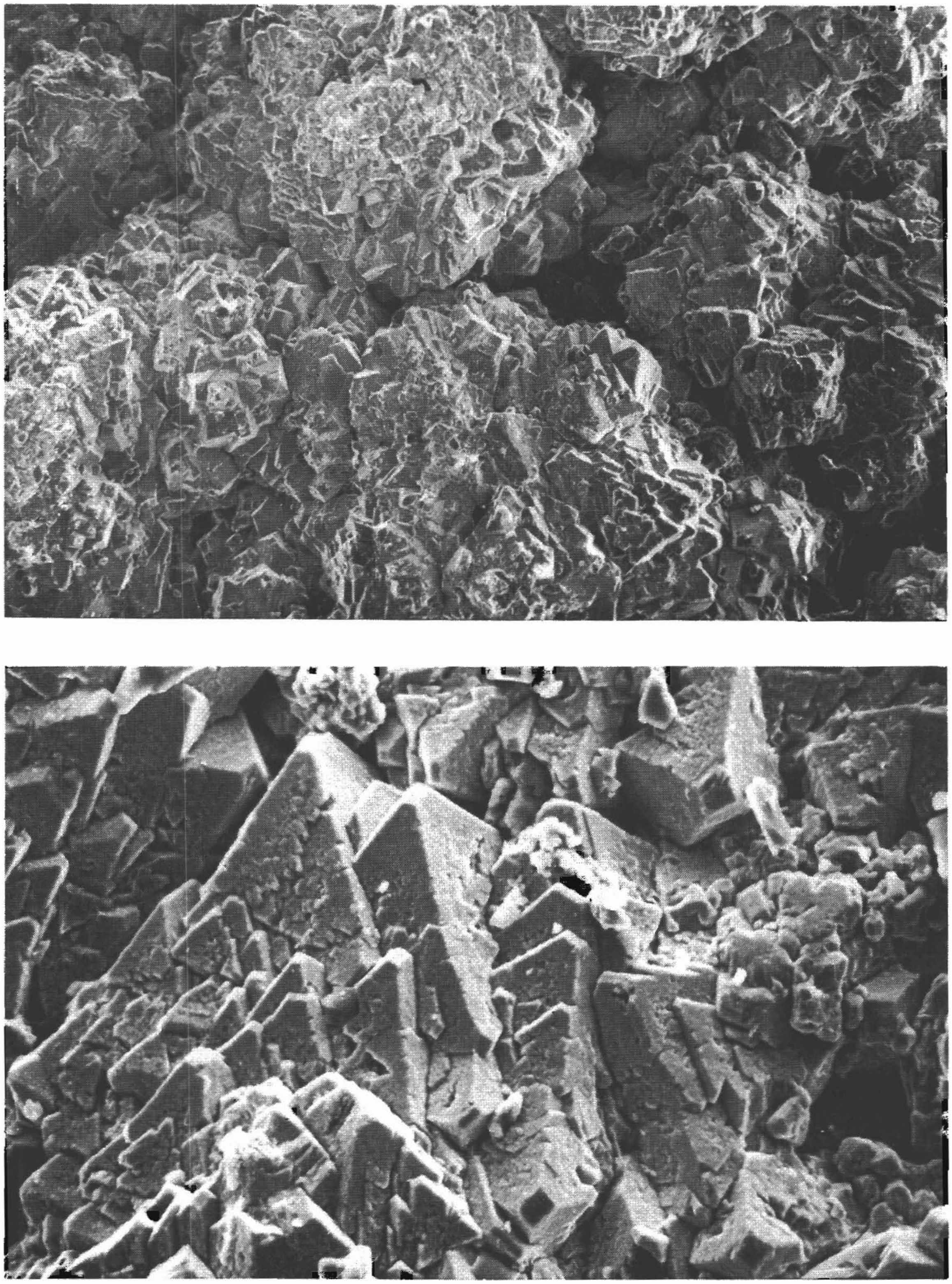


Figure 17. SEM photomicrograph of pyrite from the sand fraction of Consol 31, 14.40-14.48 m, at a magnification of 100x (top) and 750x (bottom).

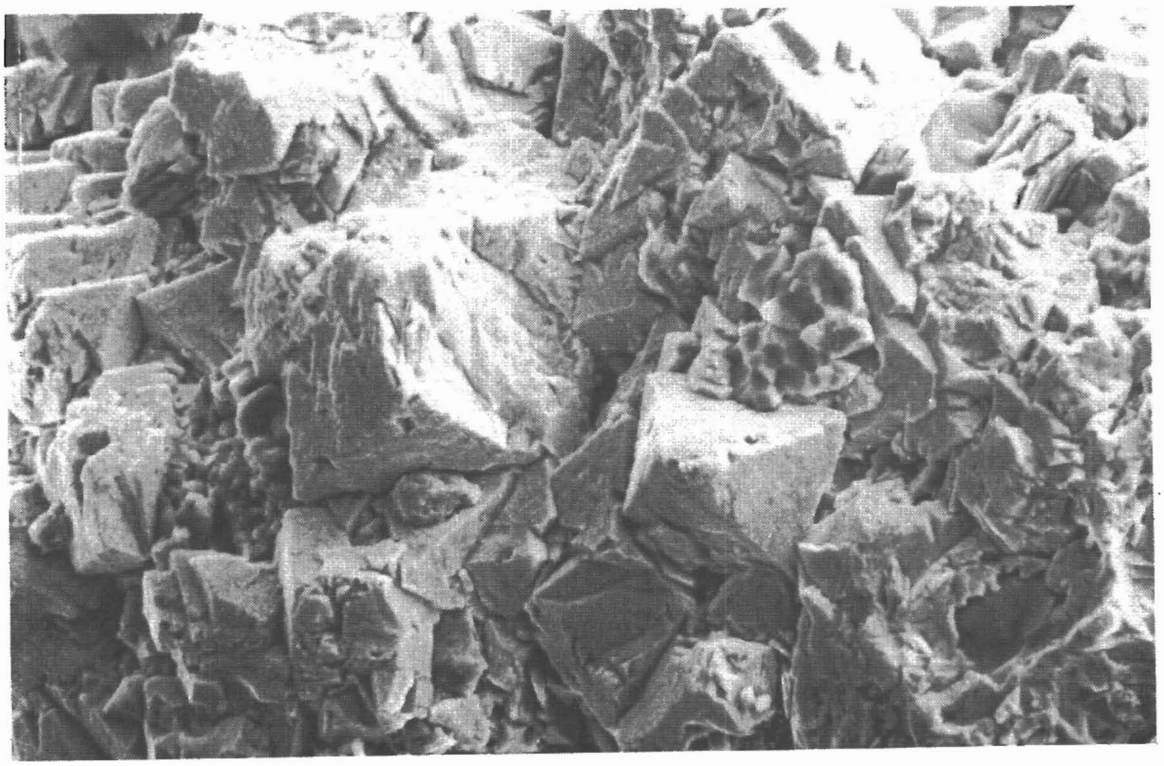


Figure 18. SEM photomicrograph of pyrite from the sand fraction of Indian Head X-2, 11.05-11.3 m (800 x).

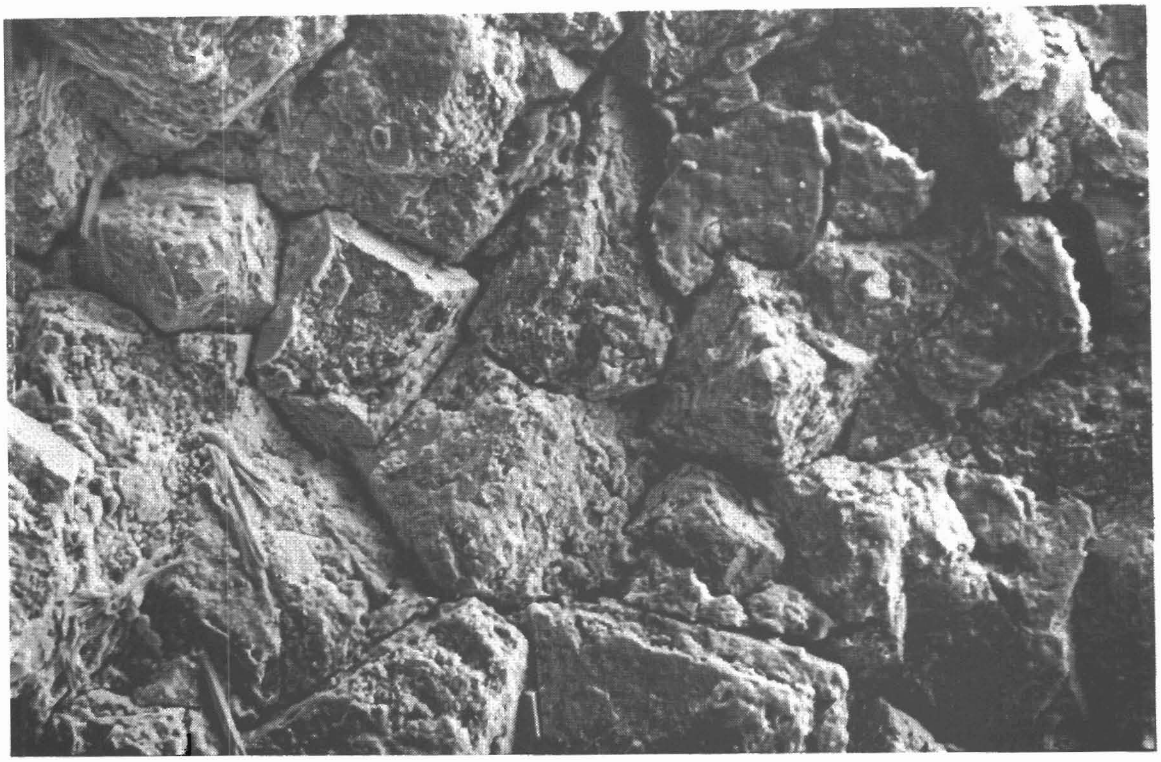


Figure 19. SEM photomicrograph of pyrite from the sand fraction of Falkirk 526, 21.26-21.34 m (300 x).

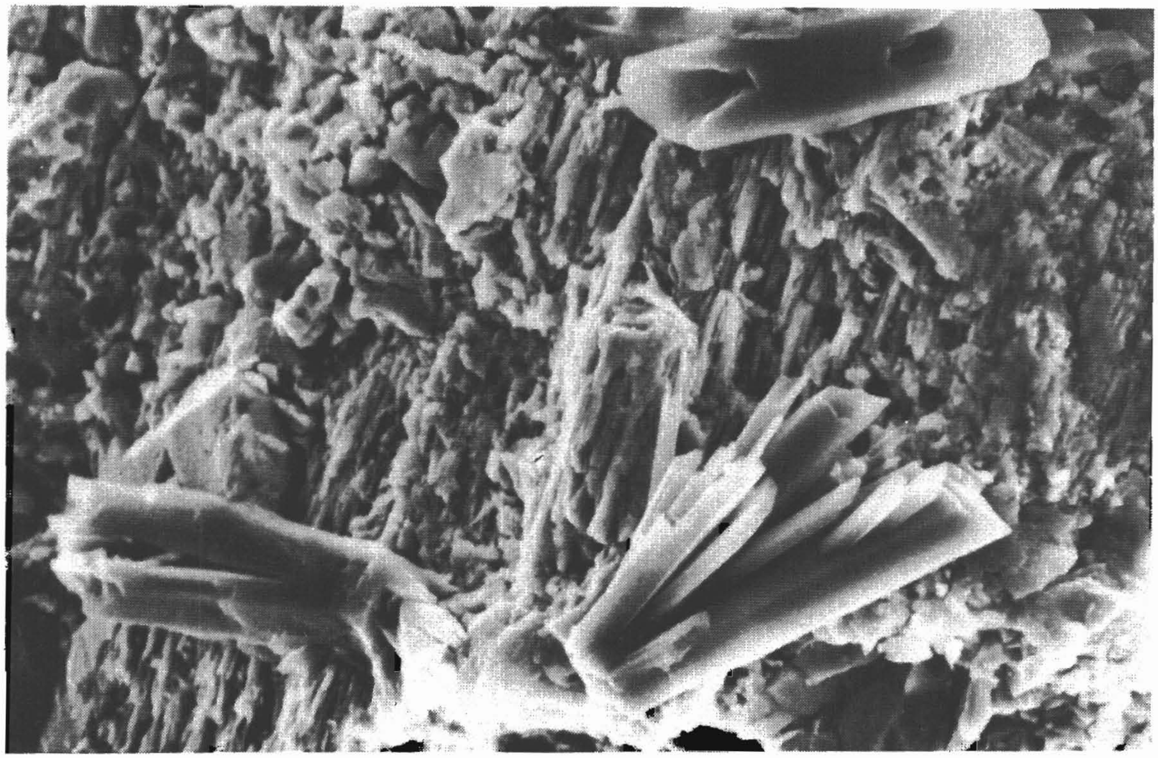


Figure 20. SEM photomicrograph of gypsum on pyrite from the sand fraction of Falkirk 576, 21.26-21.34 m (1800 x).

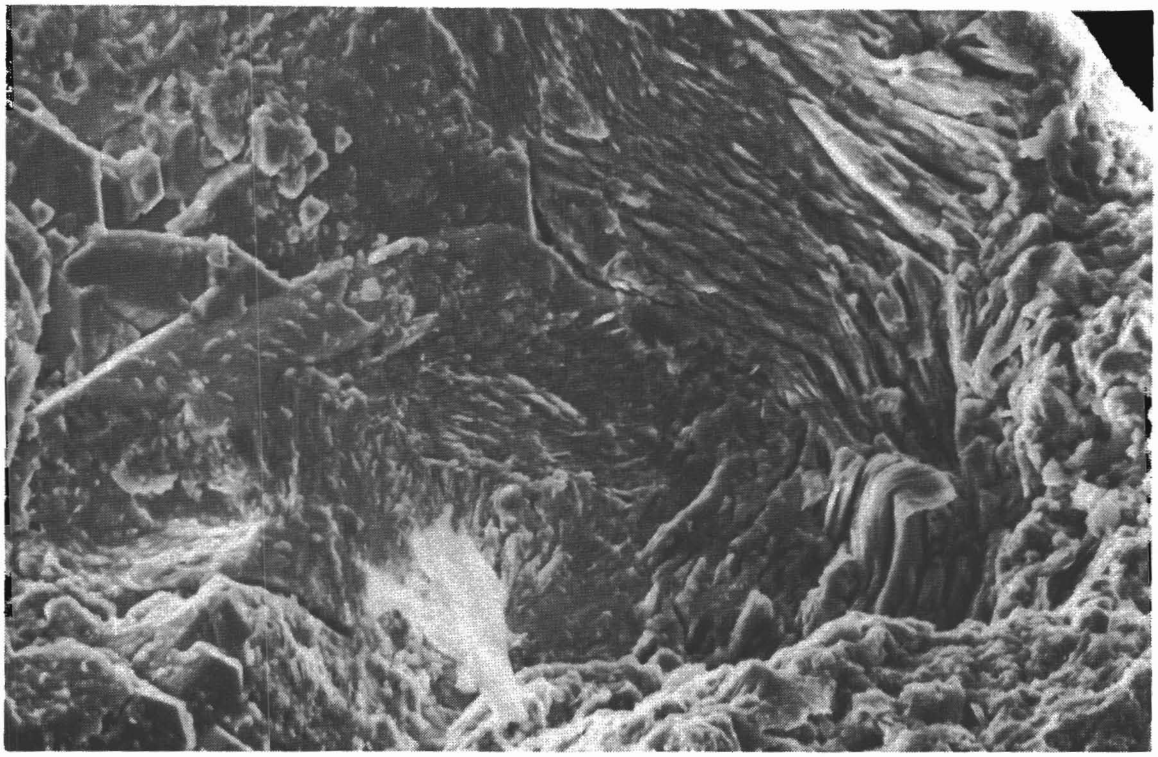


Figure 21. SEM photomicrograph of marcasite from the sand fraction of Center 361, 12.57-12.65 m (1200 x).

TABLE 12.--Results of sulfur analyses of selected overburden samples from the four North Dakota study sites. See Table 3 for lithologic description of samples.

Sample Location	Depth (ft)*	(% based on dry soil weight)		
		% S Total	% S Sulfide Elemental Residual	% S Extractable
CENTER 380	17 -19.5	0.013	0.009	0.004
	24.5-27	0.080	0.068	0.012
	27 -29.5	0.079	0.069	0.010
	34.5-37	0.156	0.151	0.005
	37 -38	0.090	0.087	0.003
	42 -44.5	0.048	0.041	0.007
	47 -48.5	0.190	0.170	0.020
	49.5-50.5	0.046	0.038	0.008
INDIAN HEAD X-2	17 -19.5	0.046	0.021	0.025
	19.5-22	0.046	0.011	0.035
	22 -24.5	0.046	0.010	0.036
	24.5-27	0.046	0.015	0.031
	27 -29.5	0.310	0.300	0.010
FALKIRK 526	27 -28.5	0.016	0.010	0.006
	37 -39.5	0.063	0.055	0.008
	39.5-42	0.026	0.025	0.001
	42 -44.5	0.023	0.020	0.003
	44.5-47	0.055	0.048	0.007
	47 -49.5	0.088	0.075	0.013
	49.5-52	0.059	0.050	0.009
CONSOL 31	22 -24.5	0.059	0.021	0.038
	34.5-37	0.078	0.061	0.017
	37 -39.5	0.047	0.032	0.015
	39.5-42	0.310	0.280	0.030
	44.5-46.5	0.044	0.034	0.010
	52 -54.5	0.030	0.025	0.005
	54.5-56	0.029	0.022	0.007

---

*Multiply by 0.3048 to convert to metres.

maximum for total sulfur of 2,000 μg/g. The average value, if an average has any meaning, is approximately 200 μg/g. In all but a few samples, the extractable sulfur represents a relatively small percentage of the total sulfur.

The sulfur concentrations do not show any specific trends with respect to depth at the various sampling sites. However, sulfur analyses were not performed on near-surface samples. The samples showing the greatest concentrations of total sulfur (Center 380, 34.5-37, and 47-48.5; Indian Head X-2, 27-29.5; Consol 31, 39.5-42) are all fine-textured (two are also carbonaceous) and unoxidized. (See table 3.) The samples having the lowest concentrations of total sulfur (Center 380, 17-19.5; Falkirk 526, 27-28.5, 39.5-42, 42-44.5) are all oxidized samples but represent a wide range of textures.

These observations are in agreement with the hydrogeochemical model which suggests sulfide dissolution, sulfate precipitation, and sporadic flushing of sulfate salts from the upper (oxidized) portion of the landscape. Thus, total sulfur concentrations in these settings typically should be greatest in unoxidized sediments.

It is assumed that original precipitation of the sulfur occurred under reducing conditions early in the history of the sediments. The fine-textured Tertiary sediments typically are assumed to have been deposited under reducing conditions in flood basin environments. The total sulfur data thus appear to substantiate this environmental interpretation and suggest that unoxidized fine-textured Tertiary sediments, when emplaced in an oxidizing environment, offer a significantly greater potential to generate sulfate than do the coarser sediments.

Saturated-Paste Extract Analyses

Data generated by analyses of saturated-paste extracts of near-surface spoils materials from various locations at the Center Mine and the USBM plot at the Indian Head Mine are presented in appendix C. These analyses were performed for the purpose of determining the general chemical characteristics of the spoils at the two study sites. The results indicate significant differences in the chemistry of spoils at the two mines.

For purposes of comparison, it is instructive to note the electrical conductivity (EC) and sodium adsorption ratio (SAR) of the spoils at these sites (app. C). The mean EC for spoils at the Center Mine is 2.9 with a standard deviation of 1.6. The mean EC for spoils at the Indian Head Mine is 5.2 with a standard deviation of 2.0. The mean SAR for spoils at the Center Mine is 3.6 with a standard deviation of 2.9. SAR values for spoils at the Indian Head site have a mean of 13.9 with a standard deviation of 5.6.

These data indicate that the near-surface spoils at the Indian Head site have the capacity to generate much more highly mineralized pore water than spoils at the Center Mine. The predominant species in solution in pore water in spoils at the Indian Head Mine are sodium and sulfate. The predominant species in solution in pore water in spoils at the Center Mine vary from sodium and sulfate to calcium, magnesium, and sulfate (app. C).

These data indicate a significant increased sodic hazard in spoils at Indian Head when compared to spoils at the Center Mine. Assuming some degree of vertical infiltration (recharge) in spoils at both mines, these data suggest a significantly greater potential for the generation of highly mineralized groundwater in the spoils at Indian Head than at Center.

Subsurface Water Flow and Occurrence

General

The general characteristics of groundwater flow in undisturbed settings in western North Dakota were discussed in the introduction. Detailed discussions of the hydrogeologic conditions in undisturbed settings at the Center, Indian Head, and Falkirk Mines can be found in Moran et al., 1978; Groenewold et al., 1979; and Rehm et al., 1980, 1982. Discussions of the hydrogeology of spoils settings at the Center and Indian Head Mines can be found in Groenewold et al., 1980, 1981; Rehm, 1982; and Rehm et al., 1980.

Figure 22 is a hydrostratigraphic cross section of the Center Mine. The location of this cross section is shown on figure 15. The hydrogeologic conditions shown on this cross section are typical of all the North Dakota study sites. As is evident from figure 22, recharge occurs over most of

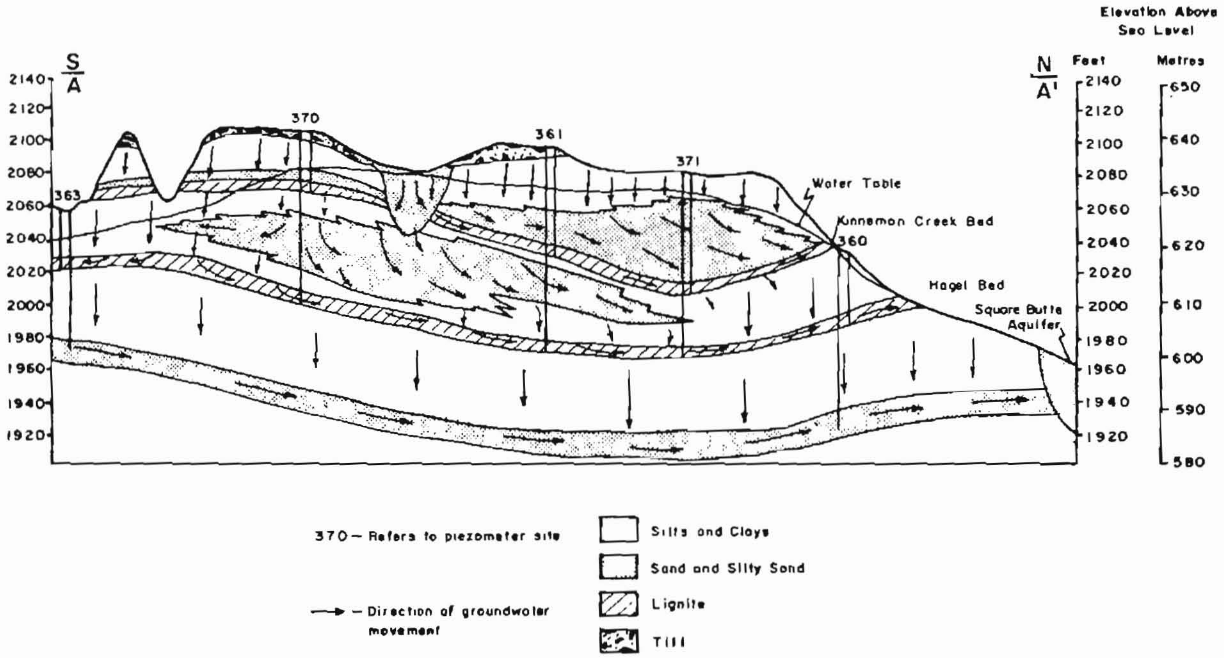


Figure 22. Hydrostratigraphic cross section of the Center Mine area near Center, North Dakota. See figure 15 for location of cross section.

the landscape. The major constraint upon subsurface water movement is the permeability contrasts between the various sedimentary units. Groundwater movement is predominantly lateral through sand and lignite aquifers and typically vertical and downward through fine-textured Tertiary and glacial sediments.

The movement of subsurface water in undisturbed landscapes in western North Dakota is relatively sluggish. The hydraulic conductivity of Tertiary sand commonly ranges from 10^{-5} to 10^{-6} m/s; lignite generally ranges from 10^{-5} to 10^{-7} m/s; fine-textured Tertiary sediments and glacial till range from 10^{-8} to 10^{-10} m/s (Groenewold et al., 1979; Rehm et al., 1980).

As discussed earlier, the chemical characteristics of subsurface water in these landscapes is dependent upon geochemical processes operating in the upper few metres of these sluggish systems. Particularly critical is alternate wetting and drying of this portion of the landscape.

Thus, for the hydrogeochemical model to be applicable to subsurface water chemical evolution in spoils settings, it is essential that similar hydrogeologic conditions exist in the spoils landscapes as exist in undisturbed settings. Most significantly, it is essential that recharge occur in the spoils. In addition, the degree of saturation and hydraulic conductivity of the saturated portion of the spoils are critical to an evaluation of both short-term and long-term aspects of chemical evolution in postmining landscapes.

Saturation of Spoils

Groundwater instrumentation in the spoils areas at the Center and Indian Head Mines indicates that the basal portion of the spoils is saturated over most of the area of the study sites. However, all piezometers screened more than five metres above the base of the spoils at both mines remained dry during the period of study. The degree of saturation appears to be largely dependent upon local relief in the underlying undisturbed sediments. Potentiometric data from the Indian Head sites indicated a slow but consistent rise over the period of the study (1977-1981). Little change has occurred at the Indian Head sites since mid-1981 suggesting that equilibrium conditions may have been established in the spoils at these sites. The saturated portion of the spoils at the Indian Head sites typically varies from 2 to 4 metres.

Instrumentation at the Center Mine indicated consistent rise in water levels in the basal portion of the spoils over the period of study (1979-1981). Water levels in these piezometers are continuing to rise suggesting that equilibrium has yet to be established in the spoils at the Center Mine. The saturated portion of the spoils at the Center Mine typically varies from 2 to 5 metres. The positions of the postmining water tables in spoils at both mines are approximately the same as in the premining settings and range from 6 to 15 metres below the surface.

Hydraulic Conductivity of Spoils

Single-well response tests (slug tests) were performed on all piezometers in spoils at Center and the USBM site at Indian Head having a sufficient column of water. The data collected were analyzed using techniques developed by Hvorslev (1951). These data are presented in table 13 and indicate that the hydraulic conductivity in the basal portion of the spoils is highly variable. Values range from 10^{-5} to 10^{-10} m/s in spoils at both mines (table 13). This range of values is within the same range as the undisturbed sediments.

Recharge in Spoils

Groundwater in spoils can be attributed to three possible sources of recharge:

1. Lateral migration from adjacent unmined units.
2. Lateral migration from adjacent surface-mine pits.
3. Vertical recharge down through the spoils.

Although not originally proposed as activities of this study, selected analyses of stable isotopes of oxygen and hydrogen and flooding experiments were conducted to better evaluate recharge in spoils.

Stable Isotopes

The concentrations of certain isotopes of oxygen and hydrogen in groundwater can be used as an aid in determining the source of ground-

TABLE 13.--Hydraulic conductivity data for the base of spoils at the Center and Indian Head Mines.

CENTER MINE[a]		INDIAN HEAD[b]	
Piezometer	Hydraulic Conductivity (m/s)	Piezometer	Hydraulic Conductivity (m/s)
9	1.4×10^{-9}	USBM 2	6.3×10^{-9}
10	5.9×10^{-6}	USBM 8	1.4×10^{-7}
16	2.8×10^{-9}	USBM 11	5.6×10^{-9}
17	5.0×10^{-7}	USBM 13	1.2×10^{-9}
23	3.1×10^{-6}	USBM 22	9.1×10^{-10}
58	7.3×10^{-6}	USBM 27	1.6×10^{-9}
69	9.5×10^{-8}	USBM 30	2.5×10^{-8}
70	9.9×10^{-8}		8.0×10^{-9}
79R	1.3×10^{-8}	USBM 32	3.6×10^{-5}
85	1.5×10^{-7}		4.6×10^{-5}
90	1.9×10^{-8}	USBM 36	7.7×10^{-8}
91	1.3×10^{-8}	USBM 43	1.0×10^{-9}
95	6.9×10^{-8}		
98	1.1×10^{-8}		
99	6.1×10^{-8}		
100	2.2×10^{-8}		
106	3.9×10^{-6}		
108	1.6×10^{-7}		
114R	1.3×10^{-6}		
115	2.9×10^{-8}		
119	4.2×10^{-5}		
120	4.5×10^{-7}		
139	4.6×10^{-10}		
140	4.9×10^{-8}		
154	9.8×10^{-7}		

---

[a] See figures 16a-j for location of piezometers.

[b] All piezometers in USBM spoils test plot. See figure 14 for location of piezometers.

water recharge. The isotopes commonly used to evaluate recharge are oxygen-18 (^{18}O) and deuterium (D). The concentrations of these isotopes are expressed as delta (δ) units in parts per thousand (‰). Colder climatic conditions tend to produce lighter (more negative) $\delta^{18}O$ and δD precipitation values. Thus snow and snowmelt generally have considerably lower $\delta^{18}O$ and δD values than rain. During the period 1978-1980 snow and snowmelt at the Falkirk site had average values for $\delta^{18}O$ and δD of -21 ‰, and -192 ‰, respectively. For the same period, rain at the Falkirk site had average values of ^{18}O and D of -6 ‰ and -42 ‰, respectively (Rehm et al., 1982).

The deuterium content of precipitation relates linearly to the oxygen-18 content by the relationship

$$\delta D\ (‰) = 8\delta^{18}O\ (‰) + 10$$

as defined by Craig (1961). The line defined by this equation is referred to as the meteoric waterline. Evaporation enriches water in the heavy isotopes resulting in less negative δ-values for both isotopes. However, the rates of enrichment of the two isotopes during evaporation differ. Thus, the slope of the line defining evaporated water is less than that of meteoric water. Groundwater resulting from infiltration from sloughs and surface mine pits will commonly show the effects of evaporation whereas groundwater resulting from direct infiltration of rain or snowmelt generally will not show the effects of evaporation. Therefore, $\delta^{18}O$ and δD contents of groundwater can be used to determine both the precipitation source (rain, snowmelt) and also the topographic source of the infiltrating water (sloughs, mine pits, non-depressional areas).

An additional isotope of use in evaluating groundwater recharge sources is tritium (^{3}H). The tritium content is expressed in Tritium Units (T.U.). The major source of tritium has been atomic testing carried on since 1950. Groundwater which is older than 1950 generally has tritium values less than 3 T.U. Higher concentrations indicate post-1950 infiltration.

The oxygen and hydrogen isotope contents of groundwater samples from various stratigraphic positions at the Center Mine are presented in table 14. The samples were analyzed in two separate groups. The one group of samples were analyzed for ^{3}H contents; the other group of samples were analyzed for ^{18}O and D contents.

TABLE 14.--Stable isotope data for selected piezometers at the Center Mine.[a]

Piezometer	Stratigraphic Position	^3H(T.U.)	$\delta^{18}O$(‰)	δD(‰)
9	Base of spoils	55.0±9		
10	Base of spoils	42.0±9		
14	Base of spoils	5.0±9		
16	Base of spoils	18.0±9		
23	Base of spoils	3.5±9		
26	Base of spoils	21.0±9		
45	Base of spoils	32.0±9		
3	Hagel bed	7.7±9		
6	Hagel bed	12.6±9		
32	Hagel bed	7.0±9		
35	Hagel bed	17.0±9		
373A	Hagel bed	1.4±8		
12	Silt 12 m below spoils	12.6±9		
24	Silt 12 m below spoils	2.1±8		
29	Silt 12 m below spoils	0.0±8		
42	Sand 3 m below spoils	7.0±9		
44	Silt 8 m below spoils	33.0±9		
31	Silt 15 m below Hagel	1.4±8		
33	Silt 18 m below Hagel	5.6±9		
34	Sand 5 m below Hagel	9.0±9		
10	Base of spoils		-15.74	-118
23	Base of spoils		-15.34	-113
69	Base of spoils		-17.43	-123
70	Base of spoils		-18.20	-127
76	Base of spoils		-18.76	-131
85	Base of spoils		-18.56	-130
95	Base of spoils		-16.34	-127
99	Base of spoils		-16.48	-115
100	Base of spoils		-17.05	-122
119	Base of spoils		-15.63	-122
132	Base of spoils		-16.52	-112
139	Base of spoils		-15.82	-112
142	Base of spoils		-17.23	-122

[a] See figures 15 and 16a-j for location of piezometers.

The tritium data indicate that the water in several piezometers in the basal portion of the spoils at the Center Mine is enriched in tritium relative to groundwater in adjacent and underlying undisturbed units. These tritium data indicate that the source of the water in the basal portion of the spoils at the Center Mine is not from adjacent unmined areas. Thus, the presence of groundwater in the spoils is either due to vertical infiltration through the spoils or lateral inflow from adjacent surface mine pits.

The oxygen-18 and deuterium data are typically very light suggesting snowmelt as the precipitation source for most of the groundwater in the spoils and unmined materials. The topographic source of recharge in spoils is of critical importance to an evaluation of the applicability of the hydrogeochemical model to spoils settings. The oxygen-18 and deuterium data generally plot along the meteoric water line indicating that the water in the spoils has undergone insignificant evaporation (fig. 23). These data indicate that the mechanism and topographic source of the groundwater in spoils at the Center Mine is vertical infiltration from nonevaporative sites, predominantly during the period of spring snowmelt, rather than lateral inflow from adjacent mine pits. Thus, the recharge mechanism in spoils at the Center Mine is very similar to that of the premining setting.

Flooding Experiments

The results of the flooding experiments represent a preliminary evaluation of data resulting from experimental methodology. This technique deserves additional utilization, offering a potentially very useful but simple method of evaluating subsurface water movement through the unsaturated zone.

As previously discussed, four flooding sites were utilized at the Center Mine. These sites were adjacent to piezometers 15, 70, 74, and 79. (See figs. 16a-j.) Figures 24 through 27 present soil moisture profiles below the ponded areas at the four sites before, during, and after flooding. Before flooding, all four sites had similar moisture profiles. Soil moisture contents varied between 13% and 17% from 1 to 4 m below ground (fig. 5). From 1 m to the ground surface the moisture content dropped steadily to values less than 10%. The point at which the soil moisture values became relatively constant roughly corresponds to the spoil/subsoil contact and

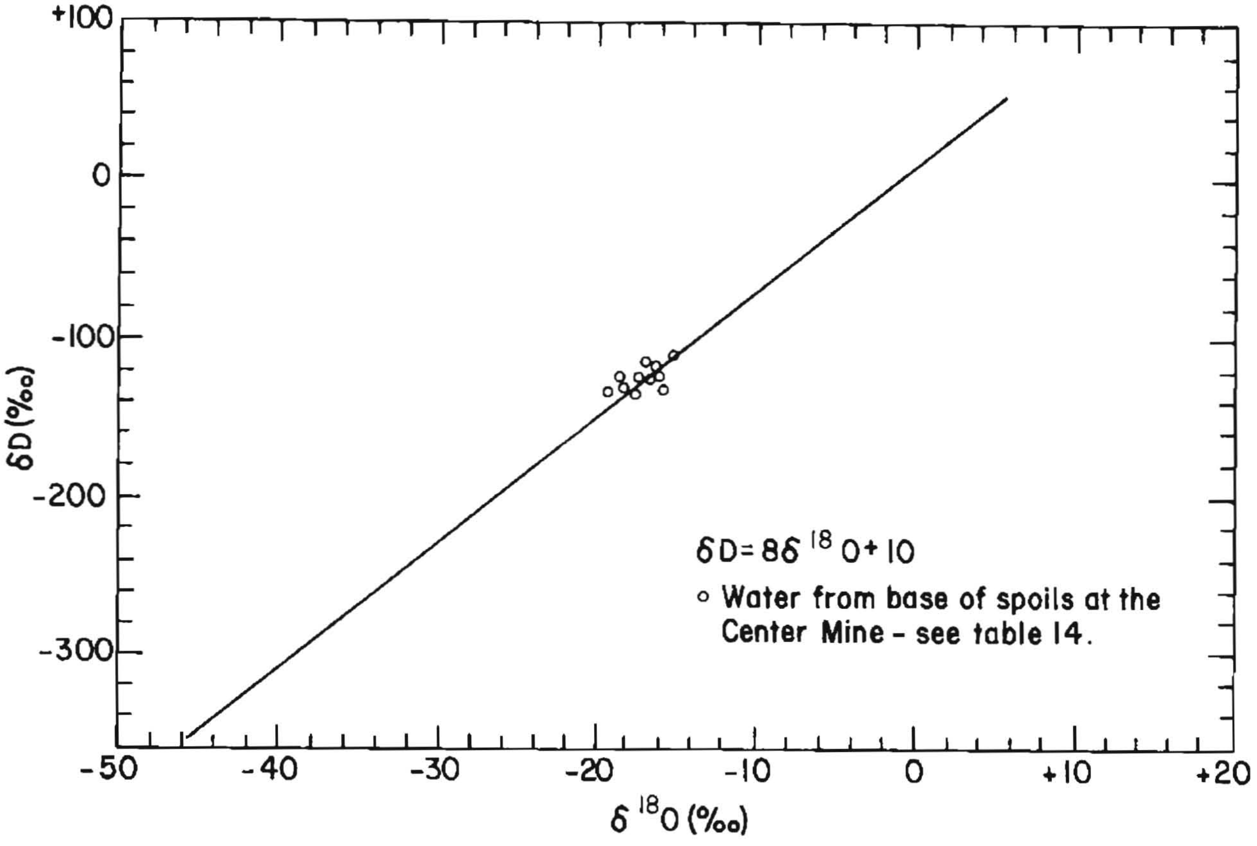


Figure 23. Deuterium and oxygen-18 correlation (meteoric water line) in precipitation and surface waters.

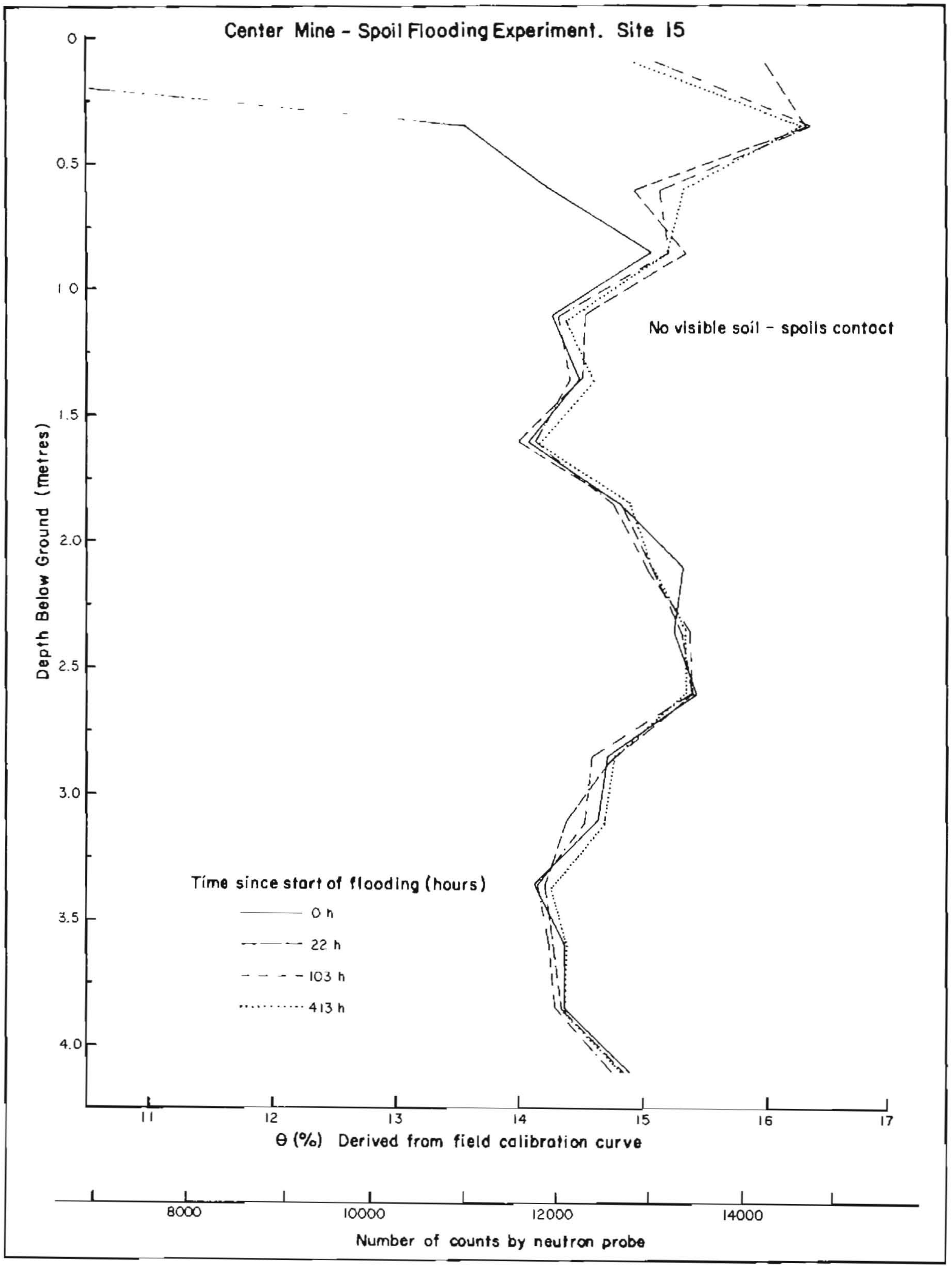


Figure 24. Soil moisture profiles below the flooded area at Site 15 before, during, and after flooding.

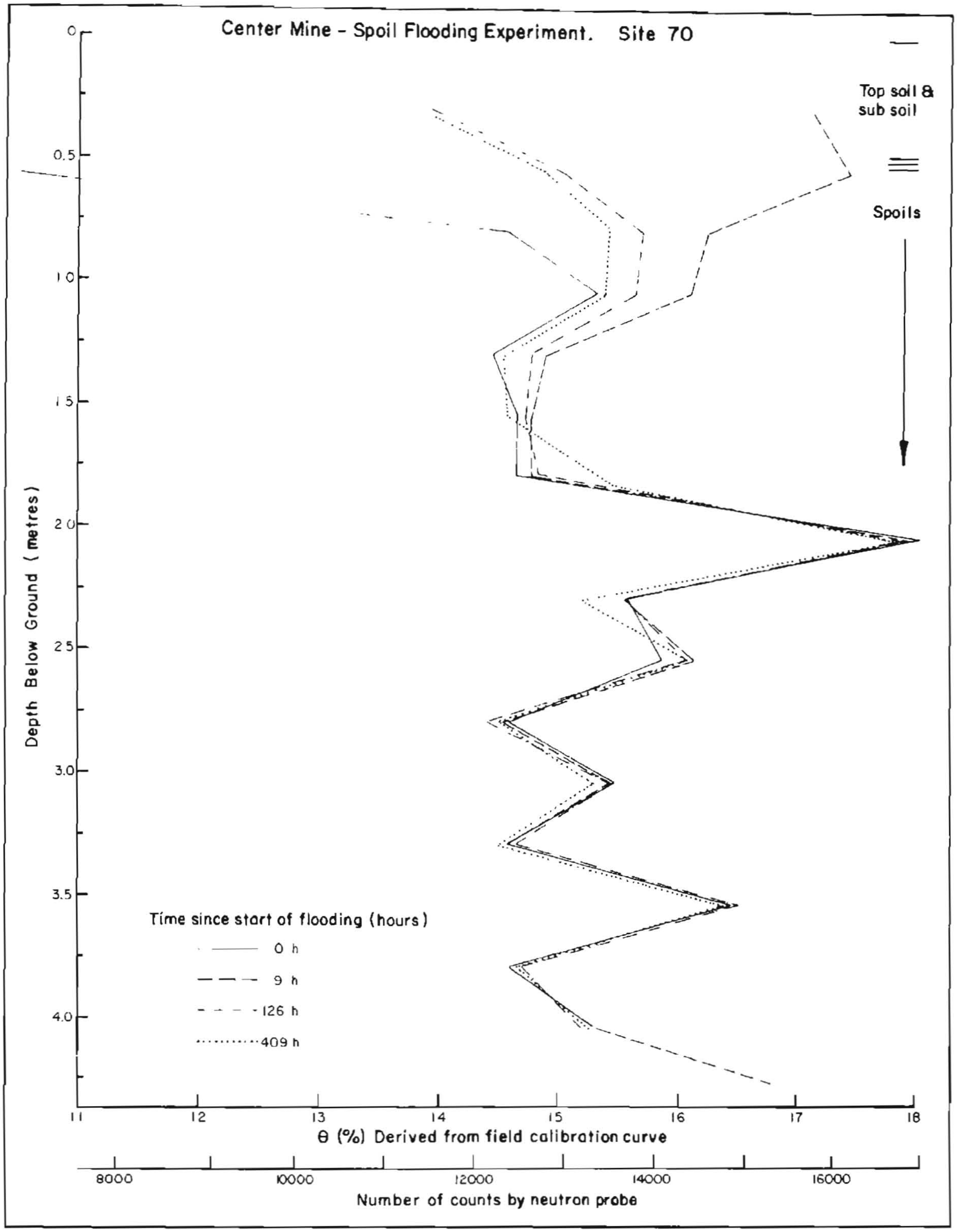


Figure 25. Soil moisture profiles below the flooded area at Site 70 before, during, and after flooding.

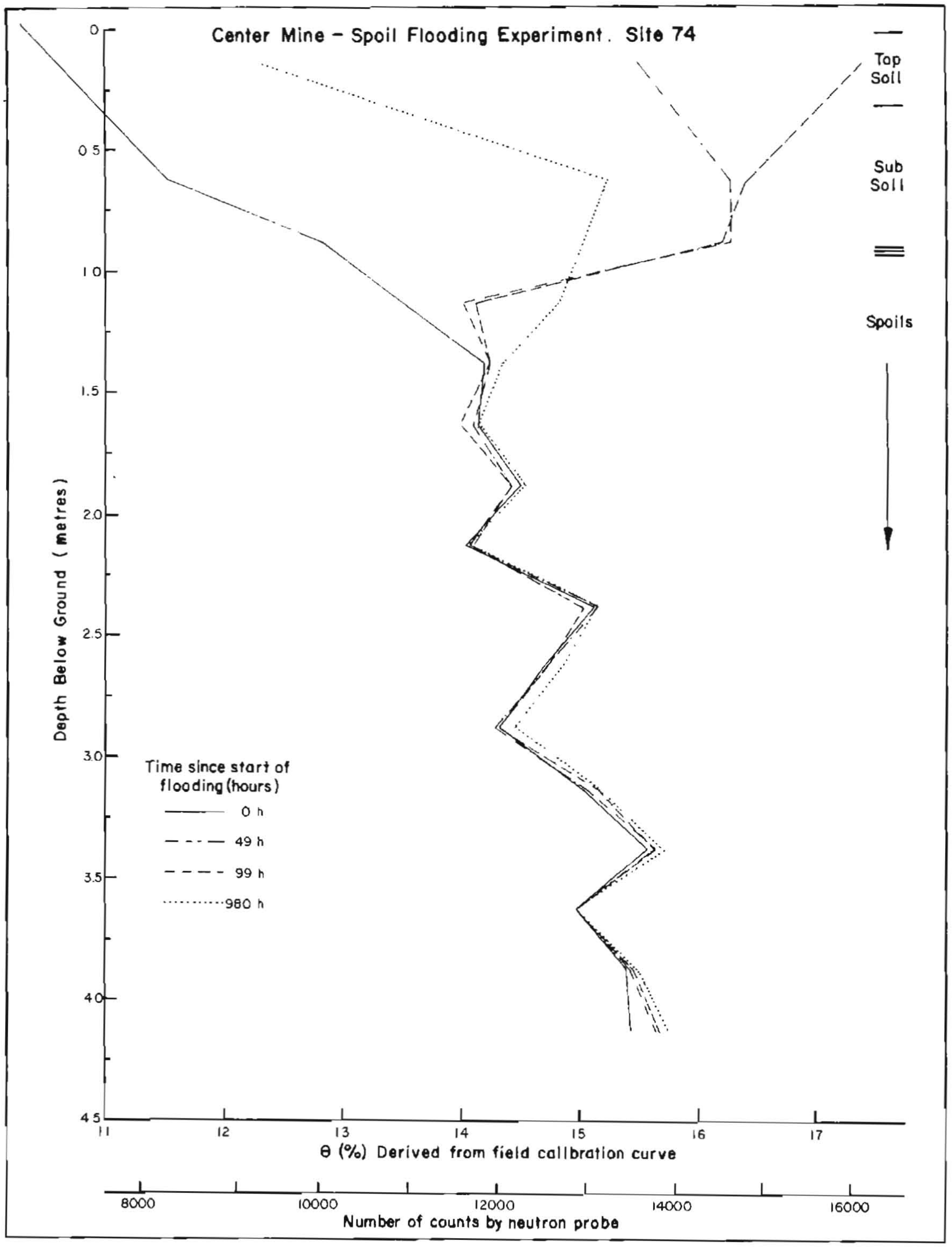


Figure 26. Soil moisture profiles below the flooded area at Site 74 before, during, and after flooding.

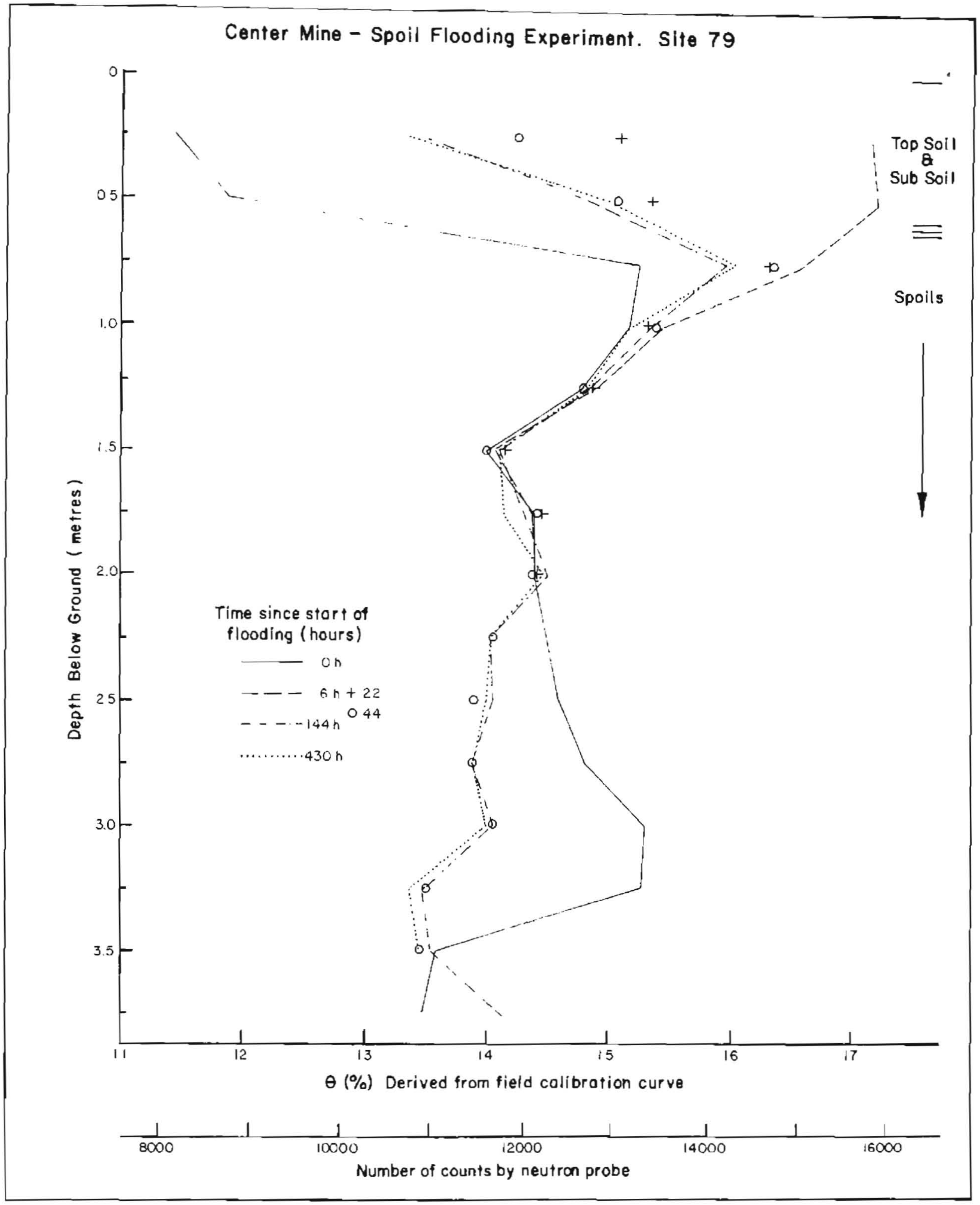


Figure 27. Soil moisture profiles below the flooded area at Site 79 before, during, and after flooding.

the approximate depth of the roots in the reclaimed areas. Only site 79 showed a consistent moistening of the spoils from 0.5 to 0.9 m.

Site 15 had the lowest overall infiltration and showed the least change in soil moisture profile (fig. 24). Part of this lack of change was probably due to the high (13.5%) moisture content in the shallow portions of the profile. Within 22 hours the profile reached its maximum degree of saturation, at a water content of 16.3%. If the porosity of the soil is assumed to be 0.40 the solum reached a saturation of 0.41. Slight increases in soil moisture extended to a depth of 1.4 m. By 400 hours the upper 0.30 m of the profile had started to dry while the moisture content continued to increase in the 0.50 to 0.90 m depth interval. No change occurred in the soil moisture content of the profile below 1.5 m (fig. 24).

A much greater response to flooding was seen at site 70 (fig. 25). Within nine hours the moisture content of the upper several tenths of a metre of the profile increased by 7.2% to a moisture content of 17.2%. The water also penetrated to a depth of 1.8 m within nine hours, 1.3 m beneath the spoil/subsoil interface. By 400 hours after the start of flooding the upper 1.5 m of the profile had begun to dry to a moisture content of about 15.5%, similar to the moisture content of the bottom 2 m of the profile. The only observed increase in water content at 400 hours occurred at a depth of 1.85 m.

Water did not move past the spoil/subsoil interface at site 74 during the first 300 hours after the flooding was started (fig. 26). The water did move laterally beneath the plywood dike and on top of the spoil surface. Cores were collected with a hand auger from above the spoil surface at distances of approximately 1 and 3 m from the northwest corner of the dike 24 hours after the flooding had started. At a distance of 1 m the water content between 0.5 and 0.9 m depth had increased from 8.0% to 10.0% to values of approximately 17.5%. The water content at 3 m remained at approximately 8.0%. From 300 to 1800 hours water slowly moved into the clayey spoils (fig. 26). By 1800 hours there was a small increase in water content at a depth of 1.37 m and an increase of about 0.75% at a depth of 1.12 m.

The response to flooding at site 79 was similar to that of 70 (fig. 27). The infiltrating water passed below the spoil/subsoil interface within the first several hours of flooding. By 20 hours the upper half metre of the profile had begun to dry but there was no evidence of continued water movement below a depth of 1.25 m.

These experiments indicate water movement below the spoil/subsoil interface at two of the four flooding sites (70 and 79). The spoil/subsoil contact is also the base of the rooting zone. Thus, recharge is occurring at two of these four sites in spoils at the Center Mine.

The stable isotope, hydraulic conductivity, and flooding data all suggest that the hydrogeologic regime in postmining settings in western North Dakota is very similar to undisturbed settings. Recharge is slow and results from vertical infiltration scattered over the landscape; the flow of subsurface water is sluggish. Given these hydrogeologic conditions in the postmining landscape, it is reasonable to assume that the same geochemical processes that are key to subsurface water chemical evolution in undisturbed settings are also applicable to postmining settings.

Subsurface Water Chemical Characteristics

Groundwater

The majority of subsurface-water chemical data from undisturbed and disturbed (spoils) settings at the Center and Indian Head Mines represent analyses of groundwater from various stratigraphic positions at those sites. These data are presented in appendix D. The groundwater chemical analyses presented in appendix D are grouped by stratigraphic position.

Groundwater chemical data were obtained from three stratigraphic positions at the Indian Head Mine. These are the Beulah-Zap bed in undisturbed areas and the base of the spoils and a lignite bed, the Spaer bed, which occurs approximately 10 m below the spoils.

Groundwater chemical data from undisturbed settings at the Center Mine are grouped within four stratigraphic designations. These are the upper lignite (Kinneman Creek bed), the lower lignite (Hagel bed), a silt and sand unit 2 to 5 m below the Hagel bed, and sandy silt units 9 to 18 m below the Hagel bed (fig. 22). Groundwater chemical data from disturbed settings at the Center Mine are grouped within three stratigraphic units. These are the base of the spoils, the silt and sand unit 2 to 5 m below the spoils, and silt and sand units 8 to 12 m below the spoils (app. D).

The hydrogeochemical model discussed in the introduction defined several key geochemical processes which are dominant in the geochemical evolution of groundwater in western North Dakota. These processes include pyrite oxidation, gypsum precipitation and dissolution, carbonate-mineral dissolution, and cation exchange. With the exception of the last, these processes are operating almost exclusively in the near-surface, unsaturated portion of the landscape.

During surface mining operations, unweathered materials from positions below the premining water table are commonly emplaced in the zone of active weathering within the postmining landscape. The hydrogeochemical model suggests that the potential for chemical degradation of subsurface water under these conditions is severe in certain mine settings. The degree of weathering, dissolution, and ion exchange, as in the premining setting, will largely be dependent upon the mineralogy of the sediments placed in the near-surface portion of the postmining landscape. Of particular concern is the potential for the generation of elevated concentrations of Na^+ and SO_4^{2-} in solution in groundwater in spoils characterized by relatively high concentrations of sodium montmorillonite and sulfides or sulfate salts.

Table 15 is a summary of field chemical data and major ions for groundwater from the various stratigraphic positions at the Center and Indian Head Mines. These data indicate considerable variability in water chemical characteristics in the various stratigraphic units. However, it is evident from table 15 that groundwater from all the stratigraphic positions at the two mines is generally very similar. The major ions in solution in groundwater from all stratigraphic positions, both disturbed and undisturbed, are sodium, calcium, bicarbonate, and sulfate.

A comparison of groundwater chemical characteristics in undisturbed units at the two mines indicates significant differences in the concentrations of major ions in solution, particularly sodium and sulfate. The total-dissolved-solids concentrations for groundwater from the Beulah-Zap bed at the Indian Head Mine is 2,427 mg/L as compared with mean total-dissolved-solids concentrations in the Kinneman Creek and Hagel beds of 1,257 and 1,537 mg/L, respectively. The mean sodium concentration for groundwater

TABLE 15.--Summary of Groundwater Chemical Data from Various Stratigraphic Positions at the Center and Indian Head Mines. See Appendix D for complete analyses.

	Stratigraphic Position		Field Temp. °C	Field pH	Field Cond. (μS/cm)	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
							mg/L							
CENTER	Kinneman Creek Bed	*$\bar{x}$	10.0	6.6	1,636	1,257	95.2	54.7	236.2	16.6	607.7	0.5	429.5	7.3
		s	2.2	0.4	409	389	54.4	24.1	119.5	9.4	187.9	0.6	186.6	6.6
		n	15	15	11	15	15	15	15	15	15	9	15	15
	Hagel Bed	$\bar{x}$	9.9	7.1	2,229	1,537	174.2	64.8	192.9	8.1	570.0	4.04	633.7	6.5
		s	1.6	0.4	874	725	118.7	48.5	169.7	4.7	198.2	7.01	459.5	5.4
		n	51	51	47	51	51	51	51	51	51	10	51	24
	Silt, Sand 2 to 5 m below Hagel	$\bar{x}$	9.6	7.2	2,585	1,873.1	135.5	51.8	432.4	8.0	748.0	-	825.9	2.5
		s	1.0	0.6	796	1,217.1	64.2	23.8	457.7	4.2	455.9	-	683.1	0.5
		n	14	14	13	13	14	14	14	14	14	1	14	14
	Silt, Sand 9 to 18 m below Hagel	$\bar{x}$	9.5	7.7	2,294.4	1,554.9	24.6	13.7	543.1	9.5	1,123.5	5.1	344.5	14.6
		s	2.7	0.4	907.1	622.4	18.4	10.9	242.0	6.0	461.0	7.0	229.4	23.6
		n	19	19	16	18	19	19	19	19	19	5	19	19
	Base of Spoils	$\bar{x}$	10.5	7.1	4,969	3,282	281	145	497	20.8	958.0	304	1,516	7.6
		s	2.8	0.6	2,181	1,326	180	103	289	11.6	294.4	2.9	789	15.6
		n	98	98	98	97	98	98	98	98	98	42	98	57
	Silt, Sand 2 to 5 m below Spoils	$\bar{x}$	10.5	7.4	4,950	3,027.9	127.1	60.5	731.2	14.2	1,220.9	5.4	1,141.5	4.9
		s	2.0	0.7	2,625	1,565.1	125.8	54.8	368.5	8.3	528.5	3.9	789.8	4.2
		n	42	42	42	40	42	42	42	42	41	13	42	23
	Silt, Sand 8 to 12 m below Spoils	$\bar{x}$	8.3	7.6	3,335	2,258.4	64.1	43.9	700.1	10.6	1,245.8	-	810.3	8.0
		s	2.2	0.6	1,298	870.2	57.0	46.6	213.7	6.8	355.7	-	728.4	5.8
		n	34	34	34	32	34	34	34	34	34	1	34	31
INDIAN HEAD	Beulah-Zap Bed	$\bar{x}$	11.3	7.5	3,355	2,427.0	88.6	35.4	668.8	26.6	1,010.8	-	868.3	18.7
		s	3.1	2.8	3,157	1,738.1	68.0	6.8	438.6	8.0	673.2	-	568.0	13.5
		n	3	3	3	4	4	4	4	4	4	-	4	4
	Base of Spoils	$\bar{x}$	12.6	7.0	8,446	5,479	256.0	164.7	1,321.1	35.7	1,087.9	3.4	2,762.5	10.3
		s	2.4	0.6	5,399	3,460	212.2	177.5	853.1	36.6	482.7	3.0	1,901.1	9.2
		n	40	38	40	40	39	39	39	39	40	33	40	39
	Spaer Bed	$\bar{x}$	9.7	7.3	5,867	2,820	36.5	23.9	880.7	12.2	1,224.0	7.1	961.5	17.8
		s	0.8	0.4	3,002	-	-	-	-	-	-	-	-	-
		n	3	3	3	2	2	2	2	2	2	2	2	2

*$\bar{x}$ = mean; s = standard deviation; n = number of samples

in the Beulah-Zap bed is 1,321 mg/L. The mean sodium concentrations for groundwater in the Kinneman Creek and Hagel beds, respectively, are 236 and 193 mg/L. Sulfate concentrations in the Beulah-Zap bed average 868 mg/L. The mean concentrations of sulfate in the Kinneman Creek and Hagel beds are 429 and 634 mg/L, respectively.

A comparison between groundwater chemical data from spoils and undisturbed units at both mines indicates that groundwater in the base of the spoils is significantly more mineralized than groundwater in the premining settings. However, as previously noted, the water in the spoils is generally very similar to groundwater in undisturbed units. Total-dissolved-solids concentrations in spoils at Indian Head average 5,479 mg/L as compared to 2,427 mg/L in the Beulah-Zap bed (table 15). Total-dissolved-solids concentrations in spoils at the Center Mine have a mean of 3,282 mg/L as compared to mean TDS values of 1,257 and 1,537 mg/L in the Kinneman Creek and Hagel beds, respectively. The mean sodium concentration, for groundwater in spoils at the Indian Head Mine is 1,321 mg/L; the sodium concentrations in spoils at the Center Mine average 497 mg/L. Sulfate concentrations in spoils average 2,762 mg/L at the Indian Head Mine and 1,515 mg/L at the Center Mine (table 15).

The data summarized in table 15 also suggest migration of the more highly mineralized groundwater in the base of the spoils to the silt and sand unit 2 to 5 metres below the spoils. Analyses of groundwater from this unit indicate a mean TDS of 1,873 mg/L in undisturbed areas as compared with a mean TDS of 3,028 mg/L in this unit in areas where the unit underlies spoils.

The groundwater chemical data from the Center and Indian Head Mines suggest that the same hydrogeochemical processes are operating in postmining settings as in premining settings. The differences between the two mines with respect to chemical characteristics of groundwater from undisturbed units is a direct reflection of mineralogical differences in the overburden at the two mines. Particularly significant is the relative abundance of sodium, montmorillonite, and sulfides in the predominantly clayey overburden sediments at the Indian Head Mine. In turn, the impact of mining activities is to further exaggerate these differences by constructing a postmining landscape which is significantly more chemically reactive than the premining setting. The groundwater chemical data from spoils at the

Center and Indian Head Mines show the same trends as the saturated-paste extract data discussed previously. The most significant impact of mining activities is observed in settings where sodic and sulfide-rich clays are emplaced in the upper portion of the postmining landscape.

Pore Water

Samples of subsurface water from pressure-vacuum lysimeters were collected at a few sites at the two mines. Although repeatedly evacuated, few of these instruments collected water samples. This reflects the sporadic recharge characteristics of these settings. Chemical analyses of water samples from pressure-vacuum lysimeters are presented in table 16. Pore water samples were obtained from four positions in spoils at the Indian Head Mine and from three positions in spoils at the Center Mine. All these analyses indicate the presence of relatively highly mineralized pore water in the upper few metres of the postmining landscapes (table 16). These data further suggest the geochemical significance of the upper few metres of the landscape. In addition, the simple fact that water is moving to these depths in spoils (typically below the rooting zone) further reinforces the conclusion that recharge does occur, although possibly sporadically, in spoils settings at both mines.

Laboratory Experiments

Exhaustive Leaching Experiments

Selected samples of overburden material were extracted with an excess of water by shaking samples at constant temperature from two to seventy-two hours. Residual solids were removed by ultracentrifugation and millipore filtration. Analysis of the extract (app. E) demonstrates that the concentration of dissolved sulfate varied with amount of water used in the extraction step and is sharply diminished in second extractions using residue from the first step. By contrast, other major ions appear in similar concentration in the extract independent of the amount of water (always in at least eightfold, by weight, excess) used for extraction. Moreover, using

TABLE 16.--Summary of chemical analyses of water collected from pressure-vacuum lysimeters at the Center and Indian Head Mines. See Figs. 14 and 16a-j for locations of pressure-vacuum lysimeters.

Pressure-Vacuum Lysimeter	Date	Depth (m)	Field Temp. °C	Field pH	Field Cond. µS/cm	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}
						mg/L						
					CENTER MINE							
15-1	07-29-81	15.1	12.00	6.95	7,000	5,131	608	321	215	55	1,288	2,403
15-1	09-03-81	15.1	-	-	-	5,130	438	421	209	62	595	2,247
74-4	05-27-81	2.70	13.50	6.65	8,000	-	447	225	920	54	-	-
74-4	07-29-81	2.70	18.50	7.30	11,200	-	393	180	1,070	-	1,439	2,689
74-5	05-16-81	2.0	11.50	6.80	4,200	-	320	147	188	13	635	1,005
74-5	05-27-81	2.0	14.50	6.80	3,400	-	263	132	176	14	-	-
74-5	07-29-81	2.0	18.50	7.15	5,000	2,888	242	113	345	18	799	1,026
74-5	09-03-81	2.0	-	-	-	2,990	141	184	338	26	368	1,282
					INDIAN HEAD MINE							
34-1	07-13-82	5.65	11.7	6.89	12,900	5,058	289	165	990	23	1,328	2,309
34-2	08-03-82	4.20	18.1	6.80	9,600	5,162	363	214	1,047	38	1,265	2,637
38-1	05-22-80	10.10	11.5	6.55	8,000	5,190	350	129	1,090	29	1,320	2,165
38-2	05-22-80	7.20	13.0	6.8	8,000	-	520	178	1,206	52	1,232	2,861

the residue for a second extraction led to results similar to the first extraction for these ions.

The most straightforward interpretation of these experiments, although not necessarily the only one, is that sulfate is present in the various overburden samples in a soluble form but in limited amounts. Leaching with an excess of water effectively extracts all available sulfate. Other major ions are controlled by the solubility product of the minerals present in the overburden and thus are found in a particular concentration for a given sample regardless of the amount of water used on previous extraction.

Accelerated Weathering Experiments

As previously discussed, a set of accelerated weathering experiments was performed which explored the effects of extremes in temperature and pH, and alternate wet/dry cycles with aeration on the production of sulfate. As can be seen from the data presented in appendix F, no effects of these extremes are observed.

Based on these data alone, two conclusions are possible: (1) reduced sulfur is easily oxidized and the pretreatment (one wet/dry cycle) is sufficient to oxidize any reduced sulfur to the extractable sulfate, or (2) on the time scale of one month were inadequate to cause significant oxidation. Work performed by the Alberta Research Council (Ed Wallick, personal commun., 1982) allows us to choose the first alternative. In that work, samples were collected and preserved under an inert atmosphere, exhaustivly leached, then aerated as leaching continued. Dissolved sulfate was seen to increase with aeration to about double its initial level. Total sulfate recovered from the leachate was consistent with amounts observed by us; and our sulfate concentrations are consistent with the total sulfur present in overburden core samples, although a direct comparison is not possible because different portions of given cores were leached and analyzed for total sulfur.

The important conclusion from this work is that exposure of reduced sulfur-bearing overburden is sufficient to cause oxidation of that reduced sulfur and add to the total sulfate load of the material.

Pan Experiments

These pan experiments were designed to test three aspects of overburden weathering: (1) effects of exposure to milder conditions than tested in the previous experiments, (2) an open system which would allow for bacterial action, and (3) demonstration of the upward mobility of salts in evaporative conditions.

As the data in appendix G corroborate, no additional sulfate is produced beyond initial treatment levels. This is consistent with the conclusion of the previous section and obviates the need for concern about bacterial action in exposed materials. The pan experiments (fig. 28) readily demonstrated the upward mobility of salts. Figure 29 is a photograph of a typical pan showing the accumulation of sulfate salts on the top of the mound of sediment. This photograph is dramatic evidence for the upward mobility of salts under evaporative conditions and is typical of all the pan experiments.

An interesting by-product of this study is provided by entries T23-28 (app. G). When leached, these samples provided highly colored solutions that prevented sulfate analysis. Figure 30 is a photograph showing the highly colored solutions. (Ctr 380, 34.5-37, is the fifth flask from the left in figure 30.) This overburden sample was highly carbonaceous as determined by visual examination. Entries T27-T28 (app. G) are for a solution generated by leaching sediment obtained directly adjacent to carbonaceous overburden sediment from the Indian Head Mine (X-2, 29.5-30). Apparently, the carbonaceous material is easily leached under mild conditions to give highly colored waters. This phenomenon has been observed in some domestic water supplies in western North Dakota.

Acid/Base Neutralization of Overburden Samples

Small amounts (typically 2.5 g) of selected overburden material from selected sites were added to distilled water. These solutions were brought to the desired pH with HCl or NaOH. Basically two types of behavior resulted; see table 17. For the middle pH ranges, 3 to 11, rapid (less than one hour) neutralization occurred and the solution assumed a pH

Figure 28. Photograph of pan experiments.

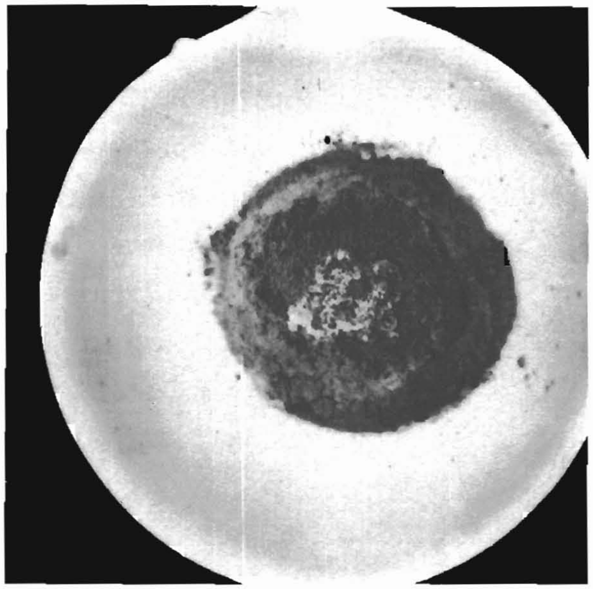


Figure 29. Photograph of typical pan experiment showing accumulation of sulfate salts on the top of the mound of sediment.

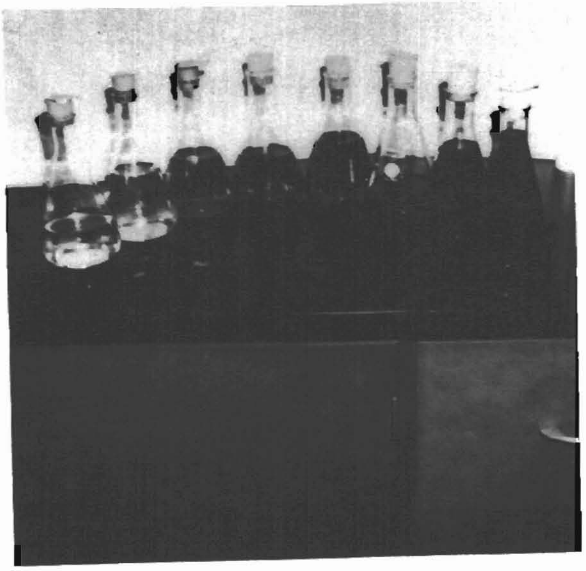


Figure 30. Photograph of solutions generated by mild leaching of overburden sediments used in pan experiments.

TABLE 17.--Results of acid/base neutralization experiments.

Sample #	Depth (ft)*	pH of Starting Water	pH After 1 h	pH At End of Run	Run Duration (h)
FALKIRK 10	32.5-35	1.12	1.12	1.02	23
	32.5-35	2.76	7.95	8.3	69
	32.5-35	4.2	8.62	8.21	22
	32.5-35	7.29	8.24	8.24	a
	32.5-35	9.7	9.5	8.8	24
	32.5-35	11.07	-	8.45	a
	32.5-35	12.89	12.84	12.54	19
CENTER 366	27-29.5	1.16	-	5.31	a
	27-29.5	2.85	-	8.00	a
	27-29.5	5.1	-	8.53	a
	27-29.5	6.8	-	8.9	a
	27-29.5	9.1	9.03	8.4	a
	27-29.5	10.75	-	8.45	95
	27-29.5	13.05	-	12.0	a
	45-47	13.29	13.28	13.01	32
CENTER 361	12-14.5	1.07	1.33	1.5	36
	12-14.5	3.05	-	8.24	a
	12-14.5	4.95	-	9.5	a
	12-14.5	7.2	-	8.45	a
	12-14.5	9.45	-	8.4	a
	12-14.5	10.89	10.89	8.62	a
	12-14.5	13.23	12.23	12.40	80

a = Run ended when pH stopped changing significantly.

*Multiply by 0.3048 to convert to metres.

typical of field collected samples of groundwater. Little change then occurred even after long periods (up to 95 hours).

At pH extremes (< 2 or > 12) very slight changes in pH occurred immediately with no subsequent changes seen for acid samples. Very basic samples experienced a slow ($\simeq 0.01$ pH unit per hour) decline in pH presumably as a result of CO_2 dissolving in the solution.

Clearly, there exists significant buffering capacity in the overburden samples chosen. The samples utilized in these experiments included a complete range of Tertiary textural types as well as glacial till. If these samples may be considered representative one could generalize to say that overburden materials of western North Dakota exhibit considerable buffering capacity.

Such capacity may be exceeded by extreme loads towards either end of the pH range. It is difficult to imagine a situation where the last statement would not be true.

DISCUSSION AND CONCLUSIONS

Key Geochemical Processes Accounting for Observed Water Characteristics in Undisturbed Settings

Significance of Wetting/Drying Mechanism

In the semiarid climate of the Northern Great Plains, and particularly North Dakota, alternate wetting and drying of the upper portion of the landscape is extremely significant to the evolution of groundwater chemistry. Much of the literature of geochemistry associated with surface mining has been developed with respect to the much more humid Appalachian region. When average rainfall exceeds average evapotranspiration, overburden deposits are subject to continual leaching. Therefore, changes in mineralization produced in the near-surface region are moved continuously downward in the overburden profile. Also, any inherent buffering capacity of the native overburden will eventually be removed by the continuous downward flow of water. In the semiarid regime, recharge to groundwater is spatially and temporally sporadic. Therefore, the overburden profile will be subjected to repeated wet/dry cycles. Alternate dissolution/precipitation of water-borne minerals will necessarily accompany these cycles. The effects of these cycles were discussed in some detail in the introduction. Our work does not change this basic discussion except to highlight the surprising ease with which sulfur mineral oxidation occurs. This will be discussed in detail below.

Sources of Calcium, Sodium, and Bicarbonate Ions

The operational model that considers calcium and bicarbonate to be the result of a low pH-driven dissolution of native calcite (along with dolomite) to produce calcium and magnesium ions is unchanged by the work reported here. Sodium is still thought to arise from cation exchange with resident clay as water infiltrates through the profile. These processes are discussed in detail in the introduction. Recall from that section that a necessary component of the model was the hydrogen ion production resulting from the oxidation of pyrite (or any reduced sulfur). The demonstration of complete oxidation of available sulfur under very mild conditions of exposure to air and moisture lends considerable credence to this basic premise.

Possible Sources of Sulfate

At any time, there are clearly two sources of sulfate which may eventually reach the groundwater via recharge from the surface: presently existing soluble sulfate salts such as gypsum; and reduced sulfur, either inorganic (pyrite or marcasite) or organic. The conceptual model outlined in the introduction suggests that presently available soluble sulfate salts derive from the oxidation of reduced sulfur. This study has produced no evidence to the contrary. For the purpose of this discussion, it is not necessary to consider the ultimate source. It is sufficient to recognize that there exists a "steady state" concentration of sulfate ions throughout the overburden profile which migrates along with infiltrating water to the groundwater. This soluble sulfate may be replenished near the surface as long as there exists reduced sulfur in the portion of the landscape where air and moisture are present. The purpose of the next two sections is to account for the relatively high sulfate concentrations in local groundwater, assuming the two sources mentioned in this section.

Available Sulfate/Sulfide in the Near-Surface Landscape Relative to Concentrations Found in Groundwater

We have now established that a finite amount of extractable sulfate exists throughout the overburden profile at all locations studied. The data indicate that this sulfate is either in the form of material readily extracted, or is readily converted to such a form. This conclusion is supported by all of the leaching and weathering experiments as well as the analysis of cores for total and extractable sulfur. Thus, while sulfate is found throughout the overburden landscape, it is possible, in principle, to exhaustively deplete it without significantly changing the total mass of the solum. This is unlikely to occur as long as the North Dakota climate remains semiarid. A change in hydrological regime to one similar to the Eastern United States would rapidly change the solum and groundwater chemistry.

The observation that the amount of available sulfate is finite raises the question of whether the available sulfate is adequate to explain the rather high sulfate concentrations found in native groundwater samples. A crude calculation may be done to answer this question. If one assumes that recharge occurs uniformly over the sampling area and that the average of values found in the sulfur analysis of core samples is representative of the total and extractable sulfur, respectively, it is possible to compare the sulfate available in some arbitrary core volume with the sulfate found in that column's groundwater.

We have selected two examples for which data is available to illustrate this calculation. The samples are representative enough of both the region and the data collected to suggest that there will be some generality to the conclusions drawn from the calculations. The first of these examples is for the Center Mine area and the second is for the Indian Head Mine area.

At Center we have assumed that the saturated zone is 20 metres below the surface and that the saturated zone has a thickness of 20 metres. The total column considered is then 40 metres deep, or about the depth of the Hagel lignite bed. If a surface area of one square decimetre is arbitrarily chosen, the total column volume is 400 dm^3. If the overburden materials are assumed to have a bulk density of 1.8 g/cm^3, the average of extractable sulfur values found for the core Ctr 380 (8.5×10^{-5}) indicates that about 180 g of sulfur as sulfate is available and about ten times that value of total sulfur is present. If the porosity of the column is 30 percent, the saturated portion of the column contains 60 litres of water. Groundwater from a piezometer completed near the core extraction site (Ctr 367A) has a sulfate concentration of 643 mg/L for a total sulfate mass of 38.6 g. If all of the extractable sulfate were to find its way into the groundwater, the potential sulfate concentration is 3,060 mg/L under the assumptions of this calculation. If all sulfur found its way into the groundwater as sulfate, that number would rise to about 30,000 mg/L.

For the groundwater sample from Ctr 367A, however, the sulfate concentration found corresponds to saturation for the measured calcium concentration. The ion product for these two species is 2.6×10^{-5}. This value is slightly in excess of the solubility product constant for gypsum, as given in the introduction, of 2.17×10^{-5} for 10°C. We do not believe the difference between the two numbers to be significant and suggest that the value just corresponds to gypsum saturation of the groundwater at this location. Clearly, sufficient sulfur is available to maintain this sulfate level. The only way one might expect a significant rise in sulfate in a disturbed landscape is to change the Na^+/Ca^{2+} ratio in the water.

Comparable calculations for the Indian Head site lead to identical conclusions even though the numbers used are superficially quite different. We made the same assumptions concerning soil properties and nature of recharge. The column depth assumed was 18 metres. The bottom four metres was assumed to be saturated. Core X-2 gave an average extractable sulfur value of 2.7×10^{-4} g/g and an average total sulfur of 9.9×10^{-4} g/g solum. Available sulfur as sulfate is then 262 g for the column. An adjacent well, IH 117, shows 1,606 mg/L sulfate, or 19 g sulfate in the column. As at Center, a considerable excess of available sulfate is present. Without solubility limitations, an ultimate sulfate potential for the groundwater is 80,000 mg/L. This is much higher than the comparable value at Center. Once again, the observed groundwater sample sulfate concentrations are determined by calcium concentrations. The ion product for sample IH 117 is 2.5×10^{-5} or the same as found at Center. Once again we conclude that for sulfate concentrations to rise significantly in disturbed landscapes, the sodium ion would have to increase to a significant degree.

Possible Mechanisms for Generating Sulfate/Sulfide

Up to this point we have demonstrated that sulfate exists in limited amounts in overburden solum, but that the amount was more than adequate to account for the observed sulfate in groundwater samples. This is true even when this value is large by "normal" sulfate standards. Despite this, the genesis of sulfur/sulfide in the overburden profile requires some further discussion. A standard mineralogical analysis of overburden sediments does not show significant (>1 percent) amounts of either pyrite or gypsum. More careful analytical methods show small (> 0.1 percent) amounts of both distributed throughout the profile. These small amounts of sulfur mineral have an important impact on groundwater chemistry largely because enough precipitation does not infiltrate to "wash" them out of the solum quantitatively.

Our conceptual model accounts for the production of sulfate from sulfide (introduction) and our experiments during this project lend strong support to this model. Some suggestion as to the initial source of the sulfide has been made. However, we have not discussed the unlikely similarity between average concentrations of oxidized and reduced sulfur. In the next paragraphs we discuss both of these topics, but this discussion is necessarily speculative as none of the work we have done was specifically designed to address these questions.

As previously discussed, reduced sulfur appears to occur most commonly in fine-textured sediments in the overburden profile. Its solubility in water in all forms is very limited, so it seems unlikely that it has been distributed directly by an infiltration mechanism. Reasonable possibilities include deposition in observed amounts in the original sediment or in situ reduction from sulfates distributed by infiltration. The last suggestion seems the least likely of these possibilities, but has not been directly investigated. Biologically assisted sulfate reduction is well known, but thermodynamics do not favor a physical counterpart.

Reduced sulfur exceeds oxidized sulfur by factors of two to ten. If a static landscape is assumed, this seems an inadequate excess to account for the observed sulfate concentrations over geologic time. Of course, the landscape is not static. Slow but constant erosion is occurring which is continually exposing reduced sediments to air. Consistent application of our model suggests that erosion will enrich solum below the eroding layer in sulfate, with no accompanying increase in sulfide. Thus, much of the sulfate presently found in overburden solum probably arises from sulfide in near-surface sediments that are no longer present. In essence, the near-surface sulfate-rich zone is a slowly downward migrating relic of thousands of years of sulfide oxidation. This zone, in turn, functions as a reservoir for sulfate which is sporadically flushed to the groundwater during recharge events. As the data in appendix E affirms, near-surface cores have considerably more leachable sulfur than those at depth.

Validity and Applicability of the Hydrogeochemical Model to Spoils Settings

Material Redistribution and Increased Availability of Oxygen

The previous discussion summarized the hydrogeochemical model as it relates to chemical evolution of subsurface water in undisturbed settings in western North Dakota. The processes and mechanisms described in the model, as refined by this study, allow us to account for the observed chemical characteristics of subsurface water in these settings. Evaluation of the applicability of the model to disturbed (spoils) landscapes requires a knowledge of the physical and chemical changes that occur in the landscape during mining operations and their potential impact on the overall hydrogeochemical regime.

As was discussed in the introduction, the premining landscape consists of various components that are more or less in equilibrium with one another and the forces acting upon them. Disruption of the landscape by surface mining typically results in two major changes in the landscape. These are: (1) redistribution of the overburden materials, and (2) increased availability of oxygen in the postmining landscape relative to premining conditions.

Redistribution of overburden by a dragline during surface mining operations has been described in detail by Winczewski (1977). That study, which focused on the Indian Head Mine, indicated that spoils handled by a dragline typically consist of non-homogeneous, semi-stratified materials. That study also indicated that during mining operations sediments from the mildly reducing environment below the position of the premining water table are often emplaced in the near-surface oxidizing environment of the postmining landscape. Conversely, it was observed that sediments from the oxidized portion of the premining landscape are often emplaced in the saturated basal portion of the spoils.

Redistribution of overburden sediment suggests the potential for significant changes in the chemical reactivity of the landscape. Emplacement of unoxidized sediments in the oxidizing, near-surface environment increases the potential for sulfide oxidation, sulfate dissolution/precipitation and cation exchange on clays. However, there is no reason to believe that such increased reactivity in the near-surface environment in any way requires changes in the model. Conversely, emplacement in the base of the spoils of sediments from the near-surface portion of the premining landscape can be expected to cause rapid dissolution of sulfate salts in those sediments. Again, there does not appear to be any reason to believe that redistribution of sediments in this manner requires reevaluation of the hydrogeochemical model.

During mining operations large volumes of air, and thus oxygen, are entrapped within voids in the spoils. At least initially, the entrapped oxygen will promote oxidation of sulfides present in the unsaturated portion of the spoils. The presence of significant volumes of oxygen in the spoils can promote the generation of highly mineralized water. However, as in the case of sediment redistribution, we know of no reason for believing that this condition in spoils requires any changes in the basic hydrogeochemical processes and mechanisms as defined in the model.

Subsurface Water Flow and Occurrence in Spoils

The hydrogeochemical model emphasizes the significance of the near-surface portion of the landscape with respect to chemical evolution of subsurface water. Of particular significance is the wetting/drying mechanism which results from sporadic recharge events. The chemistry of subsurface water in the upper approximately 150 metres of the landscape in western North Dakota is determined by geochemical processes that occur during recharge. Thus, for the model to be applicable to postmining settings, it is essential that recharge conditions in the spoils be similar to those which exist in undisturbed settings.

The vast majority of recharge in undisturbed settings in western North Dakota results from sporadic depression-focused infiltration (Rehm, et al., 1982). The stable isotope data, flooding experiments, and sporadic availability of water from pressure-vacuum lysimeters in the unsaturated portion of the spoils at positions well below the rooting zone all suggest recharge conditions similar to those which occur in undisturbed settings in western North Dakota. Thus, it is appropriate to conclude that the critical wetting/drying condition and associated geochemical processes are essentially the same in undisturbed and spoils settings.

The hydrogeologic conditions observed in the saturated basal portion of spoils at the Center and Indian Head Mines suggest very similar conditions to those which existed prior to mining. The values for hydraulic conductivity in the spoils fall within the same range as sediments in undisturbed settings. In addition, the postmining position of the water table as observed in spoils at the Center and Indian Head Mines is approximately the same as in the premining settings. It is clear, as previously discussed, that the mechanisms and rates of movement of subsurface water are critical to the hydrogeochemical processes operating in western North Dakota. The observed similarities in hydrogeologic conditions in spoils and undisturbed settings at the study sites indicate no reason to suspect that our model is not equally applicable to spoils as to undisturbed settings.

Subsurface Water Characteristics in Spoils Versus Undisturbed Settings

A summary and comparison of groundwater chemical characteristics in undisturbed settings and spoils at the Center and Indian Head Mines was presented in the results section. Comparison of premining groundwater chemical characteristics at the two mines indicates the presence of typically a (Na, Ca-SO_4, HCO_3)- to (HCO_3, SO_4)-type groundwater at both mines. The major difference in premining groundwater chemical characteristics at the two mines is the degree of mineralization. The mean TDS concentrations in groundwater from near-surface coal aquifers at the Center and Indian Head Mines are 1,257 and 2,427 mg/L, respectively (table 15).

These differences are a reflection of the mineralogy of the overburden at the two sites. The overburden sediments at Indian Head are commonly enriched in fine-textured, sodium montmorillonitic materials. The average clay content from the 13 analyses in table 7 is 57%. Overburden sediments at the Center Mine are commonly coarser-textured material that is relatively deficient in sodic clays. Here, the 26 analyses in table 7 average only 39% clay. These overburden mineralogical differences between the two mines are dramatically demonstrated by the saturated-paste extract data previously discussed. As discussed above, the Na^+/Ca^{2+} ratio is the major factor controlling sulfate concentrations in shallow groundwater in this region. Thus, the relatively sodic overburden at Indian Head produces more highly mineralized groundwater than at Center. Predominant species in solution are typically sodium and sulfate.

Groundwater in spoils at the two study sites is generically the same as in the undisturbed settings. However, groundwater in spoils at the two mines is typically two to three times as mineralized as in undisturbed settings (table 15). These conditions suggest that the same hydrogeologic and hydrogeochemical mechanisms and processes are operating in spoils settings as in undisturbed settings. These conditions further suggest that the significant difference between premining and postmining settings, with respect to subsurface water chemical evolution, is the chemical reactivity of the near-surface materials. This, in turn, is a function of interactions between overburden mineralogical variables and redistribution of those materials during mining operations.

Short-Term and Long-Term Implications of Surface Mining With Respect to Water Quality

Impacts on Groundwater

From the previous discussion we conclude that the hydrogeochemical model is equally applicable to spoils and undisturbed settings. The impacts of surface mining on groundwater quality are dependent upon site-specific variables. We consider the two most significant variables to be the mineralogy of the overburden and the mining technique.

The redistribution of overburden sediments during mining operations commonly generates a more chemically reactive landscape than was present in the premining setting. All the mining operations at the study sites included in this project utilize a dragline for overburden removel. Dragline removel of overburden promotes the "overturning" of the overburden materials (Winczewski, 1977). This study indicates that dragline removal of overburden at the North Dakota study sites results in a twofold to threefold increase in the mineralization of groundwater in spoils relative to premining conditions.

From this study we conclude that the major chemical species of particular concern in this region are sodium and sulfate. Sufficient extractable sulfur is available in most overburden sediments in this region to potentially generate very high concentrations of sulfate in solution. The sulfate concentration is controlled by the solubility of gypsum. Thus, the concentration of sulfate in groundwater in spoils will be controlled by the Na^+/Ca^{2+} ratio.

The short-term impact of surface mining on groundwater quality has been clearly documented at the Center and Indian Head Mines. These data indicate that TDS concentrations within the average range of 3,000 to 5,500 mg/L can be anticipated in surface-mined areas where a dragline was used for removal of overburden. In areas of highly sodic spoils, the concentrations of sodium and sulfate can be anticipated to be in excess of 1,000 and 2,500 mg/L, respectively.

Long-term trends are more difficult to evaluate. The key variable will be the degree of vertical infiltration (recharge) through the spoils. If recharge is minimal, an initial flush of soluble salts emplaced in the base of the spoils during mining can be anticipated. This will result in a short-term, probably several years to several tens of years, peak in the generation of highly mineralized groundwater. If recharge in the spoils is indeed similar to that in the premining landscape, the generation of highly mineralized groundwater in spoils can be anticipated to continue for a considerable period of time. Given the sluggish character of the groundwater systems in this region, we conclude that highly mineralized conditions in spoil waters will continue for hundreds and possibly thousands of years.

The previous discussion has considered the potential impact of surface mining on groundwater from the standpoint of present mining and reclamation techniques. If reclamation design considered the entire landscape, specifically, selective placement of geochemically distinct overburden materials, then the impacts on groundwater quality could be minimized.

Impacts on Pore Water and the Near-Surface Environment

The complexly interrelated components of landscapes in this region were discussed in the introduction. The focus of this study has been on the chemical evolution of subsurface water. The most significant portion of the landscape from the perspective of subsurface water chemical evolution is the near-surface (upper few metres). The quality of groundwater in both undisturbed and disturbed settings is almost totally dependent upon geochemical processes which occur in this zone. Thus, these processes determine not only the quality of water which reached the water table, but also the quality of pore water in the rooting zone.

Present reclamation techniques require the selective recovery and replacement of a maximum of 160 centimetres of soil material. At most mines in this region, the amount of available soil material is considerably less than 160 centimetres. Plant roots commonly penetrate deeper than the thickness of replaced soil material. In addition, recent research has demonstrated the upward migration of sodium from sodic spoils into the overlying solum (Power et al., 1979). Thus, if highly chemically reactive materials such as sodic and sulfide-rich sediments are emplaced immediately below the solum, it is very probable that highly mineralized pore water will be generated in the zone immediately below the solum. Two probable negative impacts will result: (1) downward migration of highly mineralized water to the water table, and (2) sodic and salt effects on plants.

We conclude, then, that the key to long-term biological productivity and groundwater quality in postmining settings in western North Dakota is the restriction of fine-textured sodic and sulfide-rich sediments, particularly if unoxidized, from the near-surface portion of the postmining landscape. The simple replacement of topsoil and subsoil materials without regard for the physical and chemical characteristics of materials below the soil zone is, at best, a temporary and elementary approach to reclamation and only by chance can such an approach result in long-term success.

Impacts on Surface Water

The impacts of near-surface hydrogeochemical processes in surface-mined lands on surface water will be dependent upon a wide range of site-specific variables. Impacts on streams are difficult to evaluate and beyond the purpose of this discussion. The focus of this discussion is small closed-surface water bodies (sloughs) which are common in several active and proposed surface-mining areas in western North Dakota.

Increasing attention is being paid to the reclamation of sloughs. These surface water bodies are not only significant as wildlife habitats, but are also the source of much, if not most, of the recharge in glaciated terrain (Rehm et al., 1982). Typically, the sloughs are also discharge sites for local flow systems which originate on adjacent uplands. Thus, the chemical/ mineralogical characteristics of the sediments that are emplaced for some distance around the reconstructed slough will likely determine the long-term quality of water in the slough. Because of the high evaporation rate in this region, salts which enter the slough are concentrated with time in the slough. If highly mineralized water is generated in the near-surface portion of the landscape surrounding the depression, and discharges into the slough, the slough will become increasingly saline and may possibly develop into a salt flat.

This possibility once again points to the significance of hydrogeochemical and hydrogeologic processes and mechanisms in the near-surface environment in western North Dakota. A proper knowledge of these processes is essential to an evaluation of all the concerns associated with landscape redesign in surface-mined lands.

Summary of Conclusions

Conclusions derived from this study can be summarized as follows:

1. Critical hydrogeochemical processes which control the chemical evolution of subsurface water in undisturbed settings in the Northern Great Plains include: oxidation of organic matter, sulfide-mineral oxidation, soluble sulfate salts precipitation and dissolution (predominantly gypsum), carbonate-mineral dissolution and cation exchange on clays.

2. These hydrogeochemical processes are operating almost exclusively in the zone above the water table. Very little geochemical activity other than calcium-sodium exchange occurs below the water table at depths less than 150 metres.

3. Alternate wetting and drying of the upper portion of the landscape is a key mechanism in the chemical evolution of subsurface water in the Northern Great Plains.

4. The hydrogeochemical processes that control the chemical evolution of water that migrates to the water table also control the chemical characteristics of pore water in the rooting zone.

5. The two major sources of sulfate to subsurface water in the Northern Great Plains are presently existing soluble salts in the overburden and reduced sulfur (either inorganic or organic).

6. Reduced sulfur occurs most commonly in fine-textured sediments but exists in limited amounts in all overburden sediment in the study area.

7. Leaching and weathering experiments indicate that sulfate is either in a readily extracted form or is readily converted to such a form. Thus, only an indirect relationship exists between bulk mineralogical composition of the overburden and dissolved constituents in subsurface water.

8. The amount of sulfate present in the overburden is finite; reduced sulfur exceeds oxidized sulfur by factors of two to ten.

9. In this region, a reasonable source of sulfate is the slow but constant erosion of the landscape which results in the continual renewal of available reduced sulfur and the slow downward migration of a zone of soluble sulfates in the upper portion of the landscape.

10. Recharge in spoils appears to be similar to that in undisturbed settings. Thus, the key wetting and drying mechanism is operating in a similar manner in spoils as in disturbed settings. In addition, this mechanism is greatly enhanced in spoils as a result of excavation and exposure of reduced sediments to the atmosphere.

11. Chemically, subsurface water in spoils is generically similar to subsurface water in undisturbed settings.

12. Groundwater in spoils at the study sites in early stages (within five years), is typically two to three times as mineralized as groundwater in undisturbed settings at these sites.

13. The chemical species of major concern in subsurface water in spoils in this region are sodium and sulfate.

14. The alkaline buffering capacity of overburden sediments in the study area is sufficient, except in highly localized settings, to buffer acid generation to subsurface and surface waters.

15. The sulfate concentration in subsurface waters in both undisturbed and disturbed settings is ultimately controlled by the sodium/calcium ration.

16. The hydrogeochemical model developed for undisturbed settings in the Northern Great Plains is equally applicable to spoils in that region.

17. The major factors determining impacts of surface mining in the Northern Great Plains on subsurface water quality are the mechanisms and rates of recharge through the spoils and the chemical reactivity of the spoils.

18. Redistribution of overburden materials during surface mining operations commonly results in increased chemical reactivity of the spoils landscape relative to the undisturbed setting. Particularly problematic is the emplacement of unoxidized sodic and sulfide-rich sediments in the near-surface oxidized portion of the spoils landscape. Emplacement of soluble sulfate salts in the base of the spoils may also cause generation of highly mineralized groundwater.

19. Large volumes of air entrapped in the spoils during mining will also likely change the reactivity of the landscape by promoting the oxidation of sulfides.

20. Infiltration of water through highly reactive spoils not only affects the quality of water in the saturated zone, but also has the potential to cause sodic and salt effects on plants.

21. Infiltration of water through highly reactive spoils may also result in the degradation of water quality in local discharge areas such as streams and sloughs.

22. If recharge in spoils is restored to approximate premining conditions, then selective handling of overburden will be required in some settings to avoid long-term degradation of subsurface water quality and attendant impacts on groundwater, surface water, and plant growth.

23. If recharge in spoils is minimized, it is reasonable to assume that the flushing of soluble salts in the base of the spoils will result in short-term degradation of groundwater and minimal impacts on surface water. Impacts on plant growth, however, may be severe depending on the mineralogy and texture of the overburden immediately below the solum.

24. Restoration of long-term groundwater, plant growth, and surface water quality in surface-mined areas requires a detailed evaluation of the geology and hydrogeologic and geochemical processes and mechanisms operating in the premining setting.

25. Replacement of soil materials on surface-mined lands without regard for the characteristics of the overburden sediments will only by chance, rather than design, result in successful plant growth, and non-degradation of subsurface and surface water quality.

REFERENCES

Alberta Environment, Earth Sciences Division, 1980, Hydrologic effects of coal strip mining in Whitewood area, Alberta: Alberta Environment, Earth Sciences Division Report.

Brekke, D. W., 1977, Mineralogy and chemistry of clay-rich sediments in the contact zone of the Bullion Creek and Sentinel Butte Formations (Paleocene), Billings County, North Dakota: University of North Dakota M.A. thesis, Grand Forks, North Dakota.

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

Cherven, V. B., 1978, Fluvial and deltaic facies in the Sentinel Butte Formation, central Williston basin: Journal of Sedimentary Petrology, v. 48, p. 159-170.

Chesnin, L., and Yien, C. H., 1950, Proceedings Soil Science Society of America, 15, 149.

Chisholm, W. A., 1965, Heavy minerals in Cretaceous and Tertiary rocks associated with uranium occurrences in Denson, N. M., and Gill, J. R., Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston basin--a regional study: U.S. Geological Survey Professional Paper 463, 75 p.

Clark, M. B., 1966, The stratigraphy of the Sperati Point Quadrangle, McKenzie County, North Dakota: University of North Dakota M.A. thesis, 108 p.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Crawford, J. W., 1967, Stratigraphy and sedimentology of the Tongue River Formation (Paleocene), southeast Golden Valley County, North Dakota: University of North Dakota M.S. thesis.

Day, P. R., 1965, Particle fractionation and particle-size analysis in C. A. Black (editor) Methods of Soil Analysis, Part 1., Monograph No. 9: American Society of Agronomy, Madison, Wisconsin.

Emanuel, R., Jacob, A. F., Karner, F. R., 1976, Mineralogy of the clay-size fraction of the Paleocene Tongue River and Sentinel Butte Formations near Medora, North Dakota: North Dakota Academy of Science Proceedings, v. 28.

Garrels, R. M., and Christ, C. L., 1965, Solutions, minerals, and equilibria: San Francisco, California, Freeman, Cooper, & Company, 450 p.

Ghering, G. E., 1976, Pressurized filtration unit: U.S. Geological Survey Water Resources Division Bulletin, April-June, 1976, p. 24-25.

Griffin, 1971, In Procedures for sedimentary petrology, Carver, Robert E., editor.

Groenewold, G. H., 1979, Hydrologic and hydrogeochemical characteristics of selected strip-mine spoils in western North Dakota: in M. K. Wali (editor) Ecology and Coal Resource Development, Pergamon Press, New York, p. 769-774.

Groenewold, G. H., and Bailey, M. J., 1979, Instability of contoured strip mine spoils--Western North Dakota, in M. K. Wali (editor) Ecology and Coal Resource Development, Pergamon Press, New York, p. 685-692.

Groenewold, G. H., Hemish, L. A., Cherry, J. A., Rehm, B. W., Meyer, G. N., Clayton, L. S., and Winczewski, L. M., 1979, Geology and geohydrology of the Knife River Basin and adjacent areas of west-central North Dakota: North Dakota Geological Survey Report of Investigation 64, 402 p.

Groenewold, G. H., and Rehm, B. W., 1980, Instability of contoured surface-mined landscapes in the Northern Great Plains: causes and implications: Soil Conservation Society of America Symposium Proceedings, Adequate Reclamation of Mined Lands?, Billings, Montana, March 26-27, 1980, p. 2-1--2-15.

Groenewold, G. H., Rehm, B. W., and Cherry, J. A., 1981, Depositional setting and groundwater quality in coal-bearing strata and spoils in western North Dakota: in F. G. Ethridge and R. M. Flores (editors) Recent and Ancient Nonmarine Depositional Environments: Models for exploration, SEPM Special Publication 31.

Groenewold, G. H., Rehm, B. W., Cherry, J. A., Koob, R. B., Moran, S. R., Palmer, C. D., and Peterson, W. M., 1980, Potential hydrogeochemical impacts of surface mining in the Northern Great Plains: Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, Lexington, Kentucky, December 1-5, 1980.

Hemish, L., 1975, Stratigraphy of the upper part of the Fort Union Group in southwestern McLean County, North Dakota: Grand Forks, North Dakota, University of North Dakota M.S. thesis, 160 p.

Hesse, P. R., 1971, A textbook of soil chemical analysis: Chemical Publishing Company, Inc., New York, p. 301-331.

Hvorslev, M. J., 1951, Time lag and soil permeability in groundwater observations: Waterways Experiment Station, Corps of Engineers, U.S. Army Bulletin 36, Vicksburg, Mississippi, 47 p.

Jacob, A. F., 1972, Depositional environments of parts of the Tongue River Formation, western North Dakota, in Ting, F. T. C. (editor), Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geological Survey Miscellaneous Series 50, 134 p.

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

Jacob, A. F., 1975, Criteria for differentiating the Tongue River and Sentinel Butte Formations (Paleocene), North Dakota: North Dakota Geological Survey Report of Investigations 53, 55 p.

Karchmer, J. H., 1970, The analytical chemistry of sulfur and its compounds: Wiley--Intersciena New York, Part 1, p. 285-353.

Kulland, R. E., 1973, Geology of the North Beulah, Center, and Glenharold lignite mines in Mercer and Oliver Counties, southwestern North Dakota: University of North Dakota M.S. thesis.

Langmuir, D., 1971, The geochemistry of some carbonate ground waters in central Pennsylvania: Geochim, et Cosmochim, Acta, v. 35, p. 1023-1045.

Moran, S. R., Groenewold, G. H., Hemish, L. A., and Anderson, C. A., 1975, Development of a premining geological framework for landscape design reclamation in North Dakota: Proceedings of the Fort Union Coal Field Symposium, Montana Academy of Science, Billings, 3:308-316.

Moran, S. R., Cherry, J. A., Ulmer, J. H., Peterson, W. M., Somerville, M. H., Schafer, J. K., Lechner, D. O., Triplett, C. L., Loken, G. R., and Fritz, P., 1976, An environmental assessment of a 250 MMSCFD dry ash Lurgi coal gasification facility in Dunn County, North Dakota: University of North Dakota Engineering Experiment Station Bulletin 76-12-EES-01, v. V, pt. 1 of 3, 126 p.

Moran, S. R., Groenewold, G. H., Cherry, J. A., 1978, Geologic, hydrologic, and geochemical concepts and techniques in overburden characterization for mined-land reclamation: North Dakota Geological Survey Report of Investigation 63, 152 p.

Moran, S. R., Cherry, J. A., Rehm, B. W., and Groenewold, G. H., 1979, Hydrologic impacts of surface mining of coal in western North Dakota: paper presented at Symposium on Surface Mining, University of Kentucky, Lexington, Kentucky, December 4-7, p. 57-65.

Parizek, R. R., and Lane, B. E., 1970, Soil-water sampling using pan and deep pressure-vacuum lysimeters: Journal Hydrology, v. 11, p. 1-21.

Power, J. F., Sandoval, F. M., and Ries, R. E., 1979, Topsoil-subsoil requirements to restore North Dakota mined land to original productivity: Mining Engineering, December, p. 1708-1712.

Raush, H. W., and White, W. B., 1977, Dissolution kinetics of carbonate rocks, Part I, Effects of lithology on dissolution rate: Water Resources Research, v. 13, p. 381-394.

Rehm, B. W., Groenewold, G. H., and Morin, K., 1980, Hydraulic properties of coal and related materials, Northern Great Plains: Groundwater, v. 18, 6.

Rehm, B. W., Groenewold, G. H., and Peterson, W., 1982, Mechanisms, distributions, and frequency of groundwater recharge in upland areas of western North Dakota: North Dakota Geological Survey Report of Investigation 75, 72 p.

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

Royse, C. F., Jr., 1967, A stratigraphic and sedimentologic analysis of the Tongue River and Sentinel Butte Formations (Paleocene), western North Dakota: University of North Dakota Ph.D dissertation.

Sandoval, F. M., Bond, J. J., Power, J. F., and Willis, W. O., 1973, Lignite mine spoils in the Northern Great Plains-characteristics and potential for reclamation: in M. K. Wali (editor), Some environmental aspects of strip mining in North Dakota: North Dakota Geological Survey Educational Series 5, p. 1-24.

Steiner, M., 1979, Petrology of sandstones from the Bullion Creek and Sentinel Butte Formations (Paleocene), Little Missouri Badlands, North Dakota, University of North Dakota M.A. thesis, 153 p.

United States Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agricultural Handbook 60, 160 p.

Wallick, E., 1982, personal commun.

Williams, T. T., Koob, R. L., and Rechard, P., 1978, Surface and groundwater problems associated with potential strip mine sites: Draft Final Report for Environmental Protection Agency R-303727.

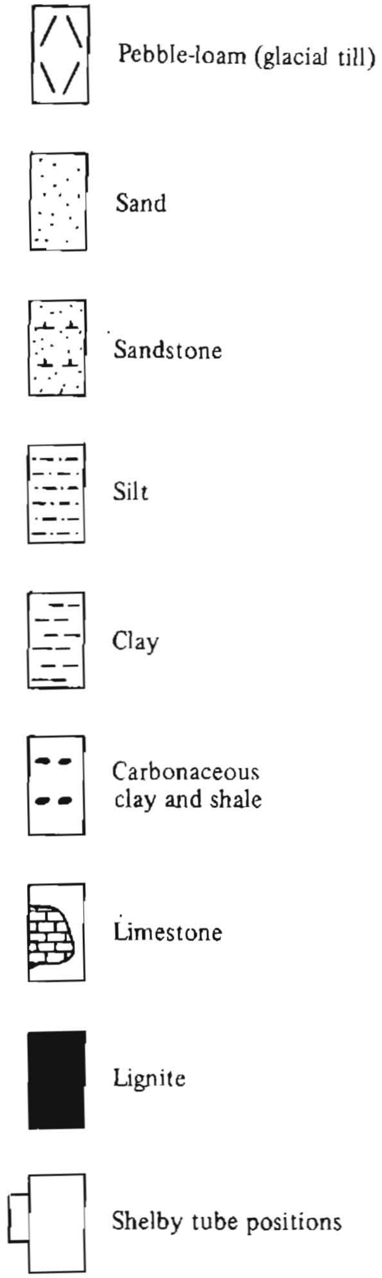
Winczewski, L. M., 1977, Western North Dakota lignite strip mining processes and resulting subsurface characteristics: University of North Dakota M.S. thesis, Grand Forks, 433 p.

Wood, W. W., 1973, A technique using porous cups for water sampling at any depth in the unsaturated zone: Water Resources Research, v. 9, 2, p. 486-488.

APPENDIX A

Descriptive Logs of Overburden Sampling Test Holes at the Four North Dakota Study Sites

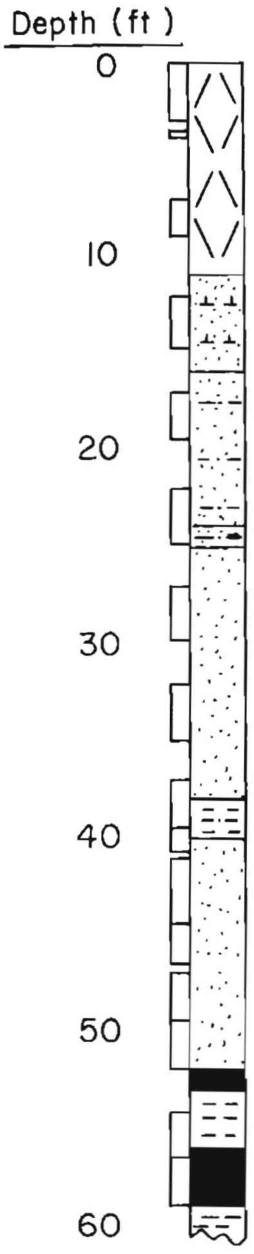
EXPLANATION OF LITHOLOGIC SYMBOLS USED ON LOGS



Depths in feet;
convert to metres
by multiplying by 0.3048

CENTER 361

T. 142 N.
R. 84 W.
Sec. 35, bbb



Pebble-loam (glacial till), brown

Sand, fine, yellow-brown
Sandstone

Sand, very fine, silty, yellow-brown

Sand, very fine, silty, slightly carbonaceous

Sand, very fine, gray-brown

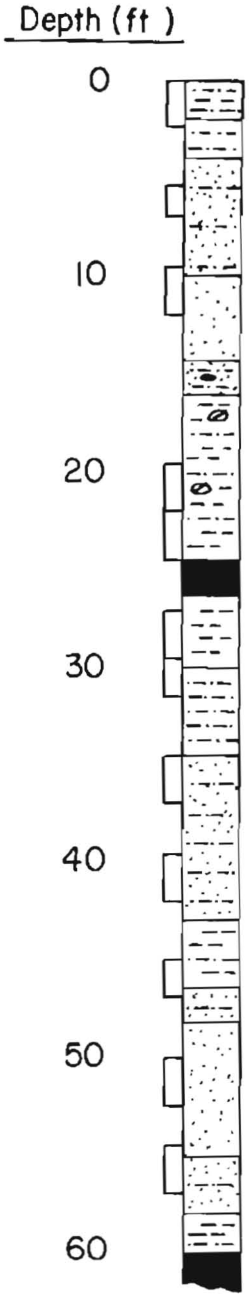
Clay, silty

Sand, very fine, gray, unoxidized

Lignite
Clay, gray
Lignite
Clay, dark-gray

CENTER 366

T. 142 N.
R. 84 W.
Sec. 28, dcc



Lithology

Silt, clayey, organic, dark-brown

Silt, light-brown

Sand, very fine, silty, yellow-buff

Sand, fine, yellow-buff

Silt, tan, with sand, carbonaceous

Clay, silty, gray-brown, with iron oxide concretions

Lignite, soft

Clay, medium-gray

Silt, gray

Sand, very fine, silty

Clay, silty, gray

Sand, very fine, silty, gray

Sand, very fine, light-gray

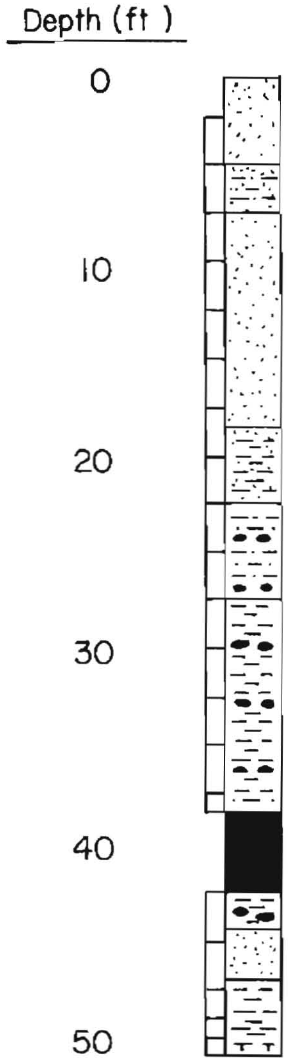
Sand, very fine, silty, light-gray

Clay, silty, gray

Lignite, medium-hard

CENTER 380

T. 142 N.
R. 84 W.
Sec. 27, ccb



Lithology

Sand, fine-grained, olive-gray, with blebs of calcium carbonate, oxidized

Silt, sandy, interlaminated with sand, fine to very fine, yellow-brown, oxidized

Sand, fine, olive- to yellow-brown, oxidized

Clay, silty, sandy, gray to olive, lignitized plant fragments, oxidized along fractures

Silt, clayey, sandy, carbonaceous, very dark brown to black, oxidized on fracture surfaces

Clay, silty, carbonaceous, dark-brown to black; laminated with very fine sand, light-gray, unoxidized

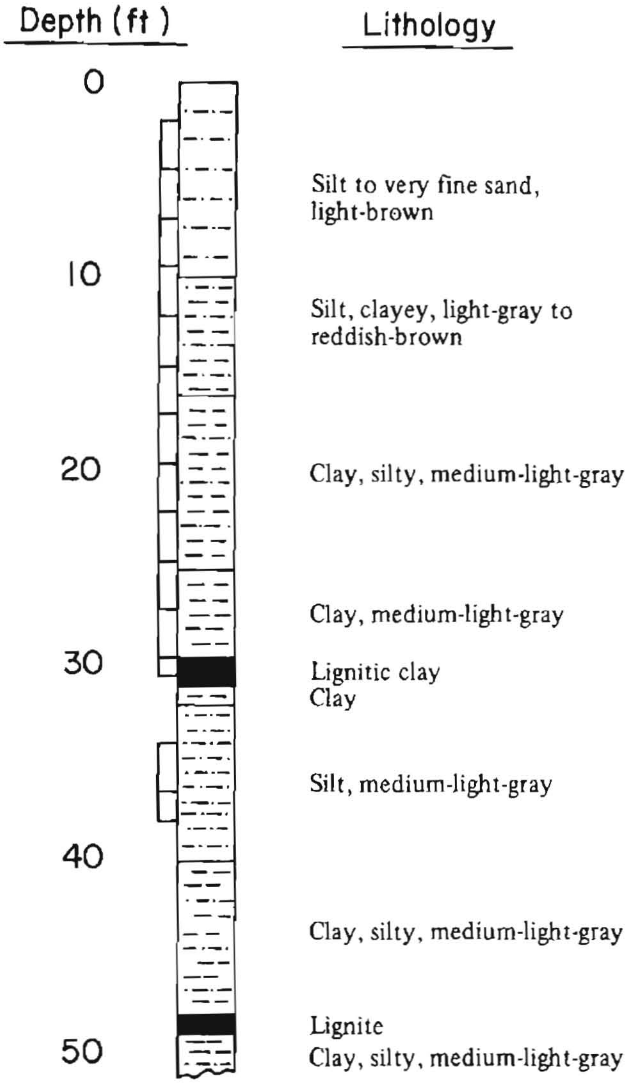
Lignite

Clay, silty, carbonaceous, dark-brownish-gray to black, unoxidized

Sand, very fine to fine, gray, unoxidized

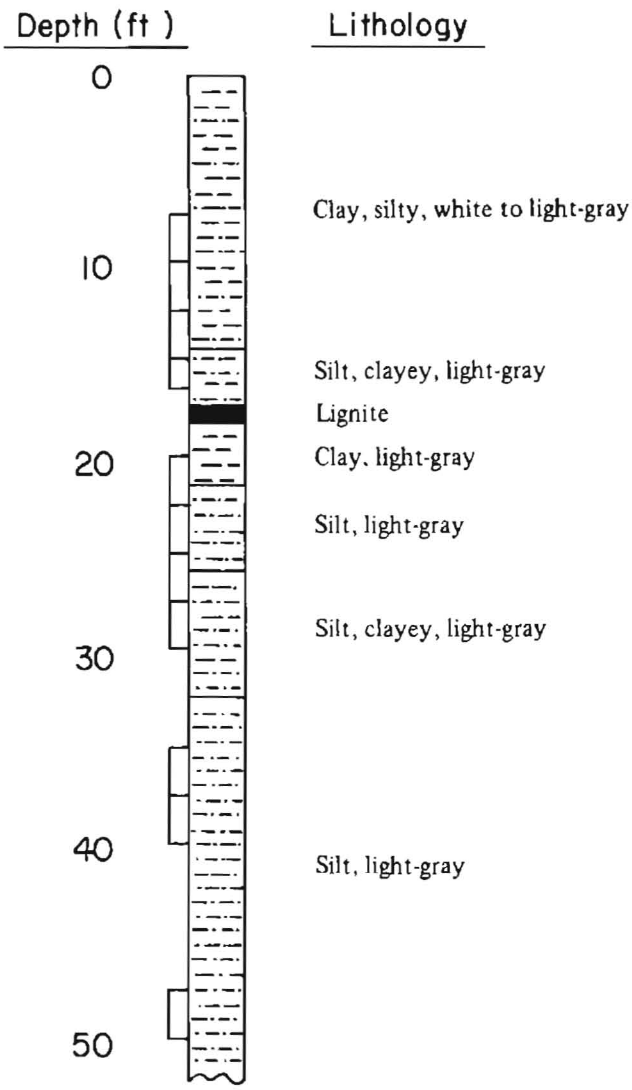
Clay, gray, unoxidized; claystone, light-brownish-gray at 50.5 feet

INDIANHEAD X-2



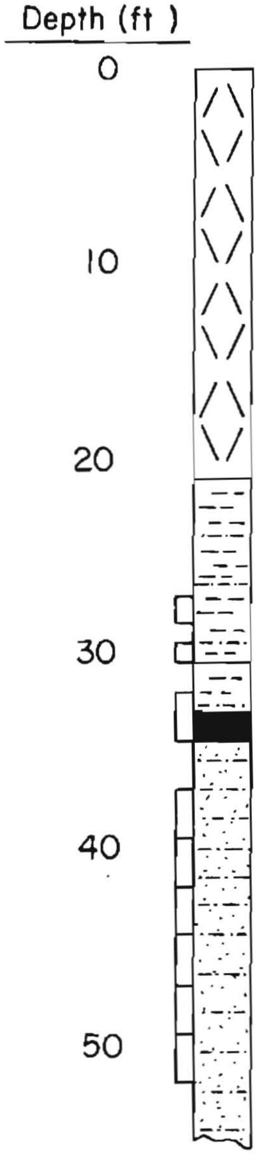
T. 144 N.
R. 89 W.
Sec. 36, abb

FALKIRK 514



T. 146 N.
R. 82 W.
Sec. 33, dcc

FALKIRK 526



Lithology

T. 146 N.
R. 83 W.
Sec. 25,ccc

Pebble-loam (glacial till), brown, oxidized

Clay, slightly silty, grayish-tan, contains orange specks, noncalcareous

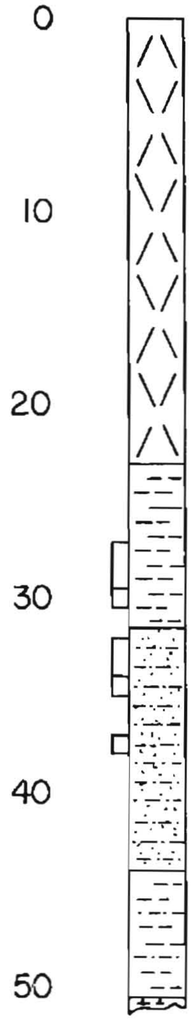
Clay, silty, grayish-tan, slightly lignitic

Sand, very fine to fine, silty, gray, lignitized plant remains; silt, sandy, gray, unoxidized

FALKIRK 561

Depth (ft) Lithology

T. 146 N.
R. 82 W.
Sec. 22, add



Pebble-loam (glacial till), yellow-brown

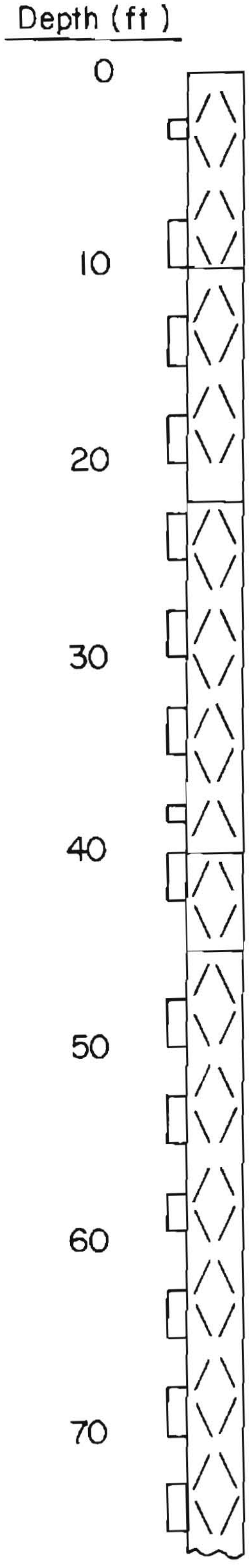
Clay, yellow-brown

Silt, sandy, yellow-brown

Clay, silty, gray

Siltstone, cemented

FALKIRK 576



Lithology

Pebble-loam (glacial till), yellow-brown to red-brown, carbonaceous and shale pebbles, iron oxide-stained

T. 146 N.
R. 82 W.
Sec. 7, ccc

Pebble-loam, olive-gray-brown, less iron oxide-staining

Pebble-loam, yellow-brown, lignitic, larger pebbles than above

Pebble-loam, becoming gray, fewer pebbles, less clay

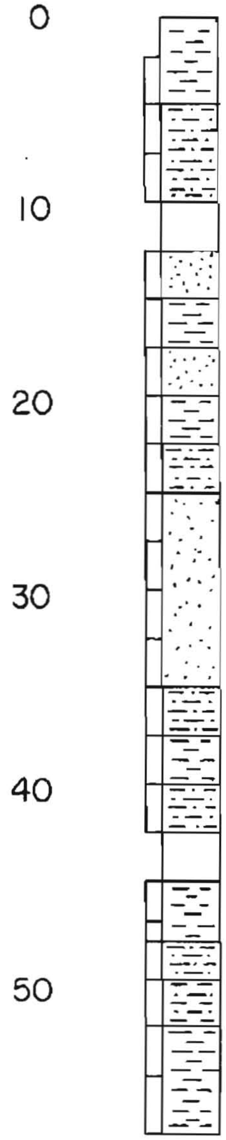
Pebble-loam, gray

CONSOL 31

T. 144 N.
R. 84 W.
Sec. 31, bdd

Depth (ft)

Lithology



Clay, silty, mottled, white-olive-gray and reddish-brown, iron and manganese oxide deposited on fractures, also blebs of calcium carbonate

Silt, clayey, mottled, gray, olive-gray, and yellow-brown, iron and manganese oxide deposits on fractures

Sand, very fine, light-olive-gray, unoxidized?

Clay, silty, yellow-brown, calcium carbonate blebs, oxidized

Sand, very fine, silty, olive, oxidized

Clay, silty, olive-gray to yellow-brown, oxidized, crumbly

Silt, olive-gray, many sand-size plant fragments, unoxidized

Sand, fine to very fine, light-olive-gray, "salt and pepper," unoxidized

Silt, clayey, gray, unoxidized; laminated with silt, light-gray

Clay, silty, gray to light-gray, unoxidized

Silt, clayey, sandy, mottled-gray to light-gray, unoxidized

Clay, silty, gray to light-gray; laminated with very fine sand, unoxidized

Silt, clayey, gray to light-gray, laminated, unoxidized

Clay, gray, and silt, light-gray, laminated, unoxidized

Clay, gray, unoxidized; claystone, light-brownish-gray at 57.5 feet

APPENDIX B

Bulk Mineralogical Data for Overburden from the North Dakota Sampling Sites

Bulk mineralogical data are for 123 samples from the bottom 3 inches (7.6 cm) of each Shelby tube and for 97 samples from the middle of Shelby tubes. Samples from the bottom of each tube are identified according to the total depth interval represented by that tube (typically 2.5 feet). Samples from the center of each tube are identified according to the actual interval represented by that sample. All depths are given in feet; convert to metres by multiplying by 0.3048.

All data are presented according to the height of the major peak for each mineral.

Explanation of Mineral and Lithology Symbols

Symbol	Minerals	2θ°
Q	Quartz	26.6
P	Plagioclase	27.8-28.0
K	Alkali Feldspar	27.4-27.6
D	Dolomite	30.9
C	Calcite	29.4
Mt	Montmorillonite	6.0-7.0
M	Mica	8.8
Ch	Chlorite	12.4
S	Siderite	31.7
Gp	Gypsum	11.6
Py	Pyrite	33.1
?	Indicated but not verified	

	Lithology
cl	Clay
sl	Silt
sd	Sand
carb	Carbonaceous
t	Till

CENTER 361

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
0 - 2.5	46	31	12	39.5	19	20.5	10	8.5	-	-	-	2.08	t
2.6 - 2.75	48	20	12	21.5	23	?	?	?	-	-	-	0.93	t
3 - 4	39.5	23	15.5	51.5	39.5	26	16	13	-	-	-	1.30	t
8.15- 8.25	58	47	16.5	29	17.5	18	12	10	-	6.5	-	1.66	t
7 - 9.5	61	32	14	33.5	15	20	15	10	-	-	-	2.23	t
12 -14.5	59	41	24	43	50	13	14	9	-	-	-	0.86	sd
18.2 -18.25	63.8	73.8	27.5	37.6	20	37	10.5	7.5	-	-	-	1.88	sd
17 -19.5	31	35	12.5	37	12.5	22.5	9.5	7.5	-	4	-	2.96	sd
23.25-23.30	58	57	24	73.5	15	55	14.5	8	-	-	-	4.90	sd
22 -24.5	59	43	15	62	14	47.5	17	11	-	-	-	4.43	sd
27 -29.5	34	34.5	27.5	31	12.5	24	8	6.5	-	1.5	-	2.48	sd
32 -34.5	60	51	23	46	15.5	26.5	11	10	-	-	-	2.97	sd
37 -39.5	40	37.5	32.5	64	5.5	49	11	9	-	-	-	11.64	sd
40.18-40.25	69.5	66	22	41	6.5	37	14	14	-	-	-	6.31	sd
39.5 -41.5	49	77.5	38	33.5	9.5	39.5	16	15	-	-	-	3.53	sd
43.2 -43.25	63.5	34.5	26	22.5	5.5	28	7.5	8	-	-	-	4.09	sd
42 -44.5	77.5	48	14	18	6	?	7	7.5	-	-	-	3.00	sd
45.16-45.25	65	98	20	27	6	35.5	8	8	-	-	-	4.50	sd
44.5 -46.5	84	40	16	14	-	11	7	7	-	-	-	-	sd
47.5 -49.5	84	51	20	36.5	11	20	15	16	-	-	-	3.32	sd
48.2 -48.25	63.5	29.5	16.5	21.5	8	30	4.5	7	-	-	-	2.69	sd
50.71-50.75	80	53	18.5	38	8	32.5	13	11.5	-	-	-	4.75	sd
49.5 -52	33	43	162	15	4.5	33	7	8.5	-	-	-	3.33	sd
49.5 -52	52.5	58	12.5	15.5	7.5	18	13	11	-	-	-	3.07	sd
55.68-55.75	65.5	33.5	16	-	-	14	22.5	10.5	-	-	-	-	cl & sl
54.5 -57	59	22	13	-	-	6	10	8	-	-	-	-	cl & sl
54.5 -57	16	30	17	-	-	8	16	8.5	-	-	-	-	sl
57 -59	62	22	14	-	-	8	15	8	-	-	-	-	cl

CENTER 366

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py.	D/C	Lith
5.67- 5.75	69	26	27	60	13.5	8.5	22	8	-	-	-	4.44	sl
5.5 - 7	91	35	16.5	54	13.5	?	14	5.5	-	-	-	4.00	sd
10.75-10.86	61	30	12	64.5	10	9.5	29.5	13	-	-	-	6.45	sl
9.5 -12	38	26.5	12	32.5	11.5	?	11.5	3	-	1.5	-	2.83	sl
19.5 -22	32.5	18	10.5	19.5	5.5	?	13	6	-	-	-	3.55	cl
23.31-23.4	37	20	12.5	24.5	75.5	11	18	12	-	-	-	0.32	cl
22 -24.5	44	15	6	30.5	25	0	10	6.5	-	-	-	1.22	cl
28.25-28.3	66	24.5	16	70	-	30.5	17	14	-	-	-	-	sd
27 -29.5	61	37	21	93.5	23	?	14	12.5	-	-	-	4.07	sd
30.25-30.29	54	19.5	8.5	32	31.5	17.5	13.5	13	-	-	-	1.02	cl, sl
29.5 -31.5	29	21.5	16.5	29	16	8	10.5	10	13	-	-	1.81	sl
35.67-35.75	53	35	14.5	73	31	21	25	17	-	-	-	2.35	cl, sl
34.5 -37	46	42.5	11	71	37	14	17.5	11.5	7.5	-	-	1.92	sd
40.75-41.15	49.5	27	13	74	27.5	32	18.5	12	-	-	9.5	2.69	sd
39.5 -42	44.5	26	12	62	30	14	19.5	13.5	10	-	-	2.07	sl & sd
45.69-45.75	36	15.5	7	9	-	11.5	15	13	-	-	-	-	cl
45 -47	38	13	-	12.5	3.5	?	14	10.5	-	-	-	3.57	cl
50 -52.5	76	36	17.5	83	20	9	13	9.5	-	-	-	4.15	sd
50 -52.5	67	42	28	100	19.5	11	27	14.5	-	-	-	5.13	sd
-55.75	68	51	49	104	18.5	54	23.5	13.5	-	-	-	5.62	sd, sl
54.5 -57	46	26	21.5	40.5	22	11.5	13.5	11.5	-	-	-	1.84	cl
54.5 -57	51	32	-	29	16	8.5	16	8.5	-	-	-	1.81	cl

CENTER 380

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
3.18- 3.25	54	86.5	15.5	34.5	28	34	15	15	-	-	-	1.23	sd
2 - 4.5	95	84	20	61.5	17.5	37	11	12	-	-	-	3.51	sd
5.69- 5.75	55	40.5	15	74	17	30	14	13	-	-	-	4.35	sd
4.5 - 7	79.5	70	26	42	14	25	11.5	11	-	-	-	3.00	sd
7 - 9.5	89	100	41.5	88	16	35.5	21.5	18.5	-	-	-	5.50	sd
10.69-10.75	54	50	18.5	72.5	17	34.5	15.5	13	-	-	-	4.25	sd
9.5 -12	68.5	68	33.5	57	27	30	16	17	-	-	-	2.11	sd
13.18-13.25	59	56	105	-	-	27	13.5	10.5	-	-	-	-	sd
12 -14.5	64.5	117	53	62	18	28	24	20	-	-	-	3.44	sd
15.69-15.75	104	77	29	54.5	13	30	15	12.5	-	-	-	4.19	sd
14.5 -17	59.5	65	24	41.5	10	17	11	11	-	-	-	4.15	sd
18.19-18.25	64	27.5	13.5	9.5	-	16	21.5	10	-	-	-	-	sl, cl
17 -19.5	68	36.5	12	-	-	13.5	17.5	7.5	-	-	-	-	cl
20.7 -20.75	54	22	14	-	-	16	20	8.5	-	-	-	-	cl
19.5 -22	82	35	15.5	17	-	8	12.5	7	-	-	-	-	sl
23.2 -23.25	86.5	30	14.5	-	-	12.5	21.5	10	-	-	-	-	sd, carb
22 -24.5	63.5	40.5	21	-	-	11.5	20	10	-	-	-	-	sd, carb
25.69-25.75	65.5	31	13.5	12	-	10	21	10	-	-	-	-	cl & sl
24.5 -27	73	32	10	10	-	7	14	8	-	-	-	-	cl
28.2 -28.25	57	25.5	65.5	11	-	12	21	12	8.5	-	-	-	sl, carb
27 -29.5	67	27.5	16	15	3.5	7	24.5	11	-	-	-	4.29	cl
29.5 -32	82	26	16.5	17	-	?	15.5	10	-	-	-	-	sl
33.2 -33.25	65.5	22	12.5	17	-	11	20.5	11	-	-	-	-	cl, sl, carb
32 -34.5	74	29	18	11.5	-	6	20	11.5	-	-	-	-	cl
35.66-35.75	69	34	12.5	15.5	-	10	29	14.5	-	-	-	-	sd, carb
34.5 -37	66	25.5	9	8.5	-	8	16	9.5	-	-	-	-	cl, carb
34.5 -37	89	44.5	24	15.5	-	7	16.5	11	-	-	-	-	cl
36.95-37	60	20	19	11.5	-	9.5	20	10	-	-	-	-	cl, carb

CENTER 380 (Continued)

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
37 -38	58	21	28	-	-	8.5	20.5	12	-	-	-	-	cl, carb
43.19-43.25	82	33.5	25.5	12.5	-	14.5	29	14.0	-	-	-	-	sd
42 -44.5	65	28	18	-	-	9	20	13	-	-	-	-	cl
45.69-45.75	72	26	13.5	-	-	8	13.5	9.5	-	-	-	-	sd, cl
44.5 -47	61	59	14	-	-	14	20	23	6	-	-	-	sd
47.10-47.25	61.5	48.5	36	11	-	22	14	17.5	-	-	-	-	sd
47 -48.5	38.5	15	8.5	18	-	10	18	12.5	-	-	-	-	cl
48.5 -49.5	56	21.5	11	74.5	-	14	14	10	-	-	-	-	sl
49.5-50.5	62	60	10.5	104	10	?	18	13	-	-	-	10.4	sd

INDIAN HEAD X-2

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
3.21- 3.25	44.5	82.5	10.5	21	?	53	11.5	13.5	-	-	-	-	sd
2 - 4.5	61	97	34	10	-	30.5	9	10.5	-	-	-	-	sd
5.7 - 5.75	65.5	67	33.5	28.5	-	46.5	14	13	-	-	-	-	sd
4.5 - 7	66.5	46	27	12.5	-	43	9	11	-	-	-	-	sd
8.18- 8.25	53	98.5	11	10.5	-	27.5	5.5	7	-	-	-	-	sd
7 - 9.5	65	79	54	17	-	59	22	21	-	-	-	-	sd
10.69-10.75	54.5	36	12	-	-	16	6	8	-	21.5	8	-	sd
9.5 -12	27.5	15	5	8.5	-	12	15	11	-	-	-	-	cl, sl
13.19-13.25	32	19	8.5	-	-	15.5	10	11	-	6.5	-	-	cl
12 -14.5	48.5	79	9	-	-	15.5	19	21	-	-	-	-	cl, sd
15.7 -15.75	54	27	9.5	16	-	28	21	21	-	-	-	-	cl
14.5 -17	48.5	29.5	11.5	12.5	9	15	15	15	-	-	-	1.39	sd & cl
18.2 -18.25	40.5	22.5	8	9	6	22.5	19	15	-	-	-	1.50	cl
17 -19.5	39	22	9	7	3.5	13	16	14.5	-	-	-	2.00	cl
20.69-20.75	39	29	8	9	4	16	13	13.5	-	-	-	2.25	cl
19.5 -22	33	28.5	7.5	7	-	18	20.5	19	-	-	-	-	cl
23.18-23.25	30.5	18	8	7	-	16.5	16	16	-	-	-	-	cl
22 -24.5	31	19	7	-	-	13.5	16.5	18	-	-	-	-	cl
26.10-26.15	44.5	26	7	8.5	6	13	16	16	-	-	-	1.42	cl
24.5 -27	32	20.5	7.5	6.5	-	8.5	13.5	15.5	-	-	-	-	cl, sl
28.19-28.25	30	14	8	-	-	10	13	14	16.5	-	-	-	cl
27 -29.5	55	42	26.5	-	-	8	15	17.5	-	-	-	-	sd, sl
29.5 -30.5	63.5	71	21.5	-	-	14.5	23.5	28	-	-	-	-	cl, carb
29.5 -30.5	57	49	32.5	-	-	9.5	16.5	16	-	-	-	-	cl, sd, carb
35.19-35.25	56	32	11	41.5	17	14	19.5	18.5	6	-	-	-	sl, sd
34 -36.5	70	62	24.5	61	18.5	11.5	14	15.5	-	-	-	3.30	sd
36.5 -38	69.5	37.5	12	20	16	8	18	15	5.5	-	-	1.25	sl

CONSOL 31

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
3.19- 3.25	42	15	7	19		14	14.5	11	-	-	-		cl
2 - 4.5	46	18	10	21	23.5	?	18	12	-	-	-	0.89	cl
5.66- 5.75	47.5	22	9	22	21	12.5	18	13	-	-	-	1.05	cl
4.5 - 7	46	19	8	26.5	25	10	17	12	-	-	-	1.06	cl
8.17- 8.25	37	14	5	27	33	13	16	10	-	-	-	0.82	cl
7 - 9.5	42.5	20	8	22	15	4	12	9	-	-	-	1.47	cl
13.21-13.25	45.5	14	8	18	21	16.5	12	7.5	-	-	-	0.82	cl
12 -14.5	72?	27	7	37?	15	?	8	5.5	-	95	-	2.47?	sd
15.71-15.75	60	33	5.5	40	41	18	16	9	-	-	-	0.98	sd
14.5 -17	56	27	11	35	23	6?	9	7	-	-	-	1.52	sd
18.2 -18.25	48.5	19.5	9	39	22.5	19	12	8	-	6	-	1.73	sd
17 -19.5	66.5	43	6.5	27.5	23.5	7.5	12.5	6	-	-	-	1.17	sl & sd
20.75-20.8	50.5	45	9.5	75	30	22.5	14	8	-	-	-	2.50	sd
19.5 -22	56.5	22	13	39	25.5	?	11	6.5	-	-	-	1.53	sl
23.21-23.25	40.5	25	8	50.5	34.5	17	18.5	11	-	-	-	1.46	cl
22 -24.5	55	23	8	29.5	28	?	10.5	6.5	-	-	-	1.05	sl
25.71-25.75	50.5	87	34	52	29	26	27.5	14	-	-	-	1.79	sd
24.5 -27	56	49	19	41.5	20	9	17	8	-	-	-	2.08	sd
28.2 -28.25	52	34	30	47.5	17	17	18	9	-	-	-	2.79	sd
27 -29.5	72	38	19	91.5	30	18	22	12	-	-	-	3.05	sd
30.71-30.75	48	27	7	31	27	22	16	9	-	-	-	1.15	sd & sl
29.5 -32	69	34.5	44	176	23	13	32.5	15.5	-	-	-	7.65	sd
33.2 -33.25	45	27	8	35	27	10	16	11	8	-	-	1.30	sl
32 -34.5	57	33.5	?	42	21	10	18	9	-	-	-	2.00	sd
35.7 -35.75	53	35.5	11.5	32.5	16	11.5	12.5	7	-	-	?	2.03	cl & sl
34.5 -37	38.5	14	5.5	15	17.5	0?	13	7.5	14.5	-	-	0.86	cl
38.2 -38.25	37	20	-	21	21	9.5	16.5	13	-	-	-	1.00	cl & sl
37 -39.5	35	15	7	15	14	8	19.5	15.5	9	-	-	1.07	cl

CONSOL 31 (Continued)

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
40.69-40.75	33	17	8	19.5	11.5	13	19	13	8	-	-	1.70	cl
39.5 -42	38.5	23	10	18	-	?	15	13	-	-	-	-	cl
45.2 -45.25	28	10.5	5.5	11.5	20	9	14	11	17	-	-	0.58	cl
44.5 -46.5	33.5	17	8	13.5	23.5	8.5	18	12.5	13	-	-	0.57	cl
46.5 -47.5	30	14	7	13	20	0?	15	10	-	-	-	0.65	cl
48.16-48.25	25.5	15	-	16	25	10.5	15.5	12.5	7	-	-	0.64	cl & sl
47.5 -49.5	34	21.5	12	23	31	7.5	22	13	-	-	-	0.74	cl
50.7 -50.75	36	17	-	20	18	11	17	12	-	-	-	1.11	cl & sl
49.5 -52	34.5	15.5	8	16	18.5	8.5	18.5	13	12.5	-	-	0.86	cl
53.19-53.25	33	15	-	15	19	7	11.5	9.5	9.5	-	-	0.79	cl
52 -54.5	30.5	15	7.5	14.5	20	5.5	17	10.5	6	-	-	0.73	cl
54.7 -54.75	56.5	15	6.5	13	16	10	15	11	-	-	-	0.81	cl
54.5 -56	31	15	6	11.5	15.5	7.5	15.5	11.5	26	-	-	0.74	cl
56.2 -56.25	36.5	16	7	11.5	15	9	14	10	6	-	-	0.77	cl
56 -56.5	23	10.5	5.5	12	20.5	7.5	15.5	9	42.5	-	-	0.60	cl

FALKIRK 514

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
8.25- 8.30	52.5	7	7	-	-	14.5	13	10	-	46	-	-	cl
7 - 9.5	47	12	8.5	-	-	13	16	9.5	-	-	-	-	cl
10.68-10.75	35.5	-	-	-	-	20.5	10	7.5	-	-	-	-	cl
9.5 -12	47	14.5	6	-	-	12.5	17	5	-	-	-	-	cl
13.19-13.25	52	23	9	-	-	26.5	23.5	6.5	-	-	-	-	cl
12 -14.5	44.5	14	9	-	-	10	14	5	-	-	-	-	cl
14.5 -16	66	21.5	19	-	-	17.5	29	12	-	-	-	-	cl
20.75-20.82	39.5	22.5	10	21	-	16	22	22.5	-	-	-	-	cl
19.5 -22	38	22	11.5	24.5	18.5	11	18.5	17	-	-	-	1.32	cl
23.25-23.30	40	25	14	33.5	42	16	27.5	20	6	-	-	0.80	cl
22 -24.5	37.5	22	11.5	31.5	23.5	10	16	15	8.5	-	-	1.34	cl
24.5 -27	44	22.5	15.5	31	23.5	13	16	16.5	-	-	-	1.32	cl
27 -29.5	48.5	53	35	34	21	7.5	9	10.5	5	-	-	1.62	sl
35.71-35.75	52	36.5	28.5	52	43	34.5	19	16.5	-	-	-	1.21	sd, sl
34.5 -37	52.5	49	20	44	25	16.5	18	15.5	-	-	-	1.76	sl
37 -39.5	48	26	17	38	24	12	16.5	13.5	9	-	-	1.58	sl
47 -49.5	44.5	28.5	16.5	73.5	29	16.5	20	18.5	7	-	-	2.53	cl

FALKIRK 526

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
27.15-27.25	40	23	12	11	6.5	23	15	13	-	-	-	1.69	cl
27 -28.5	30	20.5	10	8.5	-	10	11	9	8.5	-	-	-	cl
27 -28.5	30	17.5	9	10	-	11	12	8.5	-	-	-	-	cl
33.18-33.25	62	38.5	14.5	-	-	20.5	27	20	-	-	-	-	cl & sd
32 -34.5	62	73.5	30	42	-	14	11	13	-	-	-	-	sd
38.17-38.25	69.5	58.5	18.5	79	-	46.5	24	23	6	-	-	-	sd
37 -39.5	62	33	15.5	48	18.5	19	17	14	-	-	-	2.59	sd
40.68-40.75	65	35.5	57.5	44	8.5	20	20	16	14.5	-	-	5.18	sl
39.5 -42	70	48.5	16	51.5	13.5	17	21	16	14	-	-	3.81	sd
43.19-43.25	51	26.5	13	57.5	7	21	16.5	12	-	-	-	8.21	sl
42 -44.5	60	54	19	54.5	14	23.5	16.5	14.5	13	-	-	3.89	sd
45.69-45.75	63	38	11	68	26.5	27	20.5	16	11.5	-	-	2.57	sl
44.5 -47	67	29	12	53	12	15	14	12	-	-	-	4.42	sd
48.21-48.25	51	24.5	7.5	52	47	19	22	16.5	9	-	-	1.11	sl
47 -49.5	50.5	44	32	58.5	20	17.5	17	15	-	-	-	2.93	sl
49.5 -52	58	24.5	12	39	19.5	?	13	10	-	-	-	2.00	sl

FALKIRK 561

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
28.2 -28.25	53	73.5	29	32	-	35.5	18	17.5	-	-	-	-	sd
27 -29.5	75.5	52	29	-	-	9	6.5	6.5	-	-	-	-	sd
29.5 -30.5	25	38	9.5	15.5	18.5	14	15	8	-	-	-	0.84	cl
32 -34	45.5	98	24.5	51	20.5	27	19	13	-	-	-	2.49	sl
34 -35	52	51	17	29	12	20.5	14	10	-	-	-	2.42	cl
37 -38	41.5	45.5	12.5	24.5	11.5	16	13	12	-	-	-	2.13	sl

FALKIRK 576

Depth (ft)	Q	P	K	D	C	Mt	M	Ch	S	Gp	Py	D/C	Lith
2.21- 2.25	55.5	51	11	73.5	35	20.5	9	5	-	-	6.5	2.10	t
2.5 - 3.5	44.5	22.5	13	46	34.5	3.5	7	4.5	-	-	-	1.33	t
8.68- 8.75	44.5	27	17	64	34.5	13	6	4.5	-	-	-	1.86	t
7.5 -10	46	20	11	130	32	-	6	?	-	8	-	4.06	t
13.67-13.75	53.5	46.5	22	98.5	36	12	8	5.5	-	22	-	2.74	t
12.5 -15	61	19	11	47	18	?	?	?	-	4	-	2.61	t
18.69-18.75	53	33.5	98	94	21.5	14	9	5.5	-	13.5	-	4.37	t
17.5 -20	58	15	14	75	28	?	?	?	-	?	-	2.68	t
23.71-23.75	55	63.5	59.5	88	32	18	12	6	-	5.5	-	2.75	t
22.5 -25	85	32	14	52	19	?	?	?	-	?	-	2.79	t
28.69-28.75	66.5	25	11	50.5	19	16.5	12	5.5	-	4	-	2.66	t
27.5 -30	79	90	26	63	27	?	12	5	-	?	-	2.33	t
33.69-33.75	46	31.5	13	27	13	14	8.5	5.5	-	10.5	-	2.08	t
32.5 -35	76	96	18	57	16	-	6	6	-	6	-	3.56	t
37.5 -38.5	62	24	11	29	18	-	8	7	-	8	-	1.61	t
41.10-41.25	55.5	39	25	32	12	24	14	10	-	-	-	2.67	t
40 -42.5	46	38	13	27	9	-	10	6	-	-	-	3.00	t
48.69-48.75	50.5	34	26	34	15	19	11.5	7.5	-	6.5	-	2.27	t
47.5 -50	61	20	12	22.5	12	5	7	4	-	-	-	1.88	t
53.69-53.75	48	35.5	17.5	28	26.5	19	11	7	-	-	-	1.06	t
52.5 -55	65	29.5	9.5	24.5	16	6	6.5	3.5	-	-	-	1.53	t
58.18-58.25	64	22.5	11	51	16.5	19	14	9.5	-	-	-	3.09	t
57.5 -59.5	60	25	19.5	23.5	12.5	7.5	7.5	5	-	2	-	1.88	t
63.68-63.75	118	34	27	44.5	20	17	12	8.5	-	-	-	2.23	t
62.5 -65	75	37.5	9	24.5	14	5.5	6.5	5	-	-	4.5	1.75	t
68.66-68.75	56	29	16	49	18	16.5	11	9.5	-	-	-	2.72	t
67.5 -70	33	28	18.5	27	16.5	6	8	5	-	-	-	1.64	t
73.75-73.82	54	39.5	17.5	49.5	25.5	15	10	8	-	-	-	1.94	t
72.5 -75	32	35.5	37.5	31	14.5	?	9	5	-	2.5	-	2.14	t

APPENDIX C

Saturated-Paste Extract Data from Spoils Areas at the Center and Indian Head Mines

All samples are identified according to adjacent piezometer.
See figures 14 and 16a-j for location of sampling sites.

CENTER MINE

Piezometer Number	Depth (ft)	pH Paste	pH Extract	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	EC mS/cm	SAR
				meq/L								
19	1.4	7.16	----	5.8	---	58.8	27.3	24.19	11.30	1.9	4.3	2.2
59	.4	6.70	7.60	8.9	---	79.5	27.1	23.83	35.00	2.5	5.7	6.9
61	.4	7.34	7.50	6.0	---	48.8	9.5	10.26	23.50	1.6	3.55	7.5
63	.4	7.37	7.65	7.3	---	52.5	12.0	11.44	34.92	1.4	3.38	10.2
64	.4	8.01	7.55	2.9	---	20.7	4.5	3.51	14.50	1.2	1.78	7.3
66	.4	7.72	7.75	2.6	.05	19.6	10.6	3.79	6.70	1.2	1.20	2.5
69	1.55	7.45	7.75	3.6	.18	20.8	10.2	9.36	4.00	1.0	1.95	1.3
70	2.3	7.40	7.70	4.4	---	11.8	7.0	5.22	2.50	1.4	1.31	1.0
72	1.15	7.15	7.40	4.2	.40	30.0	12.8	10.87	9.50	1.4	1.78	2.8
74	2.6	6.80	7.20	8.2	---	124.8	51.4	50.27	30.00	1.3	7.30	4.2
75	1.6	7.80	7.60	3.6	.05	7.8	1.0	1.20	8.70	.6	1.00	8.3
79	2.2	6.95	7.15	8.8	---	11.4	11.7	4.53	3.30	.7	1.50	1.2
82	1.7	7.20	7.36	6.7	---	35.1	13.6	12.45	14.00	1.6	3.10	3.9
85	.6	7.40	7.45	3.3	.06	28.3	14.6	10.55	5.00	1.5	2.65	1.4
89	.4	7.15	7.70	5.8	---	63.9	28.1	20.69	19.00	2.0	4.50	3.9
94	.4	7.60	7.80	5.9	---	37.9	14.1	11.92	16.20	1.6	2.75	4.5
97	.4	7.80	7.70	4.4	---	20.8	5.9	5.32	12.50	1.4	1.26	5.3
99	.4	6.80	7.30	9.0	.03	65.3	32.0	30.01	12.00	.3	4.60	2.2
104	.4	7.49	8.15	6.9	.03	28.4	6.5	5.31	22.0	1.6	2.90	9.1
105	.4	7.40	7.65	5.7	---	15.5	8.8	8.6	2.2	1.6	3.42	.7
108	2.65	7.30	7.45	5.0	---	21.4	10.2	10.4	4.0	1.8	1.85	1.3
109	.4	7.50	7.60	6.5	---	21.2	4.2	4.1	18.1	1.3	1.15	8.9
112R	.4	7.32	7.45	3.6	.03	22.2	9.6	9.6	5.9	.7	1.95	1.9
114R	.4	7.10	7.60	6.9	.02	27.4	12.0	11.2	9.4	1.7	2.08	2.8
118	2.1	7.09	7.35	5.5	---	31.6	17.4	13.7	4.0	1.8	2.70	1.0
122	3.1	7.18	7.45	6.7	---	38.5	16.5	17.6	9.4	1.6	3.20	2.3
129	3.0	6.85	7.10	5.0	.15	123.7	59.2	58.0	9.7	1.9	7.00	1.3
131	2.8	7.38	7.30	3.8	.03	39.4	17.4	20.1	4.5	1.3	3.10	1.0
135	2.65	7.40	7.50	4.8	.20	13.0	6.0	5.7	5.9	.3	1.25	2.4
135	3.5	6.82	7.40	7.6	.05	60.6	28.4	32.3	5.4	1.7	4.25	1.0
139	2.7	6.70	6.90	6.5	.03	42.9	28.0	16.5	4.0	.9	2.19	.9

INDIAN HEAD MINE

Piezometer Number	Depth (ft)	pH Paste	pH Extract	HCO$_3^-$	Cl$^-$	SO$_4^{2-}$	Ca^{2+}	Mg^{2+}	Na$^+$	K$^+$	EC mS/cm	SAR
				←			meq/L			→		
1	.9	7.41	7.35	5.8	---	84.8	14.0	10.5	65.0	1.1	4.35	18.6
3	1.25	7.58	7.55	4.0	.46	114.6	22.2	22.3	75.0	1.0	7.50	15.91
7	.7	7.32	7.65	7.2	.30	101.2	18.7	13.8	75.0	1.2	7.40	18.6
9	.95	7.40	7.20	5.3	---	107.5	21.8	14.8	75.0	1.2	7.40	17.6
10	.6	4.89	6.70	2.1	.02	85.9	23.1	23.7	40.0	1.1	2.00	8.3
14	.65	7.41	7.45	6.4	.01	97.0	18.8	13.2	70.0	1.3	6.30	17.5
15	1.0	7.39	7.50	4.7	.42	65.0	10.9	13.1	45.0	1.2	5.50	13.0
17	1.0	6.99	7.20	5.4	.37	118.0	39.3	24.4	59.0	1.1	6.50	10.5
19	.8	7.19	7.75	7.1	.10	106.6	29.7	19.0	64.0	1.2	4.50	13.0
20	.95	8.00	7.40	4.9	---	37.1	1.8	2.5	37.0	.7	3.60	25.18
23	1.0	7.56	7.42	6.2	.02	9.8	8.2	.6	6.4	.8	1.80	3.1
24	1.4	7.85	7.50	7.8	---	16.4	3.3	1.5	18.5	.9	2.01	11.9
26	1.15	7.40	7.80	4.3	.05	58.1	22.9	17.6	21.0	.9	4.30	4.7
28	1.0	7.15	7.05	3.8	---	94.0	26.1	17.6	53.0	1.1	5.7	11.3
29	.95	7.18	7.70	9.6	.05	52.4	8.6	2.6	50.0	.8	7.0	21.1
33	1.55	6.10	7.30	11.7	.03	104.9	25.4	34.9	55.0	1.3	6.40	10.0
34	1.15	7.01	7.60	5.0	.05	156.6	54.7	27.6	78.0	1.4	8.70	12.16
36	.7	7.40	7.15	4.1	---	106.2	34.7	24.3	50.0	1.2	7.00	9.2
39	1.3	7.6	7.6	3.7	---	60.7	11.3	9.4	43.0	.8	5.0	13.4
40	1.0	6.8	7.2	4.0	---	87.7	28.2	19.2	45.0	1.3	6.3	9.2
41	1.0	7.75	7.80	7.6	.05	73.9	3.1	3.1	34.2	.8	3.23	19.5
42	1.25	7.60	7.70	10.3	.03	93.3	13.7	10.8	78.0	1.2	4.90	22.3
44	1.2	7.58	7.65	5.8	---	29.2	4.5	4.2	25.8	.5	2.90	12.4

APPENDIX D

Groundwater Analyses from Piezometers in Disturbed (Spoils) and Undisturbed Settings at the Center and Indian Head Mines.

See figures 12, 13, 14, 15, and 16a-j for location of piezometers.
See tables 4 and 5 for depths of piezometers.

GROUNDWATER ANALYSES - INDIAN HEAD MINE

GROUNDWATER ANALYSES - BEULAH-ZAP LIGNITE BED, INDIAN HEAD MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
IH 6	05-10-77	-	-	-	9.06	3,038	3,390	53.8	1,246	28.4	44
IH 98	13-10-77	14.0	7.83	1,475	7.61	1,508	938	116.1	365	76.7	29.9
IH 99	13-10-77	12.0	7.52	1,590	8.36	1,497	990	121.0	340	185.9	37.8
IH 117	06-10-77	8.0	7.28	7,000	9.03	5,587	4,390	124.4	1,363	63.5	30

GROUNDWATER ANALYSES - BEULAH-ZAP LIGNITE BED, INDIAN HEAD MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe ug/L
IH 6	985	31.4	1,520.1	-	1,024.7	18.9	2.0	1.6	0.48	-	243
IH 98	305	21.2	445.3	-	408.6	8.2	10.6	0.92	0.40	-	-
IH 99	278	18.5	414.8	-	434.2	10.0	21.5	>3.0	0.39	-	215
IH 117	1,107	35.3	1,662.9	-	1,605.7	37.7	-6.1	-	0.30	-	1,642

GROUNDWATER ANALYSES - BEULAH-ZAP LIGNITE BED, INDIAN HEAD MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
IH 6	306	1,000	9.2	-	-	-	33.9	-	-	-	-	-
IH 98	-	-	-	-	-	-	-	-	-	-	-	-
IH 99	395	18.7	1.5	-	-	-	13.3	-	-	-	-	-
IH 117	1,283	164	90	-	-	-	64	-	-	-	-	-

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
USBM 2	15-06-78	15.5	6.30	+8,000	7.49	8,081	6,540	-	-	370	161.7
USBM 2	04-09-80	13.0	6.10	8,500	7.44	6,010	5,330	1,465.3	975.4	347	145.6
USBM 2	10-09-81	12.5	6.50	9,000	7.20	5,590	5,920	1,401	442	305	156
USBM 8	16-06-78	16.0	6.35	+8,000	7.24	10,184	7,270	-	-	-	-
USBM 8	03-09-80	13.5	6.50	12,000	7.43	8,393	7,440	1,157	1,302	277.9	2.6
USBM 8	09-09-81	14.0	7.00	12,800	7.03	7,790	7,520	1,091	613	219	133
USBM 11	15-06-78	16.0	7.16	+8,000	7.83	10,774	8,280	-	-	190	125.5
USBM 11	03-09-80	14.0	6.90	13,000	7.46	9,938	9,400	1,355	793.1	266.6	167.7
USBM 11	10-09-81	13.5	7.05	13,500	7.44	9,200	1,014	1,407	353	329	143
USBM 13	03-09-80	14.0	6.65	15,000	7.36	9,494	8,640	2,179	1,390	419.4	275.2
USBM 13	09-09-81	16.0	7.25	11,000	7.23	7,080	7,360	1,600	552	311	200
USBM 22	19-06-78	14.5	7.27	4,000	8.13	4,545	3,330	-	-	160	62.1
USBM 22	03-09-80	12.0	6.65	6,000	7.81	4,100	3,080	717.9	1,005	187.4	60.9
USBM 22	09-09-81	13.5	7.05	7,000	7.33	4,240	3,850	761	477	169	83
USBM 27	19-06-78	14.5	6.41	5,800	7.79	6,230	5,280	-	-	430	156
USBM 27	03-09-80	13.0	6.20	7,000	7.51	5,151	4,420	2,011	964.5	381.4	257.5
USBM 30	19-06-78	15.5	6.53	5,500	7.65	6,136	4,520	-	-	110	208.4
USBM 30	04-09-80	15.0	7.75	8,800	7.20	6,090	5,090	1,388	1,066	242.5	190.3
USBM 30	10-09-81	13.5	6.65	9,000	7.13	5,250	5,580	1,317	476	320	126
USBM 32	16-06-78	15.5	-	+8,000	7.98	8,549	6,190	-	-	220	69.3
USBM 32	04-09-80	14.0	8.10	12,000	7.49	8,252	6,780	1,095	423.6	274.2	99.9
USBM 32	09-09-81	12.5	7.50	12,800	7.52	7,380	7,690	1,172	247	158	189

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
USBM 2	1,400	24.8	1,228.7	2.99	3,469	10.4	0.3	-	-	-	68.9
USBM 2	1,272	29.9	1,185	2.6	2,854	14.2	3.7	0.30	0.48	-	83,333
USBM 2	1,180	36	538	0.4	2,707	10.7	10.2	1.0	1.06	-	4,200
USBM 8	-	-	1,842.8	2.52	3,987	<1	-	0.68	-	-	1,805
USBM 8	1,567	32.8	1,581.7	3.3	3,803	9.1	-11.4	1.75	0.38	-	94,737
USBM 8	1,912	39	747	0.4	4,331	6.5	1.6	2.0	0.18	-	1,280
USBM 11	2,400	37.1	1,241.8	6.61	4,474	30.2	4.4	0.55	-	-	239
USBM 11	2,577	37.3	963.2	2.2	5,130	37.1	6.2	0.89	0.41	-	8,186
USBM 11	2,387	50	429	0.5	5,465	35.6	4.5	0.85	0.28	-	1,140
USBM 13	2,348	36.7	1,690	3.0	4,645	24.8	7.9	1.32	0.38	-	929
USBM 13	1,624	46	672	0.5	3,958	10.9	5.1	0.50	0.22	-	1,040
USBM 22	870	15.6	864.3	9.17	1,591.8	<1	3.	0.19	-	-	160.5
USBM 22	868.9	24.2	1,214	6.1	1,536	5.7	0.5	0.56	0.50	-	30,000
USBM 22	910	28	580	0.6	2,100	4.5	2.0	0.62	0.31	-	1,370
USBM 27	870	18.7	1,235.6	6.00	2,636	19	-2.	0.12	-	-	1,151
USBM 27	752.7	25.0	1,171	3.0	2,267	15.2	4.7	0.38	0.40	-	-
USBM 30	1,100	15.5	1,433.0	5.04	1,888.2	-	5.	-	-	-	651.1
USBM 30	1,251	30.0	1,297	1.6	2,462	6.2	6.5	0.70	0.35	-	3,222
USBM 30	1,272	35	580	0.4	3,153	8.6	4.	0.57	0.18	-	334
USBM 32	1,650	39.5	734.4	5.52	3,616	9.1	1.0	0.4	-	-	72.9
USBM 32	2,172	39.8	514.2	1.3	4,528	8.3	6.5	1.22	0.31	-	1,263
USBM 32	1,682	55	300	0.5	4,666	13.2	-2.2	0.74	0.18	-	193

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
USBM 2	4,172	52.2	0.72	-	-	-	<0.9	-	-	-	-	-
USBM 2	5,556	133	2.45	-	<0.2	-	-	-	-	-	110	-
USBM 2	2,976	23	0.7	-	<0.5	9	6	-	-	-	< 5	-
USBM 8	2,119	13.1	< 0.10	-	-	-	<0.9	-	-	-	-	-
USBM 8	2,941	68	0.41	-	<0.2	24	-	-	-	-	29	-
USBM 8	1,370	10	0.3	-	<0.5	11.5	4.0	-	-	-	< 5	-
USBM 11	1,772	11.0	0.52	-	-	-	<0.9	-	-	-	-	-
USBM 11	4,397	43	<0.05	-	<0.2	4.2	-	-	-	-	130	-
USBM 11	2,150	39	0.5	-	<0.5	0.8	<0.8	-	-	-	< 5	-
USBM 13	4,615	4.6	2.33	-	0.4	2.6	4	-	-	-	75	-
USBM 13	2,920	12	0.3	-	<0.5	1.6	5.5	-	-	-	< 5	-
USBM 22	576	6.7	<0.10	-	-	-	<0.9	-	-	-	-	-
USBM 22	2,250	13	0.48	-	<0.2	2.8	-	-	-	-	59	-
USBM 22	1,760	21	0.8	-	0.9	4.3	2.3	-	-	-	<5	-
USBM 27	3,527	11.2	0.61	-	-	-	1.1	-	-	-	-	-
USBM 27	-	-	-	-	<0.2	-	-	-	-	-	-	-
USBM 30	1,573	9.7	<0.1	-	-	-	<0.9	-	-	-	-	-
USBM 30	3,947	100	2.21	-	0.3	9.6	6.6	-	-	-	50	-
USBM 30	2,670	60	1.4	-	0.9	6.2	7.0	-	-	-	< 5	-
USBM 32	1,152	12.0	0.17	-	-	-	1.6	-	-	-	-	-
USBM 32	1,395	349	6.56	-	0.3	3.8	-	-	-	-	216	-
USBM 32	4,000	47	2.3	-	0.6	1.3	3.3	-	-	-	< 5	-

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
USBM 35	16-06-78	13.5	6.76	5,500	7.90	556	4,980	-	-	420	142.8
USBM 36	15-10-77	6.0	-	3,500	8.84	-	2,070	66.5	725	36.6	19.9
USBM 36	04-09-80	11.0	7.95	4,000	8.25	2,929	2,190	155.8	815.3	27.2	21.3
USBM 36	09-09-81	11.5	8.00	4,500	7.86	2,650	2,490	156	377	25	23
USBM 43	15-06-78	10.0	7.06	1,850	7.92	1,979	1,320	-	-	90	50.5
USBM 43	04-09-80	9.0	8.65	2,700	7.76	1,885	1,190	472.1	691.7	79.5	66.5
USBM 43	09-09-81	9.5	7.40	3,000	7.67	1,900	1,930	490	313	63	81

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
USBM 35	790	22.1	794.4	4.96	2,654.9	<1	- 0.6	0.31	-	-	180.2
USBM 36	813	27.0	884.5	-	182.8	9.8	36.0	<0.1	0.43	-	104
USBM 36	677.6	16.1	967.1	13.5	799	1.9	0.0	0.73	0.46	-	44
USBM 36	720	10	457	1.5	1,174	<1	4.1	0.43	0.29	-	49
USBM 43	320	10.0	834.5	5.46	534.3	5.7	- 4.8	<0.1	-	-	163.4
USBM 43	444.3	16.0	836.3	3.7	539.1	6.3	7.2	0.22	0.40	-	9,537
USBM 43	362	15	380	0.8	806	3.8	5.7	0.58	0.22	-	590

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
USBM 35	5,762	23.7	< 0.1	-	-	-	< 0.9	-	-	-	-	-
USBM 36	195	47.2	3.2	-	-	-	32.5	-	-	-	-	-
USBM 36	316	154	0.64	-	0.3	1.8	3.6	-	-	-	261	-
USBM 36	83	13.4	0.6	-	0.8	1.3	2.4	-	-	-	32	-
USBM 43	3,030	5.5	< 0.10	-	-	-	< 0.9	-	-	-	-	-
USBM 43	2,857	22	0.05	-	0.3	0.84	2.2	-	-	-	188	-
USBM 43	1,370	31	0.9	-	< 0.5	1.1	3.5	-	-	-	5	-

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
MSU 3	12-10-77	12.0	7.22	2,400	8.68	2,322	1,590	80.7	704	52.9	20.3
MSU 7	20-08-77	12.0	7.97	+8,000	7.77	16,560	15,880	2,794	1,808	524	978
MSU 7	24-03-81	9.0	6.50	32,000	7.38	13,879	15,330	3,103	1,821	300	567
MSU 9	12-10-77	13.0	6.26	6,900	8.63	5,120	8,600	1,552.4	1,151	735.8	499
MSU 9	25-03-81	11.0	6.10	13,000	6.62	6,326	9,100	3,843	1,230	1,136	242
MSU 17	20-08-77	12.0	6.76	6,000	8.08	6,390	4,438	84.2	1,238	328	231
MSU 17	25-03-81	10.0	6.80	9,000	7.31	4,475	4,390	944.1	1,073	106	163.7
MSU 18	30-08-77	16.0	7.38	+8,000	8.58	2,980	1,936	272	1,171	79	63
MSU 18	12-10-77	10.0	7.13	2,600	9.03	2,100	1,560	101.1	917	74.2	48.0
MSU 18	25-03-81	9.5	7.75	3,200	8.11	1,960	1,560	232.2	764.4	40	31.9
MSU 19	25-03-81	9.0	7.15	17,000	7.97	8,860	8,080	1,123	1,529	179	163

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO$_3$ mg/L	CO$_3$ mg/L	SO$_4$ mg/L	Cl mg/L	Standard Error %	NO$_3$ mg/L	F mg/L	PO$_4$ mg/L	Fe µg/L
MSU 3	548	30.0	858.9	-	558.6	6.6	5.5	0.38	0.37	-	206
MSU 7	3,445	238	2,205.8	-	9,408	1.8	6.2	-	0.2	-	266
MSU 7	3,873	23	2,217.4	2.4	4,274	5.4	29.5	0.71	0.1	-	851
MSU 9	977	37.8	1,404.2	-	912.6	27.1	47.8	-	0.24	-	8,766
MSU 9	902.8	20.0	1,500	0.3	4,154	9.2	2.2	-	0.11	-	33,824
MSU 17	515	88	1,510.4	-	1,792.8	5.9	-1.8	-	0.2	-	118
MSU 17	1,120	23	1,306	1.2	1,972	3.1	4.5	0.71	0.11	-	306
MSU 18	411	63	1,428.6	-	425	6.6	-7.1	-	0.3	-	-
MSU 18	589	24.4	1,118.7	-	591.4	10.0	4.6	0.48	0.33	-	77
MSU 18	461.5	12.5	921	5.5	361.3	3.7	4.3	2.1	0.1	-	50.7
MSU 19	2,487	21.1	1,849	8	4,068	12.3	6.2	1.5	0.13	-	55.8

GROUNDWATER ANALYSES - BASE OF SPOILS, INDIAN HEAD MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
MSU 3	538	44	2.7	-	-	-	29.3	-	-	-	-	-
MSU 7	1,573	771	357	-	-	-	152	-	-	-	-	-
MSU 7	769	39.4	1.5	-	<0.2	<3.2	1	-	-	-	20	-
MSU 9	14,831	210	9.2	-	-	-	47.4	-	-	-	-	-
MSU 9	4,924	54.4	4.3	-	<0.2	2.8	<1	-	-	-	12.9	-
MSU 17	1,325	118	17.3	-	-	-	30	-	-	-	-	-
MSU 17	1,116	317	3.0	-	<0.2	1.3	<1	-	-	-	<1	-
MSU 18	-	-	-	-	-	-	-	-	-	-	-	-
MSU 18	310	21.3	2.8	-	-	-	38.3	-	-	-	-	-
MSU 18	66	15.1	0.4	-	<0.2	5.0	1	-	-	-	47.4	-
MSU 19	143.5	25.6	0.8	-	<0.2	0.8	<1	-	-	-	6.8	-

GROUNDWATER ANALYSES - SPAER LIGNITE BED, INDIAN HEAD MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
MSU 6	24-03-81	9.50	7.70	2,800	8.17	1,814	1,540	56.3	899.2	20	1.5
MSU 16	25-03-81	9.00	7.20	8,800	8.03	4,821	4,100	324.3	1,131	53	46.2
USBM 1	24-03-81	10.50	6.95	6,000	-	-	-	-	-	-	-

GROUNDWATER ANALYSES - SPAER LIGNITE BED, INDIAN HEAD MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
MSU 6	499.4	9.7	1,082	7.4	264	9.9	-1.4	10.5	1.2	-	206
MSU 16	1,262	14.7	1,366	6.7	1,659	25.7	3.2	0.55	0.25	-	469
USBM 1	-	-	-	-	-	-	-	-	-	-	1,660

GROUNDWATER ANALYSES - SPAER LIGNITE BED, INDIAN HEAD MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
MSU 6	109	32.9	0.72	-	0.7	5.7	4.2	-	-	-	15.2	-
MSU 16	262	15.9	0.9	-	< 0.2	2.4	< 1	-	-	-	<1	-
USBM 1	346	19	2	-	0.4	3.4	< 1	-	-	-	7.4	-

GROUNDWATER ANALYSES - CENTER MINE

GROUNDWATER ANALYSES - KINNEMAN CREEK LIGNITE BED, CENTER MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 361A	02-03-78	6.5	7.10	975	-	-	838	-	274	102.5	46.9
Ctr 361A	12-06-79	12.0	6.50	1,650	7.49	1,505	1,400	-	-	165	94.4
Ctr 361A	02-06-81	9.0	7.0	-	7.2	1,530	1,260	709	459	140	87.0
Ctr 367A	13-05-77	9.0	6.00	2,200	7.28	1,606	1,539	731	459	152	63
Ctr 368A	13-05-77	10.0	6.52	2,050	7.95	1,909	1,499	288	712	54	29
Ctr 368A	24-08-77	16.0	6.58	2,100	7.67	2,320	1,631	221	837	75	54
Ctr 368A	11-06-79	11.0	6.25	1,950	7.30	1,800	1,450	-	-	29	30.6
Ctr 368A	02-06-81	8.6	6.5	-	7.0	1,870	1,360	170	643	33.0	21.5
Ctr 371A	13-05-77	11.0	7.49	1,350	7.78	863	843	377	429	64	44
Ctr 371A	02-03-78	7.0	7.07	1,300	-	-	904	-	488	73.2	40.1
Ctr 371A	11-06-79	11.0	6.45	1,325	7.15	1,233	960	-	-	44	64.8
Ctr 371A	20-08-80	9.5	6.50	1,300	7.08	1,143	1,400	359.5	461.6	85.4	35.6
Ctr 371A	02-06-81	9.3	6.5	-	7.2	1,150	864	307	437	55.5	41.0
Ctr 372A	20-08-80	9.5	6.65	1,800	7.01	1,594	1,520	811.2	288.3	205.0	72.9
Ctr 372A	02-06-81	10.4	6.5	-	6.8	1,620	1,390	773	377	151	96.0

GROUNDWATER ANALYSES - KINNEMAN CREEK LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 361A	115.0	11.4	334.3	-	398.8	16	0.1	5.4	0.14	-	190
Ctr 361A	158	21.5	580.3	1.41	446	5.8	10.4	0.16	-	-	638
Ctr 361A	117	18.3	561	0	617	5.0	-5.9	-	0.1	-	1,826
Ctr 367A	204	13.6	560.0	-	642.7	7.24	-1.7	< 0.1	< 0.1	-	1,300
Ctr 368A	441	14.3	868.6	-	232.6	3.72	12.4	< 0.1	< 0.1	-	562
Ctr 368A	373	48	1,021.1	-	499	< 1.0	-2.9	-	0.1	-	363
Ctr 368A	410	16.2	807.5	1.28	313	< 1	5.7	0.34	-	-	657
Ctr 368A	459	11.5	786	0	448	0	3.2	-	0.1	-	770
Ctr 371A	164	13.0	523.4	-	254.9	17.4	-0.4	0.11	< 0.1	-	45.1
Ctr 371A	187.0	14.6	595.4	-	317.7	21.0	-4.7	1.5	0.14	-	350
Ctr 371A	195	17	569.7	0.63	245	< 1	6.0	6.5	-	-	251
Ctr 371A	205	18.6	562.1	0.5	231.9	7.4	7.5	0.18	0.19	-	429
Ctr 371A	190	12.3	534	0	287	13	-1.3	-	0.1	-	470
Ctr 372A	167.4	9.4	351.2	0.3	762.5	6.8	4.1	0.51	0.20	-	15,000
Ctr 372A	157	8.65	4.61	0	747	5	-1.7	-	0.2	-	28,700

GROUNDWATER ANALYSES - KINNEMAN CREEK LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 361A	400	-	1.2	0.0	3.4	-	2.0	-	43.1	1.4	-	1.0
Ctr 361A	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 361A	440	-	-	-	-	-	-	-	-	-	-	-
Ctr 367A	461	9.0	0.34	-	-	-	13.8	-	-	-	-	-
Ctr 368A	130	11.7	0.33	-	-	-	11.5	-	-	-	-	-
Ctr 368A	95	21	3	-	-	-	-	-	-	-	-	-
Ctr 368A	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 368A	110	-	-	-	-	-	-	-	-	-	-	-
Ctr 371A	259	14.0	0.22	-	-	-	6.4	-	-	-	-	-
Ctr 371A	610	-	0.8	0.2	1.6	1.0	2.0	-	60.0	3.6	-	1.2
Ctr 371A	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 371A	351	7	0.4	-	<0.2	0.2	56	-	-	-	38	-
Ctr 371A	190	-	-	-	-	-	-	-	-	-	-	-
Ctr 372A	532	7	1.3	-	<0.2	5.1	60	-	-	-	37	-
Ctr 372A	730	-	-	-	-	-	-	-	-	-	-	-

GROUNDWATER ANALYSES - HAGEL LIGNITE BED, CENTER MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 1	28-03-78	8.0	6.93	2,200	-	-	1,811	-	660	80.0	195.0
Ctr 3	28-03-78	9.0	7.56	1,300	-	-	864	-	450	45.0	77.0
Ctr 3	05-07-78	10.0	7.22	1,325	-	-	912.0	-	338.5	77.5	58.0
Ctr 3	14-09-79	9.5	6.80	1,300	-	-	935.5	-	384.6	119.6	68.0
Ctr 5	05-07-78	10.0	7.67	920	-	-	649.0	-	437.2	8.9	2.1
Ctr 5	14-09-79	10.0	7.75	790	-	-	462.5	-	339.3	21.8	3.8
Ctr 6	28-03-78	10.5	8.00	2,150	-	-	1,422	-	688	12.0	24.0
Ctr 6	05-07-78	12.5	7.42	2,600	-	-	1,554.0	-	668.2	22.2	10.7
Ctr 6	14-09-79	10.5	7.25	2,250	-	-	1,424	-	680.7	30.9	8.6
Ctr 30	05-07-78	14.5	6.75	2,575	-	-	2,120.0	-	700.3	222.8	144.3
Ctr 30	24-09-79	11.0	6.50	2,500	-	-	2,134	-	632.8	186.8	131.0
Ctr 32	14-07-81	10.50	6.75	3,500	7.42	1,970	1,730	1,228	700.0	261	140
Ctr 35	16-11-78	6.0	6.50	3,750	-	-	3,713	-	446	337.0	202
Ctr 35	27-02-79	5.0	6.90	4,000	-	-	3,874	-	471	328.0	153.2
Ctr 45	25-02-79	10.5	6.45	3,600	-	-	3,153	-	766.1	263.7	148.0
Ctr 149	15-10-80	10.0	6.75	3,100	-	-	2,041	-	332	375	97
Ctr 149	19-02-81	10.50	6.65	3,200	-	-	2,064	-	354	343	82
Ctr 149	28-04-81	11.50	6.75	3,500	-	-	2,184	-	427	394	91
Ctr 149	28-07-81	11.50	6.85	3,000	-	-	2,194	-	439	394	105
Ctr 149	02-11-81	11.00	7.05	2,800	-	-	2,063	-	445	374	94
Ctr 151	15-10-80	8.0	7.00	1,900	-	-	1,156	-	400	239	50
Ctr 151	19-02-81	9.00	6.55	1,850	-	-	1,252	-	399	206	45
Ctr 151	28-04-81	9.00	6.60	2,000	-	-	1,428	-	373	224	50
Ctr 151	28-07-81	10.00	6.85	1,650	-	-	1,172	-	388	213	40
Ctr 151	02-11-81	9.50	7.00	1,700	-	-	1,318	-	408	218	48

GROUNDWATER ANALYSES - HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 1	181	23.2	805.2	-	745	8.5	-0.8	-	-	-	530
Ctr 3	167	17.3	549.0	-	252	10.2	5.7	-	-	-	220
Ctr 3	91.7	7.8	413.0	-	281.5	13.0	4.9	0.17	0.13	<0.1	130
Ctr 3	72.4	9.7	469.2	-	241.8	11.0	6.9	0.34	<0.01	<0.05	260
Ctr 5	188.8	5.6	533.4	-	58.9	3.0	-3.4	0.33	0.13	<0.1	150
Ctr 5	146.5	4.7	413.9	-	41.2	2.9	0.2	8.45	<0.01	<0.05	280
Ctr 6	503	8.6	839.4	-	254	3.8	12.6	-	-	-	210
Ctr 6	498.1	6.7	815.3	-	583.9	5.3	-3.7	0.25	0.65	<0.1	70
Ctr 6	523.6	5.4	830.5	-	461.9	4.5	3.7	0.80	0.15	<0.05	200
Ctr 30	167.9	8.0	854.3	-	930.4	6.5	-4.8	1.24	<0.1	<0.1	580
Ctr 30	141.4	11.8	772.0	-	819.9	3.6	-5.8	0.66	<0.01	<0.05	380
Ctr 32	154	13.0	852	1.0	755	16.8	2.3	0.21	<0.1	-	1,166
Ctr 35	387	16.8	544.1	-	2,087	3.3	-1.7	0.27	0.0	<0.05	90
Ctr 35	336.2	12.6	574.6	-	1,929	3.8	-6.2	0.59	<0.1	<0.05	100
Ctr 45	460.1	15.5	934.6	-	1,552.4	7.5	-2.2	0.30	<0.01	<0.05	50
Ctr 149	84	6.9	405.0	-	1,163	-	-0.5	-	-	-	160
Ctr 149	81	6.1	431.9	-	1,110	-	-4.6	-	-	-	30
Ctr 149	79	7.2	520.9	-	1,151	-	-2.7	-	-	-	<200
Ctr 149	72	6.7	535.6	-	1,063	-	2.4	-	-	-	<200
Ctr 149	80	6.6	542.9	-	996	-	0.7	-	-	-	400
Ctr 151	54	4.2	488.0	-	500	-	0.2	-	-	-	<20
Ctr 151	53	3.2	486.8	-	479	-	-4.6	-	-	-	70
Ctr 151	61	4.6	455.1	-	572	-	-3.5	-	-	-	<200
Ctr 151	48	4.5	473.4	-	355	-	5.5	-	-	-	<200
Ctr 151	86	6.0	497.8	-	465	-	2.4	-	-	-	1,800

GROUNDWATER ANALYSES - HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 1	1,313	-	< 0.1	0.5	0.0	-	20.9	-	92.8	3.6	-	5.1
Ctr 3	306	-	< 1	0.6	-	-	76.5	-	44.7	3.5	-	2.1
Ctr 3	360	-	< 1	0.6	0.0	1.1	0.5	-	61.9	0.3	-	0.1
Ctr 3	450	-	< 1	< 0.3	-	-	-	-	-	-	-	-
Ctr 5	60	-	< 1	0.5	0.0	6.5	3.0	-	792.0	0.8	-	0.1
Ctr 5	50	-	< 1	< 0.3	-	-	-	-	-	-	-	-
Ctr 6	153	-	< 2	0.7	-	-	21.9	-	42.7	20.0	-	2.3
Ctr 6	230	-	< 1	0.5	1.6	1.9	4.9	-	45.1	8.5	-	2.0
Ctr 6	320	-	2.1	< 0.3	-	-	-	-	-	-	-	-
Ctr 30	2,040	-	< 1	0.7	2.9	4.2	0.4	-	132.8	1.5	-	0.1
Ctr 30	3,440	-	2.6	< 0.3	-	-	-	-	-	-	-	-
Ctr 32	19,413	14	0.45	-	< 0.2	1.1	< 0.8	-	-	-	< 5	-
Ctr 35	2,520	-	4.4	< 0.3	0.4	2.2	7.1	-	65.1	10.0	-	5.3
Ctr 35	2,750	-	1.2	< 0.3	< 2	< 2	-	-	-	-	-	-
Ctr 45	1,500	-	1.2	< 0.3	-	-	-	-	-	-	-	-
Ctr 149	-	-	< 1	< 0.3	< 2	2.1	6.0	< 50	35	2.0	-	1.7
Ctr 149	-	-	< 1	< 0.3	< 2	< 2	10	< 0.5	104	2.8	< 5	< 1
Ctr 149	-	-	< 1	< 0.3	< 2	< 2	12	< 1	73	3.2	< 5	< 1
Ctr 149	-	-	< 1	< 0.3	< 2	< 2	12	< 1	41	< 2	< 10	< 1
Ctr 149	-	-	< 1	< 0.3	< 2	< 2	< 2	< 1	100	< 2	< 10	< 1
Ctr 151	-	-	< 1	< 0.3	< 2	< 2	2.9	< 50	138	< 2	-	< 1
Ctr 151	-	-	< 1	< 0.3	< 2	< 2	2.7	< 0.5	113	< 2	< 5	< 1
Ctr 151	-	-	3.5	< 0.3	< 2	< 2	5.7	< 1	95	< 2	13	< 1
Ctr 151	-	-	< 1	< 0.3	< 2	< 2	4.0	< 1	155	< 2	< 10	< 1
Ctr 151	-	-	< 1	< 0.3	< 2	< 2	< 2	< 1	128	< 2	57	< 1

GROUNDWATER ANALYSES - HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 153	15-10-80	8.5	7.45	1,550	-	-	865	-	367	195	35
Ctr 153	19-02-81	9.50	7.25	1,100	-	-	798	-	461	134	33
Ctr 153	28-04-81	9.50	7.10	1,200	-	-	817	-	474	135	34
Ctr 153	28-07-81	10.50	7.20	1,100	-	-	872	-	441	137	23
Ctr 153	02-11-81	10.00	7.30	950	-	-	971	-	394	140	25
Ctr 155	15-10-80	9.0	7.50	2,300	-	-	1,365	-	290	188	66
Ctr 155	19-02-81	10.50	7.35	2,900	-	-	1,744	-	376	250	83
Ctr 155	28-04-81	11.00	7.15	3,200	-	-	2,137	-	428	305	88
Ctr 155	28-07-81	10.50	6.80	3,400	-	-	2,404	-	453	329	92
Ctr 155	02-11-81	9.50	6.80	3,500	-	-	2,296	-	440	369	100
Ctr 157	15-10-80	9.0	7.25	1,700	-	-	1,054	-	171	159	53
Ctr 157	19-02-81	10.00	6.45	2,100	-	-	1,296	-	215	194	55
Ctr 157	28-04-81	10.50	7.30	2,200	-	-	1,447	-	292	154	51
Ctr 157	28-07-81	9.50	7.50	2,400	-	-	1,519	-	454	139	42
Ctr 157	02-11-81	9.00	7.80	2,400	-	-	1,346	-	581	110	37
Ctr 158	15-10-80	8.5	7.10	1,900	-	-	1,225	-	269	223	55
Ctr 158	19-02-81	9.00	6.65	1,900	-	-	1,338	-	273	156	56
Ctr 360BR	02-06-81	8.40	7.00	-	7.6	1,830	1,380	413	666	61.0	63.5
Ctr 361R	02-06-81	9.4	7.5	-	7.8	1,310	1,000	173	409	32.5	22.5
Ctr 362A	20-08-80	9.5	7.35	2,000	8.34	1,793	1,410	36.3	979.2	6.2	5.1
Ctr 365A	11-06-79	11.0	6.35	925	7.65	836	680	-	-	8.0	17.9
Ctr 365A	02-06-81	9.1	7.0	-	7.1	847	584	90	371	23.5	7.5
Ctr 371	20-08-80	10.0	7.00	1,400	7.73	1,324	890	94.6	545.2	30.5	4.5
Ctr 372	20-08-80	11.0	6.70	1,900	7.40	1,827	1,540	923.1	411.5	230.8	84.5
Ctr 372	02-06-81	11.4	7.0	-	7.2	1,730	1,490	791	506	166	91.5
Ctr 373A	11-06-79	14.0	7.50	3,300	8.22	2,921	2,270	-	-	13.8	14.1

GROUNDWATER ANALYSES - HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 153	41	2.9	447.7	-	362	-	-1.4	-	-	-	< 20
Ctr 153	12	3.1	562.4	-	97.7	-	-5.9	-	-	-	180
Ctr 153	16	3.1	578.3	-	84.0	-	-0.4	-	-	-	600
Ctr 153	8.2	2.8	538.0	-	52.3	-	0.2	-	-	-	< 200
Ctr 153	18	2.6	480.7	-	91.1	-	0.6	-	-	-	< 200
Ctr 155	140	6.6	353.8	-	692	-	2.1	-	-	-	< 20
Ctr 155	152	6.6	458.7	-	877	-	-0.6	-	-	-	170
Ctr 155	152	7.8	522.2	-	1,031	-	-1.3	-	-	-	< 200
Ctr 155	236	7.6	552.7	-	1,187	-	2.2	-	-	-	1,700
Ctr 155	158	9.8	536.8	-	1,171	-	0.9	-	-	-	1,400
Ctr 157	89	5.5	208.6	-	548	-	4.7	-	-	-	< 20
Ctr 157	100	4.8	262.3	-	671	-	1.1	-	-	-	1,000
Ctr 157	136	6.1	356.2	-	663	-	-4.5	-	-	-	< 200
Ctr 157	199	7.1	553.9	-	533	-	-0.3	-	-	-	< 200
Ctr 157	319	6.0	708.8	-	479	-	2.2	-	-	-	< 200
Ctr 158	99	3.0	328.2	-	612	-	5.1	-	-	-	120
Ctr 158	97	3.1	333.1	-	633	-	-5.5	-	-	-	90
Ctr 360BR	367	12.8	814	0.0	472	8.0	2.4	-	-	-	2,420
Ctr 361R	296	12.5	500	0.0	366	23.	0.6	-	-	-	1,240
Ctr 362A	593.0	6.7	1,155	19.7	174.3	2.8	6.6	0.21	1.94	-	3,333
Ctr 365A	198	7.0	454.3	1.60	99	< 1	0.1	0.10	-	-	126
Ctr 365A	203	4.85	453	0.0	120	0.0	4.0	-	-	-	1,330
Ctr 371	350.5	16.6	659.5	2.8	192.5	5.1	7.6	< 0.1	0.54	-	3,333
Ctr 372	168.4	14.1	500	1.0	741.3	8.0	4.5	0.25	0.14	-	1,714
Ctr 372	164	9.90	618	0.0	752	5	-5.6	-	-	-	5,180
Ctr 373A	810	17.2	1,098	14.34	768	< 1	4.1	5.0	-	-	-

GROUNDWATER ANALYSES - HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 153	-	-	<1	<0.3	<2	<2	2.6	<50	136	<2	-	<1
Ctr 153	-	-	<1	<0.3	<2	<2	<2	<0.5	232	<2	<5	<1
Ctr 153	-	-	1.2	<0.3	<2	<2	<2	<1	119	<2	<5	<1
Ctr 153	-	-	<1	<0.3	<2	<2	<2	<1	199	3.4	<10	<1
Ctr 153	-	-	<1	<0.3	<2	<2	2.6	<1	143	<2	<10	<1
Ctr 155	-	-	1.4	<0.3	<2	<2	4.0	<50	60	<2	-	<1
Ctr 155	-	-	<1	<0.3	<2	<2	5.7	<0.5	78	3.4	<5	<1
Ctr 155	-	-	27	<0.3	<2	<2	8.5	<1	55	<2	<5	<1
Ctr 155	-	-	<1	<0.3	<2	<2	10	<1	51	4.9	<10	<1
Ctr 155	-	-	<1	<0.3	<2	<2	<2	<1	71	<2	<10	<1
Ctr 157	-	-	<1	<0.3	<2	<2	3.8	<50	70	<2	-	<1
Ctr 157	-	-	<1	<0.3	<2	<2	8.7	<0.5	65	5.5	<5	<1
Ctr 157	-	-	1.4	<0.3	<2	<2	3.4	<1	83	2.6	<5	<1
Ctr 157	-	-	<1	<0.3	<2	<2	<2	<1	54	2.6	<10	<1
Ctr 157	-	-	<1	<0.3	<2	<2	<2	<1	49	<2	<10	<1
Ctr 158	-	-	<1	<0.3	<2	<2	2.9	<50	68	<2	-	<1
Ctr 158	-	-	2.3	<0.3	<2	<2	5.9	<0.5	113	<2	<5	<1
Ctr 360BR	750	-	-	-	-	-	-	-	-	-	-	-
Ctr 361R	140	-	-	-	-	-	-	-	-	-	-	-
Ctr 362A	183	22	0.3	-	<0.2	2.8	94	-	-	-	59	-
Ctr 365A	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 365A	350	-	-	-	-	-	-	-	-	-	-	-
Ctr 371	343	6	0.4	-	<0.2	1.8	72	-	-	-	48	-
Ctr 372	1,222	8	0.5	-	<0.2	0.8	37	-	-	-	39	-
Ctr 372	860	-	-	-	-	-	-	-	-	-	-	-
Ctr 373A	-	-	-	-	-	-	-	-	-	-	-	-

GROUNDWATER ANALYSES - SAND OR SILT 5 METRES BELOW BASE OF HAGEL LIGNITE BED, CENTER MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 34	21-08-78	11.0	7.23	4,000	-	-	-	-	1,055.9	158.7	90.2
Ctr 34	14-11-78	7.0	6.85	4,000	-	-	2,845	-	1,007	183.6	87.0
Ctr 34	18-09-79	11.0	6.55	3,600	-	-	2,774	-	924.7	145.7	82.0
Ctr 152	15-10-80	9.0	7.10	1,900	-	-	1,204	-	220	181	57
Ctr 152	19-02-81	9.50	7.50	2,300	-	-	1,454	-	464	136	34
Ctr 152	28-04-81	9.50	7.85	2,800	-	-	1,999	-	939	40	19
Ctr 152	28-07-81	10.00	8.00	2,600	-	-	1,196	-	929	38	18
Ctr 152	02-11-81	10.00	8.05	2,600	-	-	948	-	919	43	18
Ctr 156	15-10-80	9.0	7.35	1,900	-	-	1,199	-	213	176	55
Ctr 156	19-02-81	10.00	6.90	2,000	-	-	1,307	-	236	162	53
Ctr 156	28-04-81	9.50	6.40	1,900	-	-	1,318	-	230	178	50
Ctr 156	28-07-81	10.00	6.55	2,000	-	-	1,306	-	221	193	51
Ctr 156	02-11-81	10.00	6.65	2,000	-	-	1,400	-	233	214	58
Ctr 381	02-06-81	9.2	8.0	-	8.0	5,910	5,400	334	998	47.5	52.5

GROUNDWATER ANALYSES - SAND OR SILT 5 METRES BELOW BASE OF HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 34	796.7	7.70	1,288.2	-	1,275.0	2.0	2.5	0.09	0.05	<0.05	590
Ctr 34	689	12.74	1,228.5	-	1,190	2.2	1.8	0.105	0.0	<0.05	320
Ctr 34	650.2	12.5	1,128.1	-	1,044.2	2.8	2.8	0.36	<0.01	<0.05	100
Ctr 152	97	6.9	268.4	-	661	-	-0.01	-	-	-	470
Ctr 152	238	6.9	566.1	-	644	-	-6.0	-	-	-	100
Ctr 152	426	6.3	1,145.6	-	205	-	-1.7	-	-	-	<200
Ctr 152	463	6.7	1,133.4	-	251	-	3.4	-	-	-	<200
Ctr 152	449	6.4	1,121.2	-	216	-	1.0	-	-	-	200
Ctr 156	102	5.8	259.9	-	615	-	2.4	-	-	-	<20
Ctr 156	108	5.9	287.9	-	677	-	-4.2	-	-	-	<1,300
Ctr 156	91	4.9	280.6	-	626	-	-1.6	-	-	-	<200
Ctr 156	89	4.2	269.6	-	572	-	5.6	-	-	-	<200
Ctr 156	94	5.2	284.3	-	677	-	2.4	-	-	-	<200
Ctr 381	1,760	1,924	1,210	0	2,910	3	2.0	-	0.3	-	1,320

GROUNDWATER ANALYSES - SAND OR SILT 5 METRES BELOW BASE OF HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 34	380	-	11.4	0.0	1.7	0.9	6.5	-	79.5	15.8	-	1.1
Ctr 34	410	-	<1	0.8	0.4	1.6	7.3	-	58.7	11.3	-	5.2
Ctr 34	970	-	<1	<0.3	-	-	-	-	-	-	-	-
Ctr 152	-	-	<1	<0.3	<2	<2	4.3	<50	93	<2	-	<1
Ctr 152	-	-	<1	<0.3	<2	<2	7.6	<0.5	91	3.4	<5	<1
Ctr 152	-	-	1.0	<0.3	<2	<2	4.6	<1	124	<2	<5	<1
Ctr 152	-	-	<1	<0.3	<2	<2	<2	<1	173	<2	<10	<1
Ctr 152	-	-	<1	<0.3	<2	<2	<2	<1	145	<2	<10	<1
Ctr 156	-	-	<1	<0.3	<2	<2	4.5	60	53	<2	-	<1
Ctr 156	-	-	<1	<0.3	<2	<2	6.8	<0.5	77	2.1	<5	<1
Ctr 156	-	-	4.3	<0.3	<2	<2	3.2	<1	112	2.7	<5	<1
Ctr 156	-	-	<1	<0.3	<2	<2	5.9	<1	71	<2	<10	<1
Ctr 156	-	-	<1	<0.3	<2	<2	<2	<1	89	<2	<10	<1
Ctr 381	1,710	-	-	-	-	-	-	-	-	-	-	-

GROUNDWATER ANALYSES - SAND OR SILT - 9 TO 18 METRES BELOW HAGEL LIGNITE BED, CENTER MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 2	28-03-78	8.5	7.98	2,700	-	-	1,891	-	565	49.0	34.0
Ctr 2	05-07-78	14.0	7.33	1,500	-	-	1,124.0	-	402.8	28.3	18.9
Ctr 2	14-09-79	9.0	7.10	660	-	-	428.5	-	203.4	24.0	4.9
Ctr 31	17-08-78	11.0	7.70	3,000	-	-	-	-	1,226.2	71.4	34.6
Ctr 31	15-11-78	7.0	7.70	3,300	-	-	2,063	-	1,200	46.5	29.0
Ctr 31	28-02-79	6.5	7.35	3,000	-	-	2,127	-	1,229.3	38.2	24.8
Ctr 31	18-09-79	11.0	7.20	3,100	-	-	2,101	-	1,195	45.0	27.6
Ctr 33	27-02-79	3.0	7.70	3,600	-	-	2,464	-	1,158.0	24.2	10.8
Ctr 33	18-09-79	13.5	7.90	3,000	-	-	2,202	-	1,298	20.2	6.5
Ctr 360A	29-06-77	10.0	8.28	1,350	7.73	556	538	128	318	19.4	7.9
Ctr 360A	02-03-78	7.0	7.64	600	-	-	416	-	308	26.9	7.9
Ctr 360AR	02-06-81	8.9	7.5	-	8.0	2,130	1,660	.50	941	10.0	6.0
Ctr 362	29-06-77	12.0	8.40	2,200	8.29	1,599	1,443	43.3	980	3.6	2.8
Ctr 362	02-03-78	7.0	8.13	1,900	-	-	1,352	-	945	7.1	3.1
Ctr 362	11-06-79	11.0	7.30	2,100	8.20	1,883	1,430	-	-	3.5	9.2
Ctr 363	29-06-77	10.0	7.93	2,500	8.37	1,437	1,708	48.5	1,127	6.2	4.2
Ctr 363	11-06-79	12.5	7.60	2,200	8.10	2,044	1,400	-	-	9.3	10.1
Ctr 363	02-06-81	8.9	8.0	-	8.0	1,950	1,440	47	1,030	10.5	5.0
Ctr 383	02-06-81	9.8	7.5	-	7.8	2,880	2,200	113	1,460	24.0	13.0

GROUNDWATER ANALYSES - SAND OR SILT - 9 TO 18 METRES BELOW HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 2	540	33.0	689.3	-	870	16.5	- 0.5	-	-	-	270
Ctr 2	244.8	8.20	491.4	-	383.7	15.8	0.2	55.8	-	<0.1	320
Ctr 2	106.5	8.9	248.0	-	110.1	7.5	- 1.5	4.80	<0.01	0.30	120
Ctr 31	701.3	8.56	1,496.0	-	502.9	3.4	2.8	0.12	0.45	<0.05	90
Ctr 31	700	9.47	1,464.0	-	437	3.5	3.2	0.06	0.10	<0.05	520
Ctr 31	646.6	8.6	1,499.7	-	364.4	3.8	0.0	0.06	0.33	<0.05	130
Ctr 31	699.1	10.6	1,457.9	-	422.8	6.0	3.4	1.05	<0.01	<0.05	220
Ctr 33	896.6	8.46	1,412.8	-	814.2	6.8	1.2	0.56	1.10	<0.05	210
Ctr 33	736.8	5.2	1,583.6	-	557.6	17.4	- 6.1	3.00	1.0	0.20	80
Ctr 360A	109	8.6	388.0	-	31.4	107.2	-20.8	<0.1	0.38	-	96
Ctr 360A	108.8	10.6	375.8	-	74.4	20	- 8.4	0.85	0.25	-	350
Ctr 360AR	659	7.2	1,150	0	406	8	3.9	-	0.7	-	670
Ctr 362	474	5.5	1,195.6	-	196.8	19.9	- 6.8	0.14	1.88	-	456
Ctr 362	538.0	5.6	1,152.9	-	209.6	14	1.1	6.4	1.51	-	360
Ctr 362	525	8.0	1,013.9	12.64	180	<1	7.0	0.50	-	-	103
Ctr 363	559	6.5	1,374.9	-	256.3	21.9	- 6.3	0.12	0.91	-	190
Ctr 363	568	11	1,311.9	13.0	161	<1	1.9	0.24	-	-	183
Ctr 363	607	6.85	1,260	0	189	3	5.5	-	0.8	-	540
Ctr 383	899	10.4	1,780	0	378	1	5.8	-	0.5	-	2,080

GROUNDWATER ANALYSES - SAND OR SILT - 9 TO 18 METRES BELOW HAGEL LIGNITE BED, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 2	49	-	<1	0.3	2.1	-	21.9	-	52.1	13.6	-	3.3
Ctr 2	260	-	1.1	0.0	1.6	4.9	5.7	-	293.5	4.9	-	1.6
Ctr 2	290	-	<1	<0.3	-	-	-	-	-	-	-	-
Ctr 31	240	-	7.9	0.0	6.1	0.3	3.9	-	96.1	9.0	-	0.2
Ctr 31	310	-	<1	0.7	0.4	2.3	9.8	-	41.2	7.7	-	6.1
Ctr 31	220	-	<1	0.5	<2	2.5	-	-	-	-	-	-
Ctr 31	210	-	<1	<0.3	-	-	-	-	-	-	-	-
Ctr 33	110	-	12.3	0.4	<2	7.3	-	-	-	-	-	-
Ctr 33	50	-	1.5	<0.3	-	-	-	-	-	-	-	-
Ctr 360A	151	5.1	0.28	-	-	-	4	-	-	-	-	-
Ctr 360A	250	-	1.8	0.0	2.8	0.0	10.2	-	93.7	2.1	-	1.0
Ctr 360AR	70	-	-	-	-	-	-	-	-	-	-	-
Ctr 362	289	50.2	1.35	-	-	-	12.7	-	-	-	-	-
Ctr 362	270	-	1.3	0.4	3.1	1.8	8.9	-	32.6	8.0	-	2.5
Ctr 362	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 363	329	67.5	1.70	-	-	-	39	-	-	-	-	-
Ctr 363	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 363	230	-	-	-	-	-	-	-	-	-	-	-
Ctr 383	190	-	-	-	-	-	-	-	-	-	-	-

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 9	06-07-78	14.0	6.50	3,500	-	-	3,221.0	-	1,086.5	447.0	200.0
Ctr 9	24-02-79	4.0	6.95	3,800	-	-	3,060	-	1,032	379.8	203.6
Ctr 9	25-09-79	14.0	6.40	3,300	-	-	3,019	-	1,050.3	415.0	178.0
Ctr 9	14-07-81	11.00	6.70	5,200	7.21	3,370	2,890	1,838	1,145	208	321
Ctr 10D	03-06-80	10.0	6.95	6,000	-	-	3,420	-	740	379	115
Ctr 14	14-07-81	10.50	6.45	9,600	7.67	6,060	7,740	3,793	1,304	558	583
Ctr 16	01-03-78	4.5	6.80	4,000	-	-	4,335	-	298	519.0	342.0
Ctr 16	07-07-78	10.0	6.95	4,500	-	-	4,189.0	-	867.6	424.2	314.5
Ctr 16	26-02-79	6.0	7.10	3,500	-	-	3,103.5	-	748	314.0	207.4
Ctr 16	17-09-79	12.0	6.30	3,400	-	-	2,860.5	-	710.5	312.0	212.0
Ctr 16	14-07-81	9.50	6.80	5,000	7.42	3,550	3,550	1,957	729.6	351	263
Ctr 17	07-07-78	16.5	6.93	1,830	-	-	1,598.5	-	723.2	210.0	103.5
Ctr 23	28-03-78	6.0	7.65	4,000	-	-	3,866	-	943	190.0	393.0
Ctr 23	07-07-78	11.5	6.62	4,250	-	-	3,733.5	-	856.8	397.7	200.0
Ctr 23	27-02-79	5.0	6.45	4,200	-	-	3,839.5	-	843.4	402.2	218.9
Ctr 23	17-09-79	13.0	6.45	4,400	-	-	3,906.5	-	842.4	369.6	190.0
Ctr 23	09-06-80	11.5	6.60	7,000	-	-	3,906	-	866	443	210
Ctr 23	09-09-80	10.5	6.80	6,000	-	-	3,884	-	897	421	223
Ctr 23	18-02-81	8.00	6.75	6,500	-	-	4,206	-	961	454	245
Ctr 23	29-04-81	8.50	6.60	6,800	-	-	4,672	-	963	489	250
Ctr 23	28-07-81	10.50	6.95	7,000	-	-	4,761	-	950	483	235
Ctr 23	03-11-81	9.00	7.30	7,000	-	-	5,042	-	927	521	272
Ctr 28	05-07-78	15.0	6.40	3,100	-	-	2,806.0	-	801.6	308.6	211.6
Ctr 43	21-08-78	11.5	6.65	3,900	-	-	-	-	608.6	432.3	431.2
Ctr 52	19-06-80	14.0	6.60	7,400	7.57	5,601	5,180	1,397	1,008	328.9	140.2
Ctr 52	14-07-81	11.50	6.65	9,600	8.04	5,510	4,720	1,367	1,131	231	192

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 9	256.8	8.09	1,325.5	-	1,396.2	2.5	- 0.7	0.14	<0.1	<0.1	510
Ctr 9	310.3	18.64	1,259.0	-	1,315.2	2.5	1.6	0.42	<0.1	<0.05	940
Ctr 9	227.1	16.0	1,281.4	-	1,276.7	2.3	- 2.2	0.36	<0.01	<0.05	1,390
Ctr 9	277	30.2	1,395	1.0	1,427	<1	- 2.9	0.40	0.38	-	1,757
Ctr 10D	521	30	902.8	-	1,778	-	6.2	-	-	-	40
Ctr 14	519	18.6	1,584	3.4	2,971	114.8	4.0	1.5	0.22	-	1,086
Ctr 16	300.0	34.0	363.6	-	1,059.9	21.0	40.8	1.75	0.26	-	220
Ctr 16	251.0	8.95	1,058.5	-	2,088.8	10.7	- 2.5	0.52	<0.1	<0.1	1,220
Ctr 16	250.0	24.36	912.6	-	1,457.8	7.7	- 1.4	0.24	<0.1	<0.05	90
Ctr 16	248.1	23.0	866.8	-	1,279.8	7.9	3.9	0.80	<0.01	<0.05	350
Ctr 16	307	43.7	888	1.1	1,614	7.4	5.1	1.5	0.16	-	413
Ctr 17	200.0	8.39	882.3	-	686.8	4.2	- 1.7	0.24	0.1	<0.1	70
Ctr 23	419	31.0	1,150.5	-	1,872	8.0	2.4	-	-	-	130
Ctr 23	363.4	8.11	1,045.3	-	1,770.3	9.7	- 1.8	0.63	<0.1	<0.1	780
Ctr 23	413.8	17.77	1,028.9	-	1,757.5	8.8	2.6	0.60	<0.1	<0.05	1,430
Ctr 23	446.0	19.49	1,027.7	-	1,775.6	9.0	- 2.2	1.15	<0.01	<0.05	1,470
Ctr 23	382	21	1,056.5	-	1,944	-	- 1.1	-	-	-	1,950
Ctr 23	472	18	1,094.3	-	1,978	-	1.0	-	-	-	7,700
Ctr 23	441	19	1,172.4	-	1,931	-	2.5	-	-	-	1,800
Ctr 23	434	22	1,174.9	-	2,279	-	- 1.7	-	-	-	1,900
Ctr 23	428	21	1,159	-	2,298	-	- 2.0	-	-	-	2,200
Ctr 23	438	21	1,130.9	-	2,426	-	0.8	-	-	-	1,800
Ctr 28	121.9	7.75	978.0	-	1,283.5	11.4	- 5.8	0.48	<0.1	<0.1	110
Ctr 43	89.5	7.48	742.5	-	2,189.5	8.0	2.6	0.44	0.13	<0.05	100
Ctr 52	15.69	31.3	1,222.5	3.6	3,229	<1	5.2	0.18	0.44	-	-
Ctr 52	1,153	36.1	1,366	7.0	2,653	<1	0.3	0.26	0.16	-	2,480

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 9	710	-	<1	1.3	1.8	1.9	0.4	-	348.5	2.3	-	0.1
Ctr 9	4,070	-	8.8	<0.3	<2	<2	-	-	-	-	-	-
Ctr 9	3,100	-	<1	<0.3	-	-	-	-	-	-	-	-
Ctr 9	61,168	14.9	0.54	-	<0.2	0.7	2.1	-	-	-	<5	-
Ctr 10D	-	-	1.8	<0.3	<2	26	4.4	99	46	5.9	-	<1
Ctr 14	5,817	45.3	0.89	-	0.2	0.4	19.5	-	-	-	<5	-
Ctr 16	3,100	-	1.7	0.2	2.2	0.4	1.0	-	10.4	11.2	-	3.8
Ctr 16	2,290	-	<1	0.5	2.4	2.4	0.5	-	40.8	5.6	-	1.1
Ctr 16	2,710	-	<1	<0.3	<2	2.1	-	-	-	-	-	-
Ctr 16	2,910	-	4.2	<0.3	-	-	-	-	-	-	-	-
Ctr 16	2,824	16	0.24	-	<0.2	0.1	1.7	-	-	-	<5	-
Ctr 17	1,170	-	<1	0.2	0.0	5.4	0.0	-	88.7	1.9	-	0.1
Ctr 23	2,476	-	<1	-	-	-	22.1	-	52.3	9.6	-	4.3
Ctr 23	1,010	-	<1	0.5	0.5	10.1	0.5	-	89.4	7.5	-	3.3
Ctr 23	2,140	-	1.7	<0.3	<2	4.9	-	-	-	-	-	-
Ctr 23	1,750	-	5.9	<0.3	-	-	-	-	-	-	-	-
Ctr 23	-	-	<1	<0.3	<2	3.1	<2	<50	72	<2	-	<1
Ctr 23	-	-	<1	<0.3	<2	14	3.3	<50	49	12	-	4.1
Ctr 23	-	-	1.2	<0.3	<2	4.9	9.2	<0.5	71	9.1	<5	<1
Ctr 23	-	-	<1	<0.3	<2	6.9	21	<1	57	7.3	<5	1.1
Ctr 23	-	-	<1	<0.3	<2	5.3	17	<1	100	15	<10	<1
Ctr 23	-	-	1.3	<0.3	<2	7.5	6.7	<1	78	13	<10	1.0
Ctr 28	890	-	<1	0.5	1.1	1.9	0.5	-	84.1	3.2	-	0.1
Ctr 43	2.8	-	2.4	0.0	4.8	1.2	4.5	-	82.0	6.0	-	0.1
Ctr 52	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 52	5,047	31	0.21	-	0.2	1.7	1.5	-	-	-	<5	-

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 58	19-06-80	12.0	6.10	6,500	6.80	4,472	4,240	1,318	635.5	323.4	124
Ctr 58	21-08-80	11.0	7.60	5,200	6.70	4,776	4,680	1,369	618.6	306.4	146.9
Ctr 58	14-07-81	11.50	6.25	8,000	7.73	5,850	4,800	1,259	700.0	309	118
Ctr 66	03-06-80	8.0	7.10	9,600	-	-	3,800	-	1,130	156	74
Ctr 69	20-05-80	10.0	7.15	2,700	7.74	2,120	1,290	-	-	50	42.2
Ctr 69	09-06-80	10.5	7.10	2,600	-	-	1,329	-	938	64	29
Ctr 69	08-09-80	9.5	7.45	2,400	-	-	1,353	-	935	49	35
Ctr 69	18-02-81	7.50	7.65	2,700	-	-	1,903	-	951	45	32
Ctr 69	29-04-81	7.50	7.65	2,900	-	-	1,876	-	945	48	30
Ctr 69	29-07-81	9.50	7.55	2,500	-	-	1,937	-	928	37	34
Ctr 69	03-11-81	7.50	7.80	2,400	-	-	1,867	-	907	46	37
Ctr 70	20-05-80	13.0	6.60	5,000	7.44	3,270	3,280	-	-	520	167.7
Ctr 70	09-06-80	14.5	6.90	4,800	-	-	2,975	-	624	418	212
Ctr 70	08-09-80	11.5	6.85	4,200	-	-	2,938	-	629	364	209
Ctr 70	18-02-81	10.00	7.05	5,000	-	-	3,121	-	649	367	201
Ctr 70	29-04-81	10.00	7.05	5,000	-	-	3,165	-	657	365	196
Ctr 70	29-07-81	13.50	7.20	4,500	-	-	3,152	-	650	357	235
Ctr 70	03-11-81	10.00	7.30	4,000	-	-	2,844	-	586	314	206
Ctr 85	20-05-80	7.50	7.00	9,200	7.64	4,800	3,920	-	-	250	101.1
Ctr 85	09-09-80	7.5	7.30	7,000	-	-	3,722	-	684	187	105
Ctr 85	18-02-81	5.00	7.45	6,800	-	-	4,117	-	703	171	90
Ctr 85	29-04-81	5.00	7.35	6,400	-	-	4,306	-	712	162	84
Ctr 85	28-07-81	6.50	7.65	6,000	-	-	4,128	-	704	141	78
Ctr 85	03-11-81	5.50	7.80	6,000	-	-	3,997	-	699	151	82

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 58	969.4	25.4	774.5	0.39	2,791	<1	-1.2	0.47	0.16	-	141.6
Ctr 58	980.2	27.9	754.1	0.3	2,424	<1	5.9	0.17	0.46	-	370
Ctr 58	973	29.3	850	2.1	2,620	13.5	-0.5	0.32	0.13	-	198
Ctr 66	880	16	1,378.6	-	1,749	-	-5.8	-	-	-	200
Ctr 69	506.9	14	1,095.1	4.77	367.8	<1	4.8	0.26	0.13	-	314
Ctr 69	432	10	1,144.4	-	263	-	0.8	-	-	-	680
Ctr 69	428	8.8	1,140.7	-	222	-	1.8	-	-	-	260
Ctr 69	387	9.2	1,160.2	-	235	-	-4.3	-	-	-	160
Ctr 69	392	9.9	1,152.9	-	226	-	-3.1	-	-	-	300
Ctr 69	401	9.8	1,132.2	-	248	-	0.7	-	-	-	300
Ctr 69	393	9.3	1,106.5	-	225	-	-0.3	-	-	-	300
Ctr 70	204.6	25	745.8	1.62	1,884	4.7	-2.3	0.09	0.12	-	55
Ctr 70	119	19	761.3	-	1,650	-	-3.2	-	-	-	50
Ctr 70	175	16	767.4	-	1,568	-	-2.1	-	-	-	100
Ctr 70	189	21	791.8	-	1,542	-	1.7	-	-	-	<20
Ctr 70	189	22	801.5	-	1,566	-	-3.0	-	-	-	<200
Ctr 70	194	23	793	-	1,563	-	-2.0	-	-	-	<200
Ctr 70	179	22	714.9	-	1,374	-	0.8	-	-	-	<200
Ctr 85	977	24	800.4	2.72	2,372	<1	1.0	0.26	0.14	-	300
Ctr 85	877	14	834.5	-	2,051	-	0.1	-	-	-	510
Ctr 85	868	13	857.7	-	1,988	-	-1.3	-	-	-	90
Ctr 85	834	14	868.6	-	2,009	-	-4.1	-	-	-	<200
Ctr 85	867	15	858.9	-	1,992	-	-2.6	-	-	-	300
Ctr 85	860	14	852.8	-	1,861	-	-0.6	-	-	-	500

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 58	-	-	0.7	-	-	0.64	0.90	-	-	-	13.63	-
Ctr 58	500	68	0.7	-	<0.2	1.0	56	-	-	-	114	-
Ctr 58	545	45	1.14	-	<0.2	0.4	2.2	-	-	-	<5	-
Ctr 66	-	-	2.6	<0.3	<2	2.3	9.1	66	196	6.2	-	<1
Ctr 69	-	-	0.06	-	-	1.7	4.4	-	-	-	3.9	-
Ctr 69	-	-	<1	<0.3	<2	<2	<2	<50	58	<2	-	<1
Ctr 69	-	-	<1	<0.3	<2	2.7	3.5	187	105	5.9	-	<1
Ctr 69	-	-	<1	<0.3	<2	<2	<2	<0.5	84	3.6	<5	<1
Ctr 69	-	-	1.1	<0.3	<2	<2	15	<1	98	2.7	<5	<1
Ctr 69	-	-	<1	<0.3	<2	<2	4.0	<1	96	3.2	<10	<1
Ctr 69	-	-	<1	<0.3	<2	<2	3.3	<1	131	<2	<10	1.2
Ctr 70	-	-	0.10	-	-	0.6	19.0	-	-	-	13.4	-
Ctr 70	-	-	<1	<0.3	<2	<2	2.8	<50	46	<2	-	<1
Ctr 70	-	-	1.2	<0.3	<2	<2	10	127	51	3.3	-	1.3
Ctr 70	-	-	1.3	<0.3	<2	<2	12	<0.5	78	7.8	<5	<1
Ctr 70	-	-	<1	<0.3	<2	<2	14	<1	90	5.0	<5	<1
Ctr 70	-	-	<1	<0.3	<2	<2	18	<1	96	9.2	<10	<1
Ctr 70	-	-	<1	<0.3	<2	<2	3.0	<1	83	4.5	<10	1.7
Ctr 85	-	-	0.15	-	-	1.2	18.0	-	-	-	31.7	-
Ctr 85	-	-	<1	<0.3	<2	<2	5.3	96	29	27	-	4.9
Ctr 85	-	-	1.6	<0.3	<2	<2	20	<0.5	42	21	<5	3.2
Ctr 85	-	-	1.9	<0.3	<2	<2	21	<1	69	22	10	2.3
Ctr 85	-	-	<1	<0.3	<2	<2	11	<1	52	37	<10	2.0
Ctr 85	-	-	1.1	<0.3	<2	<2	25	<1	55	22	<10	5.4

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 91	19-06-80	9.0	6.65	7,400	7.44	4,451	4,320	1,791	1,175	711.5	4.1
Ctr 95	09-06-80	12.0	7.35	4,200	-	-	2,412	-	1,114	124	35
Ctr 95	09-09-80	9.5	7.50	3,800	-	-	2,038	-	1,088	41	30
Ctr 95	18-02-81	8.00	7.40	4,500	-	-	2,629	-	1,122	43	26
Ctr 95	28-04-81	8.00	7.30	4,600	-	-	3,010	-	1,120	40	25
Ctr 95	28-07-81	10.00	7.55	5,000	-	-	2,848	-	1,129	40	23
Ctr 95	03-11-81	9.50	8.00	4,000	-	-	2,886	-	1,160	41	28

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 91	841.7	26.4	1,427.3	3.06	2,497	22.6	-2.0	0.24	0.21	-	1,582.4
Ctr 95	610	10	1,359.1	-	824	-	-4.7	-	-	-	130
Ctr 95	641	8.2	1,327.4	-	582	-	-1.9	-	-	-	250
Ctr 95	714	8.3	1,368.8	-	583	-	1.4	-	-	-	60
Ctr 95	643	9.3	1,366.4	-	554	-	-2.5	-	-	-	<200
Ctr 95	711	7.8	1,377.4	-	649	-	1.4	-	-	-	<200
Ctr 95	715	12	1,415.2	-	588	-	0.5	-	-	-	200

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 91	-	-	0.18	-	-	1.48	-	-	-	-	9.5	-
Ctr 95	-	-	<1	<0.3	<2	<2	<2	88	122	3.5	-	<1
Ctr 95	-	-	<1	<0.3	2.6	3.4	12	126	201	12	-	<1
Ctr 95	-	-	<1	<0.3	<2	<2	13	<0.5	99	8.5	<5	<1
Ctr 95	-	-	<1	<0.3	<2	<2	9.2	<1	176	9.1	<5	<1
Ctr 95	-	-	<1	<0.3	<2	<2	3.6	<1	166	16	<10	<1
Ctr 95	-	-	<1	<0.3	<2	<2	4.8	<1	145	7.6	<10	5.4

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 97	18-06-80	12.5	6.80	7,000	7.40	3,644	3,240	772.8	931.9	181.5	77.8
Ctr 97	21-08-80	11.5	7.55	4,000	7.15	3,584	2,900	756.8	922.9	164.2	84.4
Ctr 97	14-07-81	11.50	6.75	5,200	7.64	3,860	3,290	748	930.5	160	85
Ctr 98	19-06-80	12.0	7.40	3,100	8.05	2,290	2,180	274.6	739.5	47.6	37.9
Ctr 98	14-07-81	12.00	7.70	4,500	8.30	2,830	1,990	214	933.9	38	29
Ctr 100	09-06-80	10.0	7.25	5,500	-	-	2,989	-	715	236	117
Ctr 100	09-09-80	9.5	7.35	5,000	-	-	3,084	-	708	194	170
Ctr 100	18-02-81	8.00	7.35	6,500	-	-	3,607	-	735	196	147
Ctr 100	29-04-81	6.50	7.30	6,000	-	-	3,445	-	731	200	137
Ctr 100	28-07-81	8.00	7.55	5,500	-	-	3,649	-	733	214	150
Ctr 100	03-11-81	7.00	7.75	4,800	-	-	3,463	-	729	218	159
Ctr 101	21-08-80	14.0	8.35	3,900	8.05	3,626	3,070	1,037	674.2	252.5	98.9
Ctr 101	14-07-81	15.00	7.15	6,000	7.86	3,540	3,120	924	641.9	223	89
Ctr 106	19-06-80	10.0	6.30	10,000	7.27	6,278	7,670	3,144	1,144	750.1	309.6
Ctr 106	14-07-81	11.00	6.70	9,200	7.64	6,060	7,040	2,473	1,177	626	221
Ctr 108	19-06-80	13.5	7.10	2,900	7.39	2,172	1,620	649.2	823.1	145.6	69.5
Ctr 108	19-08-80	15.0	7.80	2,000	7.79	1,864	1,560	638.5	818.8	145.8	66.8
Ctr 108	14-07-81	12.50	6.90	2,900	7.88	1,870	1,500	594	786	129	66
Ctr 112R	14-07-81	12.50	7.85	4,000	8.05	2,510	1,860	316	1,277	50	46
Ctr 114R	19-08-80	16.0	7.00	3,600	8.03	3,428	3,240	1,360	875.1	311.4	141.8
Ctr 115	19-06-80	10.0	6.80	8,000	7.30	4,934	5,480	2,283	892.8	441.7	287.2
Ctr 118	20-05-80	10.0	6.40	5,200	7.38	3,110	3,030	-	-	375	171.9
Ctr 118	19-08-80	12.0	7.95	2,700	7.65	2,633	2,540	1,529	511.0	388.4	136.2
Ctr 118	14-07-81	10.50	6.90	5,000	7.66	2,770	2,960	1,386	469.8	317	145
Ctr 119	20-05-80	11.0	6.70	5,000	7.75	2,610	2,420	-	-	225	194.6
Ctr 119	19-08-80	12.5	7.90	2,700	8.34	2,571	2,610	1,361	609.3	316.1	139.1
Ctr 119	14-07-81	11.50	7.60	4,500	7.52	2,880	2,280	1,272	538.9	139	225

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 97	826.5	25.0	1,132.4	2.2	1,810	<1	-3.9	0.39	0.15	-	30.63
Ctr 97	884.9	26.3	1,123	1.2	1,410	3.7	6.2	0.16	0.23	-	1,250
Ctr 97	793	22.7	1,131	2.2	1,577	<1	-1.4	-	-	-	17
Ctr 98	584.2	20.1	886.3	7.8	792	<1	0.2	0.37	0.31	-	35.6
Ctr 98	643	16.9	1,118	10.3	704	<1	-1.0	0.17	0.35	-	38
Ctr 100	554	15	872.3	-	1,586	-	-1.6	-	-	-	20
Ctr 100	562	13	863.8	-	1,577	-	1.5	-	-	-	<20
Ctr 100	552	13	896.7	-	1,634	-	-2.6	-	-	-	20
Ctr 100	520	14	891.8	-	1,568	-	-3.3	-	-	-	<200
Ctr 100	526	14	894.3	-	1,677	-	-2.1	-	-	-	700
Ctr 100	555	15	889.4	-	1,536	-	2.0	-	-	-	1,200
Ctr 101	758.5	29.7	808.2	7.1	1,567	2.3	8.2	0.18	0.25	-	875
Ctr 101	455	28.1	778	2.6	1,283	<1	-0.8	0.15	0.26	-	208
Ctr 106	902.7	35.6	1,391.6	2.0	2,952	14.0	9.8	-	<0.1	-	129.9
Ctr 106	896	50.4	1,430	2.9	2,777	4.9	4.8	2.0	0.12	-	88
Ctr 108	400.6	21.1	1,004.2	-	569.6	<1	4.4	2.0	<0.1	-	358.2
Ctr 108	422.7	20.6	989.2	4.8	501.7	2.2	8.2	0.83	0.24	-	619
Ctr 108	301	15.2	952	3.3	450	<1	0.5	0.51	0.17	-	52
Ctr 112R	567	18.1	1,542	7.9	295	10.3	-0.9	<0.1	0.22	-	51
Ctr 114R	617.2	35.2	1,050	8.9	1,458.3	10.5	6.6	0.18	0.17	-	160
Ctr 115	797.1	35.6	1,085.7	1.71	3,310	<1	-3.3	0.36	0.27	-	302
Ctr 118	270.5	21	691.4	1.31	1,724	12.2	-2.6	0.09	0.08	-	42
Ctr 118	254.5	22.2	619	2.2	1,370.4	8.2	4.0	0.13	0.14	-	267
Ctr 118	220	19.6	570.7	1.2	1,323	8.2	0.8	0.71	<0.1	-	216
Ctr 119	324.5	26	734.9	3.27	1,491	7.9	-1.6	-	0.14	-	132
Ctr 119	318.5	28.2	718.2	12.4	1,172	4.9	6.4	0.19	0.23	-	140
Ctr 119	246	25.9	655	1.0	1,208	4.6	1.1	1.65	0.16	-	143

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 97	-	-	0.28	-	-	4.80	1.30	-	-	-	15.4	-
Ctr 97	294	16	0.8	-	<0.2	7.0	26	-	-	-	8	-
Ctr 97	263	13.9	0.56	-	0.5	1.1	<0.8	-	-	-	<5	-
Ctr 98	-	-	1.34	-	-	2.90	2.22	-	-	-	27.7	-
Ctr 98	1,110	5.3	<0.05	-	0.4	0.8	2.8	-	-	-	19	-
Ctr 100	-	-	<1	<0.3	<2	<2	<2	<50	94	<2	-	<1
Ctr 100	-	-	1.1	0.35	<2	2.8	5.1	73	127	13	-	9.1
Ctr 100	-	-	<1	<0.3	<2	<2	15	<0.5	92	17	<5	<1
Ctr 100	-	-	<1	<0.3	<2	<2	24	<1	68	10	<5	<1
Ctr 100	-	-	<1	<0.3	<2	<2	4.9	<1	118	18	<10	<1
Ctr 100	-	-	<1	<0.3	<2	<2	8.4	<1	125	11	<10	1.1
Ctr 101	31	7	0.4	-	<0.2	1.8	22	-	-	-	84	-
Ctr 101	2,062	6	0.40	-	1.2	0.7	<0.8	-	-	-	7.6	-
Ctr 106	-	-	0.56	-	-	0.08	-	-	-	-	9.8	-
Ctr 106	3,080	63.2	0.34	-	5.1	0.2	<0.8	-	-	-	<5	-
Ctr 108	-	-	1.31	-	-	0.86	1.33	-	-	-	14.2	-
Ctr 108	1,461	19	0.5	-	<0.2	1.5	30	-	-	-	35	-
Ctr 108	1,307	10.2	<0.05	-	<0.2	0.9	<0.8	-	-	-	<5	-
Ctr 112R	266	2.3	<0.05	-	0.3	0.3	1.1	-	-	-	<5	-
Ctr 114R	809	16	0.4	-	<0.2	0.8	36	-	-	-	37	-
Ctr 115	-	-	0.18	-	-	3.70	1.0	-	-	-	251.6	-
Ctr 118	-	-	0.69	-	-	2.1	9.0	-	-	-	5.6	-
Ctr 118	1,220	7	0.3	-	<0.2	1.32	38	-	-	-	28	-
Ctr 118	834	3.4	0.26	-	<0.2	0.4	2.3	-	-	-	<5	-
Ctr 119	-	-	0.09	-	-	0.7	13.8	-	-	-	19.2	-
Ctr 119	771	19	0.1	-	<0.2	0.7	28	-	-	-	29	-
Ctr 119	432	5.8	0.36	-	<0.2	0.3	1.5	-	-	-	20	-

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 120	20-05-80	12.5	6.65	2,300	7.80	1,530	1,280	-	-	130	33.2
Ctr 120	19-08-80	14.0	7.15	1,700	7.95	1,528	1,320	482.8	150.8	110.9	50.1
Ctr 120	14-07-81	14.00	8.20	2,800	7.15	1,730	1,540	567	95.8	102	76
Ctr 127	19-05-80	14.0	6.45	7,000	7.29	3,310	3,800	-	-	450	249.3
Ctr 127	19-08-80	15.0	6.45	3,500	7.55	3,219	3,860	2,054	763.6	477.8	209.6
Ctr 127	14-07-81	15.00	6.60	5,000	7.43	3,220	3,530	1,887	747.8	507	151
Ctr 132	19-06-80	13.5	6.55	6,500	7.10	3,913	4,420	2,113	487.2	644.0	123.3
Ctr 132	19-08-80	12.0	6.45	4,000	7.20	4,149	4,350	2,094	478.0	833.7	3.6
Ctr 132	14-07-81	12.00	6.50	6,500	7.26	4,360	4,710	2,094	528.3	574	161
Ctr 135	14-07-81	13.00	7.30	4,500	7.50	2,890	2,500	900	728.4	188	105
Ctr 154	15-10-80	8.0	7.40	1,500	-	-	766	-	594	177	56
Ctr 154	19-02-81	8.50	6.85	1,450	-	-	971	-	567	172	47
Ctr 154	28-04-81	9.50	7.10	1,600	-	-	1,141	-	549	194	50

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 120	259.4	21	122.3	0.61	933.6	<1	-1.0	0.28	0.43	-	170
Ctr 120	264.4	23.1	181.4	1.3	745.8	<1	6.0	0.77	0.61	-	456
Ctr 120	203	21.2	117	0.1	827	7.5	3.4	2.0	0.47	-	7.8
Ctr 127	375.2	28	961.8	1.49	2,143	<1	-0.4	2.0	0.08	-	108
Ctr 127	293.6	27.4	926.3	2.6	1,674	<1	4.2	1.0	0.17	-	1,270
Ctr 127	243	24.2	910	1.1	1,599	<1	0.7	0.72	<0.1	-	880
Ctr 132	530.2	30.8	593.2	0.58	2,886	11.9	3.0	0.22	<0.1	-	984.3
Ctr 132	542.6	30.2	581.7	0.7	2,319	7.2	6.6	0.21	0.13	-	-
Ctr 132	468	38.5	643	0.5	2,820	24.4	5.1	0.55	<0.1	-	1,354
Ctr 135	454	27.6	886	1.3	1,330	<1	-4.7	-	-	-	-
Ctr 154	21	2.8	724.7	-	98.8	-	1.7	-	-	-	300
Ctr 154	18	2.6	691.7	-	103	-	-0.7	-	-	-	1,800
Ctr 154	17	2.9	669.8	-	179	-	-0.4	-	-	-	2,600

GROUNDWATER ANALYSES - BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 120	-	-	0.33	-	-	2.2	4.3	-	-	-	75.7	-
Ctr 120	259	4	0.2	-	<0.2	2.7	53	-	-	-	86	-
Ctr 120	91	2.9	<0.05	-	0.2	0.8	<0.8	-	-	-	38	-
Ctr 127	-	-	1.73	-	-	2.2	23.8	-	-	-	11.8	-
Ctr 127	3,333	6	0.7	-	<0.2	2.4	40	-	-	-	32	-
Ctr 127	1,879	16.1	0.48	-	<0.2	0.95	<0.8	-	-	-	6.0	-
Ctr 132	-	-	1.33	-	-	4.40	-	-	-	-	10.7	-
Ctr 132	1,649	16	0.8	-	<0.2	3.5	59	-	-	-	26	-
Ctr 132	2,102	18	0.62	-	0.4	1.8	<0.8	-	-	-	16	-
Ctr 135	-	-	-	-	-	-	-	-	-	-	-	-
Ctr 154	-	-	<1	<0.3	<2	<2	<2	<50	355	<2	-	<1
Ctr 154	-	-	<1	<0.3	<2	<2	<2	<0.5	307	<2	<5	<1
Ctr 154	-	-	<1	<0.3	<2	<2	<2	<1	193	<2	<5	<1

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METERS BELOW THE BASE OF SPOILS, CENTER MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 10E	03-06-80	10.0	6.85	4,400	-	-	2,220	-	675	91	56
Ctr 10F	03-06-80	11.0	7.40	2,600	-	-	1,356	-	977	24	29
Ctr 36	17-08-78	11.0	6.38	4,100	-	-	-	-	759.5	323.9	159.2
Ctr 36	15-11-78	5.5	6.85	4,400	-	-	3,749	-	691	361.8	171.0
Ctr 36	18-09-79	10.0	6.35	4,400	-	-	4,428	-	87.5	431.8	260.0
Ctr 40	16-11-78	7.0	9.25	3,800	-	-	2,769	-	328	71.2	19.2
Ctr 40	26-02-79	8.0	8.65	4,000	-	-	2,798.5	-	491.8	40.6	13.79
Ctr 40	24-09-79	12.0	8.25	4,000	-	-	2,712	-	545.3	30.9	12.7
Ctr 42	21-08-78	10.0	6.81	1,900	-	-	-	-	732.3	99.1	49.6
Ctr 42	16-11-78	8.0	7.85	2,200	-	-	1,467	-	729	59.9	40.5
Ctr 42	26-02-79	8.0	7.50	2,300	-	-	1,492	-	752	49.3	33.48
Ctr 42	24-09-79	11.0	7.60	2,200	-	-	1,413	-	794.0	34.6	26.6
Ctr 47	14-07-81	12.00	6.80	8,800	7.70	5,990	5,160	1,508	984.4	310	178
Ctr 51	20-05-80	12.0	6.80	10,000	7.62	5,880	4,810	-	-	200	91.3
Ctr 64	03-06-80	13.0	6.90	9,600	-	-	4,455	-	1,851	86	21
Ctr 64	09-09-80	12.0	6.95	8,000	-	-	3,987	-	1,677	88	33
Ctr 64	19-02-81	9.50	6.75	9,200	-	-	5,753	-	1,784	124	67
Ctr 64	29-04-81	10.00	6.60	9,600	-	-	6,663	-	1,815	170	81
Ctr 64	28-07-81	11.50	7.05	9,600	-	-	6,483	-	1,751	154	90
Ctr 64	03-11-81	10.50	7.45	9,000	-	-	7,069	-	1,780	152	98
Ctr 72	19-06-80	12.0	6.85	3,600	7.65	2,333	1,900	472.7	895.5	109.7	48.4
Ctr 89	20-05-80	7.0	6.30	12,000	7.16	5,170	5,090	-	-	450	138.3
Ctr 96	09-06-80	11.0	7.80	4,000	-	-	1,953	-	1,224	33	22
Ctr 96	09-09-80	9.0	7.95	2,500	-	-	1,926	-	1,210	30	20
Ctr 96	18-02-81	7.50	7.85	4,000	-	-	2,506	-	1,222	27	19

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 10E	471	8.5	823.5	-	1,049	-	- 8.4	-	-	-	80
Ctr 10F	372	6.4	1,191.9	-	207	-	- 8.9	-	-	-	140
Ctr 36	561.6	7.39	926.6	-	1,894.4	2.9	- 0.8	2.8	0.05	<0.05	470
Ctr 36	593	13.96	843.0	-	1,904	3.3	4.2	0.10	0.0	<0.05	440
Ctr 36	350.3	10.8	106.8	-	2,539	6.5	3.2	2.90	<0.01	<0.05	630
Ctr 40	814	11.70	400.2	-	1,422	9.0	5.7	0.19	1.25	0.11	20
Ctr 40	844.8	10.91	600.0	-	1,379.4	9.3	1.7	0.24	1.43	0.08	40
Ctr 40	880.2	8.9	665.3	-	1,435.1	11.0	0.0	0.66	1.32	0.16	110
Ctr 42	400.0	7.36	893.4	-	444.9	5.3	5.1	0.42	0.37	<0.05	120
Ctr 42	425	9.54	889.4	-	415	9.3	3.2	0.02	0.41	<0.05	100
Ctr 42	474.1	10.57	917.4	-	453.9	7.7	2.7	0.06	0.45	<0.05	100
Ctr 42	488.8	8.7	968.7	-	423.9	10.0	0.8	0.20	0.40	0.12	30
Ctr 47	1,208	34.5	1,195	2.7	2,785	8.8	3.5	0.15	0.22	-	3,250
Ctr 51	1,323.2	23	1,354.2	4.40	2,622	<1	- 0.9	0.04	0.13	-	265
Ctr 64	988	12	2,258.2	-	1,178	-	-11.0	-	-	-	60
Ctr 64	1,203	13	2,045.9	-	1,483	-	- 3.7	-	-	-	210
Ctr 64	1,556	14	2,176.5	-	1,871	-	3.3	-	-	-	220
Ctr 64	1,497	19	2,214.3	-	2,453	-	- 3.9	-	-	-	600
Ctr 64	1,618	20	2,136.2	-	2,453	-	1.8	-	-	-	500
Ctr 64	1,680	19	2,171.6	-	2,515	-	0.7	-	-	-	300
Ctr 72	577.5	23.5	1,084.9	3.77	788.4	<1	1.2	0.24	0.32	-	34.96
Ctr 89	979.4	30	1,103.5	1.26	2,257	11.8	8.3	0.42	0.13	-	5,408
Ctr 96	663	8.3	1,493.3	-	452	-	- 2.1	-	-	-	70
Ctr 96	671	6.9	1,476.2	-	409	-	- 0.3	-	-	-	290
Ctr 96	696	6.4	1,490.8	-	405	-	0.7	-	-	-	60

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 10E	-	-	<1	<0.3	<2	<2	3.9	<50	46	3.5	-	<1
Ctr 10F	-	-	<1	<0.3	<2	3.2	<2	<50	84	<2	-	<1
Ctr 36	1,080	-	3.6	0.3	2.2	1.5	8.8	-	67.6	11.3	-	1.8
Ctr 36	1,040	-	3.0	0.6	0.0	2.8	7.2	-	7.2	7.2	-	4.9
Ctr 36	2,930	-	1.0	<0.3	-	-	-	-	-	-	-	-
Ctr 40	150	-	3.0	0.2	0.9	37.6	38.8	-	52.8	36.8	-	7.2
Ctr 40	130	-	23.5	<0.3	<2	24.1	-	-	-	-	-	-
Ctr 40	170	-	2.1	<0.3	-	-	-	-	-	-	-	-
Ctr 42	120	-	14.6	0.3	6.1	1.8	3.2	-	60.2	5.4	-	0.1
Ctr 42	240	-	<1	0.7	0.9	1.3	8.5	-	53.3	2.9	-	7.2
Ctr 42	410	-	<1	<0.3	<2	<2	-	-	-	-	-	-
Ctr 42	550	-	<1	<0.3	-	-	-	-	-	-	-	-
Ctr 47	5,055	34	0.54	-	0.2	0.9	2.6	-	-	-	<5	-
Ctr 51	-	-	0.14	-	-	0.4	22	-	-	-	21.0	-
Ctr 64	-	-	<1	<0.3	<2	2.1	6.4	<50	56	7.5	-	<1
Ctr 64	-	-	1.4	<0.3	2.0	9.2	16	145	56	30	-	<1
Ctr 64	-	-	2.2	<0.3	<2	5.3	7.3	<0.5	63	42	<5	5.5
Ctr 64	-	-	2.6	<0.3	<2	8.2	28	<1	142	27	10	3.1
Ctr 64	-	-	<1	<0.3	<2	7.0	23	<1	114	57	<10	5.4
Ctr 64	-	-	3.7	<0.3	<2	6.4	45	<1	123	43	<10	5.2
Ctr 72	-	-	0.98	-	-	0.65	2.63	-	-	-	7.3	-
Ctr 89	-	-	0.29	-	-	11.7	10.0	-	-	-	41.7	-
Ctr 96	-	-	<1	<0.3	<2	2.2	2.0	<50	81	<2	-	<1
Ctr 96	-	-	<1	0.35	<2	2.0	6.1	170	98	8.7	-	52
Ctr 96	-	-	<1	<0.3	<2	<2	6.7	<0.5	72	13	<5	<1

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 96	28-04-81	8.00	7.85	4,200	-	-	2,792	-	1,621	27	18
Ctr 96	28-07-81	9.00	8.10	4,000	-	-	2,698	-	1,202	26	12
Ctr 96	03-11-81	8.50	8.50	3,500	-	-	2,625	-	1,188	35	18

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 96	709	8.2	1,977.6	-	390	-	-9.0	-	-	-	200
Ctr 96	683	7.4	1,466.4	-	426	-	2.3	-	-	-	300
Ctr 96	720	7.1	1,449.4	-	385	-	4.5	-	-	-	200

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES
BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 96	-	-	1.9	<0.3	<2	<2	11	<1	83	7.1	<5	<1
Ctr 96	-	-	<1	<0.3	<2	<2	6.1	<1	118	14	<10	<1
Ctr 96	-	-	<1	<0.3	<2	2.5	6.1	<1	81	5.0	<10	1.6

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 105	19-06-80	8.5	7.25	4,400	7.78	2,709	1,930	237.3	1,526	50.8	26.9
Ctr 116	14-07-81	11.50	7.60	4,000	8.14	2,490	1,940	234	1,014	50	27
Ctr 121	14-07-81	13.00	7.75	3,400	7.98	2,250	1,750	256	798.3	60	26
Ctr 126	19-05-80	14.5	7.50	4,200	7.89	2,510	1,710	-	-	40	43.6
Ctr 126	14-07-81	12.50	7.65	3,500	8.57	2,590	1,620	218	804.8	37	31
Ctr 129	14-07-81	11.00	7.25	4,000	7.99	2,710	2,080	415	936.2	65	61
Ctr 134	14-07-81	13.00	8.05	3,300	8.01	2,260	1,570	256	545.4	48	33
Ctr 142	19-06-80	12.5	6.40	2,350	7.75	2,483	2,130	466.8	568.8	112.2	45.5
Ctr 142	28-07-80	13.9	6.82	1,450	7.72	2,532	1,730	493.1	566.0	102.9	57.5
Ctr 148	15-10-80	10.5	7.05	5,500	-	-	3,285	-	-	489	147
Ctr 148	19-02-81	11.00	7.10	5,000	-	-	3,261	-	602	296	89
Ctr 148	28-04-81	11.00	7.60	6,000	-	-	2,661	-	930	137	48
Ctr 148	28-07-81	11.50	7.70	4,400	-	-	2,635	-	946	117	38
Ctr 148	02-11-81	12.00	8.00	3,500	-	-	2,539	-	944	92	40

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 105	847.5	18.6	1,844.1	8.66	282	<1	7.2	0.50	0.21	-	61.46
Ctr 116	589	16.5	1,221	7.8	443	7.5	1.8	0.11	0.25	-	132
Ctr 121	465	14.1	965	4.2	474	<1	-0.2	0.53	0.28	-	72
Ctr 126	687.1	15	1,118.8	6.87	739.3	<1	2.7	0.22	0.31	-	59
Ctr 126	536	15.8	949	16.1	556	<1	0.8	0.69	0.34	-	118
Ctr 129	515	16.4	1,132	5.1	673	<1	-2.6	0.25	0.70	-	462
Ctr 134	442	16.5	659	3.1	869	<1	-7.9	0.67	0.38	-	78
Ctr 142	508.3	43.9	687.7	3	1,192	<1	-5.3	<0.1	0.16	-	12.7
Ctr 142	393.7	30.5	684.8	2.8	633.7	5.8	5.9	0.40	0.38	-	1,787
Ctr 148	238	12	-	-	1,895	-	-	-	-	-	60
Ctr 148	417	9.1	734.4	-	1,511	-	-3.6	-	-	-	-
Ctr 148	510	7.9	1,134.6	-	822	-	-3.7	-	-	-	<200
Ctr 148	548	7.3	1,154.1	-	779	-	-0.7	-	-	-	<200
Ctr 148	565	7.2	1,151.7	-	635	-	0.8	-	-	-	<200

GROUNDWATER ANALYSES - SAND OR SILT 2 TO 5 METRES BELOW THE BASE OF SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 105	-	-	0.19	-	-	1.76	1.25	-	-	-	10.7	-
Ctr 116	433	7.5	<0.05	-	0.2	0.5	5	-	-	-	<5	-
Ctr 121	332	9.1	0.12	-	<0.2	0.7	<0.8	-	-	-	4.4	-
Ctr 126	-	-	0.38	-	-	0.5	7.5	-	-	-	85.0	-
Ctr 126	930	3.3	0.15	-	<0.2	1.8	<0.8	-	-	-	104	-
Ctr 129	1,516	5.4	0.09	-	<0.2	0.3	0.9	-	-	-	<5	-
Ctr 134	404	10.2	<0.05	-	0.6	0.7	2.2	-	-	-	49	-
Ctr 142	-	-	0.24	-	-	2.80	6.38	-	-	-	25.9	-
Ctr 142	1,600	13.7	0.42	-	0.45	2.39	17.9	-	-	-	132.4	-
Ctr 148	-	-	1.0	<0.3	<2	<2	14	53	53	5.7	-	3.9
Ctr 148	-	-	<1	<0.3	<2	<2	-	<0.5	115	13	<5	<1
Ctr 148	-	-	<1	<0.3	<2	<2	7.5	<1	75	8.9	<5	<1
Ctr 148	-	-	<1	<0.3	<2	<2	<2	<1	68	11	<10	<1
Ctr 148	-	-	<1	<0.3	<2	<2	2.2	<1	112	3.8	<10	1.9

GROUNDWATER ANALYSES - SAND OR SILT 8 TO 12 METRES BELOW THE BASE OF THE SPOILS, CENTER MINE

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 12	01-02-78	6.0	7.83	2,300	-	-	1,584	-	603	35	16
Ctr 12	28-03-78	5.5	7.94	2,250	-	-	1,541	-	690	13.0	62.0
Ctr 12	06-07-78	9.5	7.70	2,400	-	-	1,617	-	732	22.7	10.1
Ctr 12	26-02-79	6.5	8.25	2,300	-	-	1,560	-	744.5	122	6.77
Ctr 12	25-09-79	9.5	8.30	2,300	-	-	1,538	-	712.1	21.3	6.9
Ctr 15	31-01-78	3.0	7.78	2,800	-	-	1,968	-	822	81	52
Ctr 15	28-03-78	5.0	8.12	3,000	-	-	2,114	-	896	42.0	28.0
Ctr 15	07-07-78	9.5	7.20	3,100	-	-	2,163	-	839.2	59.6	39.0
Ctr 15	26-02-79	7.0	7.70	3,000	-	-	2,092	-	745	76.7	33.9
Ctr 15	17-09-79	11.0	6.85	3,000	-	-	2,120	-	746.6	87.6	38.4
Ctr 19A	14-07-81	10.0	7.20	2,400	7.89	1,590	1,070	352	765.3	66	46
Ctr 22	31-01-78	10.0	7.58	4,200	-	-	2,998	-	781	179	104
Ctr 22	28-03-78	6.0	6.86	4,000	-	-	3,038	-	901	70.0	186.0
Ctr 22	07-07-78	10.5	7.71	4,500	-	-	3,200	-	889.2	98.1	66.5
Ctr 22	27-02-79	6.0	7.25	3,200	-	-	2,195	-	915.4	43.2	28.7
Ctr 22	17-09-79	10.0	7.45	2,800	-	-	1,963.5	-	947	49.7	18.6
Ctr 24	01-02-78	5.0	8.00	2,200	-	-	1,902	-	1,314	36	21
Ctr 24	30-03-78	9.0	8.03	3,000	-	-	1,910	-	1,475	19.0	28.0
Ctr 24	07-07-78	9.0	7.94	2,550	-	-	1,933	-	1,360.8	11.8	12.4
Ctr 24	26-02-79	7.0	8.20	3,000	-	-	1,908	-	1,329.8	20.8	9.90
Ctr 24	24-09-79	9.5	7.50	2,900	-	-	1,911	-	1,296.0	38.4	9.9
Ctr 29	01-02-78	6.0	7.94	1,875	-	-	1,774	-	1,426	21	10
Ctr 29	30-03-78	10.0	7.98	2,700	-	-	1,726	-	1,592	8.0	12.0
Ctr 29	05-07-78	12.5	7.79	2,700	-	-	1,731	-	1,387.6	5.3	6.0

GROUNDWATER ANALYSES - SAND OR SILT 8 TO 12 METRES BELOW THE BASE OF THE SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 12	505	12.8	735.7	-	522	32	3.1	-	0.96	-	420
Ctr 12	515	11.1	841.8	-	566	12.0	4.6	-	-	-	220
Ctr 12	483.3	6.31	893.0	-	524.7	12.6	-5.7	0.13	1.58	<0.1	160
Ctr 12	448.3	3.54	908.3	-	437.8	9.5	3.9	0.43	2.25	0.07	50
Ctr 12	563.0	5.0	868.8	-	484.5	10.0	3.0	1.23	1.84	0.07	100
Ctr 15	590	14.2	1,002.8	-	821	4.0	1.0	1.7	0.62	-	240
Ctr 15	644	16.6	1,093.1	-	861	5.0	-4.5	-	-	-	240
Ctr 15	597.8	7.98	1,023.8	-	860.0	4.5	-3.6	0	0.33	<0.1	90
Ctr 15	560.3	8.92	908.9	-	754.7	2.6	0.9	0.14	0.15	<0.05	120
Ctr 15	627.7	9.76	910.9	-	961.9	3.2	0.0	1.33	<0.01	<0.05	30
Ctr 19A	364	13.9	927	3.3	266	<1	5.5	0.30	0.29	-	49
Ctr 22	720	36.4	952.8	-	1,350	19.5	5.8	0.52	0.29	<0.05	150
Ctr 22	723	25.0	1,099.2	-	1,510	8.5	1.2	0.53	<0.01	<0.05	100
Ctr 22	796.2	7.63	1,084.8	-	1,609.8	4.0	-6.4	1.02	0.40	-	420
Ctr 22	681.0	8.00	1,116.8	-	716.4	3.8	1.5	-	-	-	320
Ctr 22	643.9	6.95	1,155.3	-	486.6	3.6	3.4	0.11	0.2	<0.1	140
Ctr 24	697	10.0	1,603.1	-	384	10.6	-0.7	-	0.92	-	340
Ctr 24	730	11.1	1,799.5	-	339	7.8	-2.1	-	-	-	470
Ctr 24	685.4	6.12	1,660.2	-	302.5	7.8	-3.3	0.14	1.71	<0.1	150
Ctr 24	715.5	5.43	1,622.4	-	265.6	9.0	1.1	0.17	1.07	<0.05	60
Ctr 24	754.1	5.0	1,581.1	-	311.7	8.5	4.3	0.39	1.12	0.09	90
Ctr 29	683	9.8	1,739.7	-	229	7.6	-2.5	1.6	0.88	-	480
Ctr 29	710	9.3	1,942.2	-	154	5.0	-3.9	-	-	-	400
Ctr 29	672.6	6.36	1,692.9	-	140.9	9.0	-1.2	0.19	1.71	<0.1	190

GROUNDWATER ANALYSES - SAND OR SILT 8 TO 12 METRES BELOW THE BASE OF THE SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 12	429	-	3.8	4.6	4.5	7.6	33.3	-	88.7	10.7	-	3.2
Ctr 12	271	-	<1	0.5	0.0	6.3	17.6	-	31.6	15.6	-	2.9
Ctr 12	270	-	<1	0.1	1.8	2.8	1.6	-	194.4	5.6	-	0.7
Ctr 12	140	-	1.2	<0.3	<2	10.7	-	-	-	-	-	-
Ctr 12	180	-	1.8	<0.3	-	-	-	-	-	-	-	-
Ctr 15	388	-	0.8	0.4	4.4	4.0	12.5	-	758	11.9	-	1.6
Ctr 15	128	-	<1	0.3	0.0	2.8	16.2	-	62.0	16.7	-	1.6
Ctr 15	200	-	<1	0.5	3.9	0.4	3.5	-	80.3	8.1	-	1.5
Ctr 15	120	-	1.1	<0.3	<2	<2	-	-	-	-	-	-
Ctr 15	160	-	1.0	<0.3	-	-	-	-	-	-	-	-
Ctr 19A	552	6.7	0.18	-	0.2	0.5	1.2	-	-	-	<5	-
Ctr 22	180	-	<1	<0.3	<2	<2	-	-	-	-	-	-
Ctr 22	200	-	1.5	<0.3	-	-	-	-	-	-	-	-
Ctr 22	440	-	3.2	3.0	4.5	5.7	13.3	-	347	15.5	-	3.5
Ctr 22	164	-	< 1	1.8	-	-	16.7	-	100.3	20.4	-	4.8
Ctr 22	180	-	< 1	0.8	1.8	0.0	7.9	-	68.7	16.1	-	1.9
Ctr 24	222	-	0.2	2.2	4.5	5.2	28.7	-	105.6	5.7	-	1.3
Ctr 24	237	-	<1	0.6	-	-	9.2	-	35.8	10.6	-	0.7
Ctr 24	300	-	<1	<0.3	1.3	4.9	1.4	-	229.6	4.3	-	0.1
Ctr 24	300	-	<1	<0.3	<2	<2	-	-	-	-	-	-
Ctr 24	340	-	<1	<0.3	-	-	-	-	-	-	-	-
Ctr 29	207	-	1.0	3.0	4.2	14.0	38.3	-	109.2	3.3	-	1.1
Ctr 29	136	-	<1	0.5	-	-	20.5	-	47.2	7.7	-	0.6
Ctr 29	100	-	<1	0.7	1.1	2.1	0.9	-	752.0	5.1	-	0.1

GROUNDWATER ANALYSES - SAND OR SILT 8 TO 12 METRES BELOW THE BASE OF THE SPOILS, CENTER MINE--Continued

Piezometer Number	Date day/m/yr	Field Temp. °C	Field pH	Field Cond. µS/cm	Lab pH	Lab Cond. µS/cm	TDS mg/L	Hardness mg/L	Alkalinity mg/L	Ca mg/L	Mg mg/L
Ctr 29	24-09-79	9.5	7.60	2,500	-	-	1,714	-	1,346.4	12.5	4.3
Ctr 29	28-04-81	9.00	8.15	3,500	-	-	2,372	-	1,294	12	4.7
Ctr 29	28-07-81	9.50	8.35	3,400	-	-	2,470	-	1,299	7.3	1.9
Ctr 29	02-11-81	8.50	8.50	3,200	-	-	2,437	-	1,280	12	4.5
Ctr 38	17-08-78	10.5	6.64	6,000	-	-	-	-	1,145.1	191.5	159.4
Ctr 38	16-11-78	7.0	7.25	6,500	-	-	5,056	-	1,133	177.8	122.0
Ctr 38	24-09-79	11.5	6.80	8,000	-	-	4,905	-	1,157.0	100.5	105.0
Ctr 44	22-08-78	8.5	5.86	3,900	-	-	-	-	685.6	124.5	85.2
Ctr 44	15-11-78	5.5	6.90	4,000	-	-	2,893	-	695	140.4	77.0
Ctr 44	25-09-79	8.5	7.00	3,900	-	-	2,866	-	779.0	175.5	75.0

GROUNDWATER ANALYSES - SAND OR SILT 8 TO 12 METRES BELOW THE BASE OF THE SPOILS, CENTER MINE--Continued

Piezometer Number	Na mg/L	K mg/L	HCO_3 mg/L	CO_3 mg/L	SO_4 mg/L	Cl mg/L	Standard Error %	NO_3 mg/L	F mg/L	PO_4 mg/L	Fe µg/L
Ctr 29	696.5	4.3	1,642.6	-	166.7	8.2	1.2	0.51	1.25	0.15	70
Ctr 29	597	3.9	1,578.7	-	124	-	-2.5	-	-	-	<200
Ctr 29	623	4.1	1,584.8	-	125	-	2.7	-	-	-	<200
Ctr 29	640	6.9	1,561.6	-	117	-	1.7	-	-	-	<200
Ctr 38	1,311	7.57	1,397.0	-	2,662.4	4.9	0.9	0.46	0.10	<0.05	240
Ctr 38	1,299	15.89	1,382.3	-	2,618	4.8	-1.0	0.20	0.10	<0.05	440
Ctr 38	1,305.0	15.7	1,411.5	-	2,543	6.2	-3.7	0.23	<0.01	0.07	70
Ctr 44	738.7	7.52	836.4	-	1,519.4	7.2	0.0	0.33	0.17	<0.05	70
Ctr 44	732	20.73	847.9	-	1,386	7.5	3.1	0.10	0.11	<0.05	330
Ctr 44	750.4	17.7	950.4	-	1,430	7.5	2.6	0.23	<0.01	0.05	640

GROUNDWATER ANALYSES - SAND OR SILT 8 TO 12 METRES BELOW THE BASE OF THE SPOILS, CENTER MINE--Continued

Piezometer Number	Mn µg/L	Cu µg/L	Cd µg/L	Hg µg/L	Se µg/L	As µg/L	Pb µg/L	Al µg/L	Ba µg/L	Cr µg/L	Mo µg/L	Ag µg/L
Ctr 29	140	-	5.3	<0.3	-	-	-	-	-	-	-	-
Ctr 29	-	-	<1	<0.3	<2	<2	20	1	121	3.0	<5	<1
Ctr 29	-	-	<1	<0.3	<2	<2	3.6	1	99	4.1	<10	<1
Ctr 29	-	-	1.2	<0.3	<2	2.1	3.2	1	137	<2	<10	1.9
Ctr 38	370	-	23.7	0.0	3.0	0.0	12.2	-	69.7	29.1	-	1.9
Ctr 38	580	-	3.8	0.7	0.0	2.3	29.3	-	39.3	52.6	-	8.7
Ctr 38	770	-	1.2	<0.3	-	-	-	-	-	-	-	-
Ctr 44	370	-	25.2	0.0	4.3	2.4	11.2	-	69.2	15.6	-	1.2
Ctr 44	380	-	1.0	0.4	0.0	3.6	14.2	-	62.0	22.3	-	5.8
Ctr 44	400	-	1.4	<0.3	-	-	-	-	-	-	-	-

APPENDIX E

Analyses of Extracts from Exhaustive Leaching Experiments

EXPLANATION OF APPENDIX E

Exhaustive Leaching Experiments

I. S-1, 9, 10, 11, 12, 13, 14, 16, 17, 21, and 22 were all prepared from Ctr 361 17-19.5 at a water/sediment ratio of 32:1 (320 ml H_2O) 10 g sediment). Two variations were made. The different samples were left shaking in the water-bath for different amounts of time indicated by the number after the soil depth (2, 10, 24, 48, 72 hours). Also, samples marked DI were prepared with deionized H_2O; those marked V were vacuum-dried before being placed in water; those marked DIV were vacuum-dried and placed in deionized water. Unmarked samples were not vacuum-dried and were shaken in distilled water.

II. S-8, 30, 6, 7, and 18 were prepared from Ctr 366 54.5-57 using distilled water; water/sediment ratio = 32:1 (320 ml H_2O, 10 g sediment varying only the time in the water bath (2, 10, 24, 48, 72 hours).

III. S-2, 3, 4, 5, and 15 were prepared from Fa 10 7.5-10 in distilled water; water/sediment ratio = 32:1 (320 ml H_2O, 10 g sediment) varying only the time in water bath (2, 10, 24, 48, 72 hours).

IV. S-19, 20, 23, 24, 25, 26, 27, 28, 29, and 31 were all vacuum-dried (all samples from now on are) and were prepared at a water to sediment ratio of 32:1 (15.6 g sediment, 500 ml H_2O). Two preparations of each sample were made, one with distilled water (unmarked) and one with deionized water (DI). All of these samples were in the water bath for approximately 2 hours. It was found after these preparations that the use of distilled or deionized water made no detectable difference, so after this point only distilled water was used.

V. S-32-35 samples were prepared from Ctr 361 32-34.5 at a water/ sediment ratio of 16:1 (28.13 g sediment, 450 ml H_2O). They were left in water bath for varying times (2, 6.5, 24, 48 hours) indicated by the number after depth number.

VI. S-36-39 samples were prepared from Ctr 361 42-44.5, 16:1 water/sediment ratio, varying times (2, 6.5, 24, 48 hours).

VII. S-40-43 samples were prepared from Ctr 366 19.5-22, 16:1 water/sediment ratio, varying times (2, 6.5, 40, 48 hours).

VIII. S-44-47 samples were prepared from Ctr 366 45-47, 16:1 water/sediment ratio, varying times (2, 6.5, 24, 48 hours).

IX. S-48-51 samples were prepared from Fa 10 52.5-56, 16:1 water/sediment ratio, varying times (2, 6.5, 40, 48 hours).
(After this experiment, it was determined that the amount of time that a sample was shaken was not significant beyond 2 hours).

X. S-57-71 - in these samples four preparations were made from every sediment sample. One preparation was water/sediment ratio 32:1 (450 lm H_2O, 14.06 g sediment) and the other three were water/sediment ratio 8:1 (450 ml H_2O, 56.25 g sediment). Since three samples had the same water/sediment concentration, they were distinguished by the identifiers (1), (2), and (3). Most were left in the water bath for 2 hours; some were left in the bath slightly longer.

XI. S-72-100 - in these samples two preparations were made from every sediment sample. However, both preparations were exactly the same. Water/sediment ratio - 8:1 (450 ml H_2O, 56.25 g sediment). This was designed to evaluate reproducibility of results.

XII. S-127-191 are replications of selected conditions above. The conditions used are indicated in each case. All samples were equilibrated at 25°C for at least 2 hours.

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS

Lab Sample #	S-1	S-9	S-11	S-12	S-13	S-14	S-16	S-17
Sample Location[a]	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361
Depth (ft)	17-19.5	17-19.5	17-19.5	17-19.5	17-19.5	17-19.5	17-19.5	17-19.5
Hours eq.	2	2	2	10	24	24	24	24
Water/Sediment	32:1	32:1	32:1	32:1	32:1	32:1	32:1	32:1
Other Treat.[b]	DIV	DI	--	--	--	V	DI	DIV
pH	--	7.522	7.223	7.331	7.106	7.219	7.206	7.330
Hardness (mg/L $CaCO_3$)	47.4	49.4	47.4	53.3	51.3	51.3	55.3	59.2
Total Alk (mg/L $CaCO_3$)	29.6	50.7	30.4	42.3	38.8	40.5	37.1	37.1
Sulfate (mg/L)	9.5	47.1	47.1	47.1	47.1	47.1	43.3	9.5
Sodium (mg/L)	6.7	7.2	7.0	7.0	6.8	7.6	7.1	8.2
Calcium (mg/L)	3.6	10.5	5.7	8.1	7.1	6.6	6.1	6.5
Magnesium (mg/L)	9.3	5.6	8.1	8.1	8.2	8.5	9.8	10.5

---

[a] Abbreviation Used For Sample Locations
Ctr = Center
IH = Indian Head
Fa = Falkirk

[b] DI = Deionized Water
DIV = Vacuum-Dried and Deionized Water
V = Vacuum-Dried Soil Before Weighing

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-21	S-22	S-8	S-30	S-6	S-7	S-18	S-10
Sample Location	Ctr 361	Ctr 361	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 361
Depth (ft)	17-19.5	17-19.5	54.5-57	54.5-57	54.5-57	54.5-57	54.4-57	17-19.5
Hours eq.	48	72	2	10	24	48	72	2
Water/Sediment	32:1	32:1	32:1	32:1	32:1	32:1	32:1	32:1
Other Treat.	--	--	--	--	--	--	--	V
pH	7.311	7.153	7.187	7.189	7.344	7.316	--	7.215
Hardness (mg/L $CaCO_3$)	58.9	58.9	45.4	31.4	49.4	77.0	49.4	49.4
Total Alk (mg/L $CaCO_3$)	37.7	41.5	48.5	60.3	54.9	61.2	87.8	40.5
Sulfate (mg/L)	58.5	43.4	47.1	49	37.7	28.3	15.1	56.6
Sodium (mg/L)	5.05	5.36	14.4	17.2	16.9	19.0	21.5	10.8
Calcium (mg/L)	5.31	6.72	2.4	2.96	1.5	1.8	6.7	5.1
Magnesium (mg/L)	11.10	10.24	9.6	5.84	11.1	17.6	8.0	8.9

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-2	S-3	S-4	S-5	S-15	S-19	S-20	S-25
Sample Location	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	Ctr 361
Depth (ft)	7.5-10	7.5-10	7.5-10	7.5-10	7.5-10	52.5-55	52.5-55	32-34.5
Hours eq.	10	24	48	72	2	--	--	--
Water/Sediment	32:1	32:1	32:1	32:1	32:1	32:1	32:1	32:1
Other Treat.	--	--	--	--	--	DI	--	--
pH	7.332	7.115	7.099	7.312	7.333	7.370	7.219	7.137
Hardness (mg/L $CaCO_3$)	325.8	316.0	327.8	335.7	323.9	35.3	39.3	43.2
Total Alk (mg/L $CaCO_3$)	10.6	10.6	10.6	31.7	38.8	45.2	39.6	33.9
Sulfate (mg/L)	330.0	318.7	352.7	339.5	348.9	39.6	49.1	49.0
Sodium (mg/L)	11.4	11.7	9.9	9.8	10.2	4.6	6.09	4.55
Calcium (mg/L)	89.9	75.6	90.2	78.7	74.4	3.5	3.59	6.59
Magnesium (mg/L)	24.7	31.0	25.0	33.9	33.6	6.5	7.38	6.51

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-28	S-26	S-24	S-27	S-23	S-31	S-29	--
Sample Location	Ctr 361	Ctr 361	Ctr 361	Ctr 366	Ctr 366	Ctr 366	Ctr 366	--
Depth (ft)	32-34.5	42-44.5	42-44.5	19.5-22	19.5-22	45-47	45-47	--
Hours eq.	--	--	--	--	--	--	--	--
Water/Sediment	32:1	32:1	32:1	32:1	32:1	32:1	32:1	--
Other Treat.	DI	--	DI	--	DI	--	DI	--
pH	7.142	7.093	7.075	7.233	7.218	7.234	7.23	--
Hardness (mg/L $CaCO_3$)	43.2	43.2	29.5	47.1	51.0	21.6	39.3	--
Total Alk (mg/L $CaCO_3$)	30.2	28.3	26.4	33.9	32.1	58.4	52.8	--
Sulfate (mg/L)	49.0	39.6	17.0	43.3	66	30.2	39.6	--
Sodium (mg/L)	4.09	3.33	2.79	15.12	15.12	24.39	20.05	--
Calcium (mg/L)	5.90	3.87	2.14	7.48	8.9	2.09	3.75	--
Magnesium (mg/L)	6.93	8.16	5.87	6.92	7.00	3.98	7.28	--

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-32	S-33	S-34	S-35	S-36	S-37	S-38	S-39
Sample Location	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361
Depth (ft)	32-34.5	32-34.5	34-34.5	32-34.5	42-44.5	42-44.5	42-44.5	42-44.5
Hours eq.	2	6.5	24	48	2	6.5	24	48
Water/Sediment	16:1	16:1	16:1	16:1	16:1	16:1	16:1	16:1
Other Treat.	--	--	--	--	--	--	--	--
pH	7.212	7.155	7.069	7.156	7.014	7.014	7.010	7.055
Hardness (mg/L $CaCO_3$)	51.0	100.0	62.8	98.1	39.2	39.2	49.0	49.0
Total Alk (mg/L $CaCO_3$)	47.1	35.8	37.7	37.7	33.9	41.4	35.8	43.3
Sulfate (mg/L)	86.8	96.2	96.2	77.3	77.3	86.8	86.8	77.3
Sodium (mg/L)	7.7	9.3	9.4	9.3	5.8	7.1	6.2	7.7
Calcium (mg/L)	16.9	13.2	16.7	28.0	5.8	9.7	7.7	7.7
Magnesium (mg/L)	2.2	16.3	5.1	6.9	6.0	3.6	7.2	7.3

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-40	S-41	S-42	S-42	S-44	S-45	S-46	S-47
Sample Location	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366
Depth (ft)	19.5-22	19.5-22	19.5-22	19.5-22	45-47	45-47	45-47	45-47
Hours eq.	2	6.5	40	48	2	6.5	24	48
Water/Sediment	16:1	16:1	16:1	16:1	16:1	16:1	16:1	16:1
Other Treat.	--	--	--	--	--	--	--	--
pH	7.007	7.149	7.195	7.254	7.525	7.618	7.480	7.655
Hardness (mg/L $CaCO_3$)	109.8	78.5	133.4	129.5	23.5	29.4	27.5	23.5
Total Alk (mg/L $CaCO_3$)	32.0	35.8	41.4	45.2	86.6	96.1	97.9	97.9
Sulfate (mg/L)	190.5	86.8	152.8	199.9	77.3	<10	77.3	58.4
Sodium (mg/L)	21.9	19.3	24.3	23.7	44.4	49.5	50.4	51.2
Calcium (mg/L)	17.0	15.5	36.8	33.0	< 0.5	< 0.5	< 0.5	2.1
Magnesium (mg/L)	16.4	9.7	10.1	11.5	5.7	7.2	6.7	4.4

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-48	S-49	S-50	S-51	S-52	S-53	S-54	S-55
Sample Location	Fa 10	Fa 10	Fa 10	Fa 10	Ctr 361	Ctr 361	Ctr 361	Ctr 361
Depth (ft)	52.5-55	52.5-55	52.5-55	52.5-54	54.5-57	54.5-57	54.5-57	54.5-57
Hours eq.	2	6.5	40	48	--	--	--	--
Water/Sediment	16:1	16:1	16:1	16:1	32:1	8:1	8:1	8:1
Other Treat.	--	--	--	--	--	--	--	--
pH	7.262	7.373	7.440	7.419	--	--	--	--
Hardness (mg/L $CaCO_3$)	51.0	51.0	64.7	74.5	21.6	21.6	21.6	23.5
Total Alk (mg/L $CaCO_3$)	47.1	56.5	62.2	52.7	24.5	35.8	32.0	33.9
Sulfate (mg/L)	67.9	77.3	96.2	67.9	<1	spill	3.0	6.1
Sodium (mg/L)	13.8	14.2	15.4	16.0	2.2	6.7	6.0	6.2
Calcium (mg/L)	7.1	14.5	7.5	9.5	2.1	3.4	3.5	4.2
Magnesium (mg/L)	8.1	3.6	11.2	12.4	3.90	3.2	3.1	3.2

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-56	S-57	S-58	S-59	S-60	S-61	S-62	S-63
Sample Location	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Ctr 366
Depth (ft)	22-24.5	22-24.5	22-24.5	22-24.5	29.5-31.5	29.5-31.5	29.5-31.5	29.5-31.5
Hours eq.	--	--	--	--	--	--	--	--
Water/Sediment	32:1	8:1	8:1	8:1	32:1	8:1	8:1	8:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	27.5	33.4	35.3	33.4	31.4	23.5	29.4	27.5
Total Alk (mg/L $CaCO_3$)	33.9	37.7	35.8	43.3	45.2	41.4	43.3	45.2
Sulfate (mg/L)	6.1	33.3	21.2	34.9	30.3	<1	56.1	50.0
Sodium (mg/L)	5.0	12.1	10.8	13.3	7.5	12.5	11.2	12.6
Calcium (mg/L)	4.3	5.9	6.4	4.8	5.6	4.6	4.7	5.5
Magnesium (mg/L)	4.1	4.5	4.7	5.2	4.2	2.9	4.3	3.6

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-64	S-65	S-66	S-67	S-68	S-69	S-70	S-71
Sample Location	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10
Depth (ft)	7.5-10	7.5-10	7.5-10	7.5-10	32.5-35	32.5-35	32.5-35	32.5-35
Hours eq.	--	--	--	--	--	--	--	--
Water/Sediment	32:1	8:1	8:1	8:1	32:1	8:1	8:1	8:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	88.3	184.4	247.2	251.1	62.8	98.1	80.4	100.0
Total Alk (mg/L $CaCO_3$)	24.5	24.5	26.4	24.5	32.0	37.7	30.1	35.8
Sulfate (mg/L)	77.3	197.1	210.7	256.2	74.3	119.8	100.1	107.6
Sodium (mg/L)	3.9	11.2	14.7	12.0	6.3	14.7	12.6	14.8
Calcium (mg/L)	17.2	44.5	51.5	56.7	12.8	18.1	16.2	20.6
Magnesium (mg/L)	11.0	17.9	28.9	26.7	7.5	12.9	9.7	11.8

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-72	S-73	S-74	S-75	S-76	S-77	S-78	S-79
Sample Location	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361	Ctr 361
Depth (ft)	22-24.5	22-24.5	37-39.5	37-39.5	12-14.5	12-14.5	27-29.5	27-29.5
Hours eq.	--	--	--	--	--	--	--	--
Water/Sediment	8:1	8:1	8:1	8:1	8:1	8:1	8:1	8:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	62.3	48.1	49.3	44.2	57.2	63.1	52.1	50.5
Total Alk (mg/L $CaCO_3$)	49.8	35.0	39.7	32.3	35.8	35.8	42.8	48.6
Sulfate (mg/L)	103.1	95.5	72.8	68.2	128.9	113.7	84.9	19.7
Sodium (mg/L)	24.4	17.2	19.8	14.6	28.9	30.2	14.2	11.2
Calcium (mg/L)	10.0	7.5	8.3	8.5	9.1	10.9	10.6	8.8
Magnesium (mg/L)	9.1	7.1	7.0	5.6	8.4	8.7	6.2	6.9

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-80	S-81	S-82	S-83	S-84	S-85	S-86	S-87
Sample Location	Ctr 361	Ctr 361	Ctr 366	Ctr 366	Ctr 366	Ctr 361	Ctr 361	Ctr 366
Depth (ft)	49.5-52	49.5-52	5.5-7	5.5-7	9.5-12	44.5-46.5	44.5-46.5	9.5-12
Hours eq.	--	--	--	--	--	--	--	--
Water/Sediment	8:1	8:1	8:1	8:1	8:1	8:1	8:1	8:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	38.7	44.2	59.2	127	30.8	48.1	40.2	30.7
Total Alk (mg/L $CaCO_3$)	43.6	46.7	37.0	31.1	57.6	35.0	50.1	57.5
Sulfate (mg/L)	19.7	40.9	185.7	219.8	95.5	--	57.6	68.2
Sodium (mg/L)	6.4	6.7	56.7	55.4	37.3	9.0	11.9	43.4
Calcium (mg/L)	7.5	8.3	16.0	21.8	5.2	8.4	7.0	3.0
Magnesium (mg/L)	4.9	5.7	4.7	17.7	4.3	6.6	5.5	9.9

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-87a	S-88	S-89	S-90	S-91	S-92	S-93	S-94
Sample Location	Ctr 366	Ctr 366	Ctr 366	Ctr 366	Fa 10	Fa 10	Fa 10	Fa 10
Depth (ft)	27-29.5	27-29.5	50-52.5	50-52.5	22.5-25	22.5-25	17.5-20	17.5-20
Hours eq.	--	--	--	--	--	--	--	--
Water/Sediment	8:1	8:1	8:1	8:1	8:1	8:1	8:1	8:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	31.5	32.3	22.9	23.6	694.5	632.6	566.8	392.2
Total Alk (mg/L $CaCO_3$)	63.0	68.0	66.8	49.7	43.5	40.8	39.6	40.8
Sulfate (mg/L)	47.0	31.8	53.1	65.2	707.9	661	624.6	369.9
Sodium (mg/L)	24.2	22.7	47.8	24.9	24.9	24.0	27.5	23.7
Calcium (mg/L)	5.8	4.5	1.1	1.7	229.5	216.5	192.7	120.9
Magnesium (mg/L)	4.1	5.1	4.9	4.7	29.3	22.2	20.7	21.9

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-95	S-96	S-97	S-98	S-99	S-100	--	--
Sample Location	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	Fa 10	--	--
Depth (ft)	72.5-75	72.5-75	47.5-50	47.5-50	62.5-65	62.5-65	--	--
Hours eq.	--	--	--	--	--	--	--	--
Water/Sediment	8:1	8:1	8:1	8:1	8:1	8:1	--	--
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	95.4	118.2	534.1	335.8	157.7	109.6	--	--
Total Alk (mg/L $CaCO_3$)	70.7	69.2	48.6	50.5	70.7	59.6	--	--
Sulfate (mg/L)	72.8	118.2	585.2	247	171.3	112.2	--	--
Sodium (mg/L)	21.2	19.0	31.5	25.8	27.8	26.9	--	--
Calcium (mg/L)	19.5	15.9	167.4	77.6	22.7	36.2	--	--
Magnesium (mg/L)	11.3	19.1	231.5	34.5	24.5	4.6	--	--

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-123	S-124	S-125	S-126	S-127	S-128	S-129	S-130
Sample Location	SAMPLE	SAMPLE	SAMPLE	SAMPLE	IH X-2	IH X-2	IH X-2	IH X-2
Depth (ft)	DESTROYED	DESTROYED	DESTROYED	DESTROYED	12-14.5	12-14.5	12-14.5	17-19.5
Hours eq.					≥2	≥2	≥2	≥2
Water/Sediment					32:1	16:1	8:1	32:1
Other Treat.					--	--	--	--
pH					--	--	--	--
Hardness (mg/L $CaCO_3$)					24.8	35.6	51.6	19.6
Total Alk (mg/L $CaCO_3$)					62.3	114.3	236.2	117.7
Sulfate (mg/L)					27	55	110	56
Sodium (mg/L)					31.1	57.4	148.6	46.6
Calcium (mg/L)					<0.1	<0.1	9.4	1.3
Magnesium (mg/L)					5.9	8.7	6.8	4.0

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-131	S-132	S-133	S-134	S-135	S-136	S-137	S-138
Sample Location	IH X-2	IH X-2	IH X-2	IH X-2	IH X-2	IH X-2	IH X-2	IH X-2
Depth (ft)	17-19.5	17-19.5	24.5-27	24.5-27	24.5-27	29.5-30.5	29.5-30.5	29.5-30.5
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	16:1	8:1	32:1	16:1	8:1	32:1	16:1	8:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	27.6	20	31.6	20.4	23.6	20.4	28.4	59.6
Total Alk (mg/L $CaCO_3$)	139.8	156.5	148.5	158.4	240	42.5	72.2	76.7
Sulfate (mg/L)	65	87	27	48	89	76	157	325
Sodium (mg/L)	63.5	90.5	51.6	76.6	122.2	42.1	78.7	141.9
Calcium (mg/L)	5.1	1.1	7.5	1.4	5.9	1.3	2.9	5.2
Magnesium (mg/L)	3.6	4.2	3.1	4.1	2.2	4.2	5.1	11.3

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-139	S-140	S-141	S-142	S-143	S-144	S-145	S-146
Sample Location	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31
Depth (ft)	36.5-38	36.5-38	36.5-38	7-9.5	7-9.5	7-9.5	12-14.5	12-14.5
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	32:1	16:1	8:1	32:1	16:1	8:1	32:1	16:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	43.6	39.6	28.4	19.2	20.4	20.4	1,436	1,458
Total Alk (mg/L $CaCO_3$)	159.9	209.6	296.2	113.9	139	171.3	46.0	49.4
Sulfate (mg/L)	131	34	69	69	128	242	1,490	1,655
Sodium (mg/L)	57.8	97.5	157.4	59.5	111.5	184.7	63.9	121.5
Calcium (mg/L)	9.3	9.3	6.9	1.5	1.4	2.3	470	481
Magnesium (mg/L)	5.0	4.0	2.7	3.8	4.1	3.6	64.0	62.7

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-147	S-148	S-149	S-150	S-151	S-152	S-153	--
Sample Location	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	--
Depth (ft)	12-18.5	17-19.5	17-19.5	47.5-49.5	47.5-49.5	47.5-49.5	47.5-49.5	--
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	--
Water/Sediment	8:1	32:1	16:1	8:1	32:1	16:1	8:1	--
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	1,726	23.2	20.8	24.4	21.2	19.6	20.4	--
Total Alk (mg/L $CaCO_3$)	76	147.7	171.3	228.6	211.2	251.4	349	--
Sulfate (mg/L)	2,140	49	152	52	20	17	27	--
Sodium (mg/L)	239.2	59.8	96.3	148.9	86.7	136.8	167.7	--
Calcium (mg/L)	530	3.5	2.3	--	2.5	< 0.1	1.7	--
Magnesium (mg/L)	98.1	3.5	3.7	5.9	3.6	4.8	3.9	--

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-154	S-155	S-163	S-164	S-165	S-166	S-167	S-175
Sample Location	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31
Depth (ft)	14.5-17	14.5-17	24.5-27	24.5-27	24.5-27	32-34.5	32-34.5	46.5-47
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	32:1	16:1	32:1	16:1	8:1	32:1	16:1	32:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	--	--	--	--	--	--	--	--
Total Alk (mg/L $CaCO_3$)	--	--	--	--	--	--	--	--
Sulfate (mg/L)	18.0	23.3	12.1	45.0	72.0	<10	27.7	<10
Sodium (mg/L)	--	--	--	--	--	--	--	--
Calcium (mg/L)	--	--	--	--	--	--	--	--
Magnesium (mg/L)	--	--	--	--	--	--	--	--

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-176	S-178	S-181	S-182	S-183	S-184	S-185	S-186
Sample Location	CONSOL 31	CONSOL 31	Ctr 380	Ctr 380	Ctr 380	Ctr 380	Ctr 380	Ctr 380
Depth (ft)	46.5-47	52-54.5	2-4.5 W	4.5-7 W	9.5-12	9.5-12	9.5-12	19.5-22
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	16:1	32:1	8:1	16:1	32:1	16:1	8:1	32:1
Other Treat.	--	--	--	--	--	--	--	--
pH	--	--	--	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	--	--	--	--	--	--	--	--
Total Alk (mg/L $CaCO_3$)	--	--	--	--	--	--	--	--
Sulfate (mg/L)	15.5	<10	<10	--	<10	<10	<10	<10
Sodium (mg/L)	--	--	--	--	--	--	--	--
Calcium (mg/L)	--	--	--	--	--	--	--	--
Magnesium (mg/L)	--	--	--	--	--	--	--	--

ANALYSES OF EXTRACTS FROM EXHAUSTIVE LEACHING EXPERIMENTS--Continued

Lab Sample #	S-187	S-188	S-189	S-190	S-191
Sample Location	Ctr 380	Ctr 380	Ctr 380	Ctr 380	Ctr 380
Depth (ft)	19.5-22	19.5-22	24.5-27	24.5-27	26.5-27
Hours eq.	≥2	≥2	≥2	≥2	≥2
Water/Sediment	16:1	8:1	32:1	16:1	8:1
Other Treat.	--	--	--	--	--
pH	--	--	--	--	--
Hardness (mg/L $CaCO_3$)	--	--	--	--	--
Total Alk (mg/L $CaCO_3$)	--	--	--	--	--
Sulfate (mg/L)	10.1	39.8	< 10	11.49	38.5
Sodium (mg/L)	--	--	--	--	--
Calcium (mg/L)	--	--	--	--	--
Magnesium (mg/L)	--	--	--	--	--

APPENDIX F

Results of Accelerated Weathering Experiments

EXPLANATION OF APPENDIX F

Accelerated Weathering Experiments

S123-S126	These four runs were performed as follows:
S123	Control Sample. Placed in excess water, dried, then no further treatment until leached (16:1)
S124	As above, but heated
S125	As above, but alternate wet/dry cycles
S126	As above, but in the presence of excess oxygen

T-prefixed samples. These were treated in one of four ways as indicated in Appendix F.

A. Control Sample. Placed in excess water, dried, then held in a vacuum dessicator.

B. Placed in excess water, dried, rewet with HCl at pH = 2 and heated to 95°C and held there for the period of the experiment.

C. As above (B), but rewet with pH = 2 HCl. Alternate wet/dry.

D. As (B), but rewet with distilled water. Alternate wet/dry.

Each experiment was 28 days with one day wet/dry cycles.

RESULTS OF ACCELERATED WEATHERING EXPERIMENTS

Lab Sample #	S123	S124	S125	S126	T-1	T-2	T-3	T-4
Sample Location	IH X-2	IH X-2	IH X-2	IH X-2	Ctr 300	Ctr 300	Ctr 300	Ctr 300
Depth (ft)	4.5-7	4.5-7	4.5-7	4.5-7	4.5-7	4.5-7	4.5-7	4.5-7
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	16:1	16:1	16:1	16:1	16:1	16:1	16:1	16:1
Other Treat.	dried	dried, heated	dried, rewet, heated	dried, rewet, O_2, heated	A*	B	C	D
pH	-	-	-	-	-	-	-	-
Hardness (mg/L $CaCO_3$)	51.2	67.2	52.4	55.2	-	-	-	-
Total Alk (mg/L $CaCO_3$)	83.9	77.5	110.5	86.6	-	-	-	-
Sulfate (mg/L)	62.8	34	6.3	6.3	<10	<10	<10	<10
Sodium (mg/L)	12.9	13.6	16.9	16.8	-	-	-	-
Calcium (mg/L)	5	51	7.1	7.6	-	-	-	-
Magnesium (mg/L)	9.4	13.2	8.4	8.0	-	-	-	-

A* See key for treatment.

RESULTS OF ACCELERATED WEATHERING EXPERIMENTS--Continued

Lab Sample #	T-9	T-10	T-11	T-12	T-17	T-18	T-19	T-20
Sample Location	IH X-2	IH X-2	IH X-2	IH X-2	CONSOL 31	CONSOL 31	CONSOL 31	CONSOL 31
Depth (ft)	4.5-7	4.5-7	4.5-7	4.5-7	2-4.5 W	2-4.5 W	2-4.5 W	2-4.5 W
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	16:1	16:1	16:1	16:1	8:1	8:1	8:1	8:1
Other Treat.	A	B	C	D	A	B	C	D
pH	-	-	-	-	-	-	-	-
Hardness (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Total Alk (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Sulfate (mg/L)	<10	colored	<10	<10	38.9	21.38	< 10	20.03
Sodium (mg/L)	-	-	-	-	-	-	-	-
Calcium (mg/L)	-	-	-	-	-	-	-	-
Magnesium (mg/L)	-	-	-	-	-	-	-	-

RESULTS OF ACCELERATED WEATHERING EXPERIMENTS--Continued

Lab Sample #	T-29	T-36	T-37	T-38	T-39	T-40	T-41
Sample Location	Ctr 300	IH X-2	IH X-2	IH X-2	CONSOL 31	CONSOL 31	CONSOL 31
Depth (ft)	4.5-7 W	4.5-7 W	4.5-7 W	4.5-7 W	2-4.5 W	2-4.5 W	2-4.5 W
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	8:1	8:1	8:1	8:1	16:1	16:1	16:1
Other Treat.	B	A	B	C	B	C	D
pH	-	-	-	-	-	-	-
Hardness (mg/L $CaCO_3$)	-	-	-	-	-	-	-
Total Alk (mg/L $CaCO_3$)	-	-	-	-	-	-	-
Sulfate (mg/L)	20.3	<10	18.9	13.5	44.6	11.4	32
Sodium (mg/L)	-	-	-	-	-	-	-
Calcium (mg/L)	-	-	-	-	-	-	-
Magnesium (mg/L)	-	-	-	-	-	-	-

APPENDIX G

Results of Leaching Under Mild Conditions (Pan Experiments)

EXPLANATION OF APPENDIX G

Pan Experiments

Mounds of soil were placed in evaporating dishes and continually rewet from the bottom of the mound as air evaporation dried them. (See figs. 28 and 29.) Four different treatments were used.

A. Soil placed in excess water, sample collected for analyses, dried, and kept in a vacuum dessicator.

B. Soil placed in excess water, sample collected for analyses, dried, mounded, rewet with distilled water.

C. As (B), but rewet with pH = 2 HCl.

D. As (B), but rewet with a mixture of groundwaters collected from the study sites.

RESULTS OF ACCELERATED WEATHERING EXPERIMENTS--Continued

Lab Sample #	T-29	T-36	T-37	T-38	T-39	T-40	T-41
Sample Location	Ctr 300	IH X-2	IH X-2	IH X-2	CONSOL 31	CONSOL 31	CONSOL 31
Depth (ft)	4.5-7 W	4.5-7 W	4.5-7 W	4.5-7 W	2-4.5 W	2-4.5 W	2-4.5 W
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	8:1	8:1	8:1	8:1	16:1	16:1	16:1
Other Treat.	B	A	B	C	B	C	D
pH	-	-	-	-	-	-	-
Hardness (mg/L $CaCO_3$)	-	-	-	-	-	-	-
Total Alk (mg/L $CaCO_3$)	-	-	-	-	-	-	-
Sulfate (mg/L)	20.3	<10	18.9	13.5	44.6	11.4	32
Sodium (mg/L)	-	-	-	-	-	-	-
Calcium (mg/L)	-	-	-	-	-	-	-
Magnesium (mg/L)	-	-	-	-	-	-	-

RESULTS OF LEACHING UNDER MILD CONDITIONS (PAN EXPERIMENTS)

Lab Sample #	T-5	T-6	T-7	T-8	T-13	T-14	T-15	T-16
Sample Location	IH X-2	IH X-2	IH X-2	IH X-2	Ctr 380	Ctr 380	Ctr 380	Ctr 380
Depth (ft)	36.5-38	36.5-38	36.5-38	36.5-38	19.5-22	19.5-22	19.5-22	19.5-22
Hours eq.	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2
Water/Sediment	16:1	16:1	16:1	16:1	8:1	8:1	8:1	8:1
Other Treat.	A	B	C	D	A	B	C	D
pH	-	-	-	-	-	-	-	-
Hardness (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Total Alk (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Sulfate (mg/L)	<10	14.6	13.3	420(5)	<10	<10	32.4	411
Sodium (mg/L)	-	-	-	-	-	-	-	-
Calcium (mg/L)	-	-	-	-	-	-	-	-
Magnesium (mg/L)	-	-	-	-	-	-	-	-

RESULTS OF LEACHING UNDER MILD CONDITIONS (PAN EXPERIMENTS)--Continued

Lab Sample #	T-21	T-22	T-23	T-24	T-25	T-26	T-27	T-28
Sample Location	CONSOL 31	CONSOL 31	Ctr 380	Ctr 380	Ctr 380	Ctr 380	IH X-2	IH X-2
Depth (ft)	14.5-17	14.5-17	34.5-37	34.5-37	34.5-37	34.5-37	29.5-30	29.5-30
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	8:1	8:1	8:1	8:1	8:1	8:1	8:1	8:1
Other Treat.	A	B+NaCl	A	B	C	D	A	B
pH	-	-	-	-	-	-	-	-
Hardness (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Total Alk (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Sulfate (mg/L)	48.6	48.6	colored	colored	colored	colored	colored	colored
Sodium (mg/L)	-	-	-	-	-	-	-	-
Calcium (mg/L)	-	-	-	-	-	-	-	-
Magnesium (mg/L)	-	-	-	-	-	-	-	-

RESULTS OF LEACHING UNDER MILD CONDITIONS (PAN EXPERIMENTS)--Continued

Lab Sample #	T-30	T-31	T-32	T-33	T-34	T-35	T-42	T-43
Sample Location	IH X-2	IH X-2	Fa 561	Fa 561	Fa 561	Fa 561	IH X-2	IH X-2
Depth (ft)	17-19.5	17-19.5	27-29.5	27-29.5	27-29.5	27-29.5	47-49.5	47-49.5
Hours eq.	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥2
Water/Sediment	8:1	8:1	8:1	8:1	8:1	8:1	16:1	16:1
Other Treat.	A	B+NaCl	A	B	C	D	A	D
pH	-	-	-	-	-	-	-	-
Hardness (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Total Alk (mg/L $CaCO_3$)	-	-	-	-	-	-	-	-
Sulfate (mg/L)	20.2	414	32.4	12.1	20.3	421	<10	366
Sodium (mg/L)	-	-	-	-	-	-	-	-
Calcium (mg/L)	-	-	-	-	-	-	-	-
Magnesium (mg/L)	-	-	-	-	-	-	-	-

RESULTS OF LEACHING UNDER MILD CONDITIONS (PAN EXPERIMENTS)--Continued

Lab Sample #	T-44	T-45
Sample Location	CONSOL 31	CONSOL 31
Depth (ft)	17-19.5	17-19.5
Hours eq.	≥ 2	≥ 2
Water/Sediment	16:1	16:1
Other Treat.	D	B
pH	-	-
Hardness (mg/L $CaCO_3$)	-	-
Total Alk (mg/L $CaCO_3$)	-	-
Sulfate (mg/L)	438	<10
Sodium (mg/L)	-	-
Calcium (mg/L)	-	-
Magnesium (mg/L)	-	-