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Hydrogeochemistry of the Upper Part of the Fort Union Group in the Gascoyne Lignite Strip-Mining Area, North Dakota

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1340

Prepared in cooperation with the
U.S. Bureau of Land Management, the
U.S. Environmental Protection Agency, and the
North Dakota Geological Survey

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By ROBERT L. HOUGHTON, DONALD C. THORSTENSON, DONALD W. FISHER, *and* GERALD H. GROENEWOLD

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CONTENTS

	Page
Abstract	1
Introduction	1
Purpose of the investigation	3
Well-numbering system	3
Acknowledgments	3
Description of the study area	4
Geologic setting	5
Pre-Tertiary stratigraphy	6
Tertiary stratigraphy	7
Quaternary deposits	7
Hydrologic regime	8
Bullion Creek-Slope aquifer system	8
Mining history	10
Stratigraphy and paleoenvironment of the Bullion Creek Formation	11
Stratigraphy	11
Depositional environments	14
Petrology and mineralogy of the Bullion Creek Formation	17
Ground-water hydrology	25
Harmon lignite aquifer	25
Basal Bullion Creek-Slope aquifer	27
Spoil-pile aquifer	34
Surface-water hydrology	37
Geochemistry of ground waters	37
Precipitation chemistry	37
Root-zone soil chemistry	40
Unsaturated-zone chemistry	43
Water quality in the unsaturated zone	45
Gases in the unsaturated zone	46
Accelerated weathering experiments	48
Saturation extracts and leachable salts	50
Cation exchange	53
Ground-water quality	54
Water quality in the Harmon lignite aquifer	56
Water quality in the confined part of the basal Bullion Creek-Slope aquifer	58
Water quality in the unconfined part of the basal Bullion Creek-Slope aquifer	62
Water quality in saturated spoils	62
Surface-water quality	65
Summary	69
References cited	71
Supplementary information	75
Supplement 1. Quality of waters in the unsaturated zone	77
Supplement 2. Water quality in the Harmon lignite aquifer	80
Supplement 3. Water quality in the confined basal Bullion Creek-Slope aquifer	86
Supplement 4. Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer	96
Supplement 5. Water quality in saturated spoils	104

ILLUSTRATIONS

	Page
FIGURE 1. Map of the Northern Great Plains coal region and location of Gascoyne area	2
2. Diagram showing system for assigning location numbers to wells and test holes	3
3. Hydrogeologic map of Gascoyne study area and vicinity	4
4. Map showing structure contours of the base of the Pierre Formation or equivalents in the Williston basin and adjacent areas in Montana, North Dakota, South Dakota, and Wyoming	5
5. Stratigraphic section *A-A'*	8
6. Regional hydrogeologic section, Gascoyne study area and vicinity, eastern Bowman and western Adams Counties, North Dakota	9
7. Generalized hydrologic flow section of the Bullion Creek-Slope aquifer system	11
8. Section showing stratigraphy of lignite beds north of the Gascoyne study area, eastern Bowman and western Adams Counties, North Dakota	12
9. Thickness map of the Harmon lignite bed of the Bullion Creek Formation	13
10. Diagram of the generalized model of the paleoenvironments of deposition, Paleocene Bullion Creek Formation	15
11. Rose diagram of flow directions inferred from sedimentary structures in the Bullion Creek Formation at Gascoyne	16
12. Diagram of the cyclical lithologic sequence in the Bullion Creek Formation penetrated in well 131-099-29BBB	18
13. Depositional-facies section *A-A'*	19
14. Diagram of principal mineral and rock-fragment components in the Bullion Creek Formation	21
15. Pie diagram of the nonopaque heavy-mineral fraction in silts of the Bullion Creek Formation at Gascoyne	22
16. Map showing the relationship of the sodium-adsorption ratio (SAR) of overbank sediments immediately overlying the Harmon lignite bed of the Bullion Creek Formation to the position of channel sands	23
17. Map of hydraulic conductivities in the Harmon lignite bed of the Bullion Creek Formation	26
18. Potentiometric map of the Harmon lignite aquifer	28
19. Map showing the relationship of tritium in water from surficial aquifers to the location of sand channels	29
20. Map of change in potentiometric head in the Harmon lignite aquifer, fall 1977-fall 1981	30
21. Graphs showing the relationship of precipitation at Hettinger, Adams County, to water levels in selected wells at Gascoyne	31
22. Graph of water storage and capacity with depth in core 131-099-28BBD, August 1981	31
23. Map depicting the hydrologic nature of the basal Bullion Creek-Slope aquifer	32
24. Map of hydraulic conductivities of the basal sandstone of the Bullion Creek Formation	33

Page

FIGURE 25. Potentiometric map of the basal Bullion Creek-Slope aquifer 35
26. Map of change in potentiometric head in the basal Bullion Creek-Slope aquifer, fall 1977-fall 1981 36
27. Map of surface-water drainage and location of monitoring sites 38
28. Diagram of the relations between major geochemical processes and water chemistry 39
29. Profile diagramming changes in dry-soil bulk density with depth 42
30. Graph showing total water storage to a depth of 8.9 feet in disturbed and undisturbed soils as related to precipitation 42
31. Diagram showing well construction needed to obtain an acceptable water-quality sample and pressure-vacuum lysimeter designs 43
32. Diagram of the nitrogen-pressure extraction system for recovering pore water from core samples 44
33. Diagram of double-chambered (filterfuge) centrifuge tube used for ultracentrifuge recovery of pore water from core samples 45
34. Diagram showing variation of solute concentrations in pore water with depth in core 130-099-03BBA 45
35. Diagram of soil-gas piezometer design 46
36. Diagram of the design of apparatus for experimental soil-leaching studies 53
37. Graph showing the variation of saturation percent and pore-water specific conductance with depth in core 130-099-03BBA 53
38. Graph showing availability of exchangeable cations and leachable salts with depth in core 130-099-03BBA 55
39. Piper diagram of water quality in the Harmon lignite aquifer 57
40. Map indicating change in the pH in the Harmon lignite aquifer, 1976-81 59
41. Map indicating change in dissolved-sulfate concentration in the Harmon lignite and spoils aquifers, 1976-81 60
42. Piper diagram of water quality in the basal Bullion Creek-Slope aquifer 61
43. Map indicating change in the sodium concentration in the basal Bullion Creek-Slope aquifer, 1976-81 63
44. Map indicating change in the dissolved-sulfate concentration of the basal Bullion Creek-Slope aquifer, 1976-81 64
45. Piper diagram of water quality in spoils 65

TABLES

Page

TABLE 1. Generalized stratigraphic section for the southern Williston basin in the vicinity of Gascoyne 6
2. Characteristics of water-bearing geologic units 10
3. Mineralogy of the Bullion Creek and Sentinel Butte Formations as determined by quantitative X-ray diffraction 20
4. Chemical characteristics of root-zone soil waters from undisturbed and disturbed spoils sites, geographic variability 40
5. Chemical characteristics of root-zone soil waters from undisturbed and disturbed spoils sites, vertical variability 41
6. Chemical characteristics of spoils and undisturbed overburden materials 41
7. Chemical and isotopic composition of root-zone soils and soil gases from the vicinity of Gascoyne 42
8. Chemical and isotopic composition of soil gases from the vicinity of Gascoyne 47
9. Composition of solutions generated during accelerated weathering experiments 49
10. Composition of saturation extracts 51
11. Composition of saturation extracts 52
12. Cation-selectivity coefficients measured for the Bullion Creek Formation 56
13. Dissolved-gas concentrations in ground water, September 1976 57
14. Saturation indices for aquifer waters with respect to naturally occurring minerals calculated by WATEQF 58
15. Quality of flowing surface waters in the study area 66
16. Quality of flowing surface waters in the study area 67
17. Quality of naturally ponded surface waters in the study area 68
18. Quality of mine holding ponds and their discharges 69
19. Summary of the observed consequences of strip mining on aquifer properties and water quality 70

SELECTED FACTORS FOR CONVERTING BETWEEN INCH-POUND UNITS AND THE INTERNATIONAL SYSTEM OF UNITS (SI)

For those readers who may prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are given below.

Multiply inch-pound unit	By	To obtain SI unit
Acre	0.4047	hectare
Cubic foot per second (ft^3/s)	0.02832	cubic meter per second
Cubic inch (in^3)	16.39	cubic centimeter
Foot (ft)	0.3048	meter
Foot per day (ft/d)	0.3048	meter per day
Foot per mile (ft/mi)	0.1894	meter per kilometer
Foot squared per day (ft^2/d)	0.0929	meter squared per day
Gallon per minute (gal/min)	0.06308	liter per second
Gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter
Inch (in.)	25.40	millimeter (mm)
Micromho per centimeter at 25° Celsius (μmho/cm at 25°C)	1.000	microsiemen per centimeter at 25° Celsius
Millimho per centimeter at 25° Celsius (μmho/cm at 25°C)	1.000	millisiemen per centimeter at 25° Celsius
Mile (mi)	1.609	kilometer
Pound (lb)	453.6	gram (g)
Square mile (mi^2)	2.590	square kilometer
Ton (short)	0.9072	megagram

To convert degrees Celsius (°C) to degrees Fahrenheit (°F) use the following formula: °F = 9/5(°C)+32.

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order nets of both the United States and Canada, formerly called mean level.

Milligrams per cubic centimeter (mg/cm^3) is a unit expressing the concentration of a chemical constituent in solid material as weight (milligrams) of a chemical constituent per unit volume (cubic centimeter) of solid material.

Milligrams per liter (mg/L) is a unit expressing the concentration of a chemical constituent in solution as weight (milligrams) of solute per unit volume (liter) of water; 1 mg/L equals 1,000 micrograms per liter (μg/L).

Milliequivalents per liter (meq/L) is a unit expressing the relative concentration of a chemical constituent in solution. It is calculated by dividing concentration values expressed in milligrams per liter by the combining weight (atomic or molecular weight of ion divided by the ionic charge) of the ion in question. In equivalents, unit concentrations of all ions are chemically equivalent.

Milliequivalents per 100 grams (meq/100 g) is a unit expressing the relative concentration of a chemical constituent in a solution generated by contact with 100 grams of solid material, commonly soil.

Paste pH is the pH of the paste resulting from saturation of pulverized (<2 mm) soil or overburden with distilled water.

Saturation extract is the solution or its chemical composition resulting from saturating pulverized (<2 mm) soil or overburden with distilled water for 4 or more hours. Extract volumes depend on the volume of distilled water required to saturate the soil.

Extractable ions, in meq/100 g=(ion concentration of extract, in meq/Lx10)/(weight of sample in grams).

Soluble ions, in meq/100 g=(ion concentration of saturation extract, in milliequivalents per liter) x (saturation percentage)/1,000.

Exchangeable ions, in meq/100 g=(extractable ions, in meq/100 g) minus (soluble ions, in meq/100 g).

Saturation percentage is the weight percentage of the maximum moisture retention of pulverized (<2 mm) soil or overburden upon saturation with distilled water. One-half the saturation percentage gives an estimate of the field water capacity of unconsolidated material.

Sodium-adsorption ratio (SAR) is an expression of the relative activity of sodium ions in exchange reaction with soil and is an index of sodium or alkali hazard to the soil. It is defined as

$$SAR=\frac{Na}{\sqrt{(Ca+Mg)/2}}$$

where ionic concentrations are expressed in milliequivalents per liter.

HYDROGEOCHEMISTRY OF THE UPPER PART OF THE FORT UNION GROUP IN THE GASCOYNE LIGNITE STRIP-MINING AREA, NORTH DAKOTA

By ROBERT L. HOUGHTON[1], DONALD C. THORSTENSON[1], DONALD W. FISHER[1], and GERALD H. GROENEWOLD[2]

ABSTRACT

Hydrogeochemical investigations in the vicinity of the Gascoyne Mine in the Northern Great Plains lignite region were initiated in 1973 in response to public concern about the effects of lignite strip mining on the quantity and quality of shallow ground water. In 1974, mining of the 30-foot Harmon lignite bed in the Bullion Creek Formation of the Fort Union Group (designated Tongue River Member of the Fort Union Formation by the U.S. Geological Survey) was increased by more than an order of magnitude, with production since then exceeding 3 million tons annually. The effect of the increased mining on the hydrogeologic system may approximate that which would result from mining an undisturbed system.

Petrologic and mineralogic analyses indicate Bullion Creek strata in the Gascoyne study area were deposited in an integrated fluvial-deltaic system on the seaward end of a broad alluvial plain. The Harmon lignite bed was deposited when the rate of clastic deposition became less than that of basin subsidence.

The Harmon lignite bed is a local aquifer supplying water to livestock and domestic wells in the Gascoyne area. The lignite aquifer is recharged mainly by local precipitation and discharges mainly to the underlying basal Bullion Creek–Slope aquifer (designated basal Tongue River–upper Ludlow aquifer by the U.S. Geological Survey), which is confined by the lignite underclay. The basal Bullion Creek–Slope aquifer is developed in Fort Union sands and locally discharges to the principal surface-water drainage system in the area, Buffalo Creek and its tributaries. The sandstone aquifer is recharged by leakage from the overlying lignite aquifer.

Because recharge to both aquifers is dominated by precipitation, the quality of shallow ground waters is controlled mainly by chemical processes occurring in the unsaturated zone. Laboratory experiments with natural-aquifer sediments and waters and equilibrium geochemical modeling indicate the controlling processes are: Dissolution of soil gases generated by oxidation of organic compounds; oxidation of iron sulfide minerals; dissolution of carbonate minerals; precipitation and dissolution of gypsum; cation exchange on clay minerals and cation exchange and adsorption on lignitic materials in the unsaturated zone; and cation exchange, sulfate reduction, and calcite precipitation within the aquifer. Most of these reactions occur in the natural environment but are accelerated by mine disturbances. Because oxidation of reactable iron sulfides to sulfate salts proceeds to completion during the overburden-stripping process itself, the effects of this process on aquifer water quality cannot be alleviated by any reclamation activity. Selective replacement of near-surface overburden above the water table, however, can decrease the introduction of soluble salts into postmining aquifers.

Dewatering of the lignite aquifer within the mine to facilitate stripping has produced a large cone of depression centered on the mine in the lignite aquifer and the underlying sandstone aquifer. Although the cone of depression extends only 2 to 3 miles beyond the mine boundaries, water levels in the lignite aquifer in the mine area have been declining at a rate of 2.5 feet per year and in the sandstone aquifer by about 1.5 feet per year. Parts of the lignite aquifer removed by mining are reestablished in rubble zones at the base of spoil piles. As compaction of the spoils occurs, the ability of the rubble zone to conduct water will decrease. Thus postmine water in the spoils may be expected to decrease in quantity and deteriorate in quality.

[1]U.S. Geological Survey
[2]North Dakota Geological Survey

INTRODUCTION

The increasing demand for energy in the United States at a time when traditional petroleum resources are becoming depleted or politically inaccessible is resulting in increased dependence on coal as a fuel. Much of the accelerated coal production is occurring in North Dakota and elsewhere in the Northern Great Plains coal region, where relatively low-sulfur lignite reserves are extensive (fig. 1). Simultaneous demands for increasing surface-mining activity, agricultural production, and urban development are placing ever-increasing strains on the land and water resources of the region. Consequently, there is a need to determine how conflicting land- and water-use demands can be reconciled in both an economically and environmentally acceptable manner. Investigations of the environmental effects of surface mining have begun to provide the data base required to make land-use decisions, but failure to understand the geochemistry of water-rock interactions may seriously limit the options for future coal development in the Northern Great Plains coal region.

Hydrologic concerns associated with lignite strip mining in the Northern Great Plains coal region center around two questions:

(1) What will be the effect on ground-water resources of disrupting shallow, currently used lignite aquifers and replacing the lignite with overburden (spoils) materials?

(2) What will be the effect on ground-water quality of exposing reduced sediments (including trace-

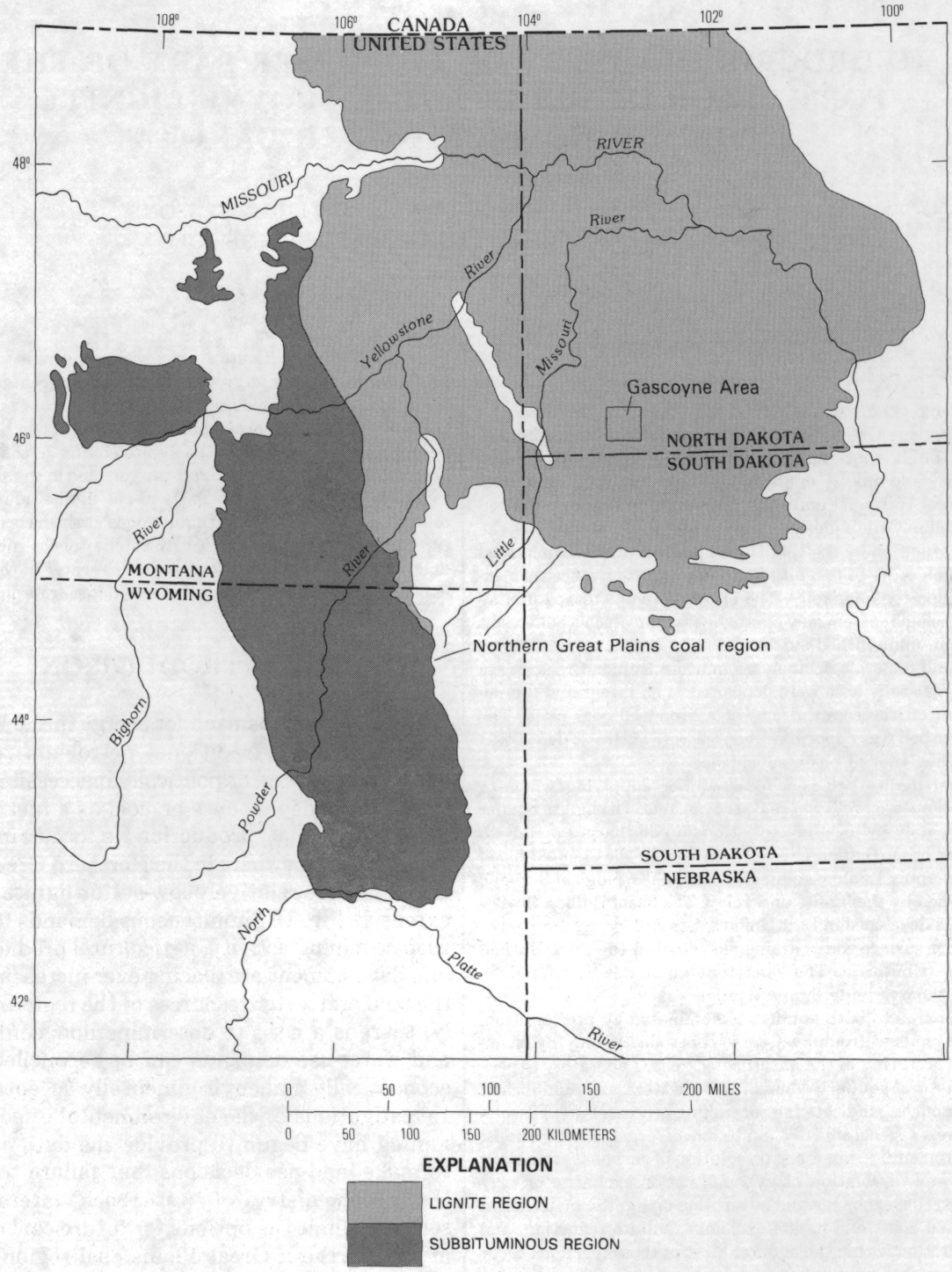


FIGURE 1.—Northern Great Plains coal region and location of Gascoyne area.

element-rich lignitic wastes) from below the water table to oxidizing conditions in the spoils?

A preliminary reconnaissance study (Ground-Water Subgroup of Water Work Group, Northern Great Plains Resource Program, 1974) and an ongoing U.S. Geological Survey research effort in southwestern North Dakota (Houghton, 1982a, b) have indicated that recent large-scale expansion of strip-mining activities at Gascoyne may indeed be affecting the water quantity and quality of the surface-water and ground-water regimes

of the area. This report presents the preliminary results of a continuing study designed to quantitatively address the second hydrologic concern above. However, hydrologic data collected throughout the duration of the study may be expected to provide answers regarding the first hydrologic concern as well.

PURPOSE OF THE INVESTIGATION

The general purpose of this investigation is to attempt to identify, measure, and evaluate hydrochemical changes that have occurred as a result of strip mining lignite near Gascoyne and identify the potential for changes in the future. Because premining data are lacking at Gascoyne, this purpose may be achieved only by identifying and modeling processes that are occurring at present and subsequently using this knowledge to attempt extrapolations to both the past and future.

WELL-NUMBERING SYSTEM

The wells and test holes referred to in this report are assigned local identifier numbers based on a system of land survey in use by the U.S. Bureau of Land Management and on a system used by the U.S. Geological Survey. The U.S. Bureau of Land Management system is illustrated in figure 2. The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. The letters A, B, C, and D are used following this numerical sequence to designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 131-099-15DAA is located in the NE¼ NE¼SE¼ of sec. 15, T. 131 N., R. 099 W. Consecutive terminal numerals are added if more than one well or test hole is recorded within a 10-acre tract.

Each well or test hole also is assigned a U.S. Geological Survey station number consisting of 15 digits. The first six digits denote the degrees, minutes, and seconds of north latitude. The next seven digits denote the degrees, minutes, and seconds of west longitude. The final two digits constitute a sequence number used to distinguish between wells within the same second of latitude and longitude. For example, well 131-099-15DAA is assigned a station number of 461007103021601, indicating it is located at 46°10′07″ north latitude and 103°02′16″ west longitude and is the first station located within 1 second of the designated latitude and longitude.

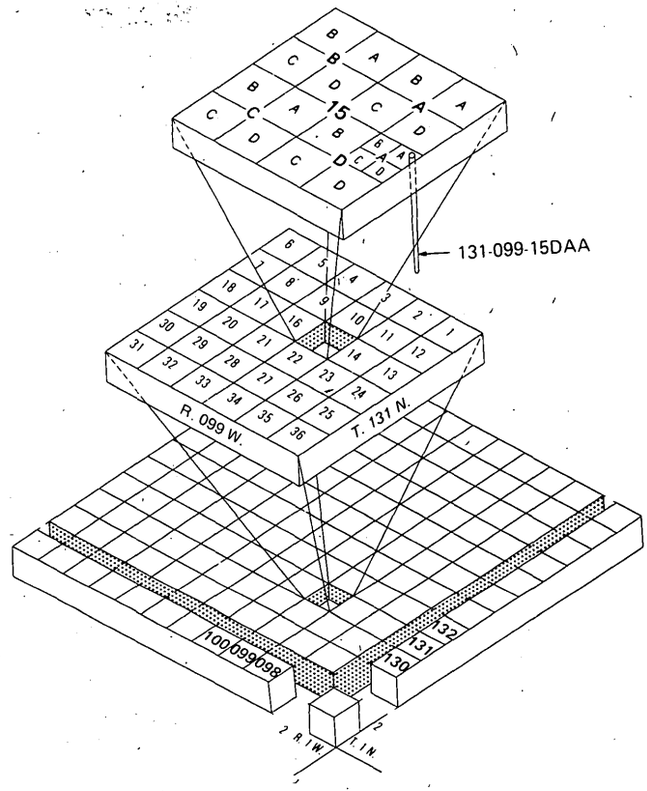


FIGURE 2.—System for assigning location numbers to wells and test holes.

ACKNOWLEDGMENTS

Geochemical studies in the Gascoyne study area were initiated by M. G. Croft (U.S. Geological Survey), who developed a preliminary quasi-three-dimensional hydrologic flow model. Throughout most of the study, investigations of unsaturated-zone hydrochemical processes have profited greatly from companion studies by two of the authors (D. C. Thorstenson and D. W. Fisher) and Herbert Haas (Southern Methodist University). Additionally, Fred Sandoval and Steve Merrill of the U.S. Agricultural Research Service's Northern Great Plains Research Center assisted in investigations of the physics of soil-water movement and provided laboratory space. The authors benefited greatly from discussions with Robert Koob (North Dakota State University), Steve Moran (Alberta Research Council), and Wayne VanVoast (Montana State Bureau of Mines and Geology). Financial support for the study was provided by the U.S. Environmental Protection Agency, the U.S. Bureau of Land Management, the North Dakota Geological Survey, and the U.S. Geological Survey. The investigation has been made possible only through the cooperation and support of the Knife River Coal Mining Company.

DESCRIPTION OF THE STUDY AREA

The Gascoyne study area consists of about 45 mi² of gently rolling grassland surrounding the Gascoyne (Peerless) Mine (fig. 3) in Bowman County, southwestern North Dakota. The area lies within the unglaciated part of the Missouri Plateau physiographic province (Fenneman, 1946). Maximum relief is about 250 ft. The climate is semiarid, and mean annual precipitation in the area is about 15 in. (Stommel, 1975).

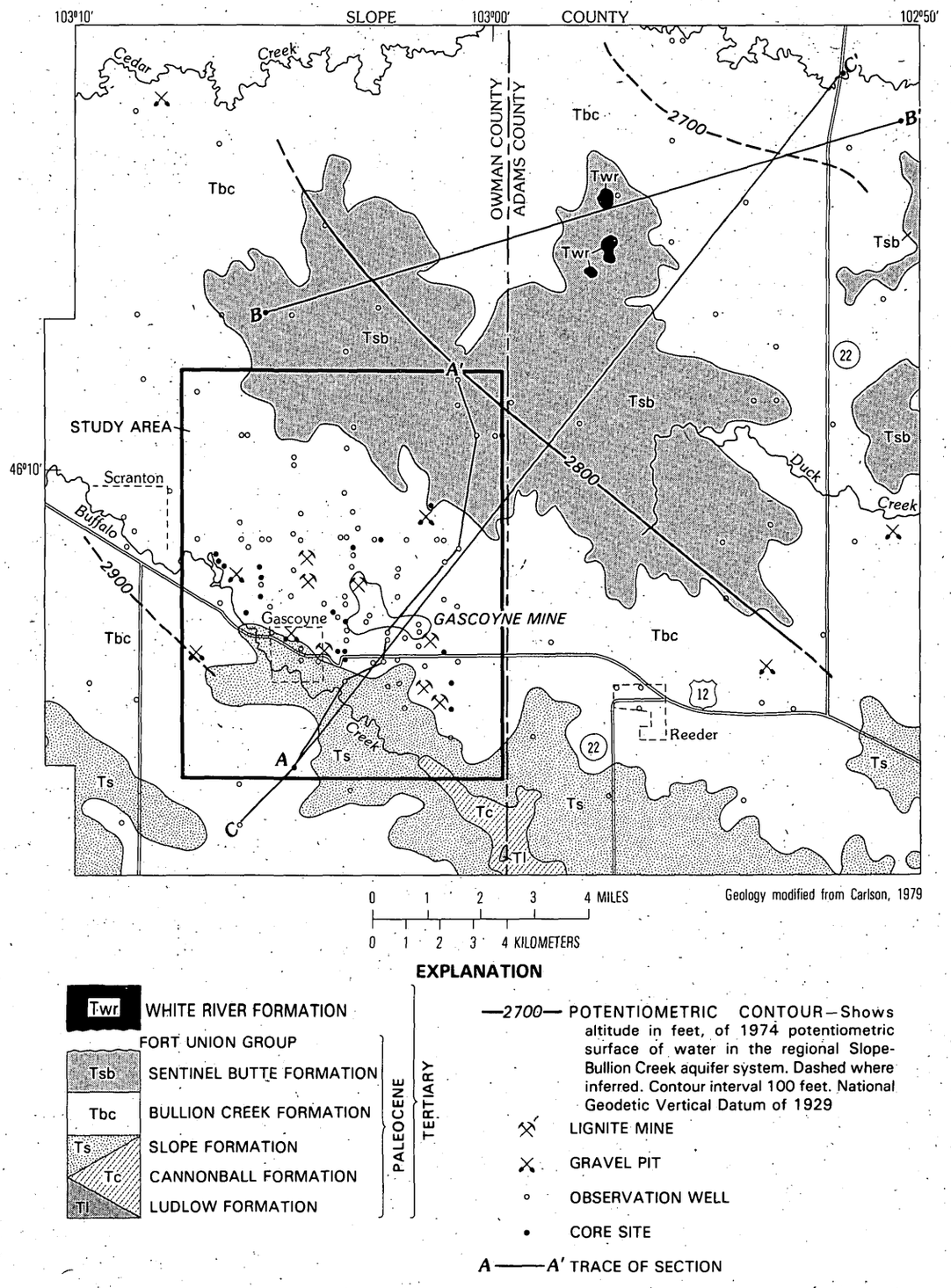


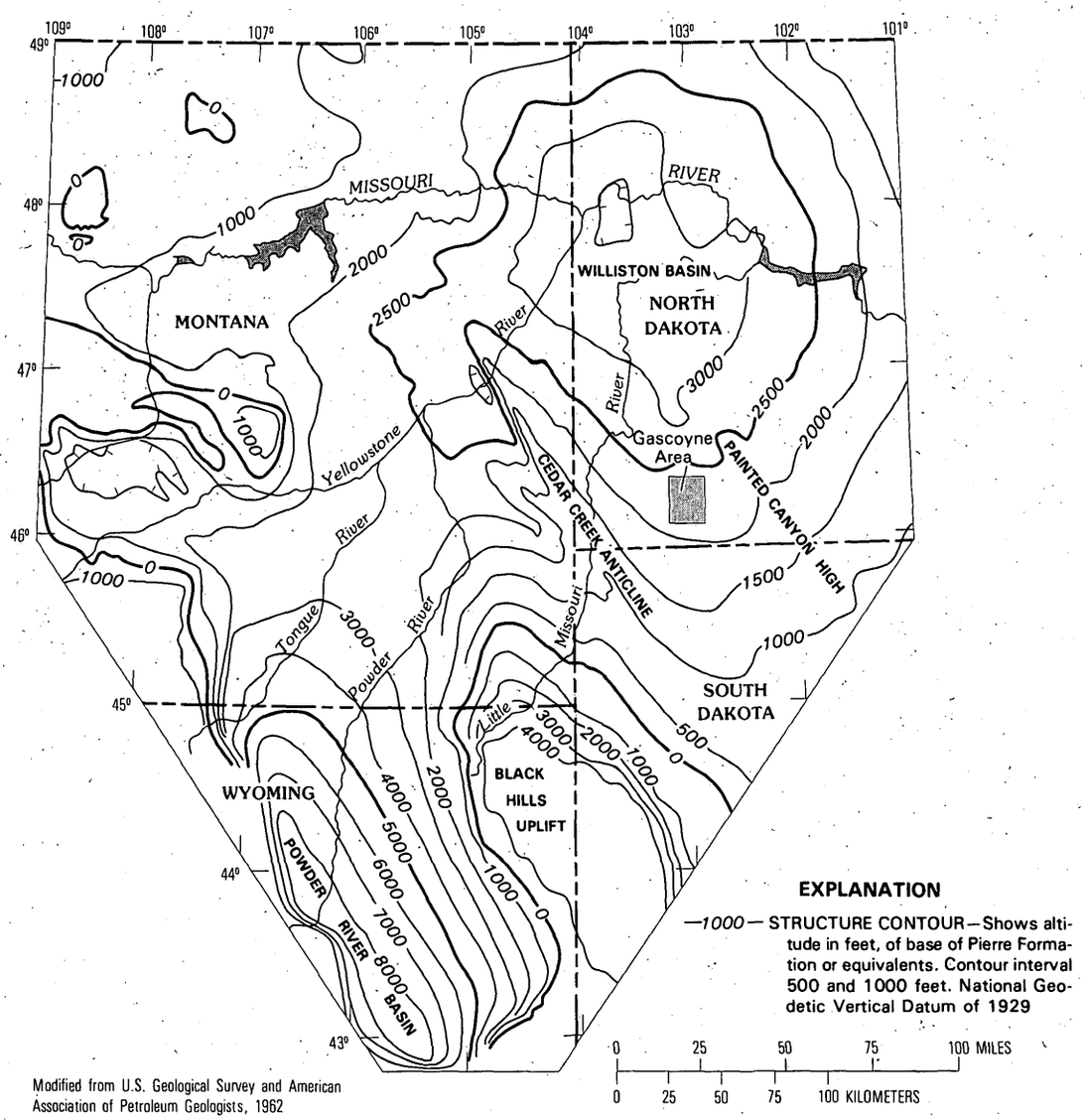
FIGURE 3.—Hydrogeologic map of Gascoyne study area and vicinity.

Principal surface-water drainage is Buffalo Creek and its tributaries, which flow southeastward to the Missouri River. The chief economic activities affecting area water quality are lignite mining and agriculture; however, petroleum exploration within the area recently has expanded and may be a factor affecting local water quality.

GEOLOGIC SETTING

The Gascoyne area is situated on the south flank of the Williston structural basin and is bounded on the southwest by the Cedar Creek anticline and on the northeast by the Painted Canyon high (fig. 4). Sedimentary strata in the area generally dip gently toward the north-northeast at about 20 to 30 ft/mi.

The Williston basin contains a nearly complete sedimentary section ranging from Cambrian to Oligocene in age (Gerhard and others, 1982). In the study area, Denson and Gill (1965) and Carlson (1979) attributed a combined thickness of about 12,000 ft to this stratigraphic succession. During Late Cretaceous and early Tertiary time, compression deformed the basin and warped the rocks into gentle northwest-trending anticlinoriums and synclinoriums, which have a secondary control on regional drainage (Carlson and Anderson, 1970). All the sedimentary rocks in the basin



Modified from U.S. Geological Survey and American Association of Petroleum Geologists, 1962

FIGURE 4.—Structure contours of the base of the Pierre Formation or equivalents in the Williston basin and adjacent areas in Montana, North Dakota, South Dakota, and Wyoming.

TABLE 1.—*Generalized stratigraphic section for the southern Williston basin in the vicinity of Gascoyne*

(Modified from Denson and Gill, 1965; J. A. Peterson, U.S. Geological Survey, written commun., 1976; Carlson, 1979)

[The nomenclature used is that of the North Dakota Geological Survey. Where the usage of the U.S. Geological Survey differs from this nomenclature, the usage of the U.S. Geological Survey is shown in parentheses]

Era (era-them)	System (series)	Sequence (unrecognized division)	Group	Formation	Thickness (feet)	Lithologic characteristics
Cenozoic	Quaternary (Holocene and Pleistocene)			Alluvium	0-30	Silt, sand, and gravel in dunes, terraces, and alluvial fans along main stream channels.
			Unconformity			
	Tertiary (Oligocene)	Tejas	White River	Brule (White River Formation, upper part) Chadron (White River Formation, lower part)	0-80	Conglomerate, sand, silt, and clay.
			Unconformity			
	Tertiary (Paleocene)	Zuni	Fort Union (Fort Union Formation)	Sentinel Butte (Sentinel Butte Member)	0-250	Dark siltstone, claystone, and sandstone with numerous thin lenses of lignite.
				Bullion Creek (Tongue River Member)	0-300	Massive gray to tan sandstone, siltstone, and shale. Contains many lenticular beds of quartzite and thick persistent beds of lignite. Claystone lenses locally associated with lignites.
				Slope (Ludlow Member, upper part)	0-150	Nonmarine equivalent of the Cannonball. Poorly consolidated unbedded or thinly laminated clays, silt, and sand with minor lignite.
				Cannonball (Cannonball Member)	0-250	Marine, dark-gray and brown sandstone and shale. Contains large, limey concretions. Intertongues with the Ludlow Formation.
				Ludlow (Ludlow Member, lower part)	0-300	Gray to light-yellow-tan thick lenticular beds of lignite.
Mesozoic	Cretaceous			Hell Creek	0-500	Claystone, sandstone, and shale.
			Montana	Fox Hills (Fox Hills Sandstone)	0-200	Marine sandstone and shale.
				Pierre (Pierre Shale)	1,700-2,250	Shale.

from the Cambrian Deadwood Formation through the Paleocene Fort Union Group[3] (designated Fort Union Formation by the U.S. Geological Survey) were affected by this folding. A more complete discussion of the developmental history of the Williston basin is presented elsewhere (Houghton, 1982c).

[3]The stratigraphic nomenclature used in this report is that developed by the North Dakota Geological Survey and differs in some places from that in use by the U.S. Geological Survey. The differences are shown in table 1.

PRE-TERTIARY STRATIGRAPHY

Several thousand feet of predominantly marine sediments consisting of sandstones, shales, carbonates,

and evaporites comprise the stratigraphic section between the Precambrian basement and the Cretaceous Pierre Formation. The Pierre consists of about 1,700 to 2,250 ft of dark-gray to brownish-black fissile micaceous and bentonitic marine shale containing abundant pyrite, selenite, and siderite (Laird, 1944; Gill and Cobban, 1973). It is overlain in ascending order by the Fox Hills Formation, the Hell Creek Formation, and the Tertiary Fort Union Group, which have a maximum combined thickness in the Gascoyne area of about 1,950 ft. As the contact between the Pierre and Fox Hills generally is transitional and difficult to determine in this area (Cvancara, 1976a), both normally are assigned to the Montana Group by the North Dakota Geological Survey. The Fox Hills Formation consists of interbedded marine grayish-white to brown glauconitic sandstone and greenish-gray shale and has been studied in detail by Waage (1968), Feldman (1972), Erickson (1971, 1974), and Cvancara (1976a). The Hell Creek Formation is comprised of continental dark-gray and brown carbonaceous sandstones and shale with local lenticular lignite zones (Frye, 1969; Moore, 1976).

TERTIARY STRATIGRAPHY

The Paleocene Fort Union Group is the oldest geologic unit exposed in the Gascoyne area. It consists of about 700 ft of sandstone interbedded with siltstone, claystone, and lignite. The Fort Union has been divided in ascending order into the Ludlow, Cannonball, Slope, Bullion Creek, and Sentinel Butte Formations (Carlson, 1979).

The Ludlow (Moore, 1976), Cannonball (Lloyd and Hares, 1915; Cvancara, 1976b), and Slope (Clayton and others, 1977) Formations are exposed in Buffalo Creek valley on the southern edge of the study area (fig. 3). The Bullion Creek Formation (Clayton and others, 1977), called the Tongue River Member of the Fort Union Formation by the U.S. Geological Survey, crops out in most of the study area but is overlain in the hills on the northern edge of the study area by sands of the Sentinel Butte Formation (Royse, 1971; Jacob 1975).

This stratigraphic sequence in the Gascoyne area is complicated by intertonguing of the Ludlow and Cannonball Formations (fig. 5). In Buffalo Creek valley, the carbonaceous sandstones and shales of the Ludlow Formation are extensively interfingered with marine shales of the Cannonball Formation. Where the Cannonball is absent, the Ludlow is unconformably overlain by the T-Cross lignite, which is basal to the Slope Formation. Interfingering of the Ludlow and Slope Formations in parts of Bowman County was considered likely by Carlson (1979), but their lithologies are too similar to differentiate formational lithosomes in the Gascoyne area.

The Bullion Creek and Sentinel Butte Formations contain the only strippable lignite reserves in the study area (Lewis, 1979). The Bullion Creek Formation consists of distinctive light-gray to buff alternating sequences of massive tan sandstone, siltstone, shale, and lignite. The most important of these lignite beds in the study area is the 30-ft Harmon lignite bed, situated about 60 ft above the base of the Bullion Creek Formation and separated from the sands of the basal Bullion Creek Formation by a lens of claystone of variable thickness. Above the Harmon, the Bullion Creek generally becomes increasingly sandy toward its contact with the overlying Sentinel Butte Formation. The HT Butte lignite is the basal unit of the Sentinel Butte Formation, which consists dominately of dark-colored silty sandstones. The formation is extensively interbedded with thin beds of lignite, which only locally are thick enough to be economically attractive.

QUATERNARY DEPOSITS

On the flood plains of Buffalo Creek and its tributaries, Pleistocene(?) and Holocene alluvium overlie the Tertiary strata. Alluvium seldom exceeds 10 ft in thickness, but restricted pockets as much as 20 ft thick have been described (Carlson, 1979). Most of this alluvium consists of dark-gray sandy silt and clay eroded from nearby older rocks. Many of the alluvial deposits support weakly developed soils of the Korchea, Savage, and Rhoades types (Opdahl and others, 1975). Generally, these soils are characterized by a thin grayish-brown A-horizon and a grayish-brown moderately permeable B-horizon of slightly alkaline loam averaging a foot thick. These soils are characteristically depleted in calcareous material.

Outside the flood plains, prairie Chernozern soils of the Amor-Reeder-Cabba association are developed on the Tertiary Fort Union to a depth that generally is less than 3 ft (Opdahl and others, 1975). These soils are characterized by a thin grayish-brown loamy A-horizon and a moderately permeable neutral or slightly alkaline B-horizon. Carbonate and sulfate deposits are common at a depth of about 2 ft.

Along the outcrop of the Harmon lignite bed, soils of the Searing and Brandenburg series are developed. They characteristically have a thin reddish-brown A-horizon; a moderately permeable neutral or slightly alkaline calcareous B-horizon that extends to a depth of several feet; and an underlying C-horizon that consists of porcellanite or scoria, a local term for baked sediment resulting from combustion of adjacent lignite.

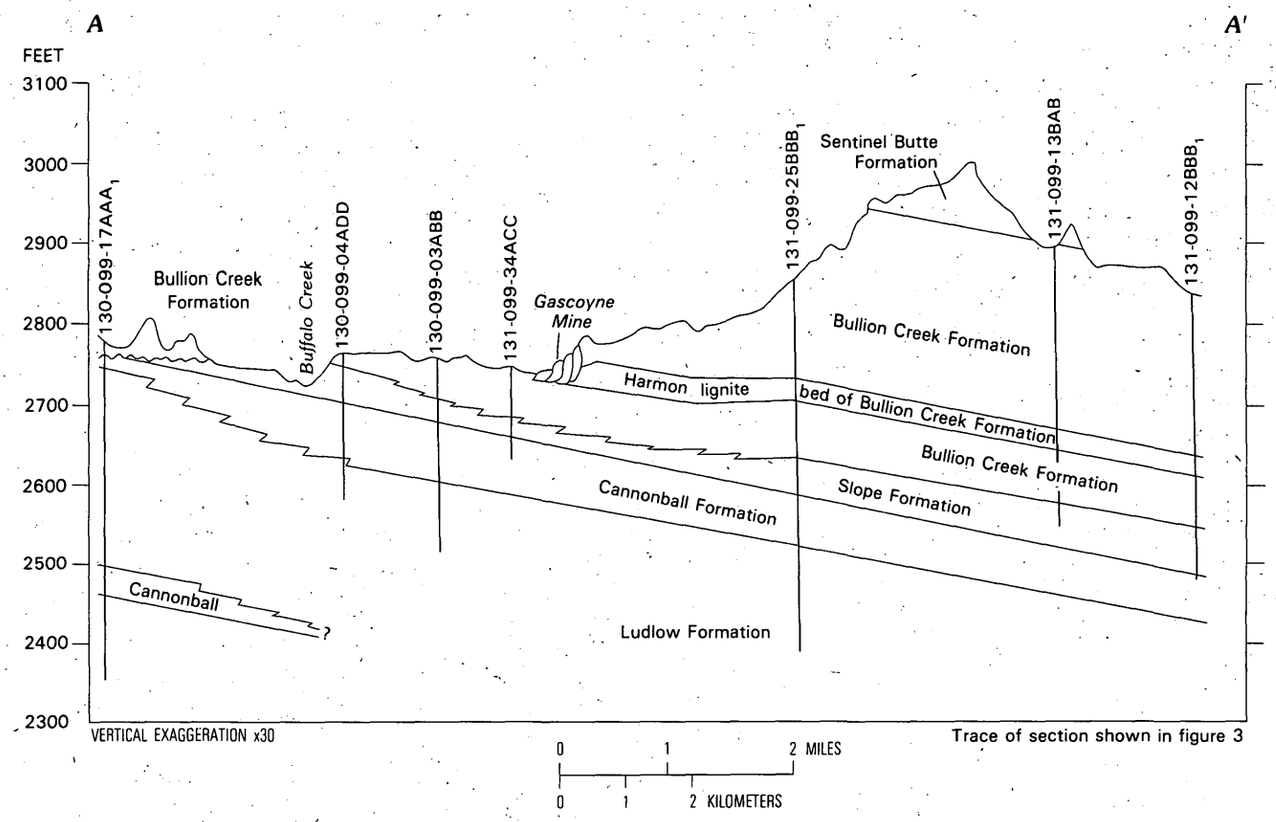


FIGURE 5.—Stratigraphic section *A-A'*.

HYDROLOGIC REGIME

The hydrologic regime of southern Williston basin strata has been a subject of interest for more than a half century. The first ground-water survey of North Dakota was prepared by Simpson in 1929. Ground-water-resource evaluations have subsequently been made for Bowman County by Croft (1974, 1978). Thorstenson and others (1979) presented a summary of hydrologic conditions determined for the Upper Cretaceous rocks of the Northern Great Plains coal region; and a site-specific administrative report on the hydrology of the Gascoyne area also has been prepared by M. G. Croft, D. W. Fisher, and D. C. Thorstenson (U.S. Geological Survey, written commun., 1979).

The strata below the Pierre Formation generally contain highly saline waters and underlie the study area at depths greater than generally is considered practical to drill for most water supplies. As the Pierre is only slightly transmissive and yields little or no water to wells, it may be considered to form the base of the fresh ground-water reservoir. Aquifers overlying the Pierre supply most of the ground water used in southwestern North Dakota (Croft, 1974, 1978).

Four regional aquifers have been identified in the area encompassing Bowman and Adams Counties (fig. 6). In ascending order of stratigraphic position, these aquifer systems are the basal Hell Creek-Fox Hills, the lower Ludlow-upper Hell Creek, the middle Ludlow, and the Bullion Creek-Slope. The characteristics of these aquifers have been discussed in detail by Croft (1978) and are summarized in table 2. For the purposes of this investigation, only aquifers of the Bullion Creek-Slope aquifer system (the upper Ludlow and Tongue River aquifer system of Croft, 1978) that are being directly disrupted by strip-mining activities or are immediately below disturbed areas are considered in detail.

BULLION CREEK-SLOPE AQUIFER SYSTEM

The Bullion Creek-Slope aquifer system of southeastern North Dakota is developed in semi-indurated medium-grained sandstones of the Bullion Creek and Slope Formations. Lignite and silty clay seams are abundant and lend considerable vertical and horizontal variation to the aquifer, which reaches a maximum thickness of 450 ft. The more extensive lignite

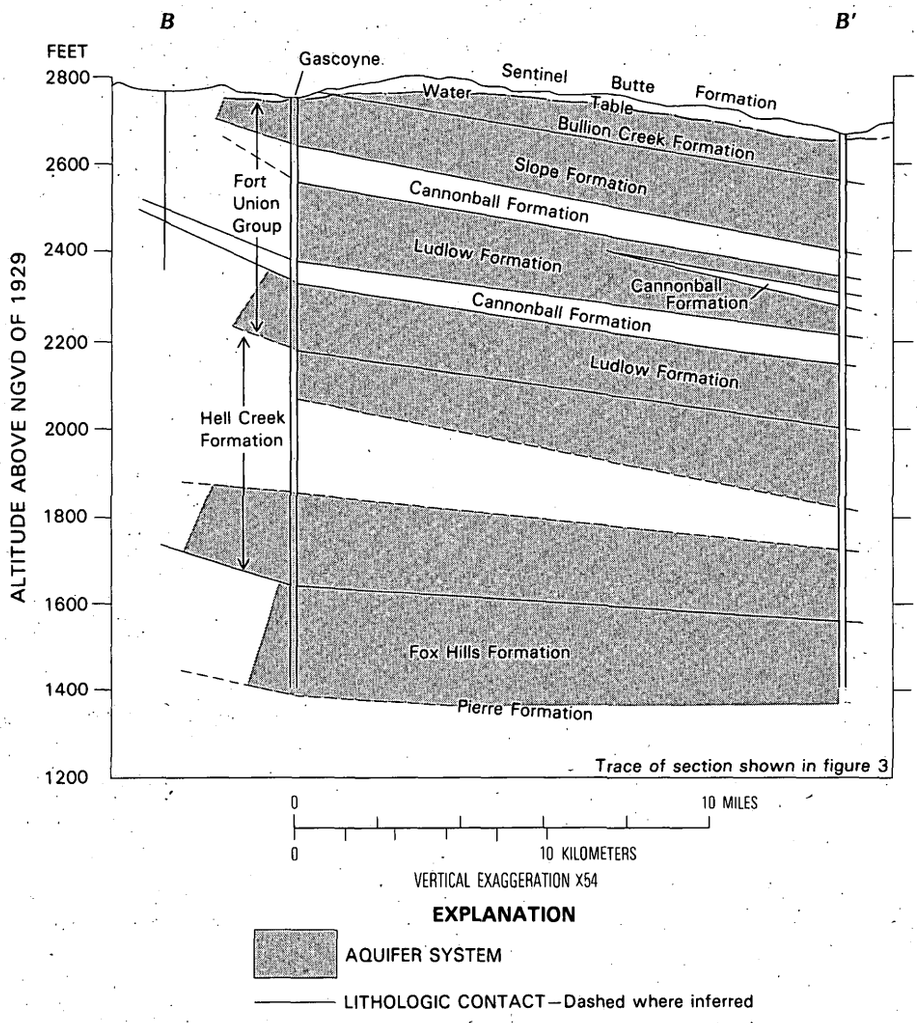


FIGURE 6.—Regional hydrogeologic section, Gascoyne study area and vicinity, eastern Bowman and western Adams Counties, North Dakota.

seams, such as the Harmon lignite bed, locally serve as important aquifers. Transmissivities are variable, dependent upon the extent and thickness of impervious lenses and the degree of fracturing in lignite seams and cemented zones within the sandstone.

The Bullion Creek-Slope aquifer system is recharged by precipitation and seepage from surface water (Croft, 1978). Regionally, discharge primarily is to the northeast in the vicinity of Cedar Creek and by seepage to underlying aquifers enroute.

In the Gascoyne area, the majority of flow in the aquifer system occurs in the basal sandstone of the Bullion Creek Formation. The Harmon lignite bed occurs about 60 ft above the base of the Bullion Creek and is separated from the basal sandstone by a gray claystone lens ranging from 1 to 48 ft in thickness. North of exposures of the Harmon lignite bed, the basal Bullion Creek-Slope aquifer is confined by this claystone; south of the lignite outcrop, it is unconfined (fig. 7).

Where the basal Bullion Creek-Slope aquifer is confined by the claystone, the overlying Harmon lignite bed constitutes a local aquifer. Compact lignite is relatively impermeable, so ground-water flow largely is restricted to fractured zones in the lignite. In the Gascoyne area, the Harmon lignite bed averages 32 ft thick, at least 20 ft of which usually is wet.

Primary recharge to the basal Bullion Creek-Slope and Harmon aquifers is from precipitation. Where confined, the basal Bullion Creek-Slope aquifer is recharged by leakage, through fractures in the confining claystone, from the Harmon lignite aquifer. In the Gascoyne study area, both aquifers discharge principally to Buffalo Creek and its tributaries (Croft, 1978).

TABLE 2.—*Characteristics of water-bearing geologic units*

[Modified from Ground-Water Subgroup of Water Work Group, Northern Great Plains Resource Program, 1974]

Group or formation	Name	Aquifer characteristics			
		Thickness (feet)	Depth (feet)	Transmissivity (ft2/d)	General water type
Fort Union Group					
Bullion Creek Formation	Bullion Creek-Slope aquifer system (includes Harmon lignite aquifer and underlying basal Bullion Creek-Slope aquifer)	60-260	10-250	0-300	Sodium sulfate to sodium bicarbonate; many water samples colored various shades of brown; dissolved solids range from 643 to 1,950 mg/L (milligrams per liter).
Slope Formation					
Cannonball Formation	Mainly confining beds	0-50	70-280	--	
Ludlow Formation	Middle Ludlow	100-200	150-400	20-200	Sodium bicarbonate; may be colored; dissolved solids range from 1,010 to 1,610 mg/L.
Cannonball Formation	Confining beds	30-50	250-460	--	
Ludlow Formation	Lower Ludlow-upper Hell Creek	260-340	430-510	250-350	Sodium bicarbonate; some samples high in sulfate and may be colored; dissolved solids range from 997 to 1,430 mg/L.
Hell Creek Formation					
	Confining beds	--	--	--	
	Basal Hell Creek Fox Hills	470	910-950	150-270	Sodium bicarbonate; most water samples are clear; dissolved solids range from 1,040 to 1,130 mg/L.
Fox Hills Formation					

MINING HISTORY

Commercial mining of lignite in the Gascoyne area became feasible upon completion of the railroad through Bowman County in 1907. By the mid-1920's, two underground mines and one strip mine in the vicinity of Scranton were operating, but all three mines went bankrupt in the depression of the early 1930's. To satisfy the energy demands of a booming industry following the end of World War II, the Helm Brothers started strip mining lignite north of the town of Gascoyne in 1946. In 1950, Montana Dakota Utilities purchased the mine and transferred operation to a wholly owned subsidiary corporation, the Knife River Coal Mining Company.

The strip mine, which was renamed the Peerless but continues to be known locally as the Gascoyne Mine, produced about 100,000 tons of lignite per year between 1951 and 1974, mainly from secs. 27, 33, 34, and 35 of T. 131 N., R. 99 W., to supply fuel requirements at thermal powerplants in Mobridge, S. Dak., and Ortonville, Minn. In 1970, the Knife River Coal Mining Company entered into a contract with the Big Stone Partners of Big Stone, S. Dak., to supply the lignite requirements (approximately 2.5 million tons per year) of a 440 megawatt plant to be constructed near that town. In January 1974, stockpiling of lignite for the plant began, and yearly production at Gascoyne was increased to approximately 3 million tons of lignite per year. Mining was expanded to include secs. 28 and 29 of T. 131 N., R. 99 W., to meet these demands.

Currently, the Gascoyne mine operates four strip-mine pits within secs. 26, 27, 28, 29, 32, 33, 34, and 35, T. 131 N., R. 99 W., mixing lignite of different sodium content from each to arrive at an optimum composition for burning. According to the company's 30-year mine plan, all lignite in secs. 26, 27, 28, 29, 33, 34, and 35 of T. 131 N., R. 99 W., eventually will be mined. The mine presently is the second largest in North Dakota; and the operator, the Knife River Coal Mining Company, claims it is the most efficient strip mine in the United States with respect to the strippable coal/overburden ratio.

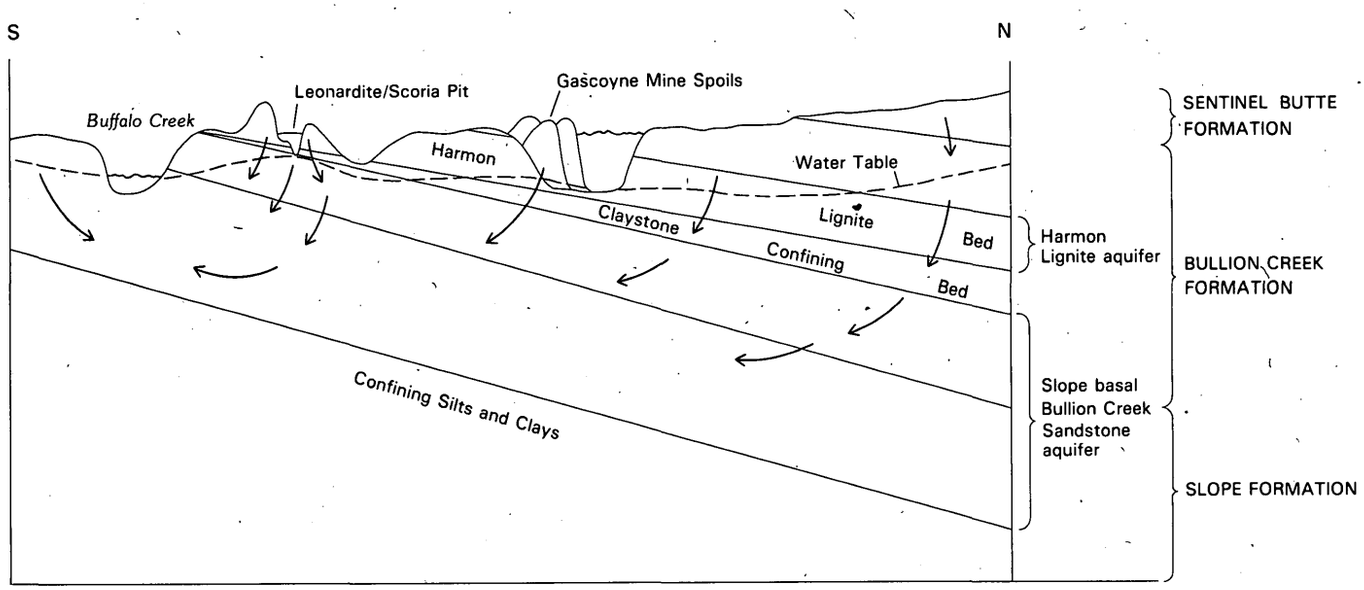


FIGURE 7.—Generalized hydrologic flow section of the Bullion Creek-Slope aquifer system. (Arrows show direction of ground-water flow.)

STRATIGRAPHY AND PALEOENVIRONMENT OF THE BULLION CREEK FORMATION

Because lithologies of the Bullion Creek Formation are highly variable in thickness and usually discontinuous, the internal stratigraphy of the formation has been poorly known, even on a local scale. Yet most current depositional models for the interval have developed from loose correlation of geographically widespread outcropping stratigraphic sections (Thom and Dobbin, 1924; Jacob, 1971, 1973; Ting, 1972; Maisano, 1975; Rehbein, 1977; Steiner, 1978; Widmayer, 1978; Flores, 1981).

High-wall maps of mine exposures collected over a 2-year period and supplemented by geophysical logs, lithologic descriptions, and drill-hole cuttings from 546 test holes and 15 core sites within the 45 mi^2 study area suggest the Bullion Creek sediments were deposited in an integrated fluvial/deltaic depositional system comprised of a distinct sequence of subenvironments. Individual mineralogic and geochemical characteristics of each lithotope appear to significantly influence local water chemistry.

STRATIGRAPHY

In the study area, the Bullion Creek Formation generally consists texturally of unbedded to finely laminated beds of clayey or sandy silt, with subordinate lenses of clay and sand common. Lignite beds serve as the principal intraformational stratigraphic horizons (fig. 8). Hares (1928), Benson (1952), and Kepferle and Culbertson (1955) recognized, in ascending order, five major lignite beds within the Tongue River Member of the Fort Union Formation (called the Bullion Creek Formation in this report)—the H, Hansen, Harmon, Garner Creek, and Meyer lignite beds. Lewis (1977, 1979) accepted this stratigraphy for lignites in the Bullion Creek Formation and recognized a small, discontinuous bed between the Harmon and Garner Creek beds he named the Local bed. Lewis also recognized the HT Butte lignite bed at the contact with the overlying Sentinel Butte Formation. However, Carlson (1979) considered the Meyer bed in Bowman County to be improperly correlated from its type locale and renamed it the Coalbank Creek bed. Carlson's nomenclature has been adopted for this report. Correlation of fossil assemblages in Fort Union coal seams indicates the lignite beds locally may be considered time equivalents (Carmichael, 1975).

In the study area, the H bed occurs about 15 ft above the base of the Bullion Creek Formation. It ranges in thickness from 2 to 4 ft and generally is clayey, grading into a carbonaceous clay along the south edge of the study area where it occurs as two 1-ft clay beds separated by 1 to 3 ft of gray silt.

The Hansen bed occurs only along the very northern edge of the study area about 25 ft above the base of the Bullion Creek. Throughout most of Bowman and Slope Counties, it apparently occurs 20 to 65 ft higher in the section (Kepferle and Culbertson, 1955). Available data from the study area are consistent with the lignite thickness map developed by Lewis (1979) for this bed,

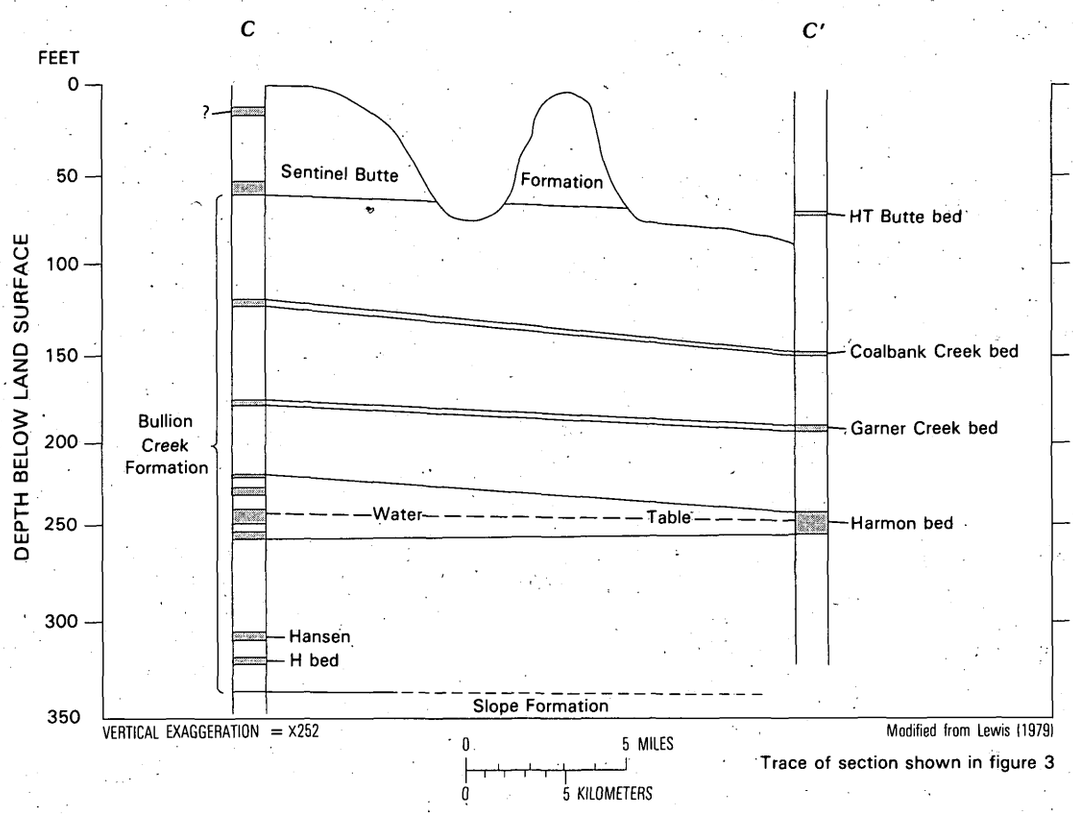


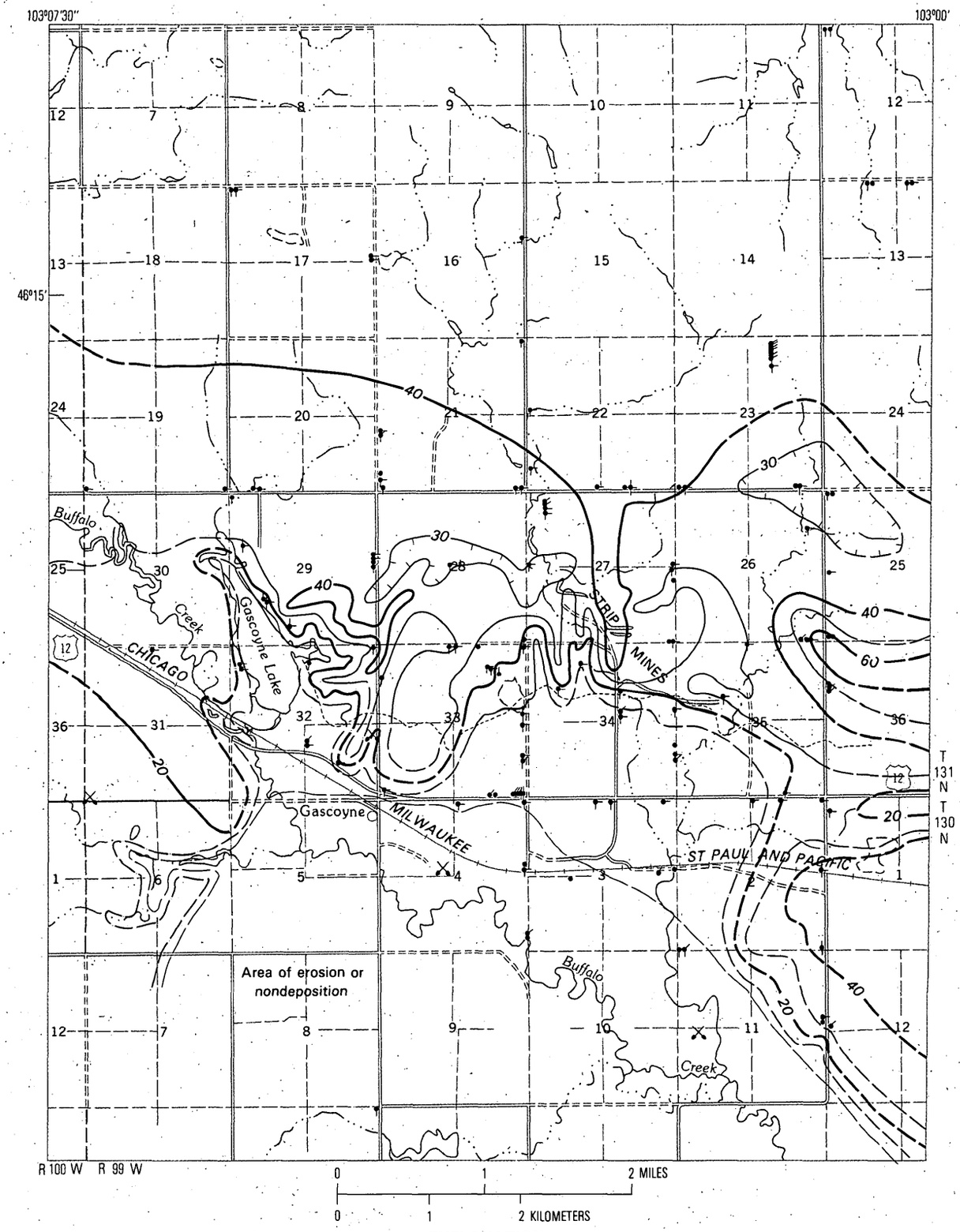
FIGURE 8.—Stratigraphy of lignite beds north of the Gascoyne study area, eastern Bowman and western Adams Counties, North Dakota. (Modified from Lewis, 1979.)

indicating it occurs as a single seam 2 to 5 ft thick. As cuttings recovered from the bed are oxidized and markedly devoid of pyrite, it seems likely that absence of the bed in most of the study area is due to removal of the unit by erosion.

This interpretation is further supported by the occurrence of a semicontinuous, 0.5- to 2-ft silcrete horizon at 20 to 30 ft above the base of the Bullion Creek over most of the southern half of the study area. The illite/feldspar ratio in the silts below the silcrete averages 2.7, 50 percent higher than maximum ratios observed in silts elsewhere in the formation and suggesting a deep-weathering origin for the horizon.

The economically most important lignite bed is the Harmon, situated about 60 ft above the base of the Bullion Creek Formation and separated from the lower sands and silts of the Bullion Creek Formation in the study area by a lens of claystone of variable thickness. The Harmon is easily identifiable in natural gamma-ray logs by its low radioactivity with respect to overlying and underlying sandstone and claystone making it an ideal marker bed. The lignite bed has been recognized in the subsurface throughout most of the Williston basin (Rehbein, 1978). Structural trends on the surface of the Harmon parallel the Cedar Creek anticline (Houghton and Davison, 1982). Lewis (1977, 1979) constructed lithology and thickness maps of the Harmon in Adams, Slope, Bowman, Billings, and Golden Valley Counties and found the bed to be generally continuous except where removed by erosion. A detailed thickness map of the Harmon lignite bed in the vicinity of Gascoyne is presented here (fig. 9).

In the study area, the Harmon lignite bed averages 30 ft thick and consists of two to three seams or splits. Leonard and others (1925) named these seams, in ascending order, the Bowman, Scranton, and I beds, but the nomenclature has not received widespread usage. For the purposes of this investigation, the seams have been designated, in ascending order, γ, β, and α—terminology that has been adopted by the Knife River Coal Mining Company. Underclays of blackjack (lignitic lithologies with too much clay or other clastic components to allow combustion) 2 to 3 ft thick are basal to each seam. Between the γ and β seams the interburden ranges from 0 to 25 ft and averages less than 2 ft in thickness. Lithologically, the interburden between the γ and β seams is very clayey and more carbonaceous than its overlying counterpart. Between the β and α seams the interburden ranges from 0 to 46 ft in thickness, averaging 6 ft, and generally is composed of gray silty clay to silt.



EXPLANATION

—20— LINE OF EQUAL THICKNESS OF THE HARMON LIGNITE BED—Long dashed where approximately located. Contour interval 10 feet

OUTCROP LINE—Top of the Harmon lignite bed

OUTCROP LINE—Base of the Harmon lignite bed

FIGURE 9.—Thickness of the Harmon lignite bed of the Bullion Creek Formation.

Adjacent to areas where the α seam has burned *in situ* and baked the overburden into scoria, a 1- to 4-ft silica-cemented horizon within the clayey silt between the β seam and the former stratigraphic position of the α seam typically occurs. Elsewhere (Houghton, 1982d), it has been hypothesized that this siliceous interval may mark a paleo-ground-water level, with excess silica being derived from diagenetic alteration of scoriaceous slag. This siliceous interval provides a locally useful bed for correlation between test holes.

The Harmon lignite bed crops out in the study area along a line subparallel to and just north of U.S. Highway 12 (fig. 9). South of the highway, the Harmon has been removed by erosion. As the claystone basal to the Harmon thins toward this outcropping, its usefulness as a stratigraphic indication south of the highway is limited.

In the northeast corner of the study area, a 4- to 13-ft lignite seam occurs 19 to 26 ft above the Harmon. Lewis (1979) correlated this bed with the Local bed of Hares (1928). Carlson (1979) considered the seam to be a local split of the Harmon.

In the vicinity of the Gascoyne Mine, a thin 1- to 2-ft bed of lignite occurs 2 to 27 ft above the Harmon. Locally the bed separates into multiple splits. Although reasonably widespread, the bed is quite erratic, thickest where the enclosing strata is clayey and generally absent where sandy. Although Lewis (1979) considered the southern depositional limit of the Garner Creek bed to be along the northern boundary of the study area, the erratic lignite bed described above appears to be continuous with lignites mapped as Garner Creek by Lewis.

Lying 24 to 62 ft above the Garner Creek, the Coalbank Creek bed occurs in the northeast corner of the study area. Its areal extent appears to roughly correspond to the line of outcropping Sentinel Butte Formation (fig. 3). The lignite bed ranges from 3 to 8 ft in thickness in the study area. Near its southern limit the bed becomes very argillaceous and separates into two carbonaceous seams each about 2 ft thick and separated by 1 to 4 ft of clayey silt.

Between the Coalbank Creek and Harmon beds, a gray silcrete commonly occurs. Although its stratigraphic relationship between the lignites is uncertain, it is apparent that the silica ledge occurs only where the Garner Creek is absent. The silcrete is best developed in sandy materials and may represent a duricrust formed on slight topographic highs within the Garner Creek swamp. Bauer (1924) described a similar silcrete from the Ekalaka lignite field of southeastern Montana. Thinning of the Garner Creek toward the silcrete subcrop supports this interpretation.

The HT Butte bed lies 60 to 80 ft above the Coalbank Creek bed and marks the stratigraphic boundary between the Bullion Creek and Sentinel Butte Formations (Royse, 1967). Its occurrence within the study area is erratic, so the bed is seldom a reliable marker for the Sentinel Butte. In the absence of the HT Butte lignite bed, the first sand overlying the Coalbank Creek bed may be taken as basal Sentinel Butte (Royse, 1968).

Within the study area, the Sentinel Butte Formation is a homogeneous dark-colored slightly silty sand occupying a drainage divide in the northern part of the study area. Comparison with Sentinel Butte exposures at Whetstone Buttes north of the study, where a complete section of 200 to 250 ft is believed present (Carlson, 1979), suggests only the basal channel sand is represented in the study area.

DEPOSITIONAL ENVIRONMENTS

Depositional modeling in intermontane basins in the Rocky Mountain region, such as in the Sand Wash Basin (Beaumont, 1979), Hanna and Carbon Basins (Glass, 1980), and Powder River Basin (Brown, 1958; Love, 1960; Weichman, 1964; Flores, 1979, 1980, 1981) has produced a regional picture of the deposition of the Fort Union Group, summarized by Weimer (1977). Coal-bearing strata throughout western North America principally are of Cretaceous and early Tertiary ages. The sediments comprising these strata were eroded mainly from Mesozoic and Paleozoic sedimentary and metamorphic rocks exposed during the Laramide orogeny. A minor volcanic component may have been introduced from the Elkhorn Mountains of Montana. Successive orogenic episodes shed an exogeosynclinal clastic wedge eastward from the Rocky Mountains to the retreating Pierre seaway. Sediment transport across the broad alluvial fan was dominated by large low-gradient meandering streams which terminated at the shorelines of fluctuating inland seas and lakes left behind by the retreating seaway.

Depositional cycles within the Williston basin were interrupted by extensional flexure of the basin's dynamic rim and tension across local antiformal structures within the basin, producing several subbasins (Maisano, 1975). Late-stage basin subsidence maintained base-level elevations within many subbasins at or near seaway level. Transitional marine environments of marshy lowlands and possible delta construction from terrestrial-fluvial systems in some subbasins to the Pierre, and later the Cannonball, seaways persisted through early Bullion Creek time (Jacob, 1976). Subsequent Fort Union strata were deposited in an alluvial system similar to those described from the intermontane basins (Royse, 1972; Groenewold and others, 1981).

Accordingly, early Tertiary depositional environments in different subbasins of the Williston centrocline could vary from marine to terrestrial. Detailed stratigraphic control within the Bullion Creek Formation in the study area permits a detailed depositional analysis of one such subbasin, that part of the southern Williston basin bounded by the Cedar Creek anticline and the Painted Canyon high. A summary of the paleoenvironment of this subbasin is presented by Houghton and Davison (1982).

Geomorphic and sedimentologic characteristics of the Bullion Creek Formation in the study area suggest fluvial channels and distributaries with bars and lags bounded by natural levees breached by crevasse splays to adjacent overbank backswamps (fig. 10). Lakes and swales in the overbank deposits and bordering uplands provide local variations.

The principal stream incising the Paleocene delta near Gascoyne was only slightly sinuous and remained relatively stationary, its location still being occupied today by the principal surface-water drainage in the area—Buffalo Creek. Multilateral channel fills volumetrically exceed overbank deposits beneath Buffalo Creek. Individual channel infill is dominated by accretion of bedload sand. Geophysical logs suggest upward fining of channel fill is poorly developed and irregular. Low relief on the basal scour surfaces of these channels and their high width/depth ratios (typically 1,000 ft/65 ft) suggest very low gradients predominated. Omikron cross-stratification and ripple marks are the principal sedimentary structures encountered. Calcite-cemented concretions elongated parallel to the long axes of these sand channels were used by Jacob (1973) to indicate flow direction in some Paleocene sands. Combined with ripple marks, these concretions suggest a generally east-southeastward flow at about 109° azimuth near Gascoyne (fig. 11).

Distributary channels intercept the principal stream from the north. The secondary channels range from sinuous in the northern half of the study area to anastomosing near their confluence with the master stream.

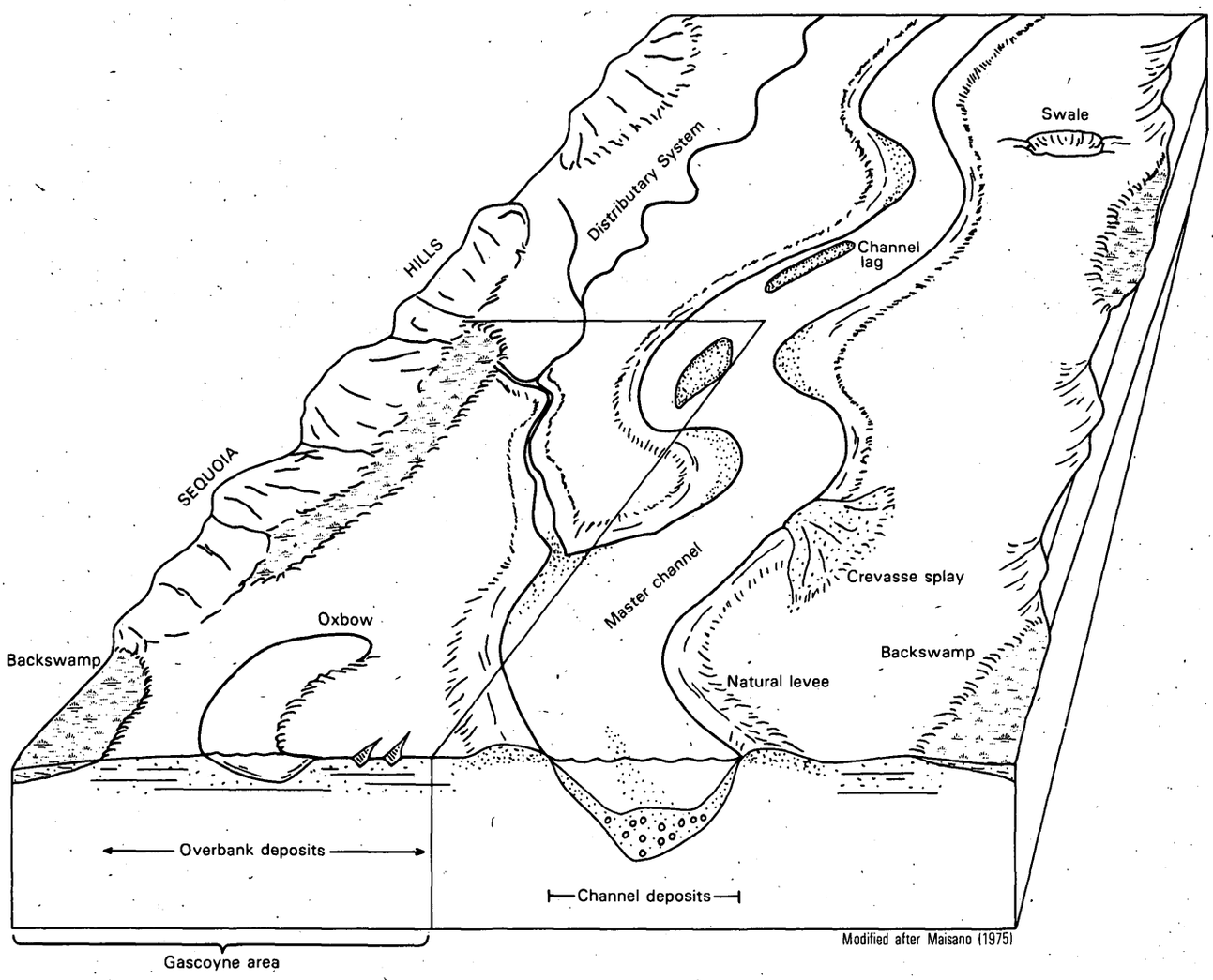


FIGURE 10.—Generalized model of the paleoenvironments of deposition, Paleocene Bullion Creek Formation.

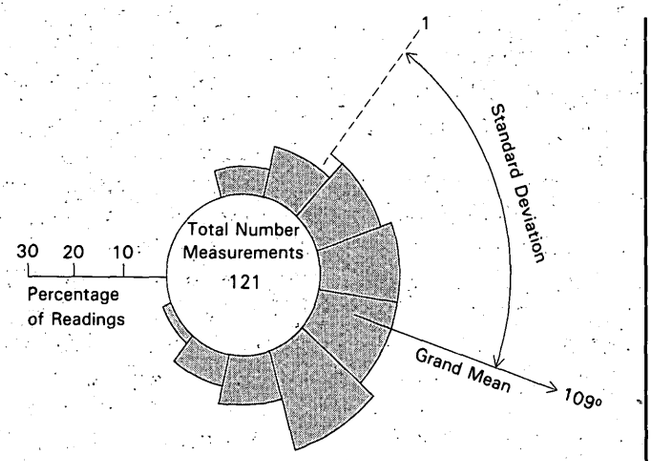


FIGURE 11.—Flow directions inferred from sedimentary structures (ripple marks and elongate concretions) in the Bullion Creek Formation at Gascoyne.

Vertically, multistory channel fills are subordinate to surrounding overbank deposits. Geophysical logs show upward fining of channel fill is well developed. Bed and bank accretion are both preserved in the mixed sand, silt, and mud infill; but point bars are the dominant depositional structure. Where only moderately sinuous, distributary channels display moderate width/depth ratios (typically 300 ft/45 ft) with high relief on their basal scour surfaces. Where braided or anastomosing, channels display lower width/depth ratios and higher scour relief; frequently multiple thalwegs prevail.

Determination of the salinity of channel waters is difficult. A single occurrence of the marine crustacean *Ophiomorpha* is not conclusive as reworking from the underlying Cannonball cannot be precluded. However, the continued presence of appreciable nontronite and sepiolite in the clay mineral fractions of the channel sands suggests strongly alkaline, hypersaline conditions in which sodium, magnesium, and silicon were the dominant cations (Millot, 1970). Diagenetic conditions in porous media should favor destruction of these clays in favor of less ordered, calcic varieties (Deer and others, 1962). Accordingly, channels must have been at least slightly brackish, perhaps transitional between the brackish Ludlow (Moore, 1976) and the freshwater Sentinel Butte (Jacob, 1976) streams. Limonite staining on most sand grains confirms the highly oxidizing nature of this porous environment.

Between distributary channel fills, flood-basin overbank deposits predominate. These gray clayey silts generally are homogeneous and only rarely varved. Reducing conditions prevailed in the flood-basin silts, as indicated by the abundance of iron chlorites and residual beidellite. Rare oxidized horizons in the otherwise homogeneous overbank silts indicate periods of desiccation were rare, indicating the study area was close to base level.

Coarse to fine silt levees separate channel fills from flood-basin deposits. The deposits generally are poorly sorted with slight horizontal lamination yielding to ripple stratification dipping to 10° away from the channel margin. Their usual yellow color, indicative of limonite staining, reveals oxidizing conditions prevailed. Limonite and goethite nodules are abundant nearest the channel walls. Successive levee deposits generally decrease in particle size upward and are underlain by reduced or only mildly oxidized silts. A similar decrease in grain size is accompanied by reduced thickness away from the channels.

The lignite beds within the study area represent two distinct depositional environments. Lignites deposited in back-basin swamps are transitional through carbonaceous clays into overbank clayey silts. Generally, these coals are irregular in distribution, occurring only in central basins between distributary channels. Lignites deposited in this environment within the study area include the H, Garner Creek, and Coalbank Creek beds of the Bullion Creek Formation, and the HT Butte bed at the base of the Sentinel Butte Formation. Backswamp coals tend to be thin (less than 5 ft thick) and relatively high in ash (9 to 12 percent) and sulfur (0.8 to 1.2 percent) contents. Woody stems still in their vertical orientations are sometimes abundant in the backswamp lignites, but much of the organic material comprising the lignites appears to have been shed from intra-drainage topographic highs. The abundance of conifer seed and leaf fossils in the backswamp lignites attests to this terrestrial input. Adjacent to the topographic highs, woody logs may comprise the bulk of the lignite.

Paleotopographic highs are indicated by radiating tributary patterns in the distributary system and eroded subsurface structural highs mantled by loamy paleosols. The abundance of petrified wood fragments in cored paleosols from these highs suggests the area was similar to the *Metasequoia* "islands" of Harr and Ting (1977). Typically, paleosols contained abundant evaporative salts such as gypsum and mirabilite, indicating a Paleocene climate in which evaporation exceeded precipitation. This suggestion is supported by the abundance of silcretes in the formation. Although extensive paleontological investigations in the Bullion Creek and Sentinel Butte Formations indicate a warm temperate climate prevailed during the interval (Sloan, 1970; Ting, 1972; Spindel, 1974), most investigators have assumed that precipitation was moderate (Brown, 1962) and exceeded evaporation (Stanley, 1965).

Thicker, more widespread lignite beds such as the Hansen and Harmon generally are uninterrupted by

distributary channels within the study area. These lignite beds were deposited when clastic deposition fell below the rate of basin subsidence, permitting broad swamps to develop across entire flood plains adjacent to principal channels (Brown, 1958; Love and others, 1963). Partings in the lignite reflect episodes of airborne volcanic ash deposition or orogenic resurgences in the clastic source area. Thus, the particulate content of flood-plain lignites is relatively low (generally less than 8 percent) and dominated by the decomposition products of airborne volcanic ash, principally beidellite and other clay minerals. The lower sulfur content (less than 0.8 percent) of the flood-plain lignites suggests fresher water was available (Mansfield and Spackman, 1965).

Within the overbank deposits in the west-central part of the study area, highly fossiliferous gravel (coquina) is found to border a freshwater limestone deposit. The laminated nature of the limestone indicates calcium carbonate precipitation was periodically interrupted. Fragile-shelled pisidium clams in the coquina indicate the gravel marks the beach of a quiet freshwater lake. Accumulation of evaporative salts in an adjacent paleosol suggests lake salinity may have been seasonally variable, perhaps altering carbonate solubilities.

Vertically, these depositional environments vary in a cyclic sequence similar to that identified by Jacob (1973) from Tongue River Member of the Fort Union Formation (Bullion Creek Formation in this report) outcrops in Adams County. Except where erosion or lateral accretion has complicated the preserved sedimentary sequence, stratigraphy in the study area consists of cycles of the following lithologic sequence: (1) Gray clay or silty clay; (2) lignite or carbonaceous clay; (3) gray to brown clayey silt; (4) yellow silt and silty sand; and (5) sand, sometimes ferruginous (fig. 12). The basal gray clays and silty clays are commonly fossiliferous and bear abundant plant remains. These clay units are interpreted as flood-basin deposits. Filling of the basins would lead to increased plant development and generally swampy conditions, resulting in formation of lignites or organic-rich shales if plant growth is retarded. Periodic extensive flooding of the basin would produce observed clayey layers (or blackjack) within the lignite. Crevassing and migration of temporary distributary channels across the basin would produce overlying clay-silt-sand sequences. The localized position of a distributary channel would be represented by clean sand deposits. Capture of the stream tributary by another channel or simply continued channel migration would result in repetition of this cycle. As channel structures apparently rarely truncate underlying strata, consistent channel migration (down-delta to the east-southeast) rather than oscillatory migration may be indicated. Recognition of this fluvial cycle in the subsurface is made possible by the upward coarsening of these strata which produces a "saw-tooth" or asymmetric "bell-shaped" pattern as described by Rehbein (1977). Use of the geophysical methods of interpreting paleoenvironment in fluvial deposits outlined by Galloway (1968), Fisher and others (1969), and Kaiser (1974) permitted development of the cross section in figure 13.

PETROLOGY AND MINERALOGY OF THE BULLION CREEK FORMATION

The petrology and mineralogy of the Bullion Creek Formation reflect the provenance, dispersal history, and postdepositional alteration of its sediments. The clastic components of all formation lithologies are subgraywackes with similar essential compositions. Silica and lesser amounts of rock fragments compose more than 75 weight percent of these rocks with accessory feldspars, micas, heavy minerals, and clay minerals comprising the remainder (table 3). These semiconsolidated strata are variably cemented by secondary carbonate, limonite, or both.

Plutonic quartz dominates the silica fraction, with little or no chert present. Most quartz grains are subangular, but a definite bimodal texture is exhibited. As all observed grains are severely damaged, pitted, or frosted, several cycles of reworking are evident.

Sedimentary rock fragments, mainly carbonates, are fairly abundant, comprising more than a quarter of the clastic fraction (fig. 14). The dolomite/calcite ratio ranges from 3:1 to 2:1. Shale inclusions, predominantly eroded from the Pierre shale (Jacob, 1975), are obvious in the sands deposited within the main channel. Volcanic rock fragments are considerably less abundant and consist principally of andesite. Metamorphic rock fragments are even more rare and consist mainly of rocks of low-grade greenschist facies. The ratio of these components indicates a supracrustal rather than plutonic source region for the Bullion Creek. Few unweathered or unaltered rock fragments occur, and most are very rounded reflecting considerable reworking. Because of their densities, rock fragments and detrital heavy minerals are common only in the higher energy environments and decrease in abundance with the mean grain size of the lithology. However, as previously noted by Fisk (1947) on the Mississippi River alluvial plain, the relative proportions of rock and heavy mineral fractions are independent of fluvial energies.

Feldspar and nonopaque heavy mineral suites similarly reflect provenance instead of local depositional environment. Potassium and plagioclase feldspars comprise up to 20 weight percent of some Fort Union

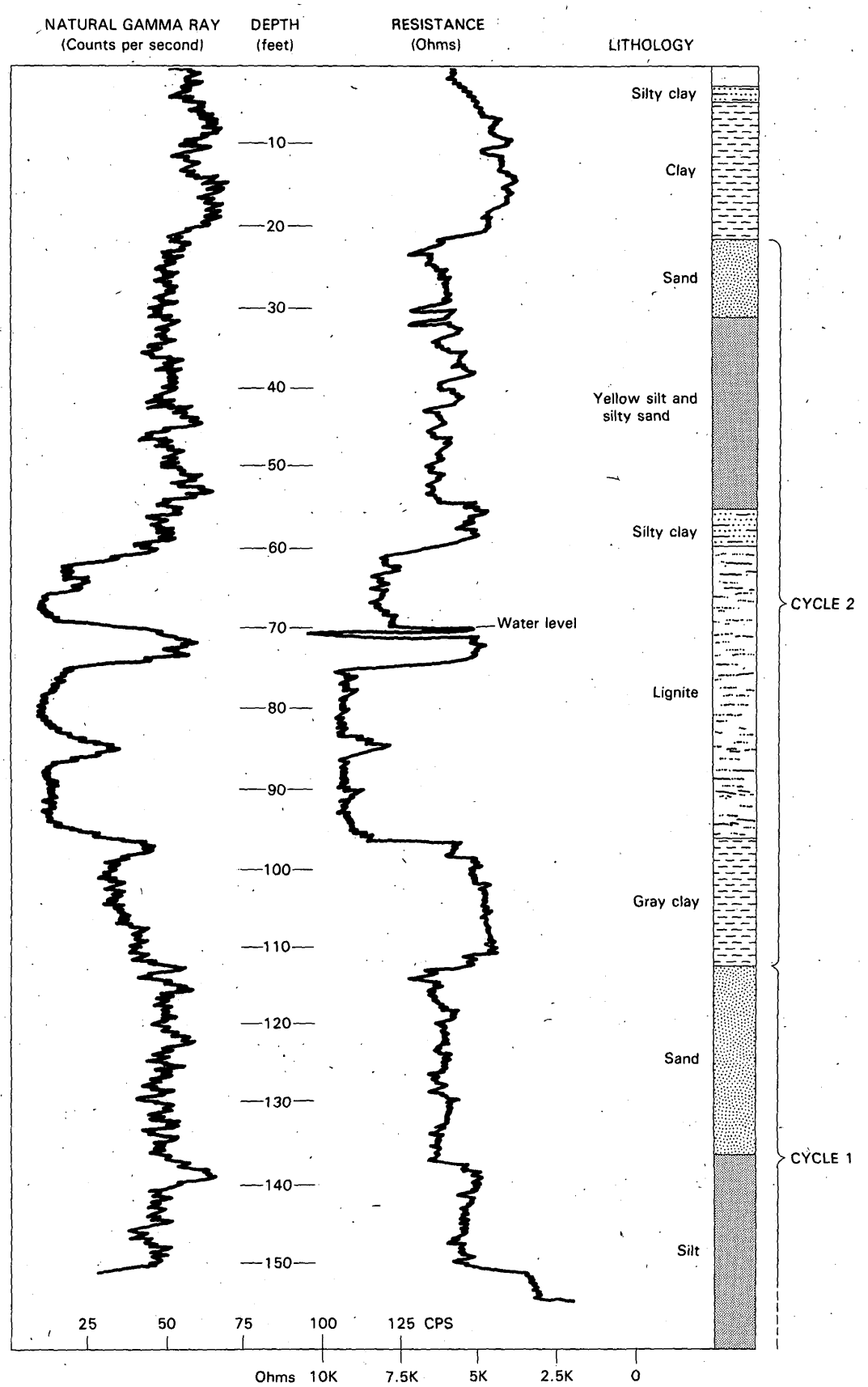


FIGURE 12.—Cyclical lithologic sequence in the Bullion Creek Formation penetrated in well 131-099-29BBB.

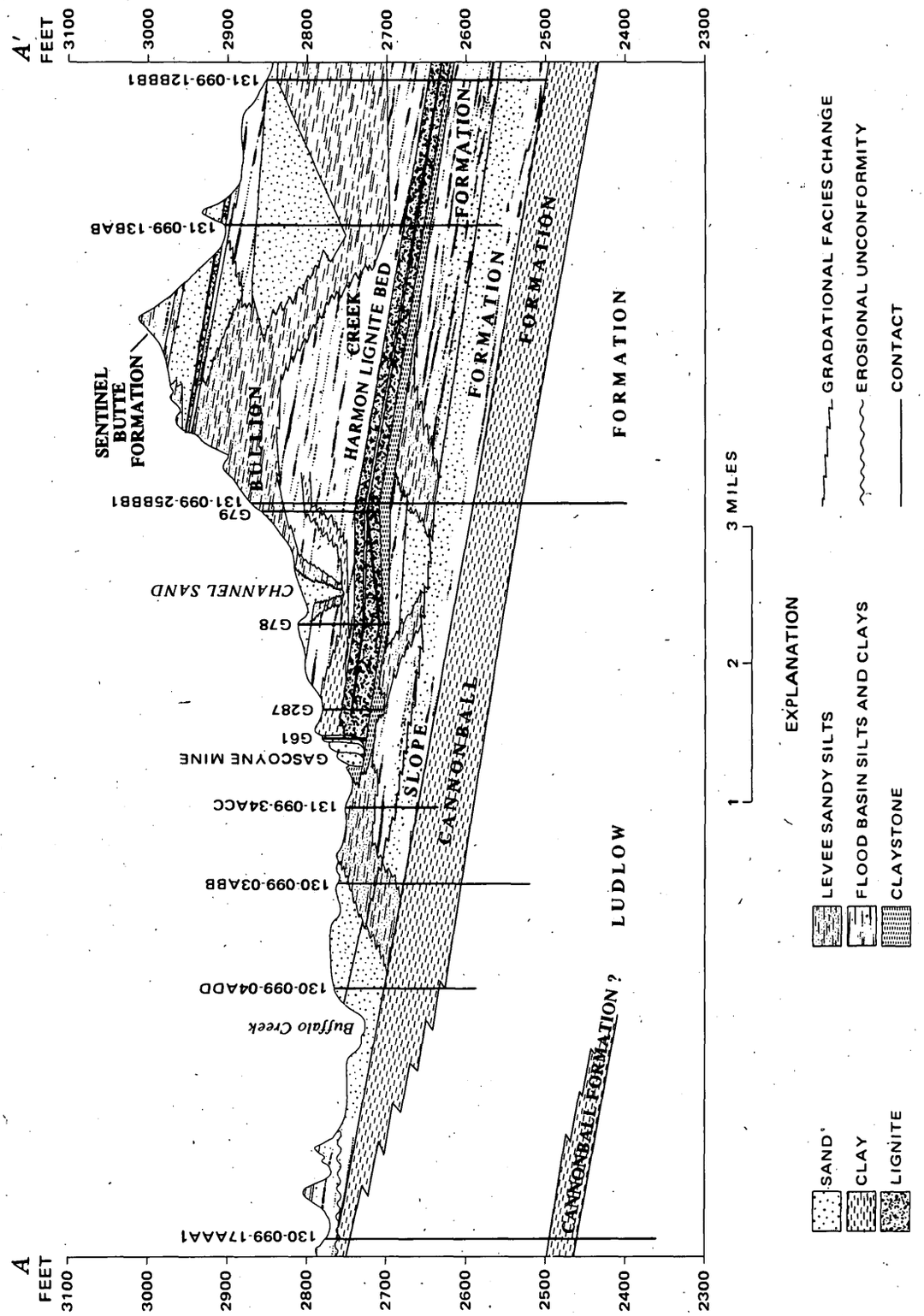


FIGURE 13.—Depositional-facies section *A-A'*.

TABLE 3.—*Mineralogy of the Bullion Creek and Sentinel Butte Formations as determined by quantitative X-ray diffraction*

[Analyses are by the U.S. Geological Survey Water Resources Division analytical laboratory and the North Dakota Geological Survey. Weight percent compositions for lignites after digestion of all organic materials in hydrogen peroxide are presented in parentheses under the column for backswamp clays. < indicates less than]

		Bullion Creek Formation								Sentinel Butte Formation			
	Backswamp clays (and lignites)		Overbank silts		Levee deposits		Channel sands		Upland highs		Channel sands		Overbank silts	
Number of samples	9 (84)		72		111		26		12		8		10	
Mineral / Weight percent	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Quartz	28 (32)	5 (13)	44	8	53	8	61	13	41	4	63	10	48	10
Potassium feldspar	3 (3)	2 (3)	4	1	11	7	13	8	6	2	8	6	5	2
Plagioclase feldspar	1 (1)	1 (1)	3	1	4	3	5	3	5	2	5	3	6	3
Calcite	0 (1)	0 (0)	7	3	2	1	1	2	9	7	2	1	5	4
Dolomite	1 (2)	1 (2)	16	5	5	3	3	2	16	0	4	2	11	6
Mica														
Muscovite	1 (trace)	1 (-)	2	2	1	1	trace	-	0	0	1	0	2	3
Biotite	- (-)	- (-)	trace	-	trace	-	trace	-	-	-	trace	-	1	0
1Md mica	2 (1)	2 (1)	-	-	-	-	-	-	-	-	-	-	-	-
Chlorite	2 (1)	2 (2)											8	4
Ripidolite	- (-)	- (-)	1	1	3	2	4	2	2	1	-	-	-	-
Diabantite	- (-)	- (-)	trace	-	2	1	2	2	1	1	-	-	-	-
Penninite	- (-)	- (-)	3	2	trace	-	-	-	-	-	-	-	-	-
Kaolinite	8 (6)	7 (6)	4	1	2	2	2	2	2	2	3	1	5	3
Illite	25 (17)	9 (4)	6	3	7	4	5	6	10	4	3	4	3	1
Smectite														
Saponite	- (-)	- (-)	trace	-	2	2	1	3	2	3	2	2	-	-
Na montmorillonite	2 (2)	2 (2)	2	1	1	1	-	-	1	1	-	-	1	2
Beidellite	0 (0)	0 (0)	trace	-	-	-	-	-	-	-	-	-	2	3
Nontronite	0 (0)	0 (0)	4	3	2	2	trace	-	1	1	trace	-	1	1
Sepiolite-palygorskite	0 (0)	0 (0)	1	1	trace	-	-	-	0	0	-	-	1	0
Pyrophyllite	3 (3)	2 (1)	-	-	-	-	-	-	-	-	-	-	-	-
Mixed-layer clay minerals	23 (12)	7 (6)	7	4	4	2	3	3	3	2	1	2	3	2
Iron sulfide minerals														
Pyrite	1 (2)	2 (2)	<1	2	0	0	0	0	-	-	-	-	<1	2
Marcasite	trace (1)	- (2)	trace	-	0	0	0	0	-	-	-	-	-	-
Gypsum	0 (0)	1 (3)	<1	2	0	0	0	0	1	2	0	1	<1	2
Mirabilite	0 (0)	0 (1)	trace	-	-	-	-	-	0	0	-	-	trace	-
Jarosite	trace (trace)	- (-)	trace	-	-	-	-	-	trace	-	-	-	trace	-
Iron oxide minerals	- (-)	- (-)	trace	-	2	1	3	3	1	2	2	3	1	1
Siderite	- (-)	- (-)	trace	-	0	0	1	1	1	2	2	1	-	-
Total	100 (84)		105		101		104		102		101		104	

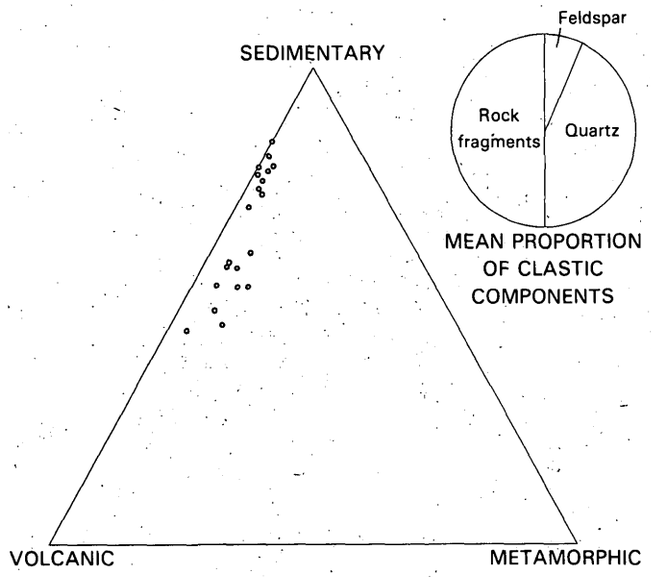


FIGURE 14.—Principal mineral and rock-fragment components in the Bullion Creek Formation.

sediments but average considerably less, reflecting the relative abundance of igneous and metamorphic rock fragments. Although Maisano (1975) found albite to be the dominant feldspar in Tongue River Member of the Fort Union Formation (now called Bullion Creek Formation) of eastern Montana and western North Dakota, albite is subsidiary to potassium feldspar in the study area and common only in association with greenschist rock fragments. The only other plagioclase present is rare andesine, associated with andesitic rock fragments. The potassium-feldspar fraction is dominated by orthoclase, but microcline and perthitic mixtures occur in some zones. Microcline and perthite were used by Love (1960) and Spindel (1974) as indicators of detritus from the Black Hills in sedimentary rocks of the Bullion Creek Formation. A Black Hills component could explain the dominance of potassium feldspars over albite in the study subbasin, when subbasins "upstream" to the west lack a significant potassium-feldspar component. Although a few fresh, discrete feldspar grains were noted, most showed signs of reworking and weathering. Grains usually were rounded and often cracked, corroded, or pitted. More than 75 percent of the feldspar grains studied were partially altered to kaolinite or chlorite. Included magnetite frequently was altered to limonite or hematite, suggesting most weathering occurred prior to deposition. Derivation from low-grade acid metamorphic terrane intruded by andesitic volcanics through multiple cycles of reworking is consistent with feldspar mineralogy.

The average total heavy mineral content of the Bullion Creek Formation in the study area is 2.19 weight percent. The nonopaque heavy mineral suite comprises 20 minerals, accounting for 50 to 80 percent of the heavy mineral component. These minerals are shown in order of frequency of occurrence and grouped by mineral stability index in figure 15. Essential minerals in the suite (those comprising more than 2 percent of the heavy mineral fraction) include chlorite, garnet, pyroxene, muscovite, epidote, zircon, iron oxides, zoisite/clinozoisite, and tourmaline. Although this suite contains a relatively large percentage of moderately stable and unstable heavy mineral varieties which might suggest a local source of primary crystalline rock (Lindberg, 1944), its composition is largely fortuitous, being controlled by the breakdown of rock fragments. The distributions of iron-rich chlorites (>4 percent Fe_2O_3), hyacinth-colored zircons, almandine garnets, and staurolite clearly are related to the distribution of greenschist metamorphic rock fragments. Similarly, prismatic zircon and apatite concentrations parallel those of volcaniclastic rock fragments.

Opaque minerals and clay minerals reflect their depositional and diagenetic environments more closely than sediment provenance. The dominant opaque minerals are oxidized and reduced forms of iron. Detrital magnetite and ilmenite concentrations closely parallel the abundance of metamorphic rock fragments and frequently are observed as inclusions in feldspar minerals. Combined, these minerals may comprise up to 8 weight percent of a sediment sample. The highest concentrations are found in point-bar or lag deposits. Very fine grained apparently authigenic magnetite deposits also occur in some overbank sediments.

Most magnetite and ilmenite grains are at least partially altered to iron hydroxyoxides. Limonite and goethite are the dominant secondary opaque minerals, often coloring entire sandy units a distinctive yellow brown. In finer overbank sediments, these alteration products generally occur as seams and lenses along joint patterns in the sediment. Hematite is common only when iron-rich sediments have been exposed near the land surface for extended periods of time. These brick-red horizons are sometimes cemented with gypsum, calcite, or both minerals into hard platy horizons above outcropping lignite seams. The occurrence of secondary iron hydroxyoxides indicates that oxidizing conditions prevailed at the time of their formation.

Reduced iron occurs in the Bullion Creek strata principally as pyrite and marcasite, totalling a maximum of 3 weight percent of the strata. However, the backswamp clays and lignites, in which most iron sulfides might be expected to have formed, display a diversity of sulfide mineral morphologies. The largest amount of pyrite in these deposits appears to exist as finely crystalline pyrite crusts coating and infilling plant impressions and other fossil debris, especially along

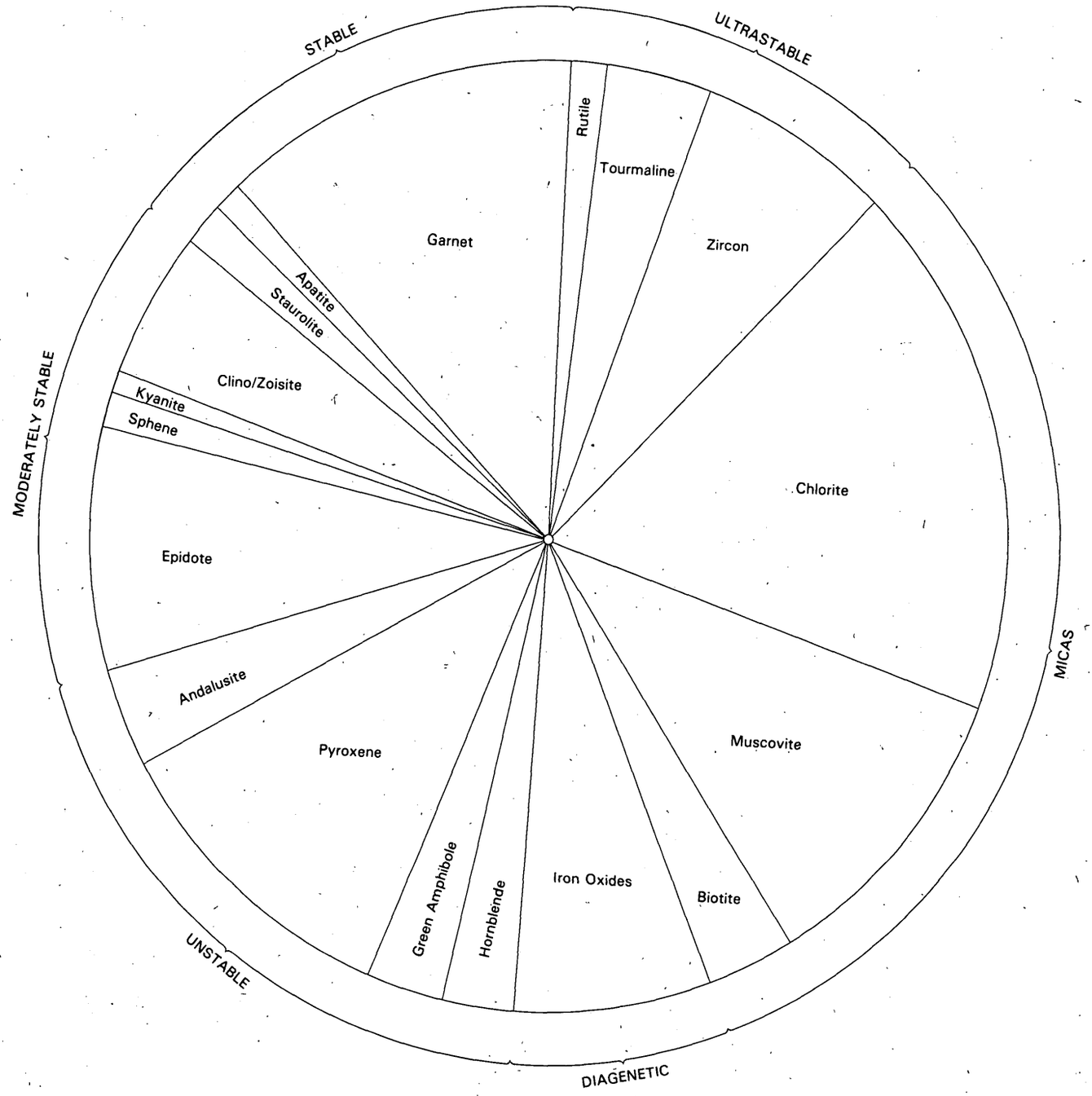


FIGURE 15.—Nonopaque heavy-mineral fraction in silts of the Bullion Creek Formation at Gascoyne. (Recalculated to 100 percent.)

laminations within the lignite. This pyrite apparently formed during decomposition of organic matter, perhaps catalyzed by bacterial action, and may reflect a significant organic sulfur contribution to the system. Disseminated throughout backswamp deposits, and especially concentrated in carbonaceous clay and blackjack deposits, are framboidal pyrite masses similar to those described by Caruccio (1970). Framboids probably owe their genesis to bacterial activity (Love and Amstutz, 1966; Richard, 1970; Javor and Mountjoy, 1976). Framboid growth is most active in high salinity environments (Czyscinski, 1975). The geographic distribution of pyrite framboids within the study area suggests the salinity of the principal stream was greater than that of tributaries. Overbank flood waters apparently increased in salinity with distance from the channel, possibly due to evaporative concentration. The apparent increase in salinity away from the channels is supported by the sodium-adsorption ratio (SAR) of saturation extracts of the sediments (fig. 16).

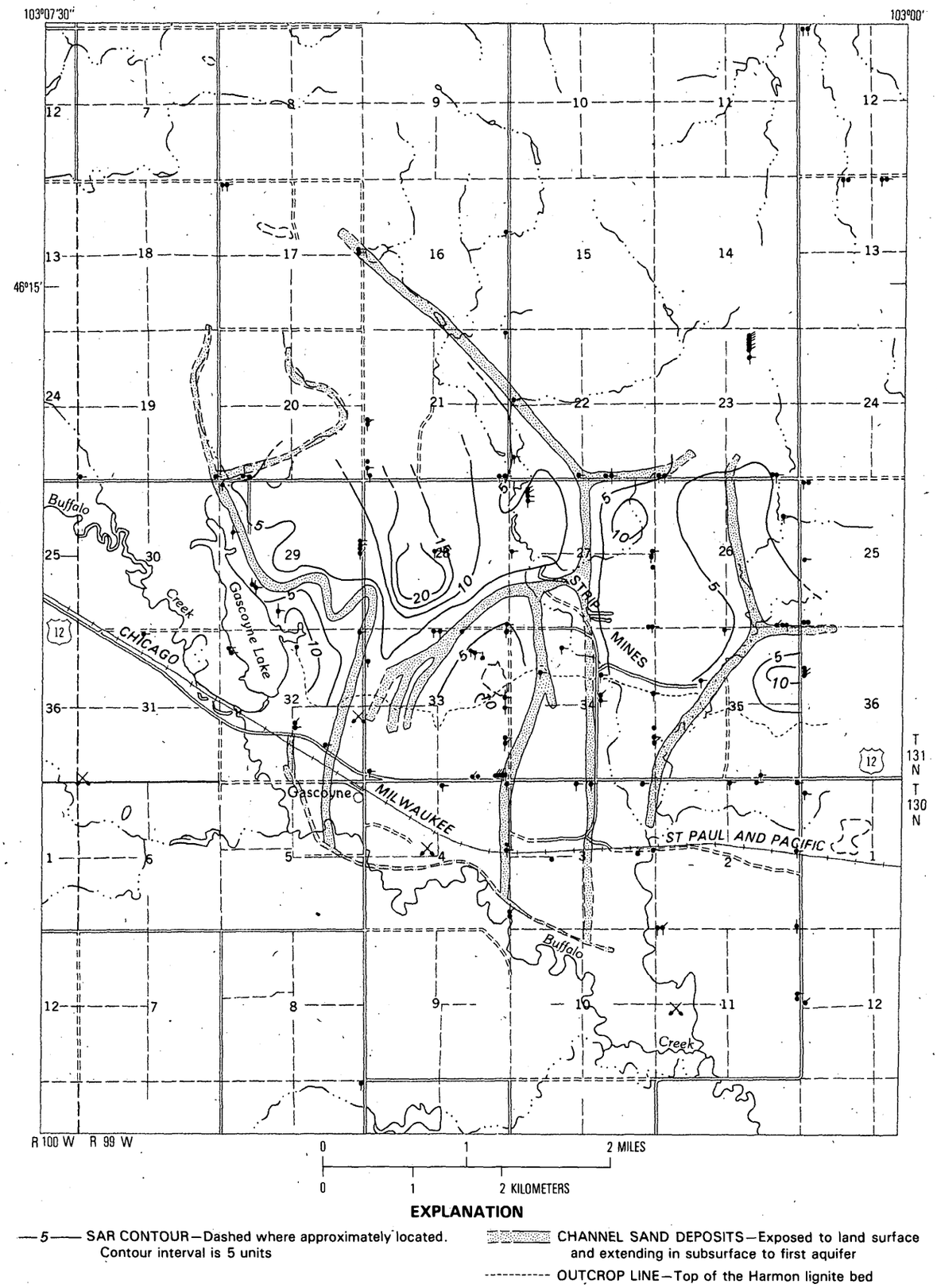


FIGURE 16.—Relationship of the sodium-adsorption ratio (SAR) of overbank sediments immediately overlying the Harmon lignite bed of the Bullion Creek Formation to the position of channel sands.

Both finely crystalline and framboidal pyrite masses appear to oxidize very rapidly in the near-surface environment. Above 10 ft in the lithologic section, these pyrite forms are always absent. When maintained in an atmosphere of water-saturated air in laboratory bowls, these pyrite forms oxidize to hydrated iron sulfates (most commonly siderotil) in less than 30 days.

Moderately to highly crystalline masses of iron sulfide range in shape from plates to cylindrical tubes to nearly perfect spheres. Within backswamp deposits most sulfide minerals of this type constitute complex rectilinear plate structures oriented along joint and fracture systems in the strata. Marcasite plates are appreciably more common than pyrite ones, indicating relatively late-stage sulfide remobilization was responsible for these minerals. Sulfide minerals of this morphology are most abundant in the 10 to 20 ft of overbank silts that most commonly overlies the backswamp deposits. Sulfide concretions commonly basal to channel deposits are probably erosional from the other environments. Lesser quantities of crystalline sulfide minerals are present throughout the section.

Fairly crystalline sulfide masses appear to require geologic time to produce significant alterations and probably represent the bulk of sulfide minerals determinable by standard X-ray diffraction techniques. Less crystalline sulfide minerals are indicated in the section only by mineral separations and total sulfur analyses. Alterable iron sulfide appears to account for only one-tenth of the sulfur content of lignite in the Harmon bed.

Clay minerals are extremely sensitive to their depositional environment. But paleoenvironmental interpretations must be made with care as diagenetic transformations cannot always be separated from authigenic clay minerals.

Clay is not abundant in the high-energy deposits of the channels. Smectites generally are absent because they may be rapidly destroyed by leaching which desaturates their cation content, commonly depleting them of silica. Iron-rich mixed-layer clays are proportionately more abundant. Ripidolite and diabantite of the chlorite group appear to be the dominant alteration products of illite and mica degradation in these sediments, indicating highly oxidizing conditions prevailed.

In the levee deposits, mixed-layer clays and chlorite are the principal clay minerals present. However, smectite degradation in the levee silts is not complete. Authigenic saponite reflects the relative abundance of dolomite and ferromagnesian minerals in the sediment which apparently supplied sufficient exchangeable cations to the system to maintain smectite stability. Saponite is a pH-sensitive smectite indicating neutral waters prevailed. It is most abundant in association with goethite-limonite-hematite minerals which probably formed as by-products of the degradation of ferromagnesian minerals in the moderately oxidizing environment of the levee deposits.

The overbank environment probably was the most active environment in the early diagenesis of the Bullion Creek Formation. Water impounded as streams flooded or as the water table rose evaporated, concentrating aqueous solutions and facilitating oxidation. Sodium montmorillonite is the principal clay mineral formed in the hydromorphic soils of the flood plain. Smectites commonly are formed by the chemical union of two or more soluble phases upon mixing of two differing water masses such as might occur when flooding channel waters encountered alkaline ground water on the flood plain. The source of the sodium cation apparently is brackish waters. Royse (1970) postulated that sodic volcanic ash introduced as airfall could have been the source of this sodium enrichment. However, the smectites comprising ash-fall zones in the Bullion Creek of the study area are relatively low sodium beidellite. Beidellite appears to have been stable in the alkaline conditions of the flood plain and shows no evidence of subsequent neotransformation which might release sodium.

Nontronite (iron smectite) is the second most abundant smectite in the overbank deposits. Nontronite formation is favored by mildly alkaline conditions in the subaerial environment, indicating the flood basin periodically was exposed to the air. The correlation of nontronite concentrations with goethite-limonite-hematite abundances indicates iron probably was near saturation in the overbank waters despite oxidizing conditions.

Smectite, by virtue of its expanding lattices, would reduce the permeability of overbank deposits when formed. Pockets of penninite chlorite and sepiolite in the overbank deposits and incised swales indicate this reduction in permeability was sufficient to initiate alkaline saturation, with silica and magnesium solubilities very high. These clay minerals are accompanied by increased secondary calcite, indicating oxidizing, hypersaline depressions periodically were freshened by flood or rain water. The disordered crystallinity of the chlorites suggests secondary transformations have occurred; however, mixed-layer clays are relatively rare, suggesting the neotransformations occurred in solutions whose compositions varied little from the original waters in which the clays were deposited.

Overbank deposits grade laterally into backswamp clays and lignites. Decomposition of organic debris in the backswamp resulted in depression of the pH of backswamp waters. The sepiolite content of overbank deposits decreases rapidly toward the backswamp, reflecting the instability of sepiolite-palygorskite silicates in acid environments. Acid leaching also affects

smectites and illites. Smectites are replaced by pyrophyllite or kaolinite and illites by polytype 1Md[4] mica in backswamp deposits.

Beidellite (ashfall) zones are almost completely replaced by kaolinite, the most stable clay mineral in the presence of acid water (Grimshaw, 1971). Kaolinite is the most abundant clay mineral in the underclays. In the lessivage zones beneath peat bogs which formed the underclays, retained acid ground water would favor fixation of aluminum under reducing conditions. In the presence of excess silica, kaolinite would be formed.

Upland highs adjacent to the backswamps are characterized by illite-rich paleosols. Illite resists diagenetic change in alkaline, poorly drained soils and is a common alteration product of detrital micas and feldspars in the Bullion Creek sediments. Calcite and mirabilite caliche zones in the soils indicate evaporation of standing water was rapid. Secondary calcite concentrations are elevated for about 30 ft below the paleosol, indicating it may have been precipitated in capillary zones just above the water table.

GROUND-WATER HYDROLOGY

Although regional flow in the Bullion Creek-Slope aquifer system of western Bowman County is to the east-northeast (fig. 3), flow within the surficial basal Bullion Creek-Slope and Harmon lignite aquifers in the study area is southwest toward Buffalo Creek (fig. 7). The exact nature of the flow reversal at depth is uncertain; but it probably occurs in the upper sands of the Slope Formation, which are isolated from the sands of the basal Bullion Creek-Slope aquifer by a clay confining bed within the study area. A preliminary ground-water-flow model of the surficial aquifers has been prepared by M. G. Croft (U.S. Geological Survey, written commun., 1979). Because the aquifers receive surficial recharge, discussions of aquifer hydrology and geochemistry will be presented in descending order.

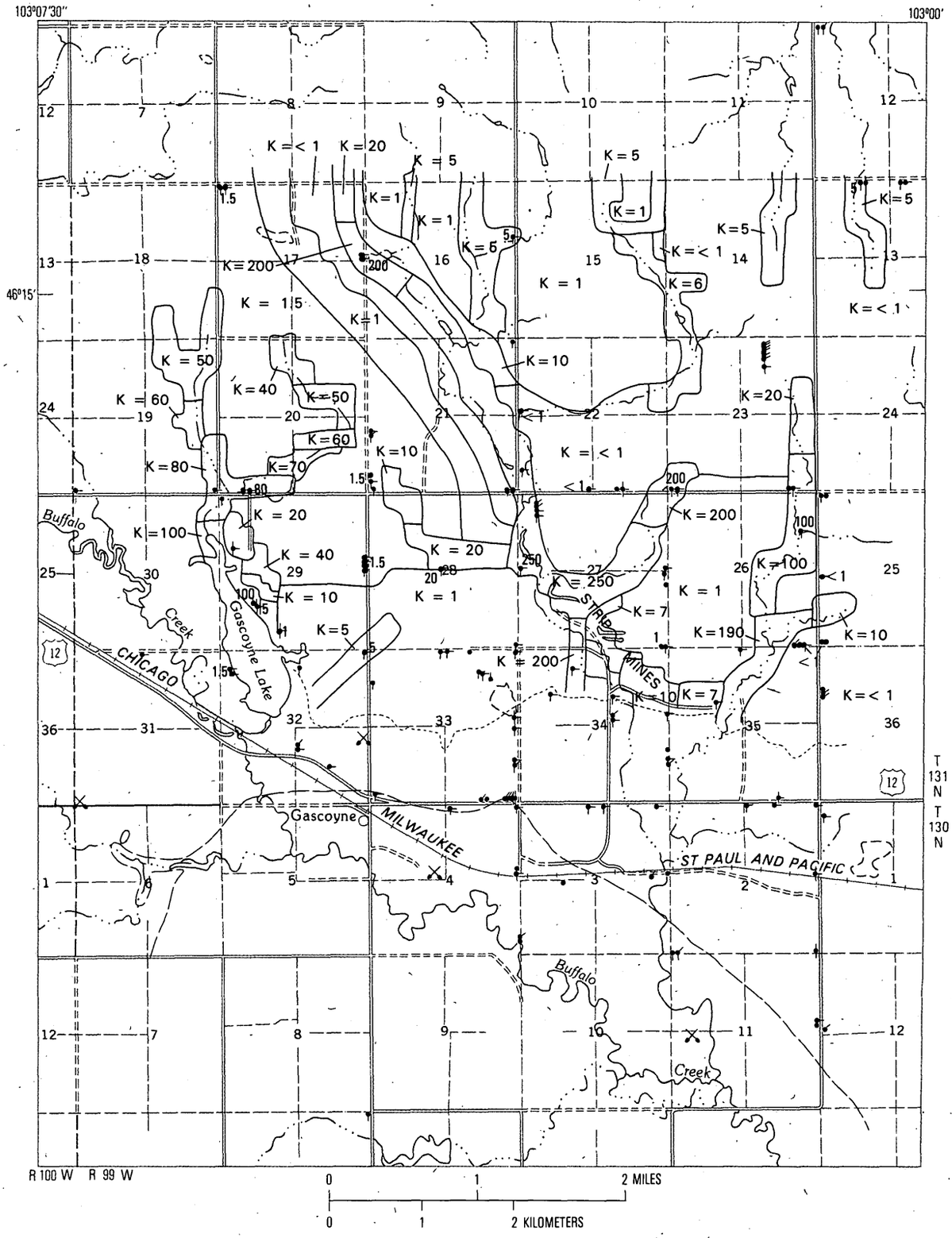
HARMON LIGNITE AQUIFER

The Harmon lignite aquifer supplies about 60 percent of the water supply for domestic and livestock use in the Gascoyne area. Within the area of active mining, the lower (γ) lignite seam is saturated, but the upper (α) seam generally is located above the water table and frequently is dry. Beneath the hills to the north, the entire Harmon lignite lies below the water table; while to the east, the water table usually lies within the middle (β) lignite seam. However, appreciable local variation may occur depending on the thickness and degree of fracturing of claystone separating the lignite seams.

Because of problems with hole stability at depth, a hole being drilled for construction of an observation well on the east side of the mine at 131-099-25CBB had to be redrilled at 10-ft spacings three times. In the first hole on the north, α and β lignite seams were dry, tight, and unfractured. The γ lignite seam, separated from β by 12 ft of claystone, was sandy and saturated. Ten feet farther south, the α lignite seam was dry, but the water table was located within the β lignite seam which was separated from the saturated γ lignite by only 4 ft of claystone. The claystone parting appeared to be highly fractured at this location. Another 10 ft farther south, only two lignite seams were present, the parting between β and γ being absent. The α lignite was saturated, whereas the combined β and γ seams were dry. The potentiometric heads in all three wells were approximately identical.

Laboratory measurements of hydraulic conductivity in the Harmon lignite aquifer range from less than 1 to more than 250 ft/d (fig. 17). The higher values for hydraulic conductivity appear to underlie sand channels in the overlying strata and may reflect fracturing of the lignite due to the water load of the sands. These values are consistent with hydraulic conductivities reported from aquifer tests in coals elsewhere (Van Voast and Hedges, 1975; Van Voast and others, 1977; Groenewold and others, 1979; Klausing, 1979). The lower hydraulic conductivities occur in unfractured parts of the lignite and are comparable to values reported by Stone and Snoeberger (1977) for unfractured subbituminous coal from a four-well aquifer test. Rehm and others (1980) determined similarly low hydraulic conductivities for other major lignite aquifers in western North Dakota. A temperature log in a well with low measured hydraulic conductivity displayed a gradient exceeding that of the underlying sandstone, consistent with its expected low permeability. Mean hydraulic conductivities of 2 to 5 ft/d appear to characterize the aquifer as a whole. Because the hydraulic conductivity of coal is controlled by fractures, anisotropy is to be expected. Observations of coal in outcrops and oriented cores in the study area indicate the presence of two principal sets of near-vertical fractures oriented at approximately N. 45° W. and N. 58° E. Erickson (1970) found lineaments in the Williston basin cluster around two directions: N. 50° E. and N. 45° W. Using a computer program prepared by Trescott, Pinder, and Larson (1976) to simulate two-dimensional ground-water flow at Gascoyne, M. G. Croft (U.S. Geological Survey, written commun., 1979) was able to simulate the 1977 potentiometric surface

[4]1Md mica is a disordered, 1-layered monoclinic mica similar to muscovite but lacking the regular symmetry of muscovite.



EXPLANATION

(K = 20) FIELD OF CONSTANT HYDRAULIC CONDUCTIVITY (K) IN FT/D DETERMINED BY NUMERICAL MODELING

•1.5 LABORATORY MEASUREMENT OF HYDRAULIC CONDUCTIVITY (K) IN FT/D

---------- OUTCROP LINE—Top of the Harmon lignite bed

——— OUTCROP LINE—Base of the Harmon lignite bed

FIGURE 17.—Hydraulic conductivities in the Harmon lignite bed of the Bullion Creek Formation.

for the Harmon lignite aquifer only by hypothesizing a hydraulic-conductivity distribution like that shown in figure 17. Croft's distribution pattern is in close agreement with laboratory measurements, and high hydraulic conductivity corridors mirror the distribution of sand channels in the overlying strata.

The potentiometric surface of the Harmon lignite aquifer slopes south toward Buffalo Creek (fig. 18). Recharge by precipitation is dominantly through the Sentinel Butte sand hills in the northern half of the study area. Additional recharge occurs through Bullion Creek channel sands where they extend from near land surface to the lignite seams. The only waters in the Harmon lignite aquifer found to contain significant amounts of tritium, indicating a component of modern waters, lie beneath the sand channels (fig. 19). Lobes persist in the potentiometric surface along the northern border of the mine. Potentiometric ridges follow channel trends, indicating recharge in these zones. Troughs in the potentiometric surface reflect the generally low vertical hydraulic conductivities of Bullion Creek silty sands which inhibit infiltration. Locally, these troughs may be influenced by seepage from the Harmon to tributaries of Buffalo Creek.

Although the general pattern of the potentiometric surface of the Harmon lignite aquifer has changed little during the last 6 years of the investigation, water levels in lignite wells in the immediate vicinity of the mine have dropped an average of 12 ft since 1977 while increasing 10 ft in the recharge area of the Sentinel Butte hills to the north (fig. 20). Since 1976, water levels in the Harmon lignite adjacent to but upgradient from mine pits have declined about 2.5 ft/yr (fig. 21). However, in the last year, water levels have changed little and may have nearly stabilized. Water levels in wells more than 2 mi away from active mining pits appear to be little changed over this interval. Pumping to dewater the lignite at the mine currently exceeds 1,000 gal/min and is believed to be the principal cause of observed water-level drops. Cessation of pumping by mine sumps locally has resulted in a sharp rise in water levels in the lignite of as much as 25 ft in 1 month's time (point C, fig. 21).

Water levels in the Harmon lignite aquifer display only dampened response to precipitation (fig. 21), suggesting infiltrating waters may require considerable time to reach the water table. Rehm and others (1980) suggested infiltrating water may require 2 to 3 years to pass through the root zone and as much as an order of magnitude longer to reach the water table. Accordingly, water storage in the unsaturated zone is appreciable as indicated by water contents measured in cores (fig. 22). Water storage below the root zone usually exceeds 40 percent of capacity. Within the root zone water storage is a function of the ratio of precipitation and evapotranspiration.

BASAL BULLION CREEK-SLOPE AQUIFER

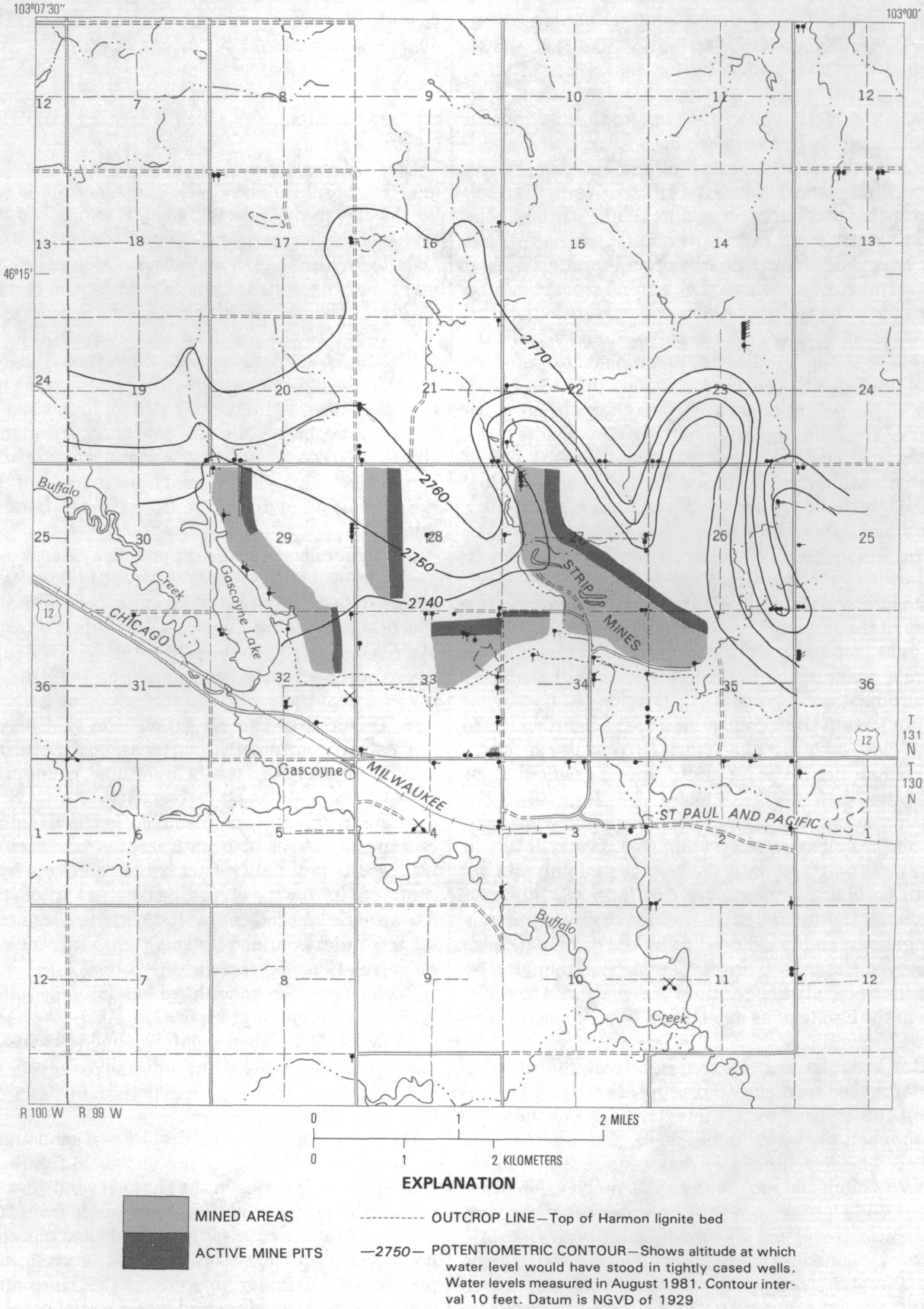
North of exposures of the Harmon lignite in the study area, the basal Bullion Creek-Slope aquifer is confined by the claystone underlying the Harmon bed (fig. 23). South of these exposures, ground water is unconfined. Detailed hydrologic interpretation along the southern margin of the mine is complicated by the transitional nature of the aquifer along the lignite outcrop.

Recharge to the confined sandstone aquifer is controlled by leakage through the claystone. Where water levels in the lignite are higher than those in the underlying sandstone aquifer, the basal Bullion Creek-Slope aquifer is recharged by the overlying Harmon lignite aquifer. Mine activities have lowered water levels in the lignite below those in the sandstone in parts of the mine area, resulting in discharge from the sandstone to the lignite.

The hydraulic properties of underclays (seat clays) are poorly known in the Northern Great Plains. Rehm and others (1980) reported hydraulic conductivities for Paleocene claystones measured by aquifer tests ranging from 8.5×10^{-4} to 9.3×10^{-5} ft/d. M. G. Croft (U.S. Geological Survey, written commun., 1979) determined that vertical hydraulic conductivities of 2.6×10^{-8} ft/d were required in the claystone lens at Gascoyne to replicate potentiometric surfaces. A laboratory consolidation test indicates a hydraulic conductivity of 1.1×10^{-7} for a single claystone cutting from the study area. As the greatest permeability in the claystone may be expected to result from fractures, regional aquifer-test results probably reflect a more accurate hydraulic conductivity for the claystone lens as a whole than the site-specific laboratory result. Water levels in the sandstone aquifer confined by this tight claystone display no correlation with precipitation (fig. 21).

Recharge to the unconfined sandstone aquifer is by direct infiltration of precipitation. As most observation wells south of the lignite outcrop line were installed in sands of the master channel or its distributary system, water levels in these wells generally mirror precipitation (fig. 21).

Hydraulic conductivities in the basal sandstone of the Bullion Creek Formation are shown in figure 24. Hydraulic conductivities in the channel sands determined by laboratory consolidation tests range from 20 to 150 ft/d (fig. 24). Water levels in wells drilled outside channel deposits display only muted correlation with precipitation, similar to wells in the Harmon lignite aquifer. A numerical ground-water model developed by



EXPLANATION

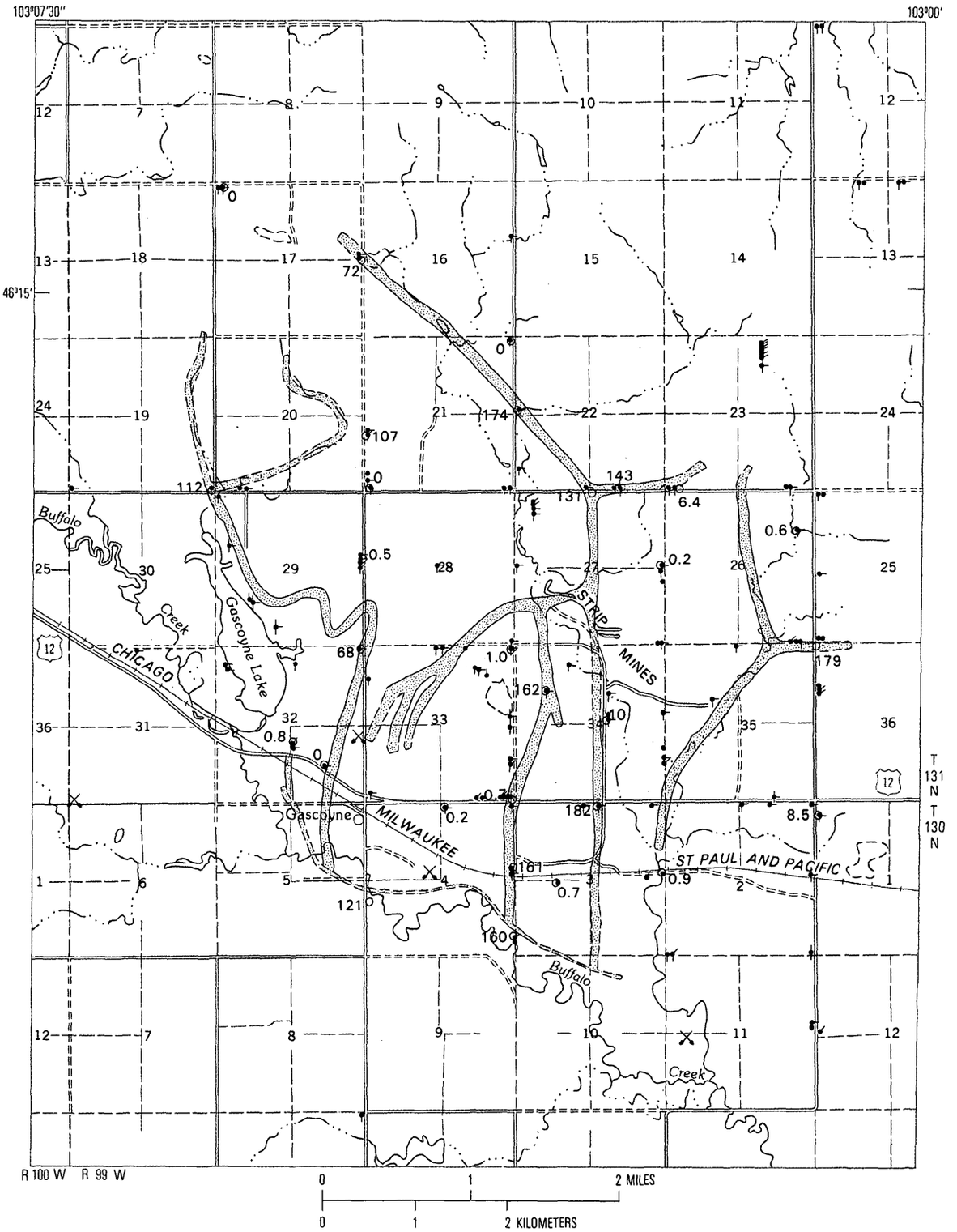
MINED AREAS

ACTIVE MINE PITS

---------- OUTCROP LINE—Top of Harmon lignite bed

—2750— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Water levels measured in August 1981. Contour interval 10 feet. Datum is NGVD of 1929

FIGURE 18.—Potentiometric map of the Harmon lignite aquifer.



EXPLANATION

CHANNEL SAND DEPOSITS—Exposed to land surface and extending in subsurface to first aquifer

○160 TRITIUM VALUES—Isotopic analysis of ground water from the Bullion Creek Formation in Tritium Units within 1 standard deviation

FIGURE 19.—Relationship of tritium in water from surficial aquifers to the location of sand channels.

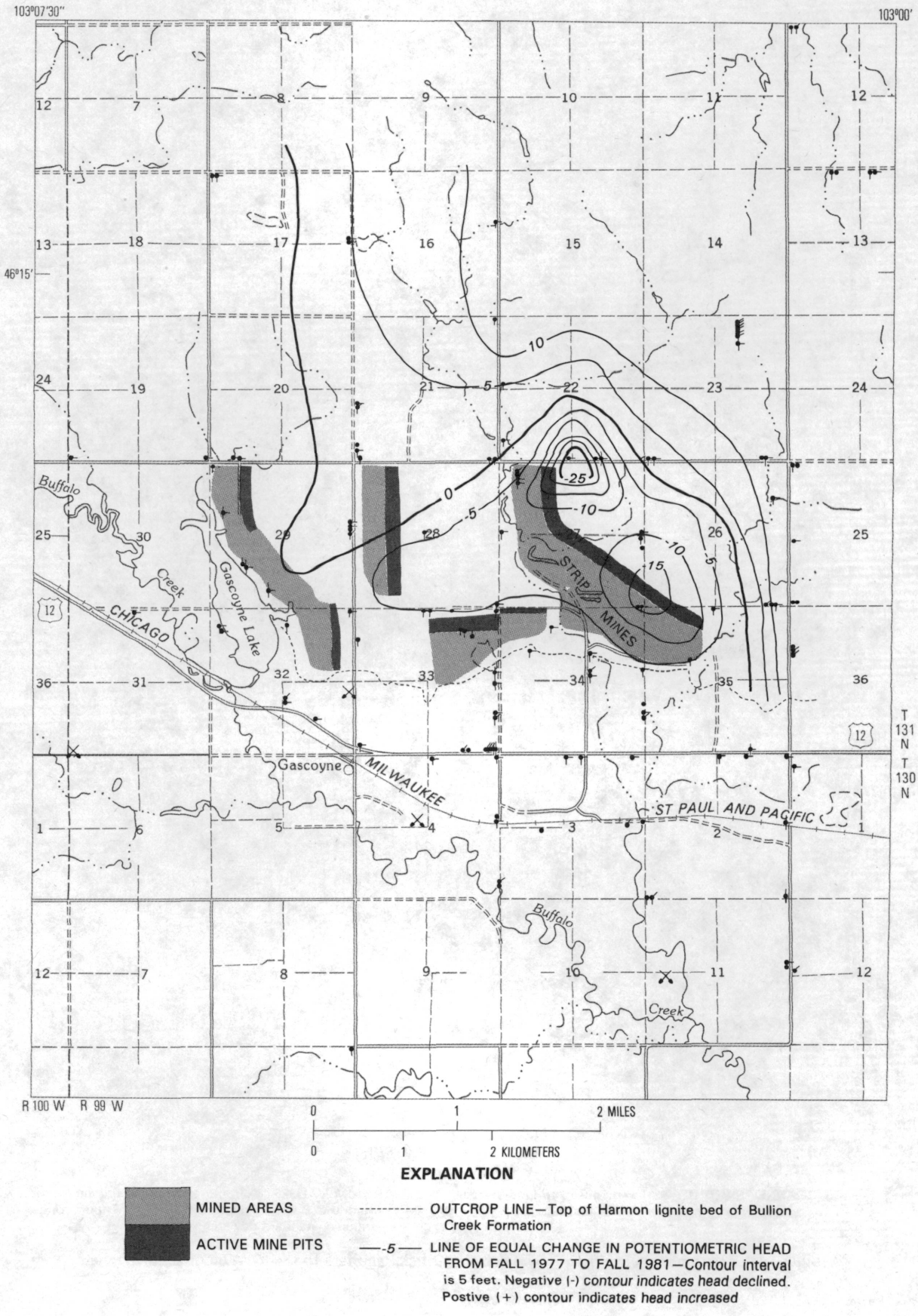


FIGURE 20.—Change in potentiometric head in the Harmon lignite aquifer, fall 1977–fall 1981.

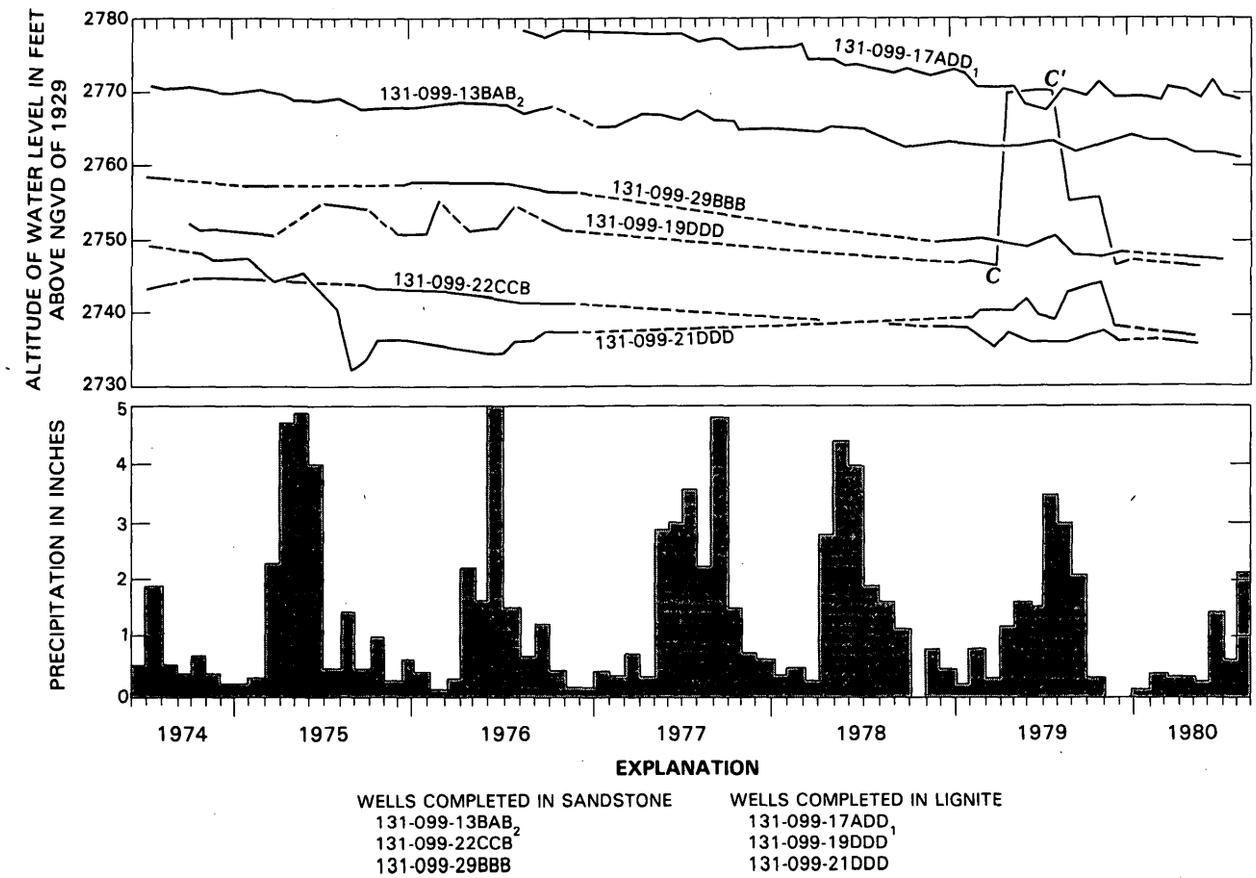
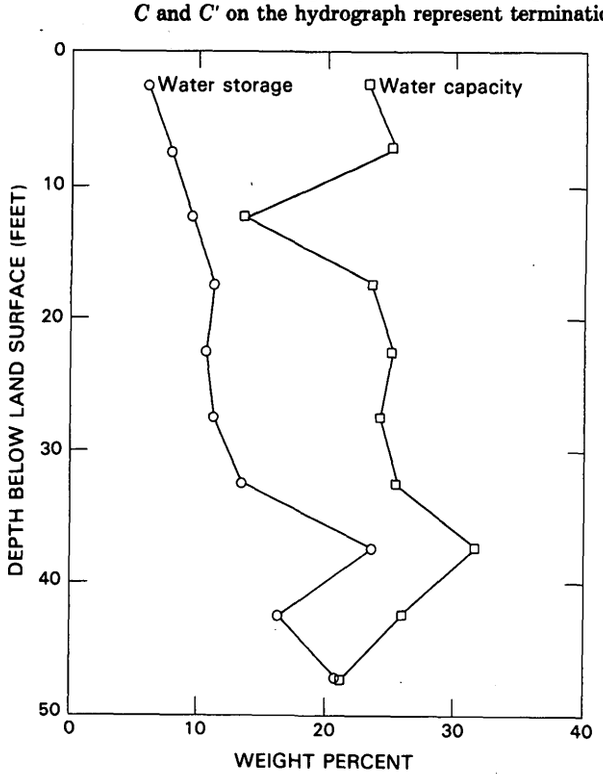


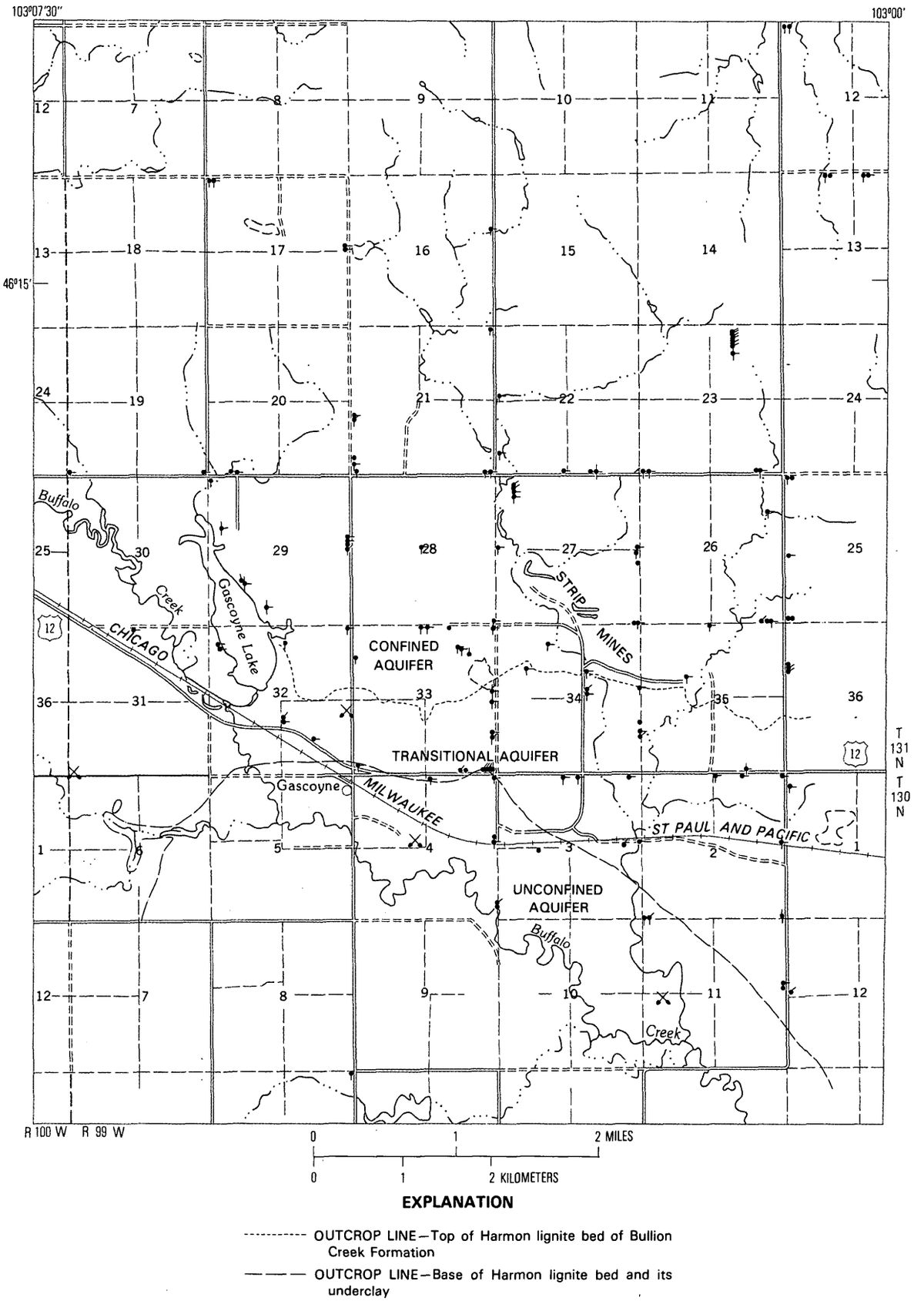
FIGURE 21.—Relationship of precipitation at Hettinger, Adams County, to water levels in selected wells at Gascoyne. (Points *C* and *C'* on the hydrograph represent termination and resumption of mine dewatering pumps, respectively.)



M. G. Croft (U.S. Geological Survey, written commun., 1979) indicates hydraulic conductivities in the overbank deposits average 1.5 ft/d. The model also indicates that higher conductivity lineaments in the basal Bullion Creek sandstone are only slightly offset to the east of those modeled in the overlying Harmon lignite aquifer. This shift is consistent with the westward migration of distributary channels, as indicated by test drilling. Measured and inferred hydraulic conductivities in the sandstone are comparable to those determined by Rehm and others (1980) for other Tertiary sandstones in the Northern Great Plains.

Short-term low-yield aquifer tests on wells completed in the confined sandstone aquifer indicate specific capacities ranging from 0.1 to 0.7 (gal/min)/ft of drawdown (Knife River Coal Mining Company, 1981). Calculated transmissivities range from 35 to 280 ft^2/d and hydraulic conductivities from 2.5 to 10 ft/d, consistent with laboratory values for overbank silts.

FIGURE 22.—Water storage and capacity with depth in core 131-099-28BBD, August 1981.

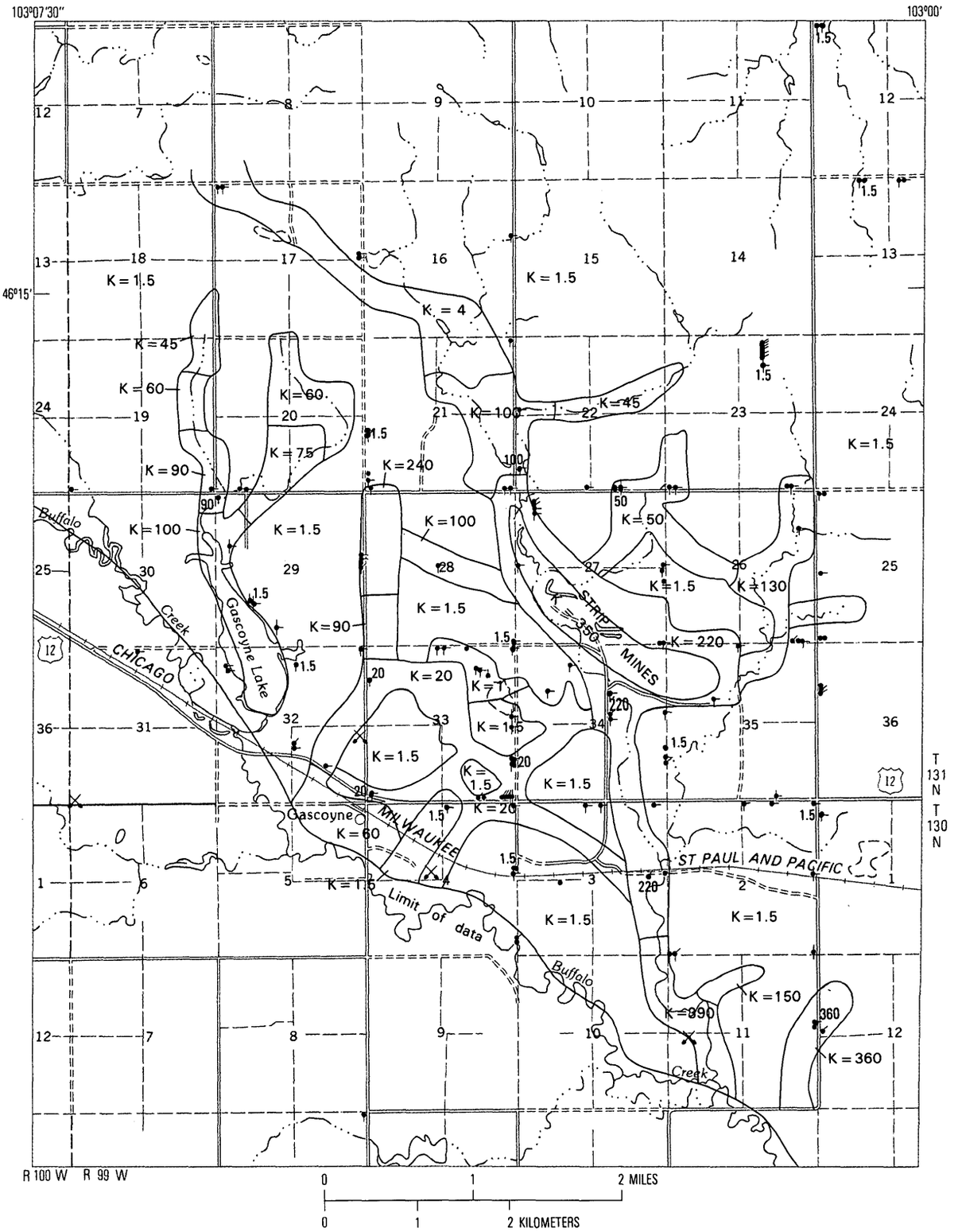


EXPLANATION

---------- OUTCROP LINE—Top of Harmon lignite bed of Bullion Creek Formation

——— OUTCROP LINE—Base of Harmon lignite bed and its underclay

FIGURE 23.—Hydrologic nature of the basal Bullion Creek-Slope aquifer.



EXPLANATION

(K=1.5) FIELD OF UNIFORM HYDRAULIC CONDUCTIVITY DETERMINED BY NUMERICAL MODELING

• 1.5 HYDRAULIC CONDUCTIVITY (K) IN FT/D DETERMINED BY LABORATORY CONSOLIDATION TESTS

FIGURE 24.—Hydraulic conductivities of the basal sandstone of the Bullion Creek Formation.

The potentiometric surface of the basal Bullion Creek-Slope aquifer (fig. 25) indicates that ground water is discharging to Buffalo Creek and its tributaries. Estimated minimum discharge to the creeks is 1×10^{-2} ft^3/s. Ridges in the potentiometric surface of the sandstone aquifer approximately correspond to the location of mapped sand channels.

Additionally, two large troughs in the potentiometric surface have developed beneath the two most active mine pits. The magnitude of these troughs has increased during mining (fig. 26) suggesting they may reflect increased vertical hydraulic conductivity due to fracturing of the sandstone and underclay by blasting within the pit areas. Additionally, acidic waters from the pit areas could infiltrate and dissolve some of the calcite cement in the underlying sandstone, increasing its permeability.

Because the premine hydrologic conditions at Gascoyne can only be inferred, the total impact of mining on the potentiometric surface is uncertain. However, extending the regional potentiometric trends indicated in figure 3 through the study area suggests the cone of depression in the potentiometric surface due to mine dewatering and aquifer disruption locally may be as much as 45 ft and extend as much as 3 mi beyond the mine perimeter. Comparison of the potentiometric surfaces of the regional and local aquifer systems may be misleading, though. The degree of connection between the basal Bullion Creek-Slope aquifer and the regional Bullion Creek-Slope aquifer system is unknown. Therefore, the inferred magnitude of depression of the potentiometric surface must be considered a maximum.

Since 1974 when mine production increased by an order of magnitude, water levels in the sandstone aquifer beneath the mine area have dropped as much as 15 ft (fig. 21). Beyond 2 mi from the mine perimeter, water-level drops were less than 2 ft during this interval. Since 1978 maximum water-level decline in the sandstone aquifer has averaged about 1.5 ft/yr, a rate which is currently continuing. Based on numerical modeling of the stressed system, reequilibration of the aquifer to mining stress may require another decade.

As discharge generally is from the sandstone to the overlying lignite in the mine area, cessation of pumping to dewater the lignite in the mine area should be accompanied by reduction of the cone of depression in the Harmon lignite aquifer. Water levels should recover to near premining levels shortly after mining activity ends in the area. Reversal of this gradient to recharge the basal Bullion Creek-Slope aquifer from the lignite will be slower, reflecting the large recurrence interval for infiltration events recharging the Harmon. As an average of 30 ft of coal is being removed by mining, reestablished water levels in the postmining landscape may rise to near land surface, especially within topographic lows in the recontoured land surface where springs and seeps may be expected to develop.

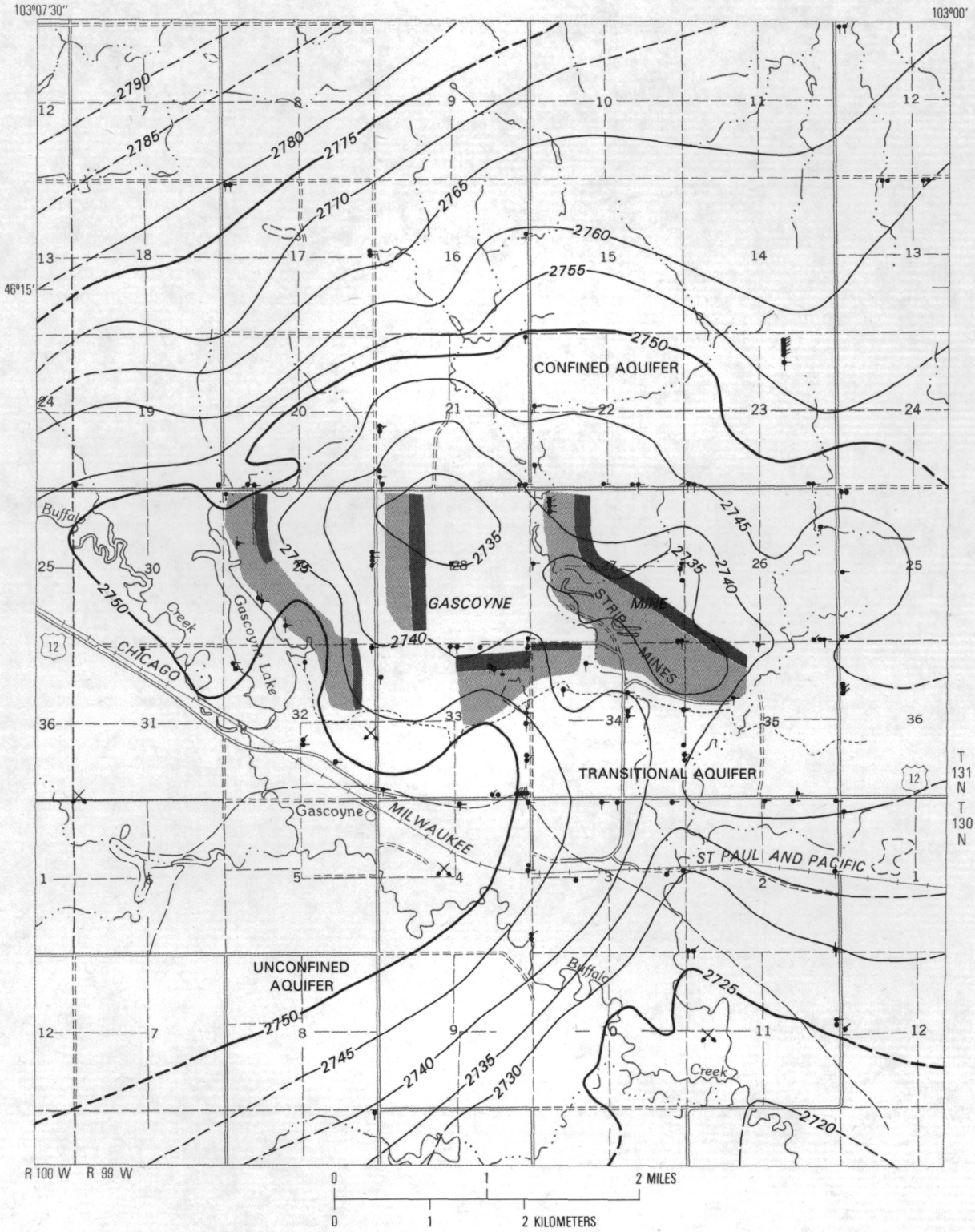
SPOIL-PILE AQUIFER

Density logs of holes drilled in spoils usually display significant density decreases near their bases, indicating an increase in void volume. The thickness of this zone of increased void volume varies greatly, but may be up to 6 ft thick in new spoils. Groenewold and Rehm (1980) have reported similar zones in mine spoils at other North Dakota mines. Formation of the rubble zone at the base of spoils is believed to be due to the techniques used to strip and recontour the overburden sediments. During the stripping process, the dragline dumps buckets of overburden in the mined pit, forming a cone of sediment. As each bucket load is dumped, the coarser material rolls down the side of the spoil pile to its base. At Gascoyne, this coarser material includes blocks of wet or clay-rich fine sediments, blocks of chemically cemented sediments, and blocks of semi-indurated overburden which was not disaggregated by the dragline's activities. As the dragline traverses the length of the active pit, conical spoil piles are elongated in the long direction of the pit into ridges, the coarse zone at their bases becoming a fairly continuous rubble bed. During recontouring, ridge crests are redistributed to valleys between successive ridges using bulldozers and scrapers—a process which accentuates the accumulation of coarser materials in the valleys, locally thickening rubble zones.

As the process of concentrating coarse debris at the base of spoils piles is active from the first dragline bucket dumped, anisotropy of hydraulic conductivity within the rubble zones apparently fails to develop. Instead, hydraulic conductivity within the rubble zone generally is random and locally related to the availability of wet, clayey, and cemented horizons in the overburden. Groenewold and Bailey (1979) reported hydraulic conductivities within the rubble zone at the Falkirk Mine in central North Dakota of 0.09 to 17 ft/d.

Above the rubble zone, the spoils are a fairly heterogeneous mixture of the premining overburden sediments. Rehm and others (1980) found the hydraulic conductivities of North Dakota mine spoils to vary by six orders of magnitude. At the Falkirk Mine, Groenewold and Bailey (1979) report hydraulic conductivities for the spoils above the rubble zone ranging from

FIGURE 25 (facing page).—Potentiometric map of the basal Bullion Creek-Slope aquifer.



EXPLANATION

MINED AREAS

ACTIVE MINE PITS

---------- OUTCROP LINE—Top of Harmon lignite bed of Bullion Creek Formation

— — — OUTCROP LINE—Base of Harmon lignite bed

—2770— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Water levels measured in October 1981. Dashed where approximately located. Contour interval 5 feet. Datum in NGVD of 1929

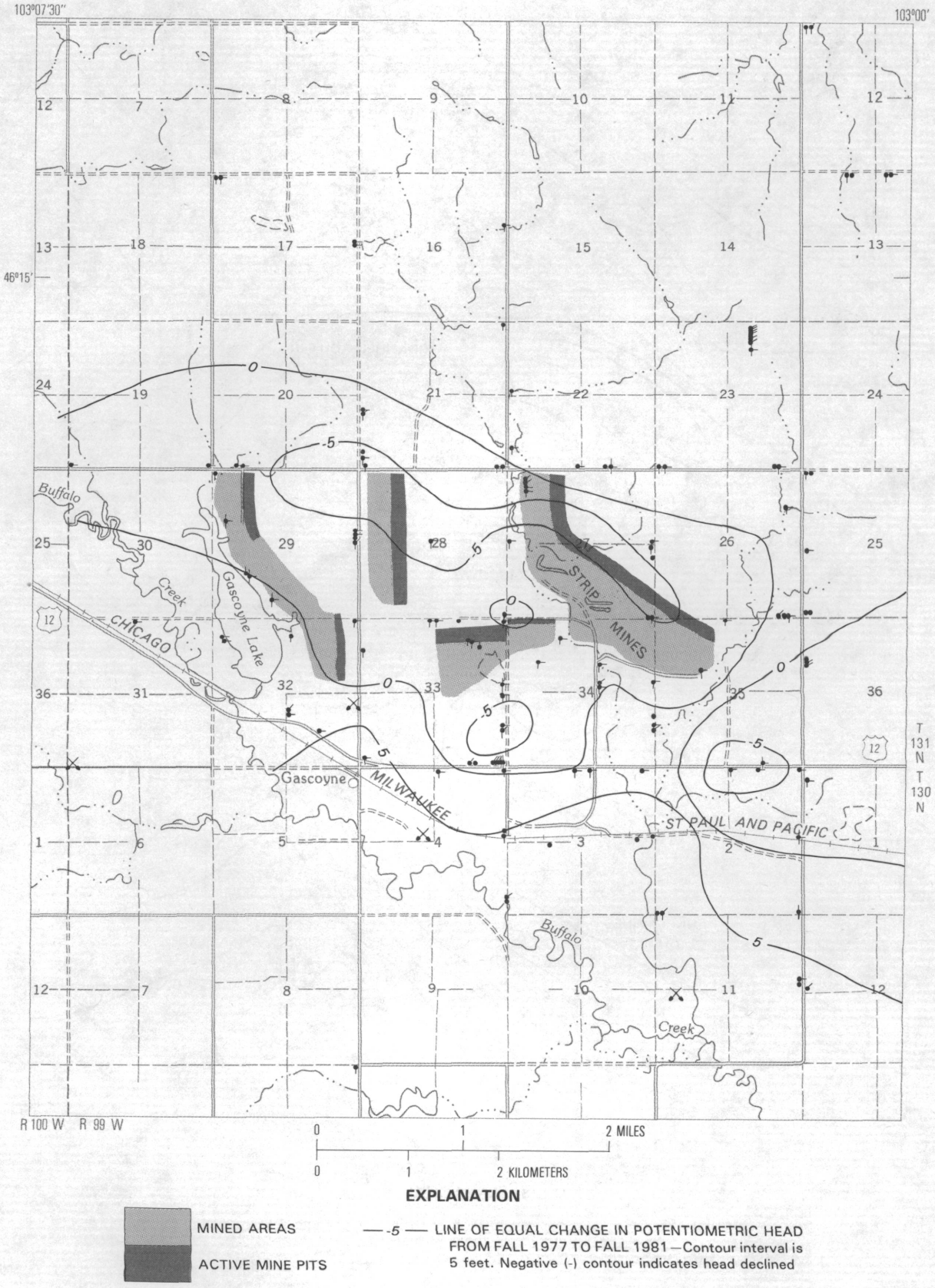


FIGURE 26.—Change in potentiometric head in the basal Bullion Creek-Slope aquifer, fall 1977-fall 1981.

6.4×10^{-4} ft/d to 4.5×10^{-2} ft/d. A single laboratory consolidation test for spoils from the Gascoyne Mine indicates a hydraulic conductivity of 1.0×10^{-3} ft/d.

Formation of spoils rubble zones on the bottom clay at the stratigraphic level of the Harmon lignite aquifer in unmined areas promotes early resaturation of the spoils by lateral flow from the adjacent lignite. Mine operation at Gascoyne has destroyed 10 observation wells in the Harmon lignite aquifer in the past 8 years. Within 3 years after mining, the altitudes of water levels in wells installed at the base of the mine spoils on top of the claystone at the sites of eight of these lignite wells were similar to those previously measured in wells completed in the lignite aquifer. The barometric response of these piezometers indicates an estimated average storage coefficient of 4.1×10^{-5}.

As consolidation of the spoils continues, voids in the rubble zone may be filled or lost due to compaction, resulting in reduced hydraulic conductivities. Groenewold and Rehm (1980) reported evidence that such permeability decreases may be occurring in spoils rubble at the Indian Head Mine in west-central North Dakota. No evidence is yet available from the Gasoyne Mine to indicate that compaction of spoils is reducing their capacity as an aquifer.

SURFACE-WATER HYDROLOGY

The hydrologic characteristics of surface-water systems within the study area are poorly defined at present. No gaging station exists on Buffalo Creek and only a single gaging station south of the mine has been installed on Buffalo Creek Tributary No. 2 (fig. 27), which drains an area of approximately 15.7 mi^2. The drainage system is well integrated with only two or three small natural lakes and several small stock ponds in the study area.

The major source of streamflow throughout the study area is snowmelt runoff. High flows occur as winter snow accumulations melt and run overland across mostly frozen ground into the stream channels. Buffalo Creek usually retains heavy ice cover until snowmelt occurs. Tributaries to Buffalo Creek within the study area usually are dry and ice free throughout the winter months. After the snowmelt period, streamflow gradually recedes to a base-flow condition in which the flow is maintained largely by ground-water discharge. Tributaries to Buffalo Creek generally reach base-flow conditions by midsummer and Buffalo Creek by late summer-early fall. Rainfall at any time during the year can cause an increase in streamflow through increased surface runoff and base flow.

Streamflow statistics for Buffalo Creek Tributary No. 2 near Gascoyne (06355310) from October 1977 through September 1980 have been presented by Haffield (1981). Discharge varied from zero to more than 400 ft^3/s. Occasionally, streamflow is augmented by mine pumpage. Minimum base flow from ground-water discharge is estimated to be about 0.01 ft^3/s.

GEOCHEMISTRY OF GROUND WATERS

Because precipitation is the principal source of recharge to the shallow aquifers in the study area, ground-water compositions should be determined largely by chemical changes occurring during infiltration of rain or snowmelt through the soil zone and the unsaturated zone to the water table. The chemical processes that can alter recharge-water chemistry during infiltration include absorption of gases generated in the soil by organic decay, dissolution of salts, cation-exchange reactions, redox reactions of solutes with minerals or organic matter, and hydrolysis reactions of silicates and aluminosilicates. A summary of the geochemical processes believed to be dominant at Gascoyne is presented in figure 28.

Although mean annual precipitation in the study area is about 15 in. (Stommel, 1975), most rainfall and snowmelt events do not introduce water below the root zone (Power and others, 1981); only exceptionally large rainfall or snowmelt events cause sufficient infiltration to produce ground-water recharge. Thus, unsaturated-zone waters may have significant amounts of time to approach equilibrium with their environment prior to reaching the water table. Slow ground-water recharge may occur by downward displacement of pore waters during each infiltration event. When exceptional infiltration events flush to the water table, recharging ground water is a mix of precipitation and pore waters. Accordingly, all water not occupying high hydraulic conductivity sand channels was found to be isotopically dead in tritium content (fig. 19).

PRECIPITATION CHEMISTRY

Precipitation in the study area has a pH ranging from 4.0 to 6.2 depending on the amount of atmospheric dust available to buffer dissolved nitrogen and sulfur oxide acids (Houghton, 1983). Precipitation during small-volume rainfall events usually possesses relatively high pH (5.4 to 6.1) because more dust is available to buffer the atmospheric moisture than is washed out during the event. Larger storms, such as might be expected to produce infiltration, wash out atmospheric dust early in their duration resulting in more acidic precipitation later in the event or in subsequent, closely spaced

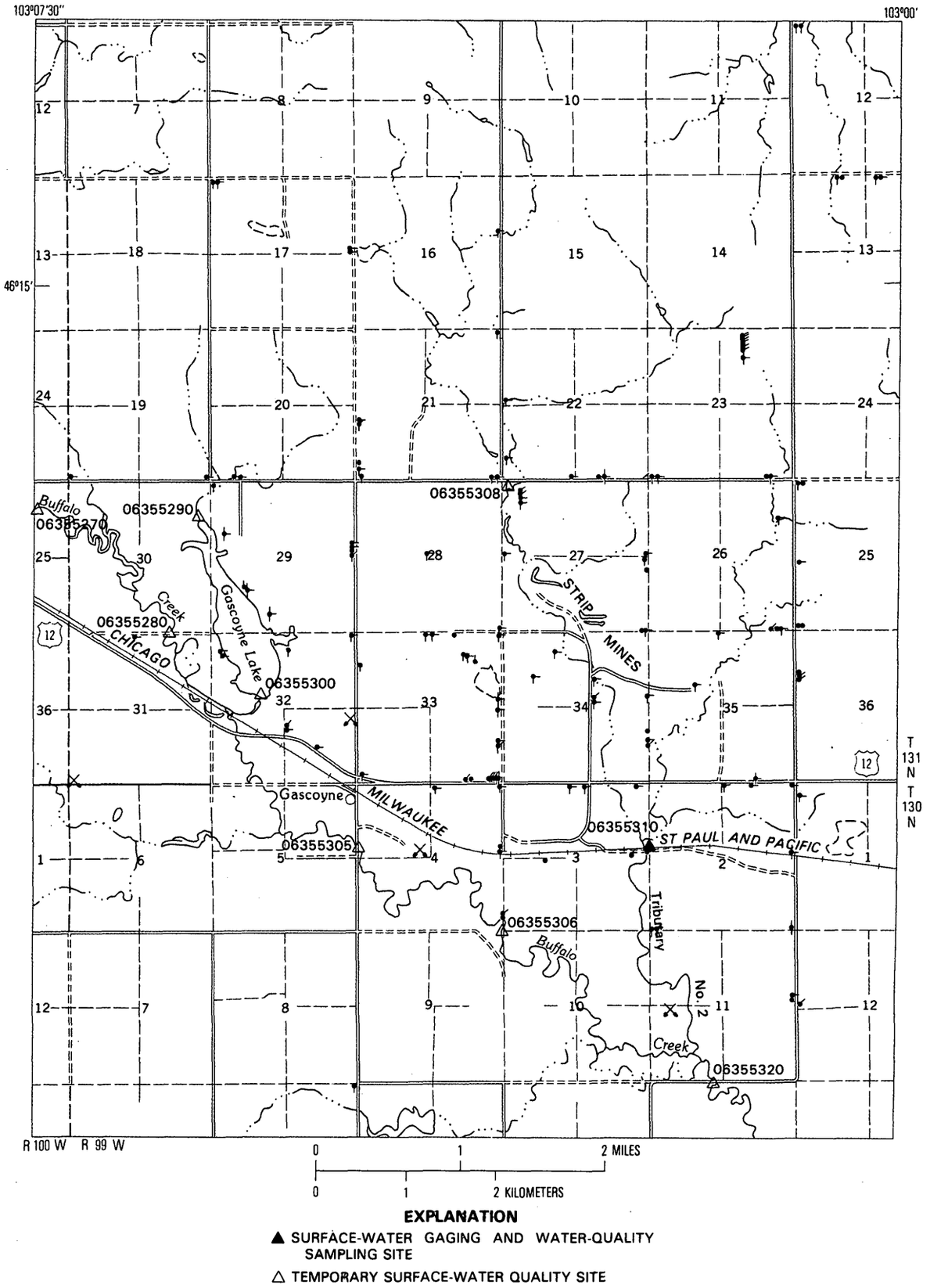
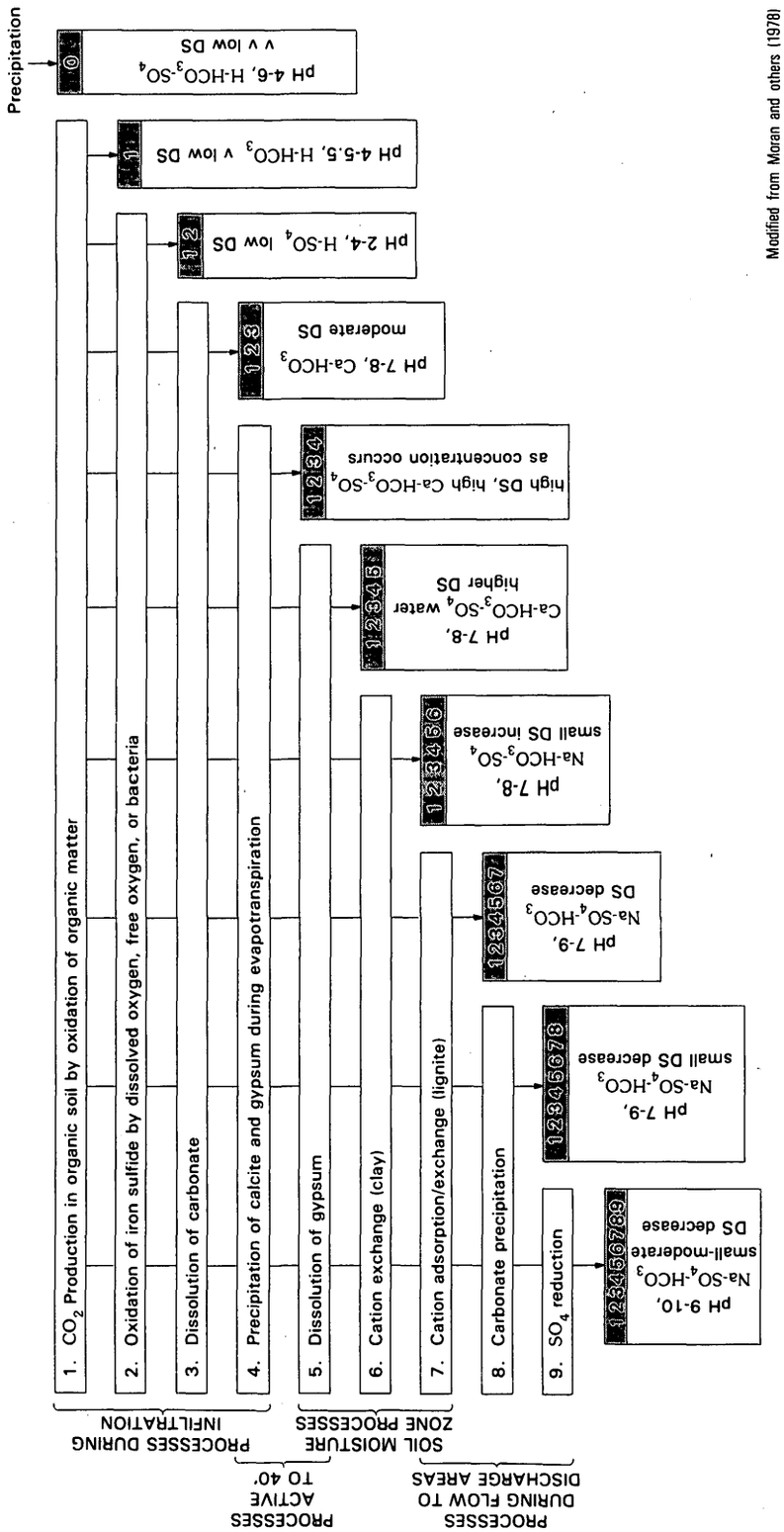


FIGURE 27.—Surface-water drainage and location of monitoring sites.



Modified from Moran and others (1978)

FIGURE 28.—Relations between major geochemical processes and water chemistry.

events. At a pH of 4, rain could account for adding about 0.052 meq/L sulfate to the near-surface pore waters, much less than the observed sulfate concentration of soil waters. In the absence of other reactions, evapotranspiration could be expected to concentrate ion concentrations about 100 times, which would reduce pH about two units. Accordingly, the acidity of precipitated water could accelerate many solute-contributing soil-zone reactions.

ROOT-ZONE SOIL CHEMISTRY

The composition of soil waters in the Northern Great Plains is governed principally by the salinity and the cation, anion, and ligand exchange and adsorption capacity of the soil; the presence of products of organic decomposition; and the quantity and residence time of the contacting water (Greenland and Hayes, 1981). Soil salinity and water content are highly variable but generally are in overall equilibrium with climatic conditions and plant water-use patterns.

Within the study area, topsoil averages 1.5 to 5 ft in thickness. Undisturbed topsoil salinity is seldom more than moderate, with the specific conductance of saturated extracts generally below 5,000 μmho/cm at mildly alkaline pH values (table 4). Although low in salts, the prairie soils possess relatively elevated sodium contents, with a mean sodium-adsorption ratio (SAR) of 3.6. SAR increases slightly with depth in the root zone.

$([Ca]+[Mg])/[Na]^2$ ratios decrease linearly with depth in the topsoil (table 5), indicating cation exchange of divalent cations for sodium probably is active. Extractable potassium, probably bound to adsorption sites on clays or organic compounds, is present in very high concentrations but is not involved in exchange reactions.

Spoils temporarily exposed to the surface prior to topsoil spreading display significantly higher salinities, with specific conductance of the saturated extract generally near 10,000 μmho/cm at mildly alkaline pH values (table 6). The mean SAR of surficial spoils in the study area is 8.8, but SAR values often are greater than 20. As the stripping process mixes stratigraphy, SAR usually is uniform in young surficial spoils profiles. The extractable potassium content of spoils usually is less than one-fifth that of prairie topsoils, indicating most potassium in topsoils may be on organic adsorption surfaces.

When topsoil is spread over the spoils, diffusion and evapotranspirational cycling of soil waters tends to homogenize soil-water compositions and equilibrate soil salinities. Topsoil on spoils is characterized by specific conductance values intermediate between undisturbed topsoil and spoils. SAR values of topsoil immediately above the spoils are relatively high, but decrease toward land surface, indicating sodium is migrating from the spoils into the topsoil. Calcium and magnesium contents, on the other hand, are depleted both at the surface and adjacent to the spoils.

Total exchange and adsorption capacities in mined and unmined soils generally are proportional to clay content. Within a single climatic zone, soil clays generally are similar to the sediments in which they are developed, so total exchange capacities are geographically variable and related to paleoenvironment. Anion exchange capacities and adsorption capacities are more closely related to the organic content of soils than clay content. Both total and anion exchange and adsorption capacities generally appear to be greatest in clayey loams developed in depressions. Nitrogen concentrations, determined as extractable nitrate after removal of ammonium ions according to the procedures of Sandoval and Power (1977, p. 18–20), are highest in soils with high

TABLE 4.—*Chemical characteristics of root-zone soil waters from undisturbed and disturbed spoils sites, geographic variability*

[μmho/cm, micromhos per centimeter at 25 degrees Celsius; meq/L, milliequivalents per liter; meq/100 g, milliequivalents per 100 grams]

Site	Undisturbed	Disturbed	Undisturbed	Disturbed
	Sodium-adsorption ratio		Specific conductance (μmho/cm)	
131-099-27BBC	2	12	1,000	7,500
131-099-29BDC	3	11	1,200	10,000
131-099-32ABA	4	25	1,800	9,900
131-099-33ABC	5	27	4,800	7,800
	Sodium (Na, meq/L)		Calcium plus magnesium (Ca+Mg, meq/L)	
131-099-27BBC	4	32	8	14
131-099-29BDC	6	43	8	31
131-099-32ABA	10	68	12	15
131-099-33ABC	20	81	33	18
	Saturation percentage[1]		Cation exchange capacity (meq/100 g)	
131-099-27BBC	45	83	22	26
131-099-29BDC	34	92	24	25
131-099-32ABA	51	100	27	26
131-099-33ABC	42	100	27	27
	Sand-silt-clay ratio		Textural class[2]	
131-099-27BBC	36-45-19	33-42-25	L	L
131-099-29BDC	55-25-20	17-38-45	SL-SCL	C
131-099-32ABA	31-49-20	19-51-30	L	SiCL
131-099-33ABC	47-26-27	14-40-46	SCL	C-SiC

[1]Measured after a rain.
[2]C, clay; L, loam; SCL, sandy clay loam; SiC, silty clay; SiCL, silty clay loam; SL, sandy loam.

TABLE 5.—*Chemical characteristics of root-zone soil waters from undisturbed and disturbed spoils sites, vertical variability*

[Extractable ion concentrations expressed in milliequivalents per liter]

Site	Depth (feet)	Extractable ion properties: Undisturbed: Sodium adsorption ratio	Undisturbed: $\frac{(Ca)+(Mg)}{(Na)^2}$	Undisturbed: (K)	Disturbed: Sodium adsorption ratio	Disturbed: $\frac{(Ca)+(Mg)}{(Na)^2}$	Disturbed: (K)
131-099-27BBC	0.5	2.3	0.50	0.02	12	0.014	0.004
	1.0	2.5	.45	.02	12	.013	.003
	1.5	3.6	.38	.02	10	.012	.003
	2.0	3.6	.34	.02	13	.011	.003
	2.5	4.3	.29	.02	10	.001	.003
	3.0	4.5	.22	.02	15	.010	.003
131-099-33ABC	.5	5.1	.08	.12	27	.003	.02
	1.0	5.1	.07	.12	26	.002	.02
	1.5	5.2	.06	.11	27	.003	.01
	2.0	5.2	.06	.12	26	.003	.01
	2.5	5.6	.05	.12	28	.004	.01
	3.0	5.9	.04	.11	35	.002	.02

TABLE 6.—*Chemical characteristics of spoils and undisturbed overburden materials*

[Values indicate mean value plus or minus (±) one standard deviation]

Number of analyses	Extractable ion properties: Sodium adsorption ratio	Specific conductance (micromhos per centimeter at 25 degrees Celsius)	Paste pH (units)
		Surficial spoils	
32	8.8±18	2,100±1,700	7.6±0.5
		Subsurface spoils	
128	16±291	9,500±6,200	7.8±0.3
		Overburden	
1,356	3.6±1.5	2,100±1,700	8.4±0.4

exchange capacities suggesting nutrient levels are partially controlled by anion exchange. However, oxidation of some of the ammonium to nitrate within the soil system cannot be ruled out as a possible source of some extractable nitrate.

Decomposition of organic material by oxidation generates carbon dioxide. Gas probes were installed at six sites around the mine. Compositions of soil gases within the root zone at an undisturbed site (130-099-11ADD) approximate atmospheric levels, except for some enrichment in carbon dioxide (table 7). The carbon-13 concentration of the soil carbon dioxide was −22.8 per mille, consistent with an organic source of gas. Organic nutrient (nitrogen and phosphorus) levels are very low, indicating source organic compounds are low in these soils. Compositions of soil gases within the root zone at a disturbed site (131-099-33DCD) are enriched appreciably in carbon dioxide and depleted in oxygen. The carbon-13 concentration of young spoils (less than 6 months by June 1977) is slightly heavier (−20.9 per mille) than at the undisturbed site. However, the carbon-13 concentration of older spoils (approximately 2.5 years by May 1979) is considerably heavier (−12.0 per mille), suggesting about half the carbon is derived from inorganic sources. Dissolution of detrital carbonate minerals probably is responsible for contributing this inorganic carbon.

Dissolution of carbon dioxide in soil waters increases the hydrogen-ion concentration in the water. Deionized water in equilibrium with atmospheric carbon dioxide will have a pH of approximately 5.7. Equilibrium with P_{CO_2} of 10^{-1} atmospheres like those observed at Gascoyne would produce water with a pH of about 4.2. Acidic waters can dissolve soil carbonates to provide divalent cations for exchange reactions. The basic pH of soil waters, etching of detrital carbonates in the soil, and the abundance of calcium and magnesium in the cation fraction of saturation extracts indicate carbonate dissolution is occurring in Gascoyne soils.

The water retention characteristics of soil materials are determined by soil texture, swell factor, and plant rootage. SAR is a good index of swell factor (Gilley and others, 1976). The relatively high SAR of spoils suggests they possess reduced permeabilities and decreased water capacities. Dry soil bulk densities, determined by pycnometer according to the procedure of Blake (1965), are increased by mining due to particle mixing. Whereas dry soil bulk density increases with depth in undisturbed soils, recently disturbed soils display relatively constant density profiles (fig. 29). Compaction reestablishes the density increase with depth in less than 3 years.

The increased dry bulk density of mined soils decreases their water-storage capacity. Water-storage

TABLE 7.—*Chemical and isotopic composition of root-zone soils and soil gases from the vicinity of Gascoyne*

[Values for carbon-13 (^{13}C) are reported in parts per mil (o/oo) relative to the PDB standard. Values for oxygen-18 (^{18}O) are reported in parts per mil (o/oo) relative to the SMOW standard. Organic nutrient analyses were performed according to the procedures of Sandoval and Power (1977)]

Location	Probe depth (feet)	Date sampled	Gas composition (N_2 (volume percent)	O_2	Ar	CO_2	Date sampled	Isotope analyses of CO_2 gas ^{13}C (o/oo)	^{18}O (o/oo)	Dry soil composition Organic nitrogen (weight percent)	Organic phosphorus
Undisturbed soil											
130-099-11ADD	4	06/29/77	77	20	1.0	0.28	06/17/77	-22.8	+28.3	0.0021	0.011
		08/23/77	78	22	1.0	.28	08/24/77	—	—	.0019	.015
Disturbed soil											
131-099-33DCD	9	06/29/77	79	19	1.0	.73	06/17/77	-20.9	+26.0	.0014	.0082
		05/23/79	79	20	1.1	.45	05/24/79	-12.0	+26.2	.0012	.0086

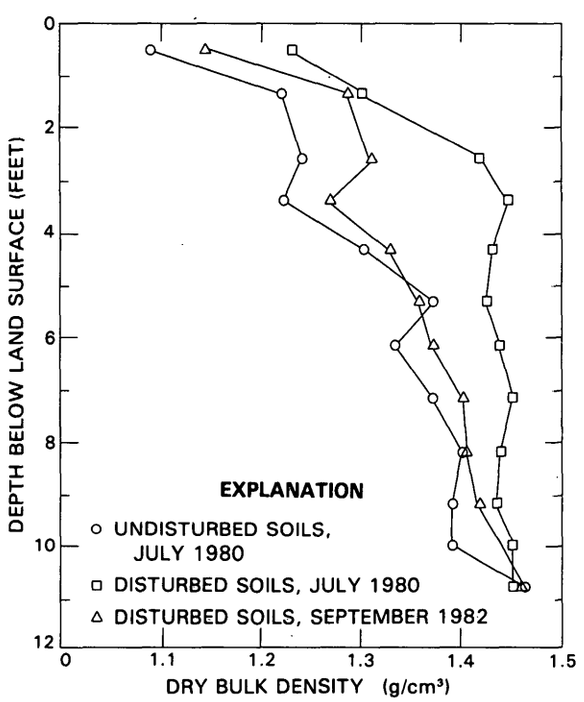


FIGURE 29.—Changes in dry-soil bulk density with depth.

measurements, using the neutron scatter method of Gardner (1965), indicate that the moisture levels of undisturbed soils in the study area respond to precipitation (fig. 30). Between precipitation events, undisturbed soils average 40 percent of water capacities. Following precipitation events, water storage commonly exceeds 50 percent of capacity. In contrast, the water storage of surficial spoils appears to be relatively unaffected by precipitation, indicating infiltration of most spoils is subsidiary to runoff. Topsoils spread on spoils tend to approach saturation, apparently due to water ponded on the surface of underlying less permeable spoils.

Because lake evaporation exceeds precipitation by a factor of 2.5 in the study area (Kohler and others,

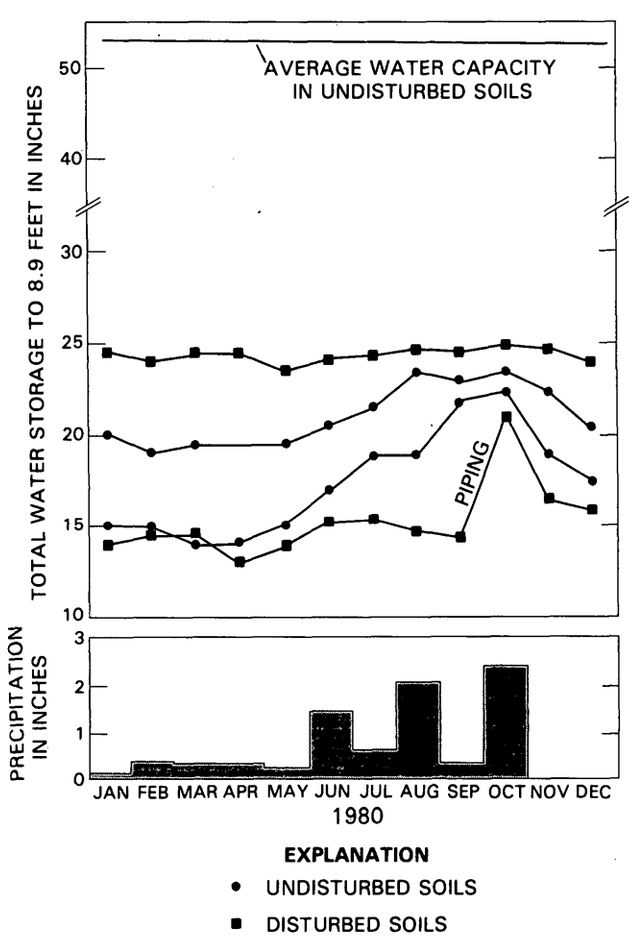


FIGURE 30.—Total water storage to a depth of 8.9 feet in disturbed and undisturbed soils as related to precipitation.

1959), vegetation places great demands on the water stored in the soils. Rootage of prairie vegetation is deep for grasses, extending to 5 ft to permit utilization of a larger percentage of the soil moisture (Gee and others, 1978). Water infiltrating the soil is trapped by

evapotranspiration processes and only flushed below the root zone during exceptional precipitation events, perhaps every 2 to 3 years (Power and others, 1981). Thus, residence time is sufficient to permit extensive chemical reaction between the soil and its waters. The specific conductance of soil waters commonly represents a two to three orders of magnitude increase over precipitation salinities. In disturbed soils, increased soil densities reduce the quantity of water available for chemical reactions, but also increase its residence time in the soil. Increased residence time in the soil zone should have little additional effect on the composition of waters infiltrating below the soil zone (Raats, 1980).

UNSATURATED-ZONE CHEMISTRY

Once water has infiltrated below the root zone, its composition is largely controlled by oxidation-reduction, dissolution-precipitation, and cation-exchange reactions. Pore waters in the unsaturated zone were sampled by a variety of methods. Where perched water zones were encountered on top of clay lenses, samples were obtained using conventionally designed wells or pressure-vacuum lysimeters (fig. 31). Where sediments remained unsaturated, pore waters were sampled by pressure-vacuum lysimeters according to the method of Wood (1973) or recovered from cores obtained by hollow-stem auger or air-rotary drilling techniques. Pore waters were extracted from cores in the field using nitrogen pressure to extract and filter the water in sealed chambers (fig. 32), or within 8 hours of core recovery by using the centrifugal force of a laboratory ultracentrifuge to filter the water in double-chambered centrifuge tubes (fig. 33). The efficiency of centrifuge and pressure-chamber methods of water

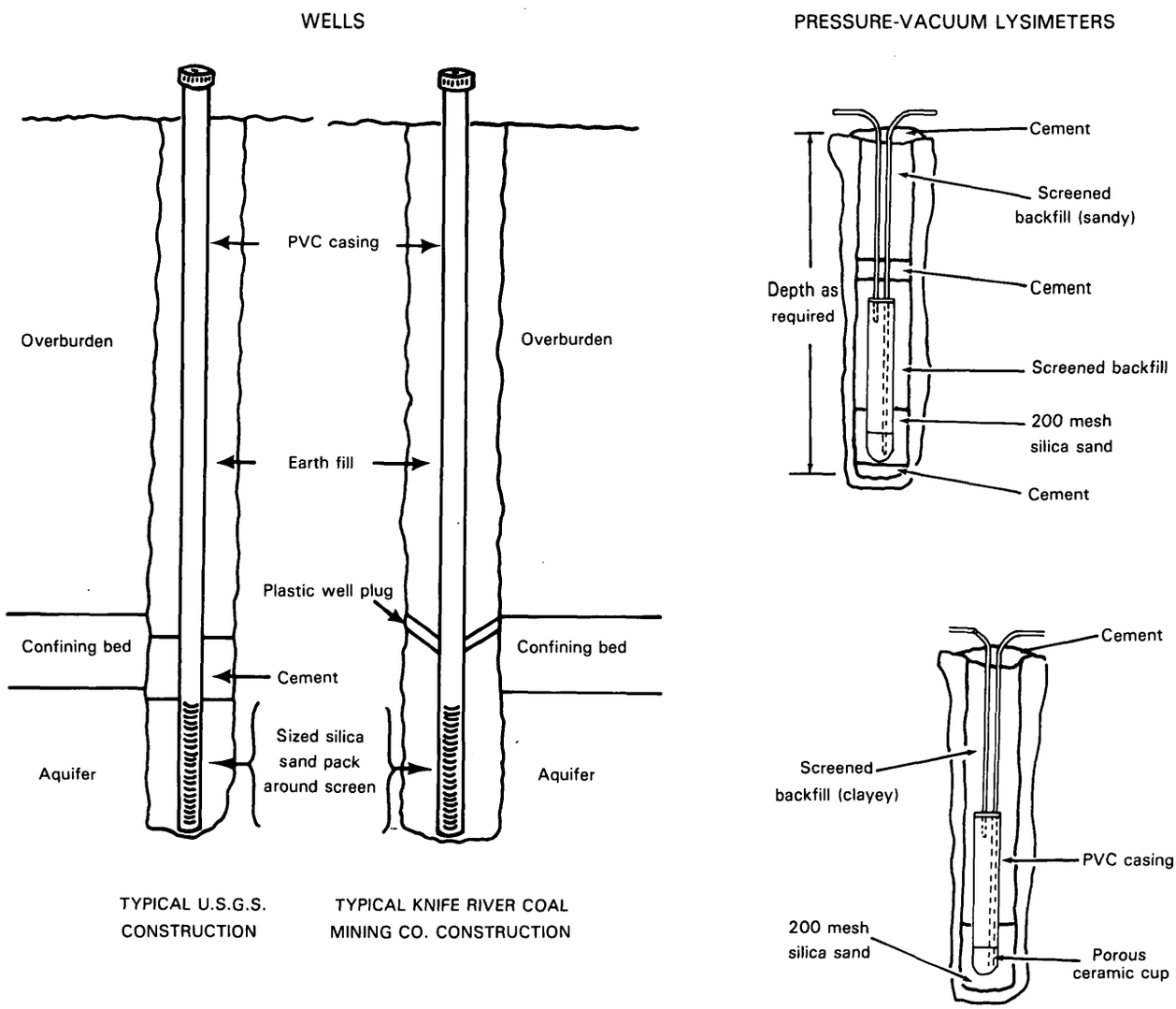


FIGURE 31.—Well construction needed to obtain an acceptable water-quality sample and pressure-vacuum lysimeter designs. (Modified from Wood, 1973.)

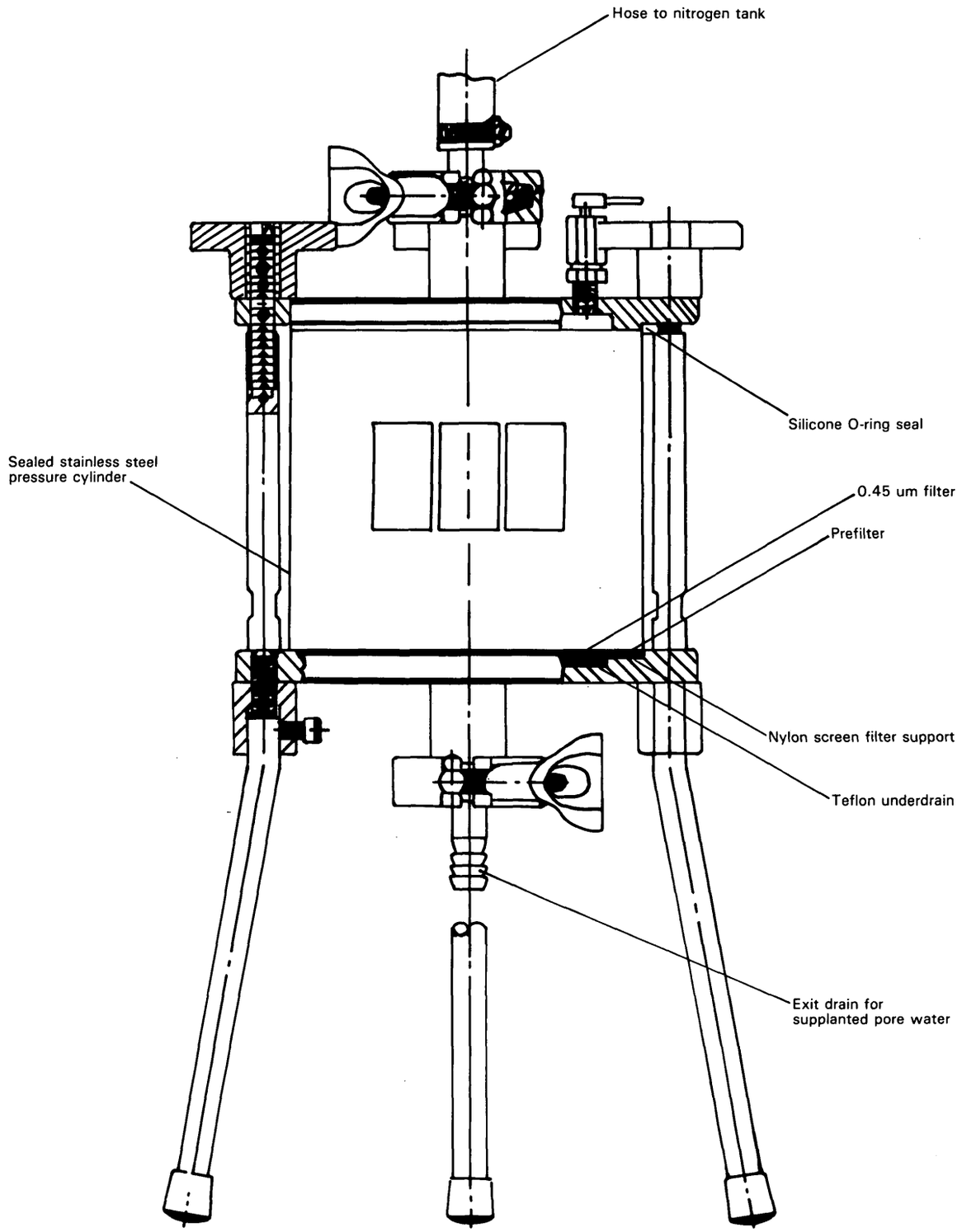


FIGURE 32.—Nitrogen-pressure extraction system for recovering pore water from core samples. (Modified from Millipore Corp., 1980.)

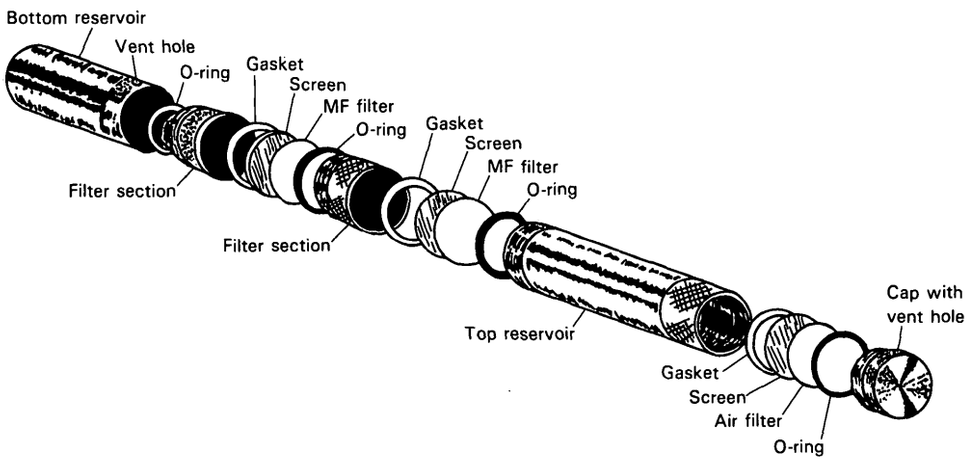


FIGURE 33.—Double-chambered (filterfuge) centrifuge tube used for ultracentrifuge recovery of pore water from core samples. (Modified from International Equipment Co., 1972.)

recovery was determined to be 72 percent and 61 percent, respectively, based on additional sediment weight loss after 48 hours at 80 °C

WATER QUALITY IN THE UNSATURATED ZONE

The dissolved-solids concentration of perched waters in the study area always is greater than that of underlying ground waters. Sulfate concentrations usually exceed 3,000 mg/L in the near-surface perched waters and decrease with depth (Supplement 1). The relatively high chloride levels (greater than 80 mg/L) in perched waters above 30 ft indicate some dissolved-solids concentration by evaporation occurs to at least this depth.

Pore-water solute concentrations decrease from the base of the topsoil, or the spoils surface where topsoil is absent, to about 10 ft in depth. Such a profile at 130-099-03BAA is shown in figure 34. Between 10 and 25 or 30 ft in the unsaturated zone, pore-water solute concentrations usually remain nearly constant. Below this zone, pore-water solute concentrations decrease again to the water table. The ratios of concentrations of solute constituents remains surprisingly constant within the unsaturated zone below the root zone, suggesting the same chemical processes are active throughout the unsaturated zone. Diffusive homogenation of water chemistry in the zone between 10 and 25 or 30 ft was attributed to evapotranspiration by Houghton (1982b).

Pore waters from the basal Bullion Creek sandstone south of U.S. Highway 12 and pore waters from Bullion Creek strata above the Harmon lignite bed do not seem to have any systematic differences in solute composition. However, pore waters in the surficial channel sand deposits were substantially lower in dissolved solids than other pore waters. Conversely, the Dissolved-solids concentrations of pore waters in spoils generally are greater than concentrations of pore waters from undisturbed sediments by as much as a factor of two.

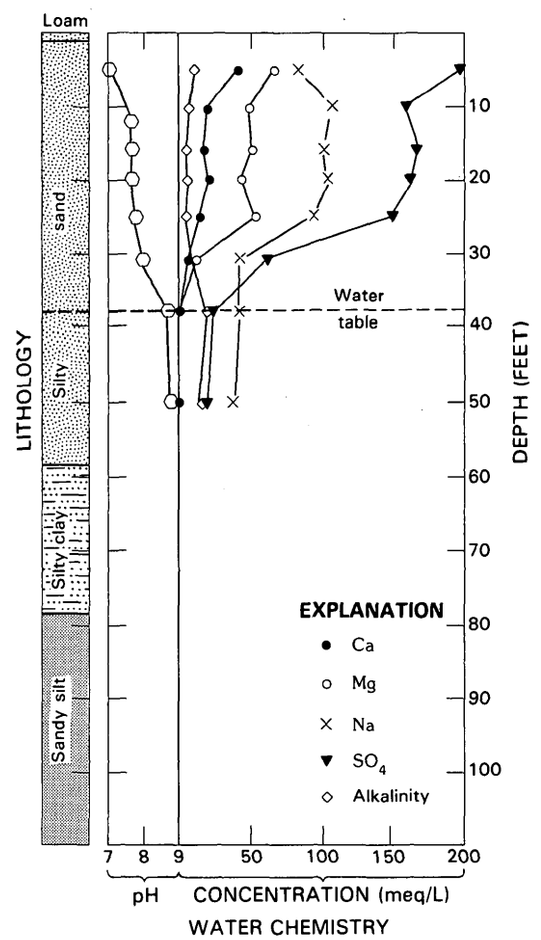


FIGURE 34.—Variation of solute concentrations in pore water with depth in core 130-099-03BBA.

GASES IN THE UNSATURATED ZONE

Soil-gas piezometers (fig. 35) designed by Weeks (1978) were installed at selected sites in and near the mine to collect soil gases at various heights above the water table. A downstream vacuum pump with an intake valve to limit gas flow rate was used to draw soil gas up into sampling containers. Each soil-gas piezometer was pumped for several minutes to displace atmospheric air, then the sampler and gas well were isolated from the pump by closing the valve. Samples were collected when the piezometer recovered to approximately atmospheric pressure. Chemical compositions of the soil gases were determined by gas-solid chromatography (Hobba and others, 1977).

Soil-gas samples for $\delta^{13}C$ and $\delta^{18}O$ isotopic determinations[5,6] of the carbon dioxide fraction were collected in evacuated stainless-steel cylinders with basically the same pumping procedure used to obtain the samples analyzed for chemical composition. Carbon dioxide gas fractions from these samples were isolated in the laboratory and analyzed by mass spectrometry.

A peristaltic pump was used to bubble soil gases to be analyzed for their carbon-14 content through an ammoniacal strontium chloride solution. The resultant strontium carbonate precipitate was treated and analyzed as described by Pearson and Bodden (1975).

The results of chemical and isotopic analyses of these samples are shown in table 8. Sequential samples generally show good agreement. Major variations in composition at a single site were found only when the gas probes became contaminated with water. In general, unsaturated-zone gases have compositions similar to the atmosphere except for higher carbon dioxide concentrations. Oxygen generally was present above the 10 volume percent level at depths less than 20 to 30 ft in undisturbed sediments (130-099-11ADD, 131-099-33DCD, 131-099-36BCC), but at only trace to low levels below those depths. Within channel sands exposed at the surface (131-099-21CCB), oxygen is present to the water table. Where oxygen levels are low, carbon dioxide levels usually exceed 10 volume percent. The carbon isotopic composition of the carbon dioxide indicates a predominantly organic origin for the carbon dioxide with an increasing inorganic component with depth due to carbonate mineral dissolution. Degassing of carbon dioxide from lignite and other organic-rich sediments or carbon-dioxide release during reduction-oxidation processes may be responsible for displacing oxygen upward in the sediments. This oxygen displacement apparently is greatest in sediments with high bulk density.

The gas probes at 131-099-36BCC were influenced by a persistent zone of perched water at the 17-ft depth overlying an impermeable clay bed at 25 ft. Unsaturated-zone carbon dioxide levels below the clay bed exceed 10 percent, and oxygen concentrations are much less than the atmospheric content of 21.9 percent. Carbon-isotopic analyses indicate that the carbon

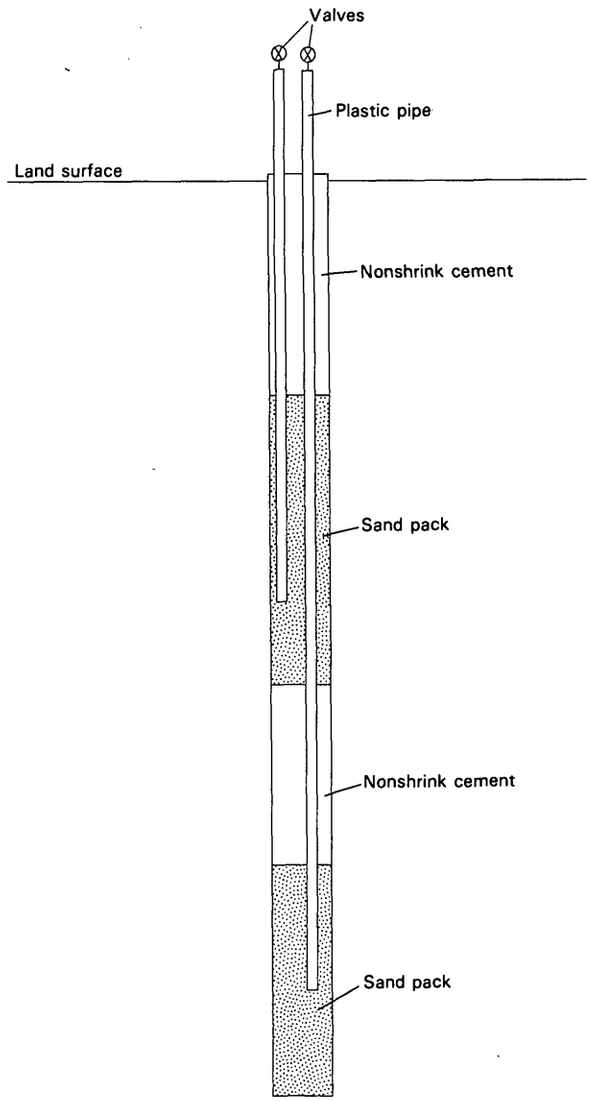


FIGURE 35.—Soil-gas piezometer design.

5 $$\delta^{13}C=\left[\frac{(^{13}C/^{12}C)\ \text{sample}-(^{13}C/^{12}C)\text{standard}}{(^{13}C/^{12}C)\text{standard}}\right]\times10^{3}\ \text{o/oo}$$

values are reported in parts per mil (o/oo) relative to the PDB standard of the University of Chicago (*Belemnitella Americana*, Cretaceous Peedee Formation, South Carolina).

6 $$\delta^{18}O=\left[\frac{(^{18}O/^{16}o)\ \text{sample}-(^{18}o/^{16}O)\text{standard}}{(^{18}O/^{16}O)\text{standard}}\right]\times10^{3}\ \text{o/oo}$$

values are reported in parts per mil (o/oo) relative to the Standard Mean Ocean Water (SMOW) of Craig (1961).

TABLE 8.—*Chemical and isotopic composition of soil gases from the vicinity of Gascoyne*

[Values for carbon-13 (^{13}C) are reported in parts per mil (o/oo) relative to the PDB standard. Values for oxygen-18 (^{18}O) are reported in parts per mil (o/oo) relative to the SMOW standard. Values for carbon-14 (^{14}C) are reported in percent modern carbon. Values for carbon-14 for 1977 were measured by the Radioisotope Laboratory, U.S. Geological Survey, Water Resources Division, Reston, Va.; later samples were analyzed by Herbert Haas, Radiocarbon Laboratory, Southern Methodist University, Dallas, Tex.< indicates less than]

Location	Probe depth (feet)	Date sampled	Gas composition (volume percent)				Date sampled	Isotope analyses of CO_2 gas		
			N_2	O_2	Ar	CO_2		^{13}C (o/oo)	^{18}O (o/oo)	^{14}C (percent modern)
Undisturbed sites										
130-099-11ADD	4	06/29/77	77	20	1.0	0.28	06/17/77	-22.8	+28.3	
		08/23/77	78	22	1.0	.28				
	16	06/29/77[1]	80	18	1.0	.02	06/25/77[1]	- 4.8	+21.2	
							07/19/77[1]	-12.6	+19.0	
131-099-33DCD	9	06/29/77	79	19	1.0	.73	06/17/77	-20.9	+26.0	
		05/23/79	79	20	1.1	.45	05/24/79			103
	19	06/29/77	79	19	1.0	1.2	06/17/77	-23.8	+25.0	
		07/19/77	79	18	1.0	1.4				
		08/23/78	79	15	1.1	4.9	08/23/78	-22.2		
		05/23/79[2]	80	14	1.0	5.7	05/23/79			10
	30	06/29/77	81	.2	1.1	18	06/17/77	-23.3	+25.1	
							07/08/77			2.4
		08/23/78	80	.06	1.1	18	08/23/78	-23.2		
		05/23/79[3]	83	1.9	1.1	16	05/23/79			1.81
	42	06/29/77	82	.06	1.1	17	06/17/77	-22.9	+25.2	
		08/23/78	80	.06	1.1	18				
		05/23/79[4]	84	.3	1.1	17				2.19
	49	06/29/77[1]	78	21	1.2	.1				
131-099-36BCC	10	09/10/76	96	1.8	1.3	.06				
		06/28/77[1]	78	21	1.0	.08	06/28/77	-34.1	+32.6	
	17	09/10/76[1]	80	16	1.0	.57				
		06/28/77[1]	81	1.2	1.7	6.3				
	25	09/10/76[3 5]	92	.9	1.2	4.8				
		06/28/77[1 5]	77	19	1.0	1.2	06/28/77	-27.3	+31.4	
	36	09/10/76	81	.1	1.4	17				
		06/28/77	77	.3	1.1	18	06/18/77	-17.7	+23.6	2.1
	45	06/30/76[6]	80.7	.03	1.16	18.1				
		06/30/76[7]	80.6	.02	1.15	18.2				
		06/30/76[8]	80.7	.02	1.14	18.2				
		09/10/76	79	.08	1.1	19				
		06/28/77	82	4.2	1.1	13				
Undisturbed channel sands										
131-099-21CCB	10	07/06/77	82	15	1.1	1.6	06/18/77	-22.7	+21.9	
		08/23/78	78	19	1.0	2.3	08/23/78	-22.4		
		05/22/79	82	17	1.1	1.1	05/23/79	-24.2		114
	19	07/06/77	80	18	1.1	1.3	06/18/77	-19.6	+26.5	
		07/19/77	80	18	1.0	1.2				
		08/23/78	79	19	1.0	1.4	08/23/78	-20.4		
		05/22/79	81	18	1.0	1.4	05/23/79	-21.8		91
	28	07/06/77	79	19	1.0	.95	06/18/77	-17.2	+26.3	
		08/23/78	80	18	1.0	1.2	08/23/78	-17.8		
		05/22/79	80	18	1.0	1.2	05/23/79	-18.5		51
	40	07/06/77[5]	77	16	1.1	2.8				
	48	07/06/77[5]	88	12	1.2	< .01				
Reclaimed spoils										
131-099-34BAC	4	09/13/76	76	11	1.0	11				
		07/03/77	78	10	1.0	12	06/18/77	-12.0	+25.6	
							07/03/77			20.6
	11	09/13/76	73	1.0	1.0	25				
		07/03/77	80	.6	1.1	19	06/18/77	-11.7	+25.6	
							07/03/77			12.2
	20	06/30/76[6]	77.1	.02	1.11	21.7				
		06/30/76[7]	77.0	.01	1.11	21.9				
		06/30/76[1 8]	72.8	.05	1.07	26.1				
		09/13/76[1]	73	.3	1.0	24				
		07/03/77[1]	79	.03	1.1	19	07/03/77	13.2		

Footnotes at end of table.

TABLE 8.—*Continued.*

Location	Probe depth (feet)	Date sampled	Gas composition (volume percent) N_2	O_2	Ar	CO_2	Date sampled	Isotope analyses of CO_2 gas ^{13}C (o/oo)	^{18}O (o/oo)	^{14}C (percent modern)
			Reclaimed spoils—*Continued*							
131-099-35BDB	9	09/13/76	83	10	1.0	5.4				
		06/28/77	79	14	1.0	6.5	06/17/77	-21.6	+28.7	
	19	09/13/76	87	6.2	1.1	5.8				
		06/28/77	80	12	1.1	7.9	06/17/77	-21.6	+24.4	
							07/05/77			18.1
	29	06/30/76[6]	87.6	.05	1.22	11.1				
		06/30/76[8]	87.0	.43	1.24	11.3				
		09/13/76	88	.2	1.2	11				

[1]Liquid water in recovered sample.
[2]Sample also contained 0.01 percent nitrous oxide.
[3]Sample also contained 0.01 percent methane.
[4]Sample also contained 0.08 percent methane.
[5]Well pressure recovered very slowly after pumping.
[6]Sequential sample obtained with 5 minutes of pumping at a rate of approximately 1 cubic foot per minute.
[7]Sequential sample obtained with 15 minutes of pumping at a rate of approximately 1 cubic foot per minute.
[8]Sequential sample obtained with 60 minutes of pumping at a rate of approximately 1 cubic foot per minute.

source is largely organic ($\delta^{13}C$ = <−17 o/oo) and old (only 2.1 percent modern carbon). Oxidation and degassing of lignitic materials apparently are generating the low oxygen and high carbon dioxide gas concentrations in this zone.

Gas compositions in reclaimed spoils (131-099-34BAC and 131-099-35BDB) generally were depleted in oxygen and enriched in carbon dioxide. Carbon-14 data indicate only 12-20 percent of the carbon dioxide was generated from modern carbon. The $\delta^{13}C$ values indicate a sharp increase in the inorganic carbon contribution to the gas relative to undisturbed sediments, indicating carbonate mineral dissolution is the principal carbon dioxide source to spoils gas.

ACCELERATED WEATHERING EXPERIMENTS

Strip mining removes mineral assemblages that are stable in their natural environment and places the assemblages in a different physiochemical environment. During mining at Gascoyne, overburden is removed from environments, many of which were reducing based on the presence of methane in unsaturated-zone gases, and exposed to atmospheric oxygen. Spoils piles may stand for years prior to being smoothed and reclaimed. Because stripping generally inverts the stratigraphic section, sediments which were deepest and thus least likely to be exposed to oxygen in their natural environment are emplaced closest to the surface in the reclaimed land. Because the water table lies within the lignite at Gascoyne, reducing conditions in the overburden are limited to microenvironments. Only the partings between the coal seams are removed from reducing conditions below the water table and exposed to surface oxidation. At other mines in the State, a larger part of the overburden is saturated. In turn, surficial oxidized sediments may be replaced at the base of the spoils pile where reducing conditions would normally occur.

The principal steps involved in the reequilibration of mine spoils to their new conditions are oxidation-reduction and solubility reactions. Oxidation-reduction spoils reactions may be accelerated under controlled laboratory experiments, making their identification and quantification easier.

To simulate introduction of new spoils into the oxidizing environment, cored strata from various paleoenvironments and depths in the study area were leached of soluble salts with oxygen-free water using the method of Sandoval and Power (1977, p. 4-6) and sealed in laboratory bombs. The bombs were filled with distilled water through which a continual stream of oxygen was bubbled.

After 30 days, reacting fluids were found to be enriched in sulfate, sodium, and bicarbonate and were characterized by slightly basic pH values (table 9). Petrographic analyses of the sediments before and after accelerated weathering experiments suggest that all framboidal and colloidal forms of pyrite were removed by oxidation. Similarly, detrital carbonates show signs of etching, and secondary gypsum occurs in excess of its solubility in all cores except 131-099-29CDB. Iron oxyhydroxides encrust most mineral grains. The basic pH values are somewhat puzzling since sulfide oxidation is a strongly acid-producing reaction. Buffering of system pH by organic materials is thus likely.

TABLE 9.—*Composition of solutions generated during accelerated weathering experiments*

[See text for details. All samples were leached of soluble salts prior to "weathering" with oxygenated water. Analyses were performed by the U.S. Geological Survey National Water Quality Laboratory, Denver, Colo. < indicates less than]

Depth (feet)	pH	Specific conductance (micromhos per centimeter at 25 degrees Celsius)	Concentration in milliequivalents per liter						
			Ca^{2+}	Mg^{2+}	Na^{+}	SO_4^{2-}	Cl^{-}	F^{-}	Alkalinity
Core 131-099-29CDB1—Clay parting between Beta and Gamma seams of the Harmon lignite (backswamp).									
36-37	7.2	2,010	5.2	8.0	13.3	24.2	0	0.1	2.2
Core 131-099-22DCC2—Clayey silt overburden (overbank).									
30-31	7.8	1,060	1.5	3.9	8.4	12.5	<.1	.1	1.4
Core 130-099-04AAA—Silt overburden (overbank).									
47-48	8.0	715	1.5	2.2	5.7	8.2	0	<.1	1.3
Core 131-099-21CCC3—Sandy silt overburden (levee).									
30-32	8.4	315	.3	.4	3.5	1.6	0	0	2.5

Petrographic examination of natural spoils shows that they are similarly depleted in "oxidizable" pyrite well below the level of free oxygen in the pile. Apparently, only framboidal and colloidal forms of pyrite are oxidizable in an historical time scale. Oxidation occurs very rapidly, probably during the actual mining process. By the time reclamation begins, all "oxidizable" pyrite has already been converted to sulfate.

The speed in which sulfide oxidation apparently occurs suggests the process may be catalyzed by sulfur-oxidizing bacteria. *Thiobacillus ferroxidans, Ferrobacillus ferroxidans,* and *Thiobacillus thioxidans* bacteria have been identified in the interior of cores and pyrite nodules from the study area (G. G. Ehrlich, U.S. Geological Survey, oral commun., 1976). However, it is uncertain whether the microbes identified were active or dormant. Olson and others (1980) have reported active sulfur oxidation by *Thiobacillus ferroxidans* in spoils waters from the Decker and Colstrip mines in southeastern Montana.

Pyrite oxidation may be summarized by the general reaction

$$4FeS_2+15O_2+14H_2O \rightarrow 4Fe(OH)_3+16H^+ +8SO_4^{2-} \quad (1)$$

and is one of the strongest acid-producing reaction processes known to occur in natural geologic systems. This process is responsible for the acid mine-drainage problem which has been so environmentally damaging in the Appalachian region of the United States and in many other mining regions of the world.

In a system not limited by available oxygen or iron sulfide, reaction waters would reach a minimum pH near 2 with sulfate concentrations approaching 9.4 meq/L due to limits on the solubility of ferric iron. As sulfate concentrations in shallow pore waters at Gascoyne are one to two orders of magnitude greater than this level, other sources and (or) concentration processes must actively control sulfate levels.

Once acidified, mine waters become highly corrosive to a variety of minerals. At the Gascoyne mine as at most western United States strip mines, acidic waters generated by sulfide oxidation immediately are buffered by dissolution of carbonate minerals which are present in excess. Carbonate-mineral dissolution will proceed to water saturation very rapidly, within hours or days, unless limited by relative surface area or flow concerns (Raush and White, 1977). The dissolution reactions for dolomite and calcite may be expressed as follows:

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

$$CaCO_3+H^+ \rightarrow Ca^{2+}+HCO_3^-. \quad (3)$$

It is apparent from these reactions that carbonate dissolution consumes H^+ and therefore effectively increases the pH of the reactant water. Under equilibrium conditions, carbonate dissolution might be expected to generate solutions with pH values of 7 to 8 and bicarbonate concentrations of 3 to 8 meq/L in a CO_2-$CaCO_3$ system. As observed bicarbonate concentrations in experimental and natural pore waters typically are 1.5 to 3 times greater than this range, another process must be affecting bicarbonate concentrations.

As detrital dolomite is more abundant than calcite in the Bullion Creek sediments, initial reaction fluids of accelerated weathering experiments tend to be magnesium sulfate-bicarbonate type waters. Upon evaporation

of early reaction fluids, secondary epsomite and polyhalite may exceed gypsum concentrations. However, as the reactions proceed, the waters become progressively more sodic and calcium concentrations exceed magnesium levels. Apparently sodium is derived by cation exchange of the divalent ions for sodium on clay surfaces. The rapid decline in magnesium concentrations in the reaction fluids suggests the magnesium exchange for sodium on clays is favored over calcium exchange, at least initially.

It is apparent from equations 2 and 3 that higher concentrations of bicarbonate may be achieved if additional sinks for Ca^{2+} and Mg^{2+} are considered. In a semiarid climate like that of North Dakota, evapotranspiration processes are effective in concentrating shallow pore waters above their saturation levels in many evaporative salts. With continuing evaporation, divalent sulfosalt precipitation would result in bicarbonate enrichment in the pore waters and is consistent with the secondary minerals produced upon evaporation of late-stage solutions generated by accelerated weathering experiments. Calcite precipitation also should occur fairly readily, which would result in concentration of magnesium relative to calcium in residual pore waters. That the reverse concentration is observed supports preferential exchange of magnesium over calcium for sodium on formation clays.

SATURATION EXTRACTS AND LEACHABLE SALTS

Water-soluble mineral phases deposited in the unsaturated zone during periods of evaporation may be a significant source of solutes to the ground-water system when redissolved in infiltrating fluids. The contribution of soluble minerals to pore-water compositions may be approximated using saturation-extract experiments.

Saturation-extract compositions determined for cuttings samples collected during rotary drilling with air and analyzed using the method of Sandoval and Power (1977) after 1 hour of static saturation are presented in table 10. Saturation extracts obtained from core samples using leaching procedures similar to those described by Barrett and others (1980) are presented in table 11. The procedure of Barrett and others (1980) was modified as follows. After saturation percentages were determined, sufficient water was supplied to maintain core saturation while continuously cycling leachate back to the core top (fig. 36). Cycling rates were maintained at about two saturation volumes per 12 hours with experiments terminated after 24 hours.

Saturation-extract compositions determined by the two experimental methods generally were in agreement. However, extracts derived from cores in the unsaturated zone usually were nearer saturation with respect to gypsum than extracts from cuttings. This difference may reflect the relatively limited area available to reacting fluids percolating through core samples as opposed to disaggregated cuttings. Also, competing chemical reactions such as ion exchange may have less opportunity to occur in the core samples. Accordingly, extracts of the cored samples may be more representative of soluble-salt compositions.

Petrographic examinations of cores before and after saturation-extract experiments indicate gypsum is the dominant soluble salt above the water table within the study area. The secondary nature of the gypsum observed in the unsaturated zone is confirmed by its absence below the water table, even where the ground water often is saturated with respect to that mineral.

Extract compositions were found to vary with depth and with sediment texture and lithology. Coarse-textured sediments are characterized by low saturation percentages (<35) and low SAR values (1 to 10), reflecting past leaching by infiltrating fluids. Clay-rich sediments displayed high saturation percentages (>100) and very high SAR values (10 to 40), reflecting reduced exposure to leaching solutions. In clastic sediments of the Bullion Creek Formation, saturation extracts are dominated by sodium, the alkaline earth elements, and sulfate. In extracts of lignitic sediments, sodium is always the dominant cation and bicarbonate is present in concentrations in the same range as sulfate. Only lignite zones are characterized by acidic paste pH levels.

Superimposed on textural and lithologic variations in extract composition is a consistent relationship between saturation-extract composition and depth. In the unsaturated zone, saturation percentages increase and specific conductances decrease with depth (fig. 37). The calcium plus magnesium concentrations of saturation extracts are approximately the same level as the sodium concentrations. Between the base of the root zone and abou 10 to 15 ft in depth, magnesium tends to dominate the divalent cation fraction of extracts. Below that level, concentrations of these divalent ions are more nearly equal and calcium frequently is the dominant divalent cation. Saturation-extract compositions of samples collected from the 10 to 30 or 35 ft depth are nearly constant, suggesting composition of all depths within the region is controlled by the same processes. Below 30 or 35 ft, extract solute concentrations continue to decrease to the water table. Below the water table, saturation-extract compositions reflect equilibration with ground-water compositions.

Dissolution of gypsum, which may be expressed as:

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O, \qquad (4)$$

is a kinetically rapid process. This process may exert

TABLE 10.—*Composition of saturation extracts*

[Tabulated data are from selected test well drill cuttings and high wall samples representative of the Bullion Creek Formation in the Gascoyne area. Cation exchange capacities tabulated as "DEN" were determined by the U.S. Geological Survey, National Water Quality Laboratory, Denver. Colo., using cesium-137 (U.S. Geological Survey Bulletin 1140-B); cation exchange capacities tabulated as "NDSL" were determined by the North Dakota State Laboratories using an ammonia-acetate solution on a sodium-saturated sample after the method of Sandoval and Power (1977). Paste pH data were furnished by F. M. Sandoval, U.S. Agricultural Research Service, Mandan, N. Dak., using procedures outlined by Sandoval and Power (1977). Exchangeable cation data were determined by the North Dakota State Laboratories using an ammonia-acetate solution. "T" indicates a trace occurrence. The textural classification was determined using standard sieve methods: CL, clayey loam; L, loam; Lgn, lignite or lignitic materials; Si, silt; SiC, silty clay; SiCL, silty clay loam; SiL, silty loam; SiS, silty sand; SSi, sandy silt. μmho/cm at 25 °C, micromhos per centimeter at 25 degrees Celsius; meq/100 g, milliequivalents per 100 grams; meq/L, milliequivalents per liter; < indicates less than]

Depth below land surface (feet)	Texture	Cation exchange capacity (meq/100 g)		Exchangeable cations (meq/100 g)				Paste pH	Saturation percentage (weight percent)	Saturation extract: Specific conductance (μmho/cm at 25 °C)	Sodium-adsorption ratio	Ca	Mg	Na	CO_3	HCO_3	Cl	SO_4
		DEN	NDSL	Na	K	Ca	Mg					(concentrations in meq/L)						
Test well 131-099-23CCC																		
0- 5	CL	2.7	27	8.0	0.43	9.0	10	8.0	114	10,760	13.7	20.7	56.7	85.1	0	1.2	0.1	161
5- 10	SiC	---	21	4.35	.42	8.0	14	8.0	104	11,760	14.2	20.1	66.3	93.5	0	.8	<.1	179
10- 15	SiC	3.2	6.2	2.71	.45	4.0	4.0	8.0	102	8,500	12.3	21.0	38.1	66.9	0	.6	<.1	125
15- 20	SiC	2.3	8.9	.74	.19	4.0	4.0	8.0	105	8,140	11.5	21.0	37.2	62.0	0	.5	<.1	119
20- 25	SiC	2.6	24	.31	.05	21	7.0	7.6	103	5,490	7.2	17.8	25.4	33.5	0	1.0	<.1	76
25- 30	SiC	---	9.5	.60	.22	5.4	3.5	7.9	103	4,210	6.5	13.0	17.8	25.5	0	1.1	<.1	55
30- 35	SiC	---	12	.97	.27	6.0	6.0	7.9	91	5,970	8.0	19.6	27.6	38.4	0	1.0	<.1	84
35- 40	SiCL	2.9	14	1.14	.21	8.0	6.5	7.8	87	3,460	6.2	10.3	13.6	21.5	0	1.1	.1	43
40- 45	SiC	---	8.8	.42	.18	5.0	3.5	7.9	85	3,150	7.1	7.9	10.0	21.3	0	2.3	.1	37
45- 50	SiC	---	5.3	.20	.15	2.0	3.3	7.7	90	2,900	8.4	5.9	6.8	21.1	0	2.7	<.1	31
50- 55	SiC	---	11	.36	.30	8.0	3.0	8.1	88	2,410	10.6	3.2	3.6	19.7	0	2.2	<.1	25
55- 60	SiC	2.5	26	2.74	.35	15	9.0	7.8	86	3,370	10.0	6.6	6.7	25.8	0	1.9	.1	37
60- 65	SiC	22	17	2.18	.27	6.0	12	7.6	87	2,970	17.9	2.4	2.5	28.1	0	4.7	<.1	28
65- 70	Lgn	69	32	3.74	.31	15	13	6.9	96	5,270	23.5	5.0	5.3	53.5	0	12.2	.1	52
70- 75	SiCL	74	33	3.68	.26	16	13	7.4	83	3,060	25.6	1.7	1.7	33.4	0	8.5	<.1	28
75- 80	Lgn	81	41	4.47	.25	22	14	7.1	94	6,320	27.9	6.0	6.0	68.4	0	16.5	.2	63
80- 85	Lgn	73	---	---	---	---	---	7.0	95	6,990	30.5	5.5	6.1	73.6	0	18.6	.2	66
85- 90	Lgn	81	---	---	---	---	---	7.1	92	5,270	30.2	3.4	3.6	56.5	0	13.4	.1	70
90- 95	SiCL	50	---	---	---	---	---	7.4	82	3,150	26.4	1.4	1.4	31.5	0	5.6	.1	28
95-100	SiCL	67	---	---	---	---	---	7.5	80	2,660	28.0	1.0	1.0	27.3	0	5.1	<.1	24
100-102	Lgn	70	---	---	---	---	---	6.9	91	8,650	24.7	12.0	1.3	84.3	0	13.4	.3	90
High wall at 131-099-27BBB																		
0- 1	SiL	19	14	0.31	0.09	7.0	6.5	8.1	71	850	2.7	1.4	3.4	4.2	0	3.9	0.1	5
1- 2	SiL	14	41	---	---	---	---	8.1	69	2,620	2.2	10.0	18.7	8.2	0	2.0	.1	35
2- 3.5	SiL	11	18	.05	0	7.0	11	8.1	73	3,310	3.4	6.1	26.3	13.8	T	2.0	.4	43
4- 5	CL	9.1	10	.18	.03	7.5	4.0	7.9	89	6,310	4.5	10.1	52.2	25.0	T	1.9	.8	85
5- 6	Si	4.0	3.5	.26	.04	2.5	1.0	8.0	52	9,720	4.4	18.6	96.2	33.2	0	.4	2.4	145
6- 7.5	CSi	9.2	8.6	.16	.02	5.4	3.0	7.9	69	4,190	3.2	15.2	32.4	15.5	0	1.0	1.6	60
8- 9	Si	3.2	1.8	.06	.10	2.8	.8	7.8	48	4,430	2.3	21.6	36.1	12.4	0	.8	1.6	68
9- 11	Si	4.3	4.5	.10	.06	2.1	2.1	7.8	54	3,020	2.2	17.0	18.3	9.1	0	1.3	.4	42
11- 12	Si	6.2	2.3	.09	.09	1.5	.5	7.6	56	2,180	1.4	12.6	11.0	4.7	0	1.4	.2	26
12- 13	SSi	2.3	3.2	.39	0	1.4	.5	7.6	39	3,420	2.3	17.5	20.6	9.9	0	.7	.8	46
13- 14.5	SSi	2.7	2.0	.01	.01	1.7	.9	7.5	38	3,560	3.0	18.7	18.9	13.2	0	1.0	.4	50
15- 16	Si	9.8	7.3	.06	.07	6.9	.8	7.8	47	1,190	2.2	3.9	3.9	4.4	0	1.4	.1	11
16- 17	Si	5.5	3.5	.04	.06	2.5	3.5	7.6	45	2,190	3.6	8.5	9.0	10.8	0	2.2	.1	26
17- 18	SSi	2.4	2.9	.04	.02	1.6	1.2	7.3	36	3,750	2.3	6.4	15.6	9.3	0	.3	.2	40
18- 22	SSi	2.0	2.3	.50	.04	.5	2.5	7.6	39	8,670	5.8	18.2	58.0	35.9	0	1.1	1.4	109
22- 24	SSi	3.5	4.2	.30	.05	6.0	5.0	7.7	40	2,800	8.1	6.5	6.9	21.1	0	.8	.2	34
24- 29	Lgn	---	---	---	---	---	---	6.0	92	5,120	14.6	8.9	12.0	49.2	0	11.5	.3	56

an important control on shallow ground-water composition when infiltration events leach the unsaturated zone of available soluble salts. If gypsum is dissolved in deionized water at 8 °C, equilibrium concentrations of 26 meq/L sulfate may be achieved (Cherry, 1968). Even higher concentrations are possible if an additional sink for calcium is available. As gypsum dissolution is a reversible process, repetitive sequences of evaporation and dissolution can result in shallow pore waters with very high sulfate concentrations. Under conditions where evaporation significantly exceeds precipitation, as it does in North Dakota, capillary attraction may significantly increase the effective depth of operation or evapotranspiration to as deep as 40 ft (Bolt, 1976). Capillary attraction may be responsible for the nearly constant concentrations of pore water and soluble salts between 10 and 30 or 35 ft at Gascoyne.

The highest specific conductances associated with

TABLE 11.—*Composition of saturation extracts*

[Tabulated data are from cores representative of the Bullion Creek Formation in the Gascoyne area. Cation exchange capacities tabulated as "DEN" were determined by the U.S. Geological Survey, National Water Quality Laboratory, Denver, Colo., using cessium-137 (U.S. Geological Survey Bulletin 1140-B); cation exchange capacities tabulated as "NDSL" were determined by R. L. Houghton using procedures outlined by Sandoval and Power (1977). The textural classification was determined using standard sieve methods: L, loam; SiC, silty clay; SiS, silty sand; SSi, sandy silt. μmho/cm at 25 °C, micromhos per centimeter at 25 degrees Celsius; meq/100 g, milliequivalents per 100 grams; meq/L, milliequivalents per liter; < indicates less than]

Depth below land surface (feet)	Texture	Cation exchange capacity (meq/100 g)		Exchangeable cations (meq/100 g)				Paste pH	Saturation percentage (weight percent)	Saturation extract								
		DEN	NDSL	Na	K	Ca	Mg			Specific conductance (μmho/cm at 25 °C)	Sodium-adsorption ratio	Ca	Mg	Na	CO_3	HCO_3	Cl	SO_4
												(concentrations in meq/L)						
Core 130-099-03BBA																		
1- 2	L	3.6	33	7.4	0.56	9.2	10	8.0	62	9,581	13.5	18.8	51.4	80.2	0	2.6	0.3	148
5- 6	SiS	2.4	22	3.53	.38	7.4	13.5	8.0	32	10,140	14.0	19.1	52.2	83.5	0	1.8	.3	162
8- 9	SiS	2.8	26	4.05	.45	6.0	9.9	7.96	34	11,420	15.1	21.6	58.9	96.0	0	2.2	.3	180
15- 16	SiS	1.48	13.3	4.01	.44	5.1	5.2	7.79	30	7,470	12.6	14.2	38.3	64.2	0	1.4	.2	119
20- 21	SiS	1.2	9.2	3.31	.33	3.3	3.3	7.92	32	6,650	11.7	11.9	32.1	55.3	0	1.1	.1	109
24- 25	SiS	1.1	9.0	3.22	.32	3.2	3.3	7.76	33	4,580	6.9	10.2	27.6	29.9	0	1.1	.1	75
30- 31	SiS	1.5	13	2.23	.28	5.4	6.7	7.98	33	3,290	5.5	8.1	21.8	21.3	0	1.1	.1	51
36- 37	SiS	1.5	13	1.24	.42	7.8	5.1	7.98	34	4,770	8.5	9.5	25.6	35.7	0	1.1	.1	78
40- 41	SiS	1.4	12.7	.19	.11	7.7	6.1	8.23	30	2,460	6.1	5.2	14.0	18.9	0	1.3	<.1	38
43- 44	SiS	1.2	11	.10	.08	8.5	3.2	8.44	27	2,190	8.0	3.5	9.5	20.4	0	2.3	<.1	33
50- 51	SiS	1.3	11	.13	.06	5.5	6.6	8.80	31	2,140	8.4	3.2	8.8	20.6	0	2.6	<.1	32
55- 56	SiS	2.2	20	.24	.13	13.3	8.3	8.48	31	1,660	9.9	1.9	5.3	18.8	0	3.1	<.1	23
60- 61	SiC	2.0	18	.32	.18	9.6	10	8.71	98	2,120	8.4	3.1	8.4	20.2	0	1.0	<.1	34
64- 65	SiC	2.7	24	.31	.21	12	14	8.82	96	1,840	18.5	1.1	2.9	26.2	0	.8	<.1	27
70- 71	SiC	2.5	23	.28	.19	12	13	8.63	102	3,660	22.0	2.6	6.9	48.0	0	6.6	<.1	51
75- 76	SiC	2.0	18	2.6	.63	7.9	---	---	104	2,270	19.8	1.3	3.5	30.6	0	2.0	<.1	34
80- 81	SSi	1.1	10	2.5	.61	7.5	---	---	37	5,110	29.9	2.9	8.0	69.9	0	19.8	.2	60
85- 86	SSi	2.9	26	.3	.19	13	---	---	39	5,240	30.2	3.0	8.1	71.2	0	17.3	.1	65
90- 91	SSi	3.0	27	.20	.13	14	---	---	41	4,380	31.1	1.9	5.2	58.5	0	3.2	<.1	69
95- 96	SSi	3.1	28	.30	.22	14	---	---	35	1,850	23.7	1.0	2.2	30.0	0	1.9	<.1	23
100-101	SSi	3.1	28	.28	.19	14	---	---	38	2,220	19.6	1.0	2.6	26.3	0	4.9	<.1	35
105-106	SSi	3.3	29	.34	.26	15	---	---	41	5,810	36.3	2.7	7.3	81.2	0	1.4	<.1	90

saturation extracts obtained by either method were from samples just below the root zone, or about 10 ft (fig. 37). Large concentrations of evaporative salts commonly are present at this depth (fig. 37). Iron sulfide concentrations in unoxidized sediments at depth would be insufficient to generate the observed quantity of sulfate minerals or dissolved ground-water sulfate. In fact, if all the sulfide present in the unsaturated Bullion Creek strata were converted to sulfate, it would not account for the presently observed concentration of gypsum. For example, at site 130-099-03BBA, the water table is approximately 38 ft below the surface. Based on the data presented in table 11, the mean concentration of extractable sulfate in this interval is approximately 5.53 mg/cm^3. If a surface area of 1 cm^2 arbitrarily is chosen for consideration, the total volume of the soil column would be 1,160 cm^3. Thus, the column would contain 6.41 g of extractable sulfate, principally as gypsum. Total sulfur analyses for unweathered Bullion Creek sediments average 0.1 weight percent (Groenewold and others, 1983). Thus, pyrite was undetectable in most X-ray diffraction analyses summarized in table 3. The column of 1,160 cm^3 may be considered to have a mean bulk density of 1.8 g/cm^3 and therefore would have a weight of 2,090 g, about 2.09 g of which occurs as sulfide minerals. Thus, insufficient sulfide minerals currently exist to account for coexisting sulfate minerals. Similarly, the saturated thickness at 130-099-03BBA is about 52 ft. With a mean porosity of 30 percent, and a ground-water sulfate concentration of 4,580 mg/L, the saturated column would contain 2.18 g of sulfate, just slightly more than could be generated from the available sulfide minerals alone.

The source of this excess gypsum is uncertain. One possible source for the excess sulfur is the Paleocene strata which have been removed by erosion in the last 40 million years. In the vicinity of the mine, approximately 250 ft of Sentinel Butte sands are absent. Based on the average iron sulfide content of the Sentinel Butte Formation, about 200 ft of the formation would have to contribute sulfur to explain the observed sulfate zone. Heavy minerals such as pyrite are concentrated as soil lag deposits during erosion (Reineck and Singh, 1980). Over the years, oxidation of iron sulfides exposed at the surface generate sulfate which is concentrated at the base of the root zone by evapotranspirational processes. As evaporation exceeded precipitation for much of the Tertiary, only a fraction of the deposited gypsum

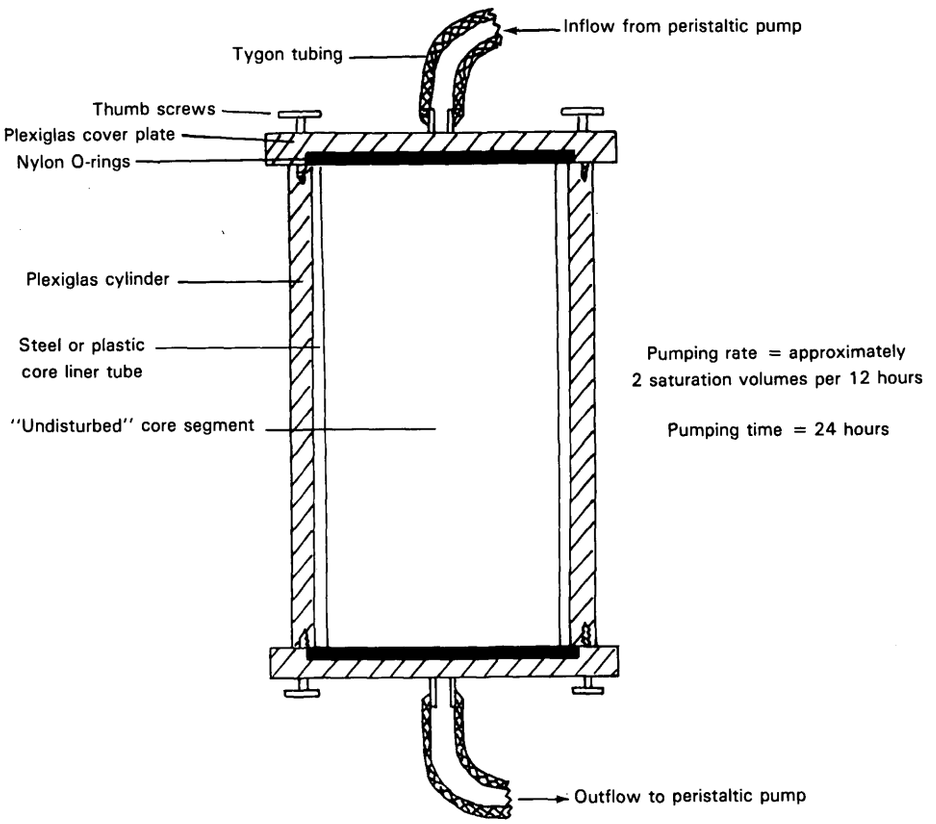


FIGURE 36.—Design of apparatus for experimental soil-leaching studies.

would dissolve during infiltration events. Accumulated sulfate salts would move downward with erosion and become increasingly concentrated to produce the gypsiferous horizons which occur today. Another source that might contribute to excess gypsum levels is wind-blown dust from areas of gypsum precipitation from saline seeps such as occur south of the mine.

The extremely high sulfate concentration of most pore waters and many ground waters (>15 meq/L) in the study area indicates a sink for calcium permits dissolution of large quantities of gypsum. The most likely calcium sink is cation exchange.

CATION EXCHANGE

Clay minerals typically have significant amounts of adsorbed cations on their surfaces with cation concentrations in equilibrium with contacting water. If the composition of the contacting water changes, the clay will exchange cations with the water until it achieves new equilibria (Langmuir, 1918; Kerr, 1928; Vanselow, 1932; Helferich, 1962). The adsorptive capacity of a clay is largest for expandable clay minerals like the smectites and less for fixed-structure clay minerals like illite

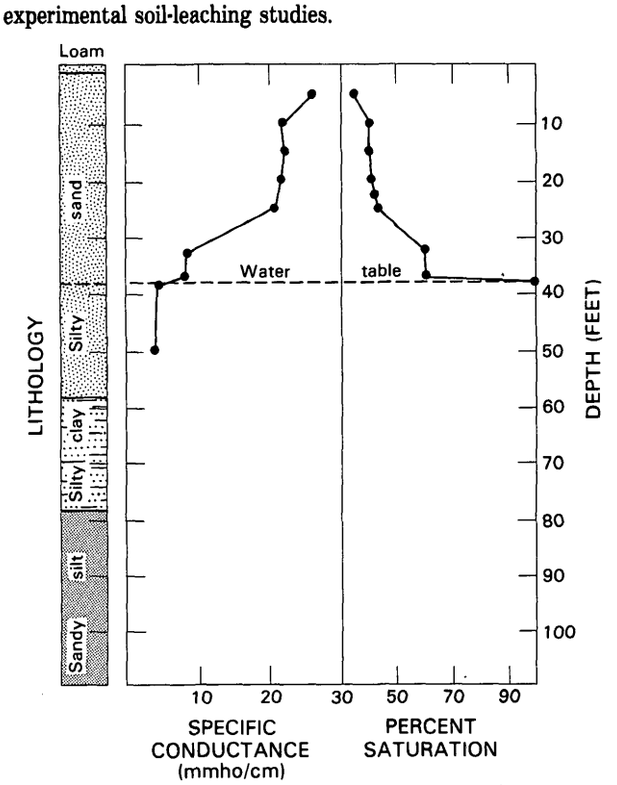


FIGURE 37.—Variation of saturation percent and pore-water specific conductance with depth in core 130-099-03BBA.

(Marshall and Krinbill, 1942; Grim, 1968; Grimshaw, 1971). As cation exchange could provide the additional sink for calcium required to explain the high bicarbonate and sulfate concentrations of pore waters and saturation extracts, cation-exchange capacity (CEC) and cation-selectivity coefficients (CSC) were determined for all represented lithologies and depths.

Laboratory column experiments of cation-exchange capacity have been subject to extensive criticism because of nonuniform packing of sediment in the columns (James and Rubin, 1979). Accordingly, in cooperation with scientists of the U.S. Agricultural Research Service, Northern Great Plains Research Center, a unique column was developed for this investigation to accommodate undisturbed core segments. Water-saturated core segments should more closely approximate the sediment surface area actually in contact with aquifer water than disaggregated and repacked material. As cation-exchange capacity is a function of exchangeable surface area, this experimental configuration should more precisely simulate natural conditions. Remaining experimental procedure was consistent with that of Sandoval and Power (1977). Cation-exchange data obtained using this column are slightly lower than results from traditional columns of packed, disaggregated material, probably reflecting lower available surface area. However, trends and selectivity coefficients determined by the two methods are proportional, indicating the experimental procedure is reliable.

About 50 percent of the clay minerals in the Bullion Creek Formation of the study area are smectites and mixed-layer clay minerals with high cation-exchange capacities in the range of 10 to 35 meq/100 g of dry sediment. Above 15 ft, clay minerals in the strata are saturated with alkaline earths. With depth, the percentage of exchange sites occupied by sodium increases; but below the water table, sodium is nearly absent as an exchangeable cation (fig. 38).

Thus, cation-exchange reactions in the Bullion Creek sands and silts are dominated by the following reaction:

$$Ca^{2+} + 2NaX \rightarrow 2Na^{+} + CaX$$

where NaX and CaX represent cations in the adsorbed state. Cation selectivity coefficients for Ca^{2+} relative to Na^{+} are defined as

$$K_{Na^{+}}^{Ca^{2+}} = \frac{[CaX]\ [Na^{+}]}{[NaX]\ [Ca^{2+}]^{1/2}},$$

where

[CaX], [NaX] are activities of calcium and sodium on the ion exchanger and

[Na^{+}], [Ca^{2+}] are equilibrium activities of the ions in the aqueous phase (Gapon, 1933).

To calculate selectivity coefficients, equilibrium activities were computed for exchange solutions using WATEQF (Plummer and others, 1978). Selectivity coefficients range from 1.2 to 84 with a mean value of 13.9 (for solutions with equal concentrations of calcium and sodium, table 12), indicating exchange of calcium for sodium is strongly favored. In general, the selectivity coefficients are consistent with the replaceability series of Gedroiz (1922), with the clay minerals favoring calcium over magnesium, magnesium over potassium, and potassium over sodium. Accordingly, replacement of sodium by calcium is the most strongly favored exchange. Only when magnesium concentrations exceeded twice the calcium concentration, such as characterize some near-surface pore waters, was exchange by magnesium favored over calcium.

Clay minerals are not the only components of Bullion Creek strata possessing appreciable cation-exchange capacity. Organic compounds in soil and clay or lignite zones may have large exchange capacities (Malquori, 1944; Francis, 1949; Whitehurst, 1978). Organic ligands also have a high adsorptive capacity (Bolt and others, 1976). Highest cation-adsorption capacities for lignin are exhibited under basic conditions. It is believed that the pH dependence of this process reflects an increased loss of volatile aromatic organic compounds from the lignite structure at high pH values (Godwin and Manahan, 1979). The severing of volatile compounds from lignite structures increases the number of sites available for adsorption.

Cation-exchange experiments indicate the combined cation-adsorption and cation-exchange capacity of the Harmon lignite bed is one to two orders of magnitude greater than that of the Bullion Creek clays (tables 10 and 11). Lignite exchange sites still contain abundant exchangeable sodium, suggesting adsorption sites are filled first. Organic leaching of soluble aromatic-aliphatic organic compounds from the lignite, after the method of Frizado (1979), reduced the exchange capacity of one lignite core by half, indicating these humic compounds are responsible for most of the adsorptive sites.

Combined cation exchange and adsorption on clays and organic compounds account for the increasingly sodic nature of infiltrating pore waters with depth.

GROUND-WATER QUALITY

Only wells cased with PVC, packed with silica sand around screened intervals, and sealed with low-sodium cement or a plastic packer (fig. 31) were sampled for water quality. Sampling was achieved using air-squeeze or gas-reciprocating pumps after evacuating the well of ten times its standing volume of water. After 1979,

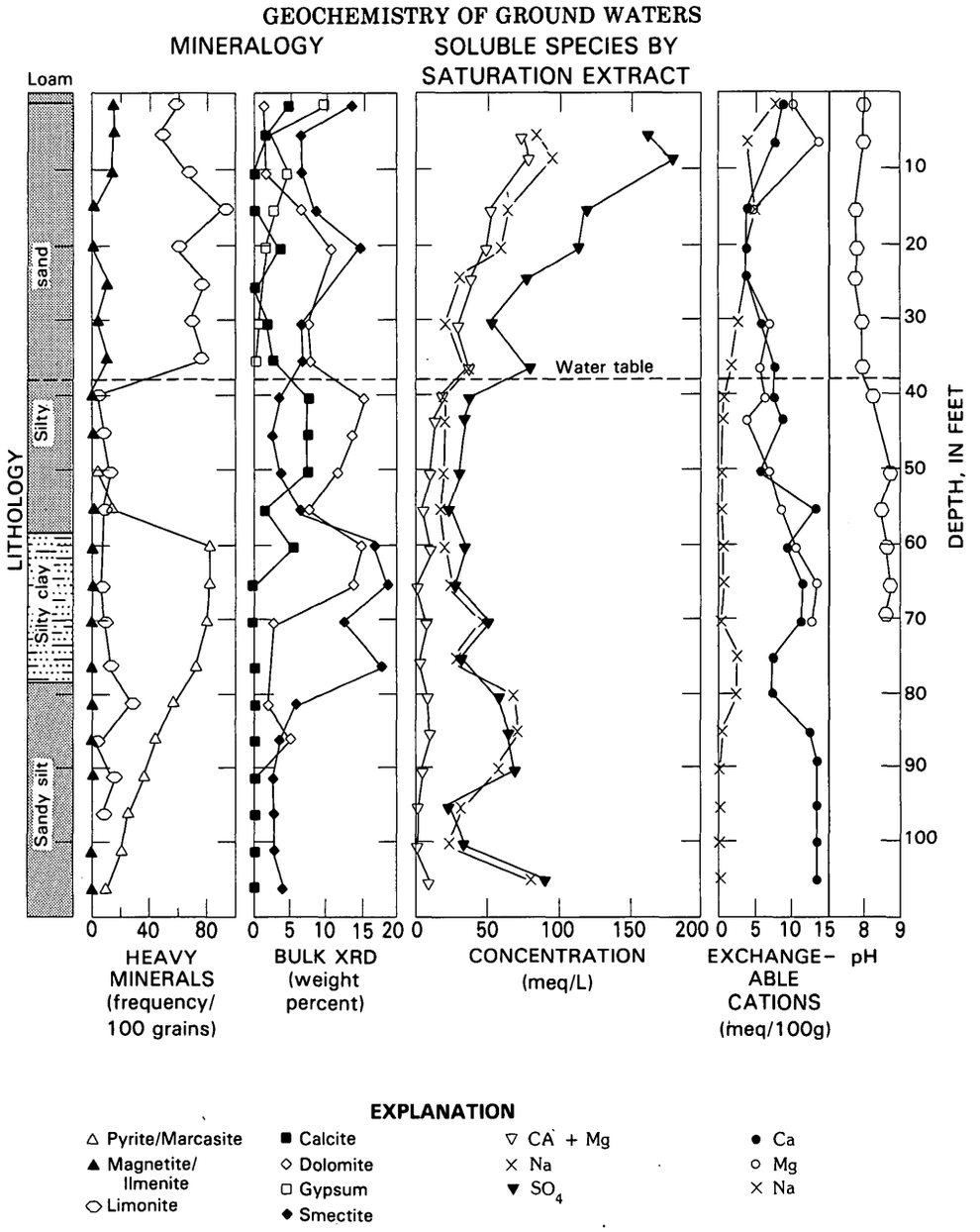


FIGURE 38.—Availability of exchangeable cations and leachable salts with depth in core 130-099-03BBA.

temperature, pH, specific conductance, and dissolved oxygen levels were measured using down-hole probes prior to sampling. Field alkalinity was determined by incremental titration using procedures outlined by Yurewicz (1981). Sulfate, sulfide, nitrate, nitrite, ammonia, and carbon dioxide concentrations were also determined in the field using ion-selective electrode methodology (Covington, 1979).

Additional samples for dissolved gases in ground water were collected and analyzed by the method described by Hobba and others (1977). The results of these analyses are presented in table 13.

Nearly all the waters analyzed were anoxic or very slightly oxygen bearing. Exceptions all occurred in wells emplaced in channel sands. Dissolved carbon dioxide concentrations were surprisingly low, corresponding to partial pressures ranging from 2×10^{-4} to 5×10^{-3} atmospheres. Apparently free carbon dioxide absorbed in the soil zone by recharge water or degassed from lignitic material is almost completely converted to the bicarbonate ion in the ground waters. Sulfide levels in the ground waters were highly variable, ranging from 0 to 12 mg/L. The strong hydrogen sulfide gas odor emanating from some waters indicates sulfate reduction is occurring, but no confirming evidence was found.

Major year-to-year changes in the composition of ground water from some wells has occurred. Additionally, significant geographic variation in aquifer water

TABLE 12.—*Cation-selectivity coefficients measured for the Bullion Creek Formation*

Location	Sample depth (feet below surface)	Cation selectivity coefficients calculated for the ionic ratios indicated in reacting solutions							
		Ca^{2+}/Na^{+} 0.20	Ca^{2+}/Na^{+} 1.1	Ca^{2+}/Na^{+} 2.3	Ca^{2+}/Na^{+} 4.4	Ca^{2+}/Na^{+} 6.3	Mg^{2+}/Na^{+} ($Mg^{2+}>Ca^{2+}$) 1.1	Mg^{2+}/Na^{+} ($Mg^{2+}<Ca^{2+}$) 1.1	Ca^{2+}/K^{+} 1.1
131-099-27DDD[1]	0- 5[2]	1.1	1.2	0.8	0.9	1.1	1.1	1.2	1.0
	35- 40	7.1	9.5	11.5	22.7	63.2	7.4	2.1	14.6
	40- 45	10.4	14.9	13.5	12.0	10.2	9.3	2.3	16.2
	55- 60	10.5	13.7	25.1	—	42.3	8.8	2.6	21.7
	65- 70	5.7	7.0	9.7	5.7	2.9	5.1	1.9	9.3
	110-115	12.5	13.8	16.2	23.3	22.5	10.0	3.6	15.4
	115-120	3.0	2.2	2.0	2.2	2.1	1.7	1.1	2.1
131-099-23ABD1[3]	5- 18	6.5	8.7	10.8	22.2	51.4	6.6	2.0	10.6
	18- 21	6.3	8.5	10.2	22.6	57.3	6.4	2.5	11.2
	21- 24	5.9	8.2	10.5	21.7	48.2	6.5	2.2	10.6
	24- 27	6.2	8.2	9.9	22.0	53.3	6.3	2.5	11.1
	27- 30	6.5	8.4	9.5	22.4	50.6	6.1	2.2	10.7
	30- 33	6.0	8.3	10.3	22.2	51.1	6.6	2.3	10.8
	33- 36	6.1	8.5	9.7	22.3	53.4	6.2	2.2	10.3
	36- 39	5.8	8.5	10.4	22.4	53.9	5.9	2.4	11.0
	39- 42	8.2	9.7	11.2	22.8	58.6	6.5	3.2	25.4
	42- 45	8.9	13.2	15.6	27.5	58.1	6.6	.4	18.5
	45- 48	8.4	13.6	12.8	30.7	52.4	6.8	.8	20.2
	48- 51	10.3	14.8	25.2	34.1	49.9	7.8	.6	17.3
	51- 54	11.5	12.8	18.4	29.6	50.3	8.2	.6	22.2
	54- 57	11.3	15.5	27.2	33.8	49.1	8.8	.8	24.6
	57- 60	10.8	15.1	22.6	24.8	36.1	9.4	.4	18.2
	60- 63	9.3	11.6	14.2	11.8	18.6	11.4	.4	9.7
	63- 66	8.5	12.6	10.7	9.9	9.8	9.9	.7	10.5
	69- 72	7.7	10.7	7.9	7.5	3.3	13.6	.5	9.2
	72- 75	8.8	13.6	11.1	15.6	12.4	10.0	.6	15.3
	75- 78	9.6	14.2	8.5	22.6	21.7	9.4	.3	13.2
	78- 80	10.2	12.7	12.6	28.6	22.4	9.7	.6	11.9
	80- 83	13.4	13.8	13.2	19.4	24.7	10.1	.2	12.5
	84- 87	9.9	14.4	11.8	26.3	29.1	10.0	.6	16.7
	90- 93	11.6	12.9	12.1	39.5	26.2	13.8	.5	15.0
	93- 96	14.9	13.6	10.9	29.9	24.6	11.4	.8	16.3
	100-103	13.6	15.2	12.6	32.3	25.2	11.8	.3	18.3
	130-133	4.3	2.8	9.2	2.2	2.1	3.6	.5	8.3
	150-155	3.6	2.2	5.8	3.1	2.8	4.4	.9	7.7
	177-180	3.9	2.7	6.6	2.8	3.7	3.0	.4	8.3
130-099-01ABB[3]	20- 25	11.1	84	74.9	27.9	17.4	93.6	.2	13
130-099-03ABB[3]	20- 25	12.6	68.2	88.4	59.2	26.6	81.0	.4	98.5

[1]Analyses by M. E. Crawley on drill cuttings.
[2]This zone is near exchange equilibrium.
[3]Analyses on core samples.

quality is exhibited by each aquifer. Nevertheless, some fairly well defined compositional trends are evidenced. For convenience, ground-water compositions from wells screened in the Harmon lignite aquifer (Supplement 2), the confined basal Bullion Creek–Slope aquifer (Supplement 3), the unconfined basal Bullion Creek–Slope aquifer south of the lignite outcrop line (Supplement 4), and continuations of the Harmon lignite aquifer reestablished in the spoils (Supplement 5) are presented and discussed separately.

WATER QUALITY IN THE HARMON LIGNITE AQUIFER

Ground water in the Harmon lignite aquifer predominantly is sodium sulfate-bicarbonate in type (fig. 39), with dissolved-solids concentrations ranging from 575 to 8,740 mg/L. Highest solute concentrations occur along the outcrop line of the lignite bed. Lowest solute levels occur beneath channel sands exposed to the surface. Alkalinities are nearly uniform throughout the aquifer.

Saturation indices for minerals in contact with the lignite waters were calculated using WATEQF (Plummer and others, 1978). Selected results are presented in table 14. In general, waters of the lignite aquifer are slightly oversaturated with quartz, calcite, and dolomite and slightly undersaturated with gypsum and other sulfosalts. However, along the outcrop line, lignite waters may approach saturation or even be slightly oversaturated with gypsum.

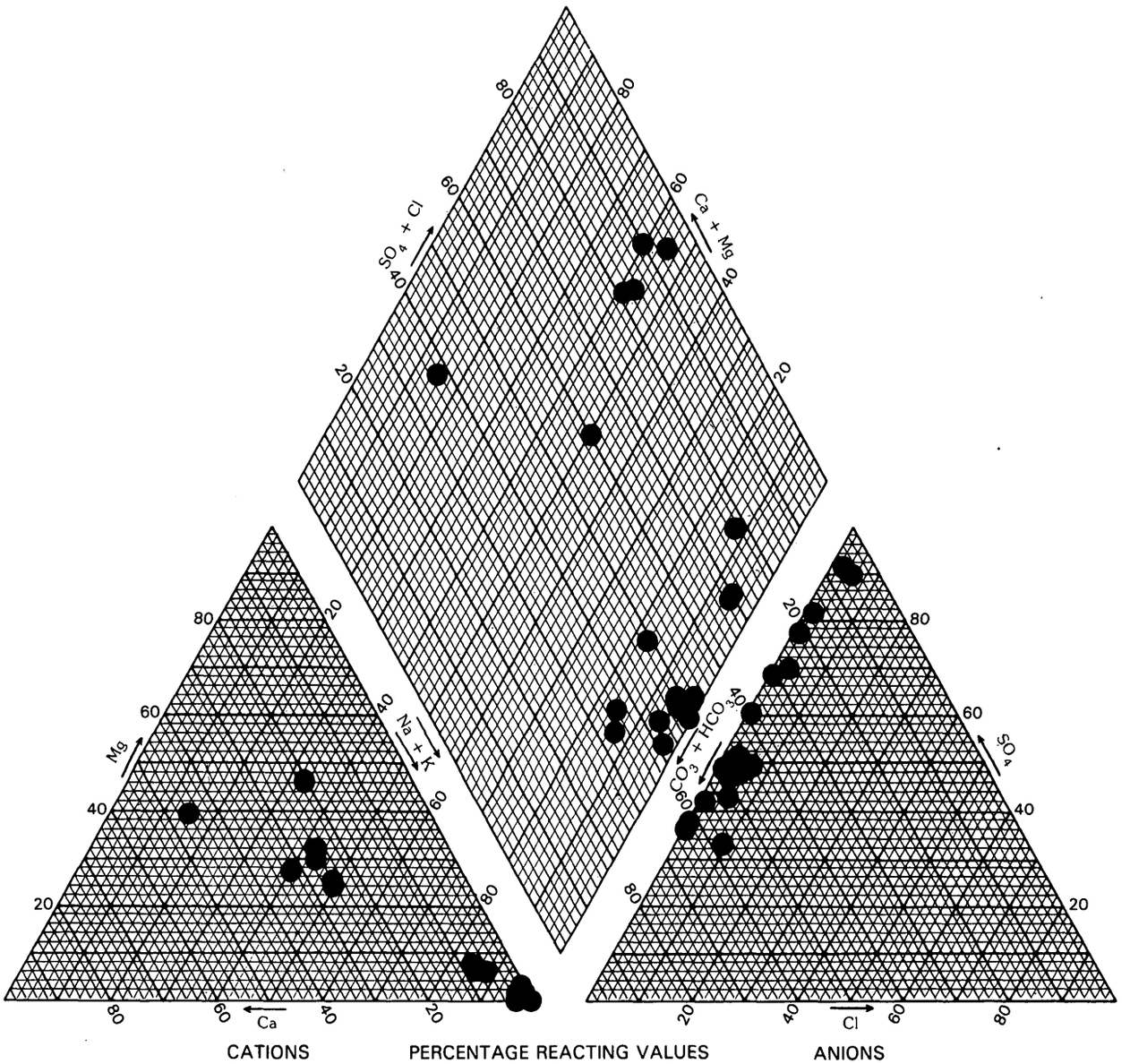


FIGURE 39.—Piper diagram of water quality in the Harmon lignite aquifer.

TABLE 13.—*Dissolved-gas concentrations in ground water, September 1976*

[Aquifer code 125TRVL indicates the basal sandstone of the Bullion Creek Formation; code 125HRMN indicates the Harmon lignite bed of the Bullion Creek Formation. < indicates less than]

Well number	Aquifer	Depth of well (feet)	Temperature (degrees Celsius)	N_2	O_2	Ar	CH_4	CO_2
				(milligrams per liter)				
130-099-03ADD	125TRVL	64	11.6	37	1.0	1.53	0.01	0.5
131-099-26ADA	125HRMN	120	9.4	24	<.02	.93	.01	1.8
131-099-27DDD1	125TRVL	112	10.8	30	<.02	1.03	.02	2.3
131-099-29ADD1	125TRVL	118	12.6	24	<.02	.91	.01	2.2
131-099-32DBC	125TRVL	30	15.2	36	<.02	.58	.01	8.4
131-099-33BAA1	125TRVL	150	11.2	42	.11	.77	.01	<.05
131-099-33BAA2	125HRMN	90	9.2	31	<.02	.92	.02	.02
131-099-33DAD2	125TRVL	82	9.8	25	<.02	.90	.01	12

TABLE 14.—*Saturation indices for aquifer waters with respect to naturally occurring minerals calculated by WATEQF*

[Negative saturation indices indicate undersaturation and positive values indicate saturation. Aquifer code 125HRMN indicates the Harmon lignite bed of the Bullion Creek Formation; code 125TRVL indicates the basal sandstone of the Bullion Creek Formation]

		Log ion activity product/equilibrium constant								
Well number	Aquifer	Anhydrite	Gypsum	Mirabilite	Calcite	Aragonite	Dolomite	Siderite	Quartz	Calcium smectite
131-099-26ADA	125HRMN	-1.93	-1.56	-3.74	0.51	0.20	1.01	-11.62	0.34	4.01
131-099-33BAA2	125HRMN	-1.65	-1.29	-3.66	1.15	.84	.17	-19.24	.22	-2.40
130-099-03ADD	125TRVL[1]	-1.67	-1.32	-2.74	.17	-.13	.93	-14.14	.42	-.82
130-099-04BAA	125TRVL[1]	-.71	.32	-3.20	-.25	-.57	-.51	-10.57	.63	5.17
131-099-27DDD1	125TRVL[2]	-2.60	-2.24	-4.90	.70	.40	1.08	-11.22	.39	3.19
131-099-29ADD1	125TRVL[2]	-2.52	-2.18	-4.41	.37	.08	.70	-11.81	.32	1.72
131-099-32DBC	125TRVL[1]	-1.26	.95	-4.26	.79	.51	1.31	-10.86	.33	2.45
131-099-33DAD2	125TRVL[1]	-.41	.05	-2.04	.59	.29	1.24	-11.32	.75	---
131-099-27BBC1	Spoils	-.36	.46	-2.41	.54	.33	1.28	-13.12	.62	5.39

[1]Installed in the unconfined part of the basal Bullion Creek-Slope aquifer.
[2]Installed in the confined part of the basal Bullion Creek-Slope aquifer.

Between 1974 and 1981, ground-water quality upgradient from the mine and downgradient along the lignite outcrop line has remained relatively unchanged. However, within the mine area and immediately downgradient from it, deterioration in water quality has been observed. The pH of lignite waters in the immediate vicinity of active mine pits has decreased since 1976 but remains slightly basic (fig. 40). Similarly, sulfate concentrations downgradient but adjacent to active mine pits have increased by up to 25 percent (fig. 41).

WATER QUALITY IN THE CONFINED PART OF THE BASAL BULLION CREEK-SLOPE AQUIFER

Ground water in the confined part of the basal Bullion Creek-Slope aquifer primarily is sodium bicarbonate-sulfate in type (fig. 42). Dissolved-solids concentrations are less than in the overlying Harmon lignite aquifer, ranging from 653 to 2,570 mg/L (Supplement 3). However, alkalinities in the confined sandstone aquifer are nearly identical to those in the lignite aquifer, averaging only 1 meq/L higher. Chloride, fluoride, and boron levels are similarly higher in the sandstone aquifer; and calcium, magnesium, potassium, strontium, and sulfate are relatively enriched in the lignite aquifer.

Saturation indices for minerals observed to be present in the formation show the confined sandstone aquifer is slightly oversaturated with calcite, dolomite, and quartz and undersaturated with gypsum (table 14). Because of the transitional nature of the aquifer in the vicinity of the lignite outcrop line, no consistent pattern of compositional change toward the outcrop can be resolved. However, sulfate concentrations are greatest along the outcrop line.

Water in the confined part of the sandstone aquifer characteristically is deeply colored. A secchi disk lowered into a pail of water from a typical well in the aquifer became invisible after a submergence of 2 in. However, turbidity as measured nephelometrically proved to be an unreliable guide to the degree of coloration in a water sample. Nephelometric measurements on successive dilutions of sample water were observed to increase instead of decrease. This type of fluorescent response is characteristic of some groups of organic compounds. Thus, the source of the color is presumed to be organic matter leached from the overlying lignite during recharge. Dissolved organic carbon concentrations in the confined part of the sandstone aquifer have an observed mean of 38 mg/L, four times the mean of dissolved organic carbon concentrations in either the unconfined part of the aquifer or the lignite aquifer.

Chemical characterization of dissolved organic matter causing this coloration was attempted on a sample from 131-099-27DDD1 with only partial success. The sample had an initial dissolved organic carbon concentration of 165 mg/L. Adjusting sample pH to values greater than 10.5 or less than 6.5 caused precipitation of a dark-brown substance, leaving the water nearly clear. Analysis by electron impact gas chromatography mass spectrometry (GC/MS) of the organic constituents remaining in solution indicated the presence of 1.2 μg/L of 1,1'-oxybisethane; 1.0 μg/L of 2-ethoxy-benzothiazole; 1.6 μg/L of 3,7,11-tridecatrienenitrile, 4,8,12-trimethyl; and 30 μg/L of combined unidentifiable organic constituents. The remaining carbon apparently was precipitated during initial pH adjustments. Oil shale chemists frequently call this precipitate "leonardite" (Jerry Leenheer, U.S. Geological Survey, written commun., 1982), a term which should be avoided to prevent confusion with the geologists' term for oxidized lignite.

Reductive degradation of the precipitate responsible for coloration using sodium amalgam and hot water after the method of Burges and others (1964) followed by ether extraction permitted GC/MS analysis of 80 percent of the "leonardite." This analysis indicated the precipitate was composed of three general classes of organic compounds: (1) Simple organic compounds like

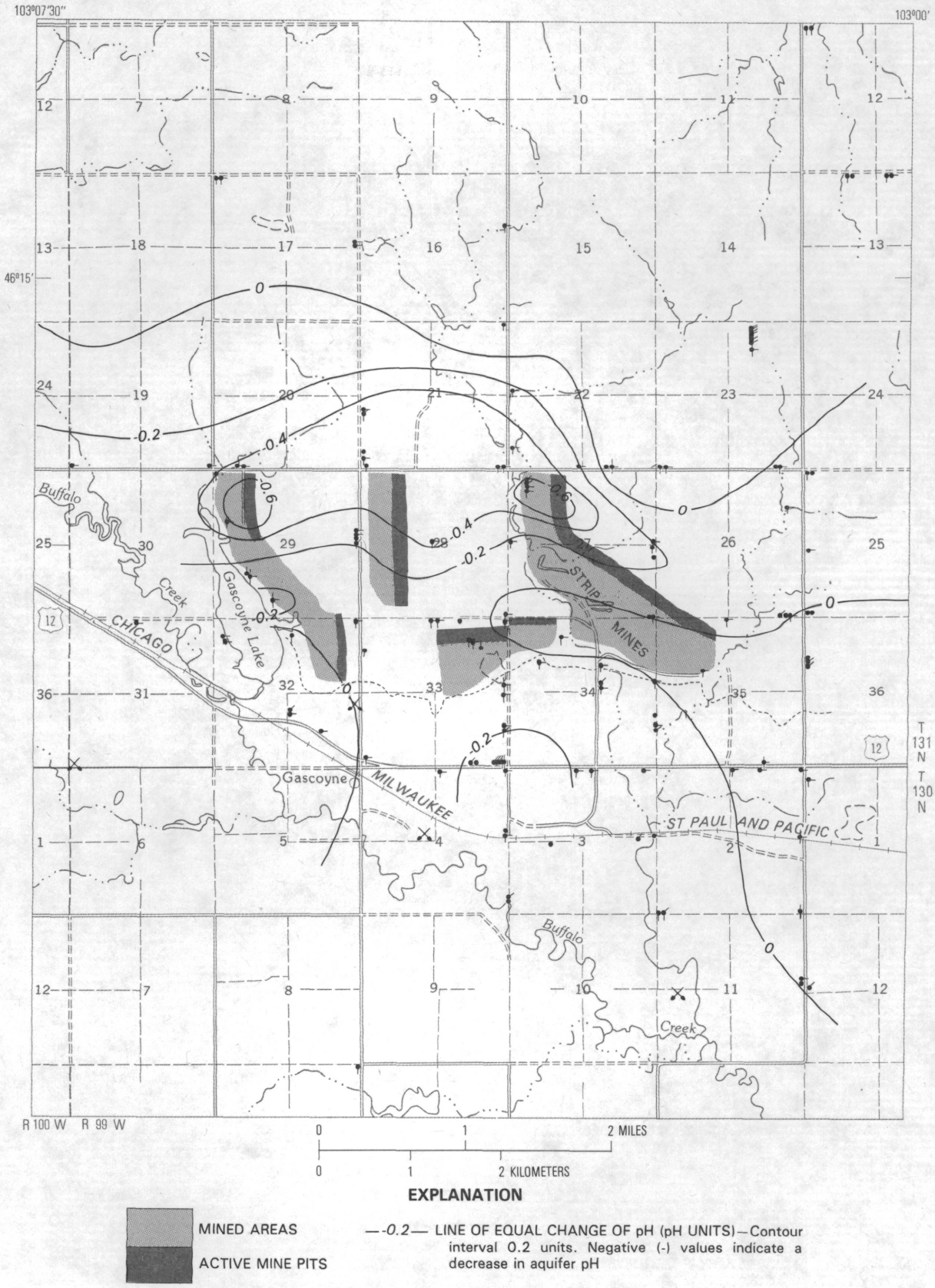


FIGURE 40.—Change in the pH in the Harmon lignite aquifer, 1976–81.

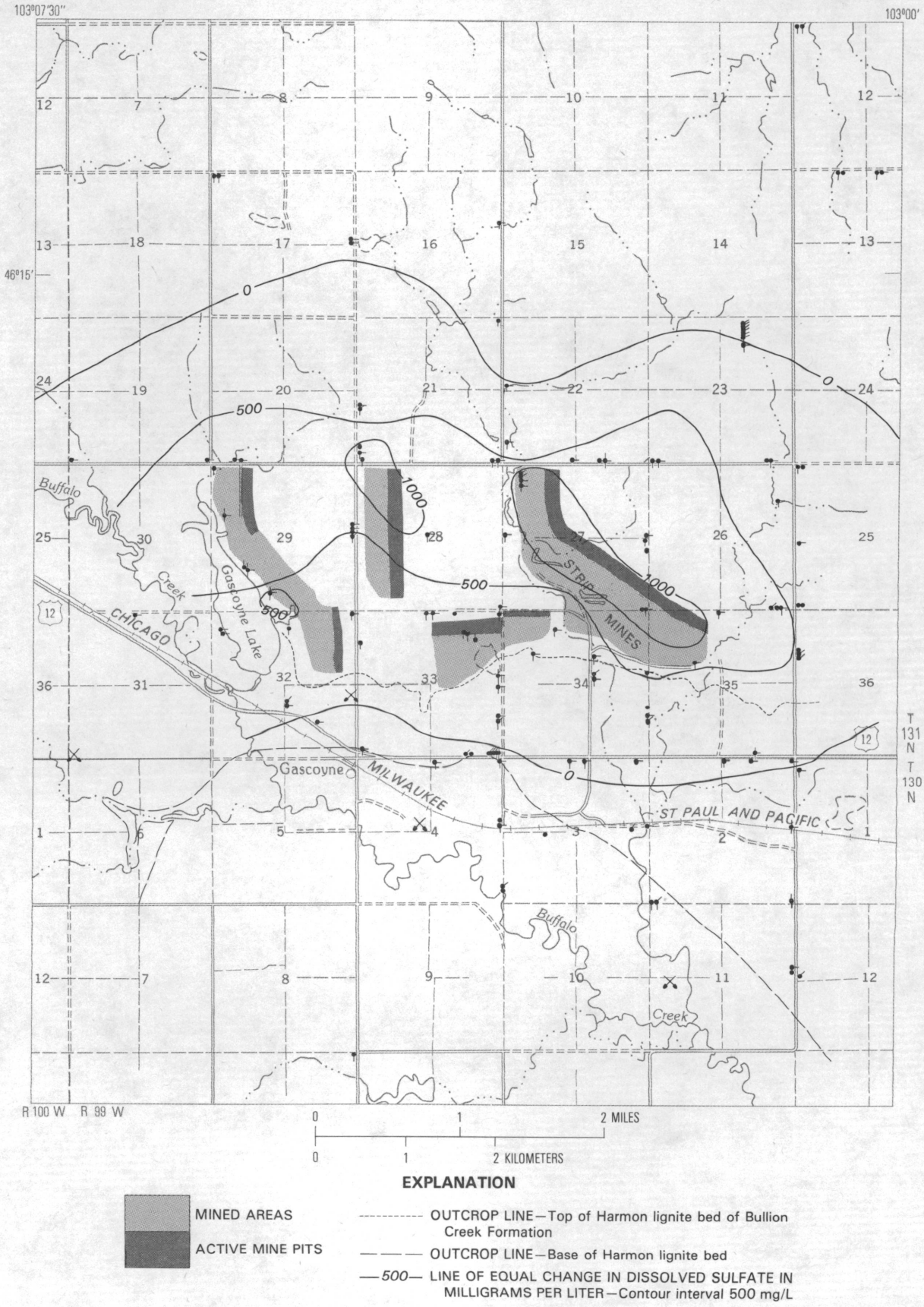


FIGURE 41.—Change in dissolved-sulfate concentration in the Harmon lignite and spoils aquifers, 1976–81.

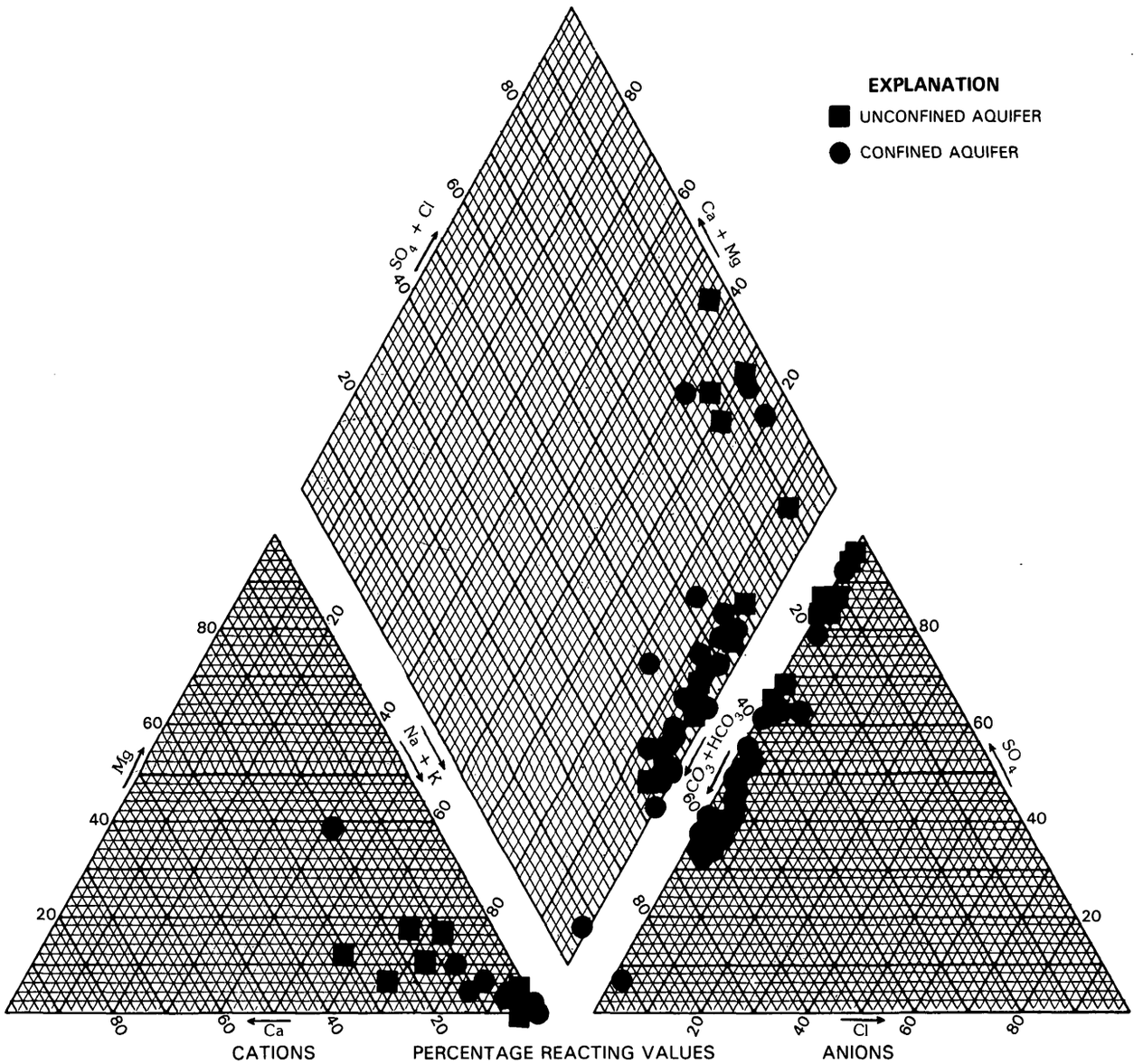


FIGURE 42.—Piper diagram of water quality in the basal Bullion Creek-Slope aquifer.

phenol and benzoic acid; (2) compounds with biologic precursors, including vanillic and substituted cinnamic acids which derive from lignin; and (3) complex organic compounds that cannot be directly related to biologic precursors, including methylhydroxy-benzenes. A similar suite of constituents was extracted from a sample of Wyodak coal from Gillette, Wyo., during oxidation experiments by Bimer and others (1978). The methylhydroxy-benzenes were the most abundant constituents present. Methoxyl groups usually occurred in the 3 position or the 3,5 positions on the benzenes, comparable to the position of methoxyl groups on lignins. This relationship would suggest that vitrinite, the principal maceral component of lignite, is the source of water coloration. Petrographic examination of highly oxidized lignite (leonardite) from along the crop line indicates extreme alteration of vitrinite macerals has occurred with complete destruction of fossil plant structure within macerals. The ease with which hydroxybenzenes may be oxidized may thus account for the rapidity of lignite weathering.

Volatilization of methoxyl groups from the benzenes composing vitrinite may account for some of the methane observed in soil gases. Loss of these methoxyl groups could also account for some of the relatively high adsorption-exchange capacity of lignites, a property which is observed to increase with lignite oxidation and methoxyl loss.

Between 1976 and 1981, ground-water quality over most of the aquifer's areal extent has remained relatively constant. However, beneath active pits, sodium (fig. 43) and sulfate (fig. 44) concentrations increased by up to an order of magnitude. Dissolved organic carbon concentrations also appear to have increased slightly, perhaps signalling increased oxidation of lignite in the vicinity of mine pits.

Similarly, the concentrations of chalcophila trace elements have increased adjacent to active mine pits. The elements displaying consistently significant enrichment (3–10 times) include cadmium, copper, iron, and zinc. Houghton (1982e) has suggested that these elements occur as substitutions for iron in pyrite and are released during pyrite oxidation.

WATER QUALITY IN THE UNCONFINED PART OF THE BASAL BULLION CREEK-SLOPE AQUIFER

Dissolved solids in the unconfined part of the basal Bullion Creek–Slope aquifer ranged from 781 to 7,790 mg/L. Waters range from sodium sulfate to sodium sulfate-bicarbonate in type (fig. 42). Solute concentrations are highest downgradient of the lignite outcrop line, but a large area of high dissolved-solids concentration exists adjacent to Buffalo Creek where the aquifer is close to the surface. Saturation indices (table 14) suggest the aquifer locally is saturated with gypsum as well as calcite, dolomite, and silica.

Adjacent to the lignite outcrop line, the unconfined lignite aquifer is enriched in boron, beryllium, and selenium. Similar enrichments produced during laboratory-accelerated weathering of lignite cores were reported by Houghton (1982e), suggesting these elements are released during oxidation of organic compounds. Hydroxybenzenes such as those identified in the "leonardite" fraction of dissolved organic carbon compounds are known to have strong capacities for chelating boron and certain other elements. Loss of chelated elements during lignite oxidation could account for the observed enrichments in boron and related elements. As hydroxy benzenes are extremely susceptible to degradation by oxidation, the reaction should proceed rapidly along the lignite crop line where the boron enrichments are observed.

Some ground water in the transitional part of the sandstone aquifer (such as that in well 130-099-02ABB) is characterized by unusually high pH (>10). Hydroxide alkalinity and high dissolved silica levels indicate silicate hydrolysis reactions contribute significantly to the observed composition of these strongly alkaline waters. WATEQF equilibrium calculations indicate the waters are in equilibrium with quartz and that $H_3SiO_4^-$ is an important anion species in these waters. The distribution of high pH waters appears to correlate with the occurrence of scoria in the overburden. Houghton (1982d) has described indications of extensive hydration of scoria slag in the Gascoyne area, such as the presence of zeolites in glass phases present in scoria. Houghton postulated the leaching of silica from scoria slag during hydration reactions could be the source of silica to silica-cemented horizons in the overburden commonly associated with scoriated areas. Hydrated slag also could be the source of silica for the high pH waters. Fluids resulting from interaction of recharge water with alkali or alkaline earth silicates such as scoria would be strongly alkaline as well as high in silica.

No significant change in the quality of the unconfined sandstone aquifer has been observed during the life of the investigation. An increase of less than 200 mg/L in dissolved-sulfate concentrations occurred in the unconfined sandstone aquifer between 1976 and 1981.

WATER QUALITY IN SATURATED SPOILS

Where reclaimed spoils have become resaturated, water quality generally is poor. Dissolved-solids concentrations ranged from 4,400 to 11,000 mg/L (Supplement 5), nearly double the salinity of the lignite aquifer before mining. Increases in sodium, calcium, sulfate, boron, strontium, lithium, and zinc concentrations are observed. Because infiltration from the surface through spoils is slow, most resaturation is due to lateral flow from the undisturbed lignite aquifer. The water quality of the saturated spoils primarily results from *in situ* chemical reactions and not from unsaturated zone processes as it was in the lignite aquifer. The principal source of solutes to the water in young saturated spoils is dissolution of soluble salts formerly concentrated beneath the root zone but emplaced at the base of the spoils during the stripping process. Accordingly, spoils waters commonly are saturated with gypsum (table 14) and characterized by relatively high calcium/sodium ratios (fig. 45). Eventually, this solute source will be solubilized and depleted. However, before that event occurs, infiltrating precipitation will introduce limited amounts of fresh solutes produced from new oxidized sulfide sources within the spoils pile. During the life of this investigation, no improvement in spoils-water quality has been observed. It is estimated that one pore-water volume must leach the spoils to return soil salt levels to their premine geochemical salt balance. Such leaching would require approximately 120 years given the average hydraulic conductivity and water storage of spoils. Transport of degraded aquifer water from the area would require even longer.

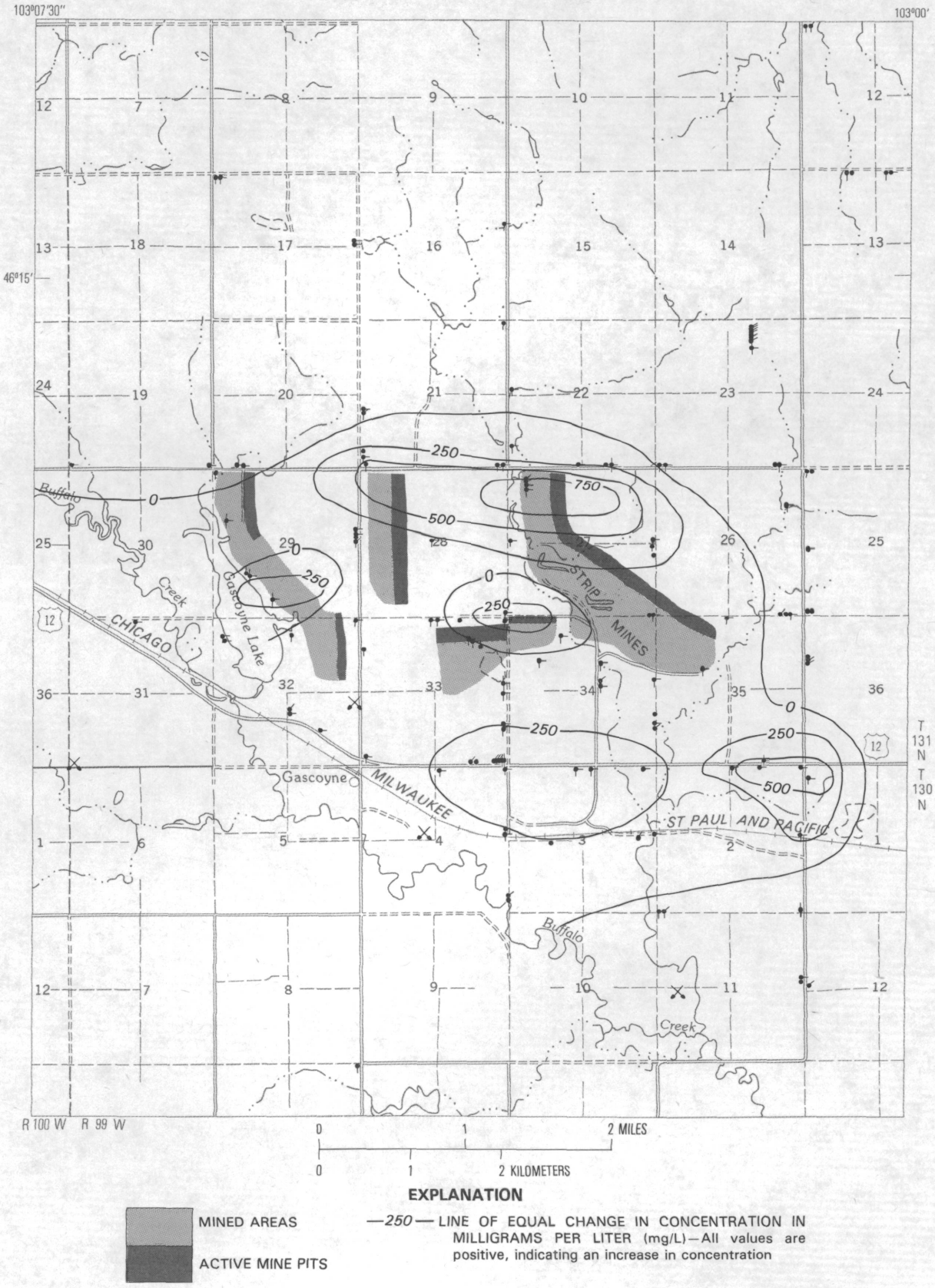


FIGURE 43.—Change in the sodium concentration in the basal Bullion Creek-Slope aquifer, 1976-81.

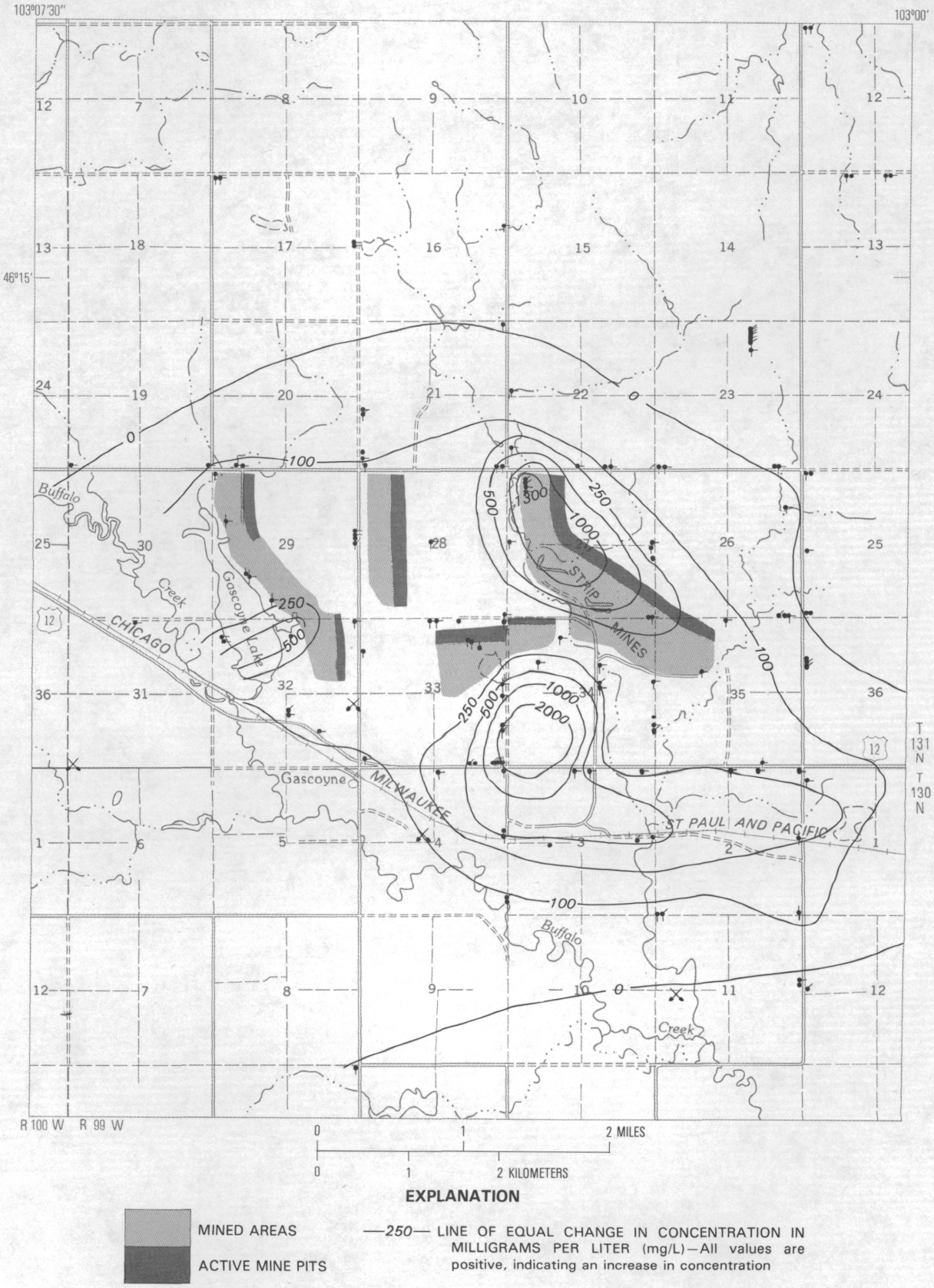


FIGURE 44.—Change in the dissolved-sulfate concentration of the basal Bullion Creek-Slope aquifer, 1976-81.

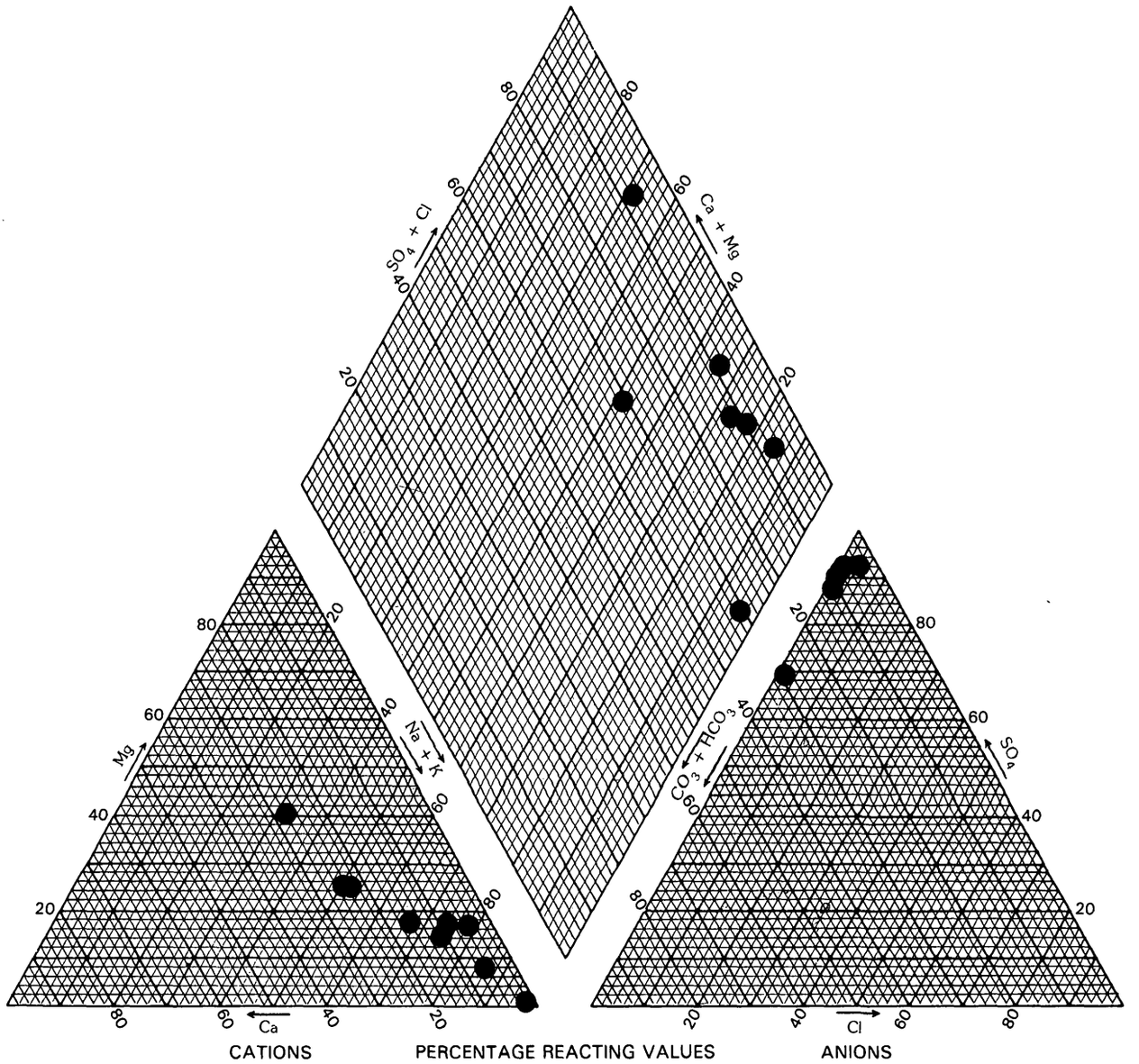


FIGURE 45.—Piper diagram of water quality in spoils.

Thus, the time necessary to reestablish the water quality in the aquifer is fairly large. This type of mining impact on water quality could be minimized by selectively replacing strata rich in soluble salts (usually the 5- to 10-ft layer immediately beneath the root zone) above the water table and isolated from clay-rich and organic-rich strata which might serve as a significant sink for calcium during reclamation. In this manner, the rate at which solutes entered the ground-water system would be limited by the relatively slow process of infiltration.

SURFACE-WATER QUALITY

The quality of surface waters in the area varies considerably with the rate of flow (tables 15, 16). During snowmelt periods when flow rates are relatively high, water quality in Buffalo Creek tributary (06355310) downstream from the mine generally is acceptable, with the dissolved-solids concentration less than 2,000 mg/L. When flow consists mainly of non-snowmelt surface runoff, the dissolved-solids concentration of the tributary is as much as 5,000 mg/L, approximately 40 percent of which is attributable to sulfate. Calcium is the dominant cation. During low-flow periods when flow is maintained by ground-water discharge, dissolved-solids concentrations may exceed 7,000 mg/L, with sodium and sulfate the dominant dissolved ions. At such times, the water may be at or near saturation with gypsum and mirabilite.

Significant amounts of particulate coal are washed from spoil banks and mine roads during runoff events

TABLE 15.—*Quality of flowing surface waters in the study area*

[Analyses not indicated otherwise were performed by the U.S. Geological Survey National Water Quality Laboratory, Denver, Colo. μmho/cm, micromhos per centimeter at 25 degrees Celsius]

Sampling date	Instantaneous streamflow (cubic feet per second)	pH	Specific conductance (μmho/cm)	Concentrations of dissolved constituents in milligrams per liter									
				Ca	Mg	Na	K	SO_4	Cl	F	Alkalinity	SiO_2	Dissolved solids
06355270 Buffalo Creek near Scranton													
03/09/77	5.4	7.9	1,210	40	31	200	9.4	420	6.8	0.1	219	9.4	895
09/12/77	.15	8.3	11,400	80	320	1,500	21	4,285	14	.4	320	13	6,680
03/29/78	5.8	7.2	126	10	4.5	6.7	7.4	18	2.6	.1	44	7.7	84
09/26/78	.25	8.4	8,560	71	98	1,350	18	3,110	13	.5	280	14	5,040
04/08/79	3.2	8.1	1,100	49	27	160	5.7	330	4.1	.2	250	10	768
09/22/79	.10	8.4	11,100	91	169	1,700	9.9	4,100	16	.6	335	11	6,550
04/07/80	6.4	7.6	474	30	16	50	5.9	75	2.0	.1	170	7.4	290
10/01/80	.13	8.3	12,300	95	210	1,850	10	4,550	21	.6	360	13	7,250
05/03/81	2.1	7.8	1,535	53	49	260	9.8	310	3.8	.3	600	5.6	1,050
05/31/81	2.3	7.9	1,410	43	43	230	8.6	280	4.8	.2	470	7.8	900
10/01/81	.17	8.4	11,800	110	570	2,000	35	6,400	54	.4	500	.4	9,910
06355280 Buffalo Creek near Tipton Ranch													
10/01/81	.20	8.3	9,290	105	360	1,600	26	4,390	52	.6	610	1.8	7,180
06355290 Buffalo Creek Tributary No.1 north of Gascoyne Lake													
10/01/81	.20	8.1	8,910	25	280	1,410	21	3,590	31	.7	510	.9	5,890
06355300 Gascoyne Lake at Dam													
04/23/74[1]	—	8.4	2,770	89	55	500	7.2	1,100	7.8	.7	431	4.8	1,980
05/01/74[1]	—	7.4	2,910	220	160	300	6.2	1,500	14	.5	300	6.4	2,430
06/04/74[1]	—	8.5	4,040	130	210	590	18	2,000	13	.4	426	.3	3,390
09/29/76	—	7.9	4,200	110	73	810	15	1,700	33	.4	422	8.9	3,010
11/01/81	—	8.0	9,550	30	450	1,600	40	4,700	53	.8	490	.7	8,000
06355305 Buffalo Creek south of Gascoyne at Gascoyne Road													
10/01/81	.32	8.2	6,780	100	180	1,200	20	2,800	46	.8	760	.8	5,000
06355306 Buffalo Creek east of Gascoyne													
10/01/81	.34	8.1	6,800	100	178	1,230	18	2,790	48	.8	690	.8	5,100
06355308 Buffalo Creek Tributary No. 2 above Gascoyne Mine													
10/05/76[1]	1.1	8.7	4,480	150	60	920	13	1,900	16	.4	608	8.5	3,670
10/05/76	1.1	8.4	5,000	120	96	930	15	2,000	16	.8	588	6.8	3,620
11/02/76	.22	8.4	4,200	130	99	850	12	1,900	14	.8	581	6.5	3,390
03/01/77	.15	8.2	6,300	160	200	1,300	18	3,300	19	.9	646	11	5,680
04/05/77	1.2	8.2	5,100	130	150	850	12	2,300	15	.7	480	7.4	4,110
05/03/77	.06	8.3	5,400	140	140	1,200	15	2,700	18	1.4	800	8.9	4,760
06/01/77	1.1	8.3	5,800	150	190	1,000	14	2,900	9.1	.9	210	5.7	4,710
07/05/77	.24	8.4	3,880	120	98	710	11	1,800	8.9	.7	490	1.9	3,000
08/08/77	.30	8.3	3,850	120	100	800	12	1,800	11	.8	540	1.7	3,160
09/07/77	.12	8.0	5,190	130	180	950	16	2,600	14	.9	480	6.7	4,270
10/04/77	1.3	8.1	3,499	110	120	580	14	1,600	9.7	.7	360	8.4	2,710
11/01/77	.38	8.1	4,531	120	160	830	12	2,100	11	.9	530	5.7	3,700
10/01/81	.41	8.2	3,670	120	130	730	12	1,900	10	.9	430	6.2	3,010
06355310 Buffalo Creek Tributary 2 below Gascoyne Mine[2]													
10/16/74[1]	.32	8.2	6,750	210	140	1,400	13	3,400	16	1.2	730	7.3	5,560
10/01/81	.47	7.9	10,800	230	380	1,950	16	5,510	29	.7	610	7.9	8,830
06355320 Buffalo Creek below Tributary No. 2													
10/01/81	.81	8.0	10,300	170	340	1,900	20	5,100	41	1.2	520	1.3	8,610

[1]Chemical analyses performed at the North Dakota State Water Commission Laboratories.

[2]Station 06355310 has been in continuous operation since October 1974 with monthly water-quality samplings. A statistical summary of the data from 1978 through 1980 is presented in table 16. Analyses presented above are designed to provide the reader with general information on the temporal variation that has been observed at the station.

TABLE 16.—*Quality of flowing surface waters in the study area*

[°C, degrees Celsius; ft^3/s, cubic feet per second; mg/L, milligrams per liter; μg/L, micrograms per liter; μmho/cm, micromhos per centimeter at 25 degrees Celsius. Data collected at periodic intervals, October 1977 through September 1980]

Water quality constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown		
	Sample size	Maximum	Minimum	Mean	Standard deviation	75	Median 50	25
06355310 Buffalo Creek Tributary 2 below Gascoyne Mine								
Temperature (°C)	39	25.00	0.00	7.69	7.52	13.00	7.50	0.50
Streamflow, instantaneous (ft^3/s)	39	86.00	.02	9.24	17.06	15.00	1.30	.18
Specific conductance (μmho/cm)	38	8,000.00	555.00	3,746.97	2,181.63	5,700.00	3,750.00	1,592.50
Oxygen, dissolved (mg/L)	25	13.80	3.80	8.74	2.58	10.70	9.00	6.90
Oxygen, dissolved (percent saturation)	14	111.00	29.00	80.43	22.01	96.00	82.00	70.75
pH (units)	27	8.70	7.20	8.21	.30	8.40	8.20	8.10
Carbon dioxide, dissolved (mg/L as CO_2)	17	22.00	.80	5.76	4.81	7.55	4.70	2.45
Bicarbonate (mg/L as HCO_3)	17	871.00	153.00	567.06	232.66	739.00	640.00	411.50
Carbonate (mg/L as CO_3)	17	36.00	.00	6.00	11.44	9.50	.00	.00
Nitrogen, total (mg/L as N)	26	4.10	.57	1.69	.77	2.23	1.50	1.20
Nitrogen, organic, total (mg/L as N)	7	2.30	.74	1.39	.51	1.60	1.30	1.00
Nitrogen, ammonia, total (mg/L as N)	7	.33	.08	.19	.09	.30	.18	.11
Nitrogen, NO_2+NO_3, total (mg/L as N)	26	3.00	.00	.25	.62	.14	.05	.01
Phosphorus, total (mg/L as P)	26	.66	.04	.12	.12	.11	.10	.06
Phosphorus, dissolved (mg/L as P)	26	.14	.00	.04	.03	.06	.03	.02
Carbon, organic, dissolved (mg/L as C)	25	77.00	13.00	34.40	17.60	43.00	32.00	21.00
Carbon, organic, suspended (mg/L as C)	20	13.00	.30	2.10	2.96	2.43	.90	.50
Hardness (mg/L as $CaCO_3$)	27	2,300.00	260.00	968.89	433.91	1,200.00	1,000.00	700.00
Hardness, noncarbonate (mg/L as $CaCO_3$)	27	1,300.00	120.00	499.63	267.36	680.00	430.00	320.00
Calcium, dissolved (mg/L as Ca)	27	180.00	30.00	113.74	42.91	150.00	113.00	80.00
Magnesium, dissolved (mg/L as Mg)	27	460.00	36.00	166.56	88.86	230.00	160.00	110.00
Sodium, dissolved (mg/L as Na)	27	1,900.00	130.00	812.22	429.86	1,100.00	840.00	550.00
Sodium, percent	27	92.00	17.00	63.74	12.39	68.00	64.00	61.00
Potassium, dissolved (mg/L as K)	27	32.00	8.10	14.93	4.76	17.00	15.00	11.00
Chloride, dissolved (mg/L as Cl)	27	34.00	3.90	13.80	6.68	18.00	14.00	9.10
Sulfate, dissolved (mg/L as SO_4)	27	5,400.00	460.00	2,160.37	1,126.38	2,700.00	2,300.00	1,500.00
Fluoride, dissolved (mg/L as F)	27	1.50	.10	.79	.33	1.00	.80	.60
Silica, dissolved (mg/L as SiO_2)	27	15.00	.40	5.40	4.20	7.50	4.80	1.60
Arsenic, dissolved (μg/L as As)	8	5.00	1.00	2.75	1.39	4.00	2.00	2.00
Arsenic, total (μg/L as As)	2	4.00	2.00	—	—	—	—	—
Barium, dissolved (μg/L as Ba)	8	100.00	.00	50.00	46.29	100.00	50.00	.00
Barium, total recoverable (μg/L as Ba)	2	200.00	100.00	—	—	—	—	—
Beryllium, dissolved (μg/L as Be)	2	3.00	3.00	—	—	—	—	—
Beryllium, total recoverable (μg/L as Be)	2	.00	.00	—	—	—	—	—
Boron, dissolved (μg/L as B)	15	5,100.00	3.60	2,558.91	1,452.53	3,400.00	2,800.00	1,300.00
Chromium, dissolved (μg/L as Cr)	8	10.00	.00	2.50	4.63	7.50	.00	.00
Chromium, total recoverable (μg/L as Cr)	2	.00	.00	—	—	—	—	—
Cobalt, dissolved (μg/L as Co)	2	8.00	8.00	—	—	—	—	—
Cobalt, total recoverable (μg/L as Co)	2	1.00	.00	—	—	—	—	—
Copper, dissolved (μg/L as Cu)	8	25.00	.00	7.88	10.70	20.00	3.00	1.00
Copper, total recoverable (μg/L as Cu)	2	6.00	2.00	—	—	—	—	—
Iron, dissolved (μg/L as Fe)	15	400.00	.60	100.71	97.24	140.00	70.00	40.00
Manganese, dissolved (μg/L as Mn)	10	2,100.00	1.70	335.17	628.43	262.50	135.00	67.50
Manganese, total recoverable (μg/L as Mn)	2	220.00	100.00	—	—	—	—	—
Molybdenum, dissolved (μg/L as Mo)	8	25.00	.00	7.38	11.01	19.75	2.50	.00
Molybdenum, total recoverable (μg/L as Mo)	2	3.00	3.00	—	—	—	—	—
Nickel, dissolved (μg/L as Ni)	2	1.00	1.00	—	—	—	—	—
Nickel, total recoverable (μg/L as Ni)	2	21.00	.00	—	—	—	—	—
Vanadium, dissolved (μg/L as V)	2	8.00	8.00	—	—	—	—	—
Zinc, dissolved (μg/L as Zn)	8	40.00	8.00	21.38	10.27	28.25	20.00	12.50

TABLE 16.—*Continued.*

Water quality constituent	Descriptive statistics					Percent of samples in which values were less than or equal to those shown		
	Sample size	Maximum	Minimum	Mean	Standard deviation	Median 75	Median 50	Median 25
06355310 Buffalo Creek Tributary 2 below Gascoyne Mine								
Zinc, total recoverable (μg/L as Zn)	2	30.00	20.00	—	—	—	—	—
Aluminum, dissolved (μg/L as Al)	8	90.00	.00	28.75	29.00	37.50	30.00	2.50
Lithium, dissolved (μg/L as Li)	8	210.00	40.00	101.88	53.98	132.50	95.00	58.75
Lithium, total recoverable (μg/L as Li)	2	140.00	50.00	—	—	—	—	—
Selenium, dissolved (μg/L as Se)	8	1.00	.00	.38	.52	1.00	.00	.00
Selenium, total (μg/L as Se)	2	.00	.00	—	—	—	—	—
Solids, residue at 180°C, dissolved (mg/L)	27	9,280.00	848.00	3,893.30	1,905.66	5,040.00	4,250.00	2,710.00
Solids, dissolved (tons per acre-foot)	27	12.60	1.15	5.29	2.59	6.85	5.78	3.69
Mercury, dissolved (μg/L as Hg)	8	.20	.00	.08	.09	.18	.05	.00
Mercury, total recoverable (μg/L as Hg)	2	.20	.00	—	—	—	—	—
Sediment, suspended (mg/L)	26	232.00	2.00	69.65	63.25	122.00	46.00	11.00
Sediment, discharge, suspended (tons per day)	26	9.40	.00	.60	1.89	.18	.07	.02

or deposited in the stream bed as airfall throughout the year. Annual snowpack in the vicinity of the mine is less than elsewhere in the study area, because the thin layer of coal dust which coats snow near the mine increases sublimation during sunny days. Therefore, the magnitude of spring runoff in the vicinity of the mine is reduced.

Most degradation of surface-water quality at low flow is due to evaporative concentration of solutes in lowland marshes surrounding the tributary and Buffalo Creek. These marshes are fed mainly by relatively high-solute ground water rather than direct precipitation. Ponded water bodies usually are surrounded by soils encrusted with mirabilite and less abundant gypsum. The "popcorn" texture of these deposits implies evaporative concentration to the point of saturation with highly soluble salts. Ponded brines commonly display extremely high alkalinity and sulfate, fluoride, potassium, strontium, magnesium, and sodium concentrations (table 17). However, surface-water quality deterioration, especially at low flow, also may be due to the leaching of solutes from mine spoils by surface runoff and to surface discharge of ground water degraded by mining.

Water accumulated in mine pits due to precipitation, surface runoff, and aquifer seepage is pumped into holding ponds throughout the mine area. Holding-pond water is pumped through ion-exchange and adsorption vats to reduce dissolved-solids concentrations prior to discharge back into the surface-water system. Discharge primarily is to Gascoyne Lake and Buffalo Creek tributary. Analysis of holding-pond and discharge water quality is reported in table 18. Except during snowmelt, discharge water is of better quality than the receiving surface waters. As discharge usually is timed to occur during low-flow periods, mine discharges may be responsible for significantly improving the quality of local surface waters and extending the period of flow of intermittent Buffalo Creek tributaries. Recreational uses of Gascoyne Lake during late summer are maintained only through mine discharges.

Table 17.—*Quality of naturally ponded surface waters in the study area*

Location	Source	Sampling date	pH	Concentration of dissolved constituents in milligrams per liter: Ca	Mg	Na	K	SO_4	Cl	F	HCO_3	Dissolved solids
130-099-01ACC	Stagnant pond	08/22/78	7.8	755	4,500	16,700	306	54,000	150	27	2,782	81,300
		10/01/81	7.6	860	5,120	19,000	350	59,200	170	31	3,000	92,700
130-099-01BCB	Partly stagnant pond	08/22/78	7.9	263	370	1,230	21	3,800	9.4	6.0	769	6,430
		10/01/81	8.0	170	340	1,900	20	5,100	41	1.2	520	8,610
130-099-02ADA	Stagnant pond	08/22/78	8.0	548	20,000	68,500	413	230,000	164	64	3,000	329,200
130-099-02ADD	Stagnant pond	10/01/81	7.9	650	450	95,000	165	199,100	135	50	2,700	297,200

Table 18.—*Quality of mine holding ponds and their discharges*

[Analyses not indicated otherwise were performed by the U.S.Geological Survey National Water Quality Laboratory, Denver, Colo.]

Sampling Location	Date	pH	Concentrations of dissolved constituents in milligrams per liter								
			Ca	Mg	Na	K	SO_4	Cl	F	Alkalinity	Dissolved solids
Mine holding ponds											
131-099-34CCB	08/27/78[1]	7.9	144	230	450	5.5	1,600	7.2	1.4	348	2,900
131-099-21DDA	10/02/81	8.5	62	43	620	13	1,100	22	.9	480	2,240
131-099-27BBB	10/02/81	8.5	54	77	980	13	2,100	12	1.3	450	3,660
131-099-27DBA	10/02/81	8.4	68	48	720	9.5	1,400	17	1.6	460	2,620
131-099-29BBB	09/30/81	8.2	56	36	410	13	740	19	.7	420	1,660
131-099-29BCC	10/01/81	8.3	100	94	800	14	2,000	16	.5	390	3,330
Mean		8.3	81	88	663	11	1,490	16	1.1	425	2,735
Standard deviation		.2	35	73	216	3.3	523	5.3	.4	49	728
Discharges from mine holding ponds											
131-099-29AAA	08/16/80	8.2	53	40	420	14	740	18	.8	410	1,410
131-099-29BBB	11/17/81	8.3	51	38	490	14	920	22	.6	458	1,870
131-099-34BDB	11/17/81	8.3	69	48	720	10	1,500	16	1.5	437	2,670
Mean		8.3	58	42	543	13	1,053	19	1.0	435	1,983
Standard deviation		.1	9.8	5.3	157	2.3	397	3.1	.5	24	638

[1]Chemical analysis by J. C. Chemerys, Office of the Regional Hydrologist, Northeastern Region, U.S. Geological Survey, Reston, Va.

SUMMARY

Sedimentologic and mineralogic analyses of the Bullion Creek Formation of the Fort Union Group near Gascoyne indicate sands and silts were deposited adjacent to a low-gradient, slightly sinuous stream situated beneath the present position of Buffalo Creek. The salinity of the stream was fairly high, resulting in the formation of sodium smectites in the overbank deposits. The Harmon lignite bed of the Bullion Creek Formation formed when basin subsidence exceeded clastic deposition on the alluvial plain.

In the Gascoyne area, the Harmon lignite bed is the surficial aquifer where present. Mine dewatering has lowered water levels in the lignite aquifer about 2.5 ft/yr from 1976 to 1980. Where the lignite is present, an underclay confines the underlying basal Bullion Creek-Slope aquifer. Elsewhere, the sandstone is the surficial aquifer. The surficial aquifers are locally recharged by precipitation, with infiltration greatest in exposed channel sands. Where confined, the sandstone aquifer is recharged by leakage from the overlying lignite aquifer. Dewatering of the lignite has reduced recharge to the confined sandstone aquifer, dropping water levels in the sandstone aquifer about 1.5 ft/yr since 1976 in the mine area. Both aquifers locally discharge to Buffalo Creek and its tributaries, maintaining streamflow when runoff contributions are minimal. Due to mine dewatering activities, average streamflow actually has increased, permitting increased recreational use.

Ground-water quality in both aquifers is controlled by processes in the unsaturated zone, including dissolution of soil gases, oxidation of iron sulfide minerals, dissolution of carbonate minerals, precipitation and dissolution of soluble salts such as gypsum, and cation exchange on clay minerals and organic compounds. Cation exchange, sulfate reduction, and calcite deposition modify compositions within the aquifers.

Undisturbed aquifers predominantly are sodium sulfate-bicarbonate in type with moderately high (>2,000 mg/L) dissolved-solids concentration. Adjacent to mine pits, both near-surface aquifers are enriched in sodium, sulfate, cadmium, copper, iron, and zinc. Aquifers reestablished in spoils are severely degraded, with dissolved solids exceeding 4,400 mg/L.

Future mine development in the Northern Great Plains lignite region probably will occur principally in the relatively thick, shallow lignite seams of the Bullion Creek Formation in western North Dakota and eastern Montana. A summary of the hydrogeochemical consequences of strip mining in the Bullion Creek Formation observed at Gascoyne is presented in table 19.

Hydrogeologic investigations in the region have concentrated on mine activities in the overlying Sentinel Butte Formation. Hydrochemical studies at Gascoyne suggest the impact of mining in the saline Bullion Creek

Table 19.—*Summary of the observed consequences of strip mining on aquifer properties and water quality*

[ft/d, feet per day; ft/y, feet per year; mg/L, milligrams per liter; < indicates less than; << indicates much less than]

Aquifer characteristics	Effects on				
	Lignite aquifer away from mine	Lignite aquifer near mine	Spoils aquifer replacing lignite	Basal sandstone aquifer near mine	Basal sandstone aquifer away from mine
Potentiometric surface.	Stable beyond about 2-4 miles from mine boundaries.	Cone of depression within mine area continues to deepen about 2.5 ft/y, but new surface may be approaching reequilibrium. Water levels rebound rapidly (in a few months) to near predisturbance levels when mine dewatering stops.	Resaturation of the rubble zone at the base of the spoil pile requires about 1 year. Water levels approximate premine altitudes within about 3 years. Compaction of the pile with time may lower water table; however, removal of the lignite bed during mining results in the water table being nearer land surface than in premine condition.	Cone of depression within mine area continues to deepen about 1.5 ft/y and extends about 3-5 miles beyond mine boundaries. Current cone in the regional aquifer system may be up to 45 ft deep. New surface may require about 10 years to reequilibrate. Water-level rebounds following cessation of mine dewatering are proportionately slow.	Beyond about 3-5 miles from mine boundaries, local potentiometric surface remains stable. However, the regional aquifer system may be depressed for nearly 8 miles beyond the mine boundaries.
Hydraulic conductivities in aquifer materials.	Range from <1-200 ft/d with a mean of 2-5 ft/d. Hydraulic conductivities reflect natural joint systems in the lignite.	Generally are greater within mine area, up to 250 ft/d, reflecting the effects of mine blasting.	Conductivities are homogenized by mine processes and generally range from <<1-20 ft/d. Later compaction may further reduce this range.	Conductivities are increased within the mine area by blasting to a maximum observed of 350 ft/d.	Conductivities range from 1.5-150 ft/d, reflecting original environment of deposition.
Recharge potential.	Stable. Weathering forms mineral crusts on lignite outcrops which naturally limit their potential as recharge zones.	Increases slightly during mining when mine pits expose unweathered lignite directly to precipitation and runoff.	Homogenization of spoils during stripping eliminates zones of high hydraulic conductivity, thus effectively reducing recharge potential. Additional compaction of the pile with time may be expected to further reduce recharge potential. Reduced water storage in unsaturated spoils reflects the greater potential of the spoils to cause runoff.	Fracturing of confining claystone basal to the lignite by mine blasting permits active mine pits to serve as areas of direct recharge. Pumping to dewater mine pits causes a flow reversal in the mine area where the confined basal sandstone recharges the lignite in pit areas as well.	Recharge potential reflects differences in hydraulic conductivity due to differing environment of deposition where basal sandstone is unconfined. Where the basal sandstone is confined, it is recharged from the overlying lignite aquifer by leakage through the seat clay.
Water quality.	Sodium bicarbonate-sulfate water in type. Dissolved solids range from 575-8,740 mg/L. pH slightly basic.	Sulfate becomes the dominant anion, increasing by as much 1,200 mg/L. Dissolved solids increase slightly. pH decreased as much as 0.6 units. Minimum pH observed is near 7.	Calcium-sodium sulfate water in type. Dissolved solids range from 4,400-11,000 mg/L. Water enriched in Na, Ca, SO_4, B, Sr, Li, and Zn.	Water enriched by as much as 2,000 mg/L in sulfate and 900 mg/L in sodium. A lesser enrichment in bicarbonate also occurs. pH decreases slightly.	Sodium bicarbonate-sulfate water in type. Dissolved solids range from 653-7,790 mg/L. pH generally moderately basic.

strata may differ from the impacts recognized elsewhere (Moran and others, 1978; Groenewold and others, 1979). Although the chemical processes that occur in the Northern Great Plains are essentially the same throughout, differences in the mineralogy of coal-bearing formations affect the rate and extent to which different reactions may proceed. In the Bullion Creek Formation, sodic clays and lignites are more abundant than in other Tertiary coal-bearing systems. The sodic sites provide sinks for exchangeable calcium and magnesium, which in turn drive reactions involving the dissolution of sulfosalts. Because the exchange capacity of the Bullion Creek Formation exceeds that of the Sentinel Butte Formation, mine disruptions probably will result in waters

with greater dissolved solids unless reclamation practices are invoked to reduce exchange processes.

Selective replacement of overburden back into mine pits could accomplish a significant reduction in the dissolved-solids load reaching shallow aquifers within the mine area. The greatest reduction in dissolved-solids load could be accomplished by retaining the soluble-salt layer at the base of the root zone in the unsaturated zone. Solubilization of these sulfate salts would not then be greatly increased over current dissolution rates. Secondly, when emplacing salt-rich sediments in the spoils pile, they should be isolated from clay- or organic-rich sediments to minimize exchange reactions which would increase salt solubility. Sulfide oxidation apparently is so rapid during overburden disruption that no reclamation practices can reduce its effect on the input of new soluble salts into the unsaturated zone. However, if equilibrium conditions are not altered by exchange processes, salt dissolution will not exceed naturally occurring rates.

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SUPPLEMENTS 1-5

SUPPLEMENT 1.—*Quality of waters in the unsaturated zone*

[Analyses not indicated otherwise were performed by the U.S. Geological Survey National Water-Quality Laboratory, Denver, Colo. "Geologic unit" indicates the geologic bed or formation sampled: 125HRMN = Harmon lignite bed of the Paleocene Bullion Creek Formation of the Fort Union Group, 125TRVL = basal sandstone of the Paleocene Bullion Creek Formation, 120TRTR = spoils formed from mining the basal sandstone of the Paleocene Bullion Creek Formation. Dissolved oxygen values on unsaturated waters must be considered to be maxima because some aeration could occur during sampling. <indicates less than]

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)
Unsaturated lignite										
460830103044503	131-099-29ADD3	125HRMN	80	76-08-24	1000	1520	7.6	8.0	0	566

STATION NUMBER	DATE OF SAMPLE	ALKA-LINITY FIELD (MG/L AS CACO3)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)
460830103044503	76-06-24	466	4	230	0	42	30	310	14	23

STATION NUMBER	DATE OF SAMPLE	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SILICA, DIS-SOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)	PHOS-PHORUS, DIS-SOLVED (MG/L AS P)	BORON, DIS-SOLVED (UG/L AS B)
460830103044503	76-06-24	460	7.6	.4	14	1130	1160	.01	<.010	1000

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
Unsaturated sandstone									
460645103022701	130-099-03ADC	125TRVL	25	76-06-17	1000	19300	7.2	7.0	.0
		125TRVL	25	76-06-17	1800	8000	7.3	7.0	--
		125TRVL	25	81-05-28	1510	19900	7.0	6.6	2.4
461050103010003	130-099-11ADD3	125TRVL	31	77-06-29	1000	--	7.7	8.7	--
		125TRVL	16	77-07-09	1000	--	8.7	8.6	--
		125TRVL	16	78-08-23	1000	21700	7.7	9.0	--
		125TRVL	--	81-10-01	1000	--	--	--	--
460553103005301	130-099-12BCC	125TRVL	16	78-05-10	--	8000	5.3	9.5	--
		125TRVL	16	81-10-01	1000	--	--	--	--
460902103043603	131-099-21CCB	125TRVL	40	81-10-10 1/	1001	2370	7.1	--	--
460804103010103	131-099-26DDD3	125TRVL	20	78-05-11	--	8000	7.1	10.0	--
		125TRVL	20	81-10-02 1/	1002	--	--	--	--
460823103021602	131-099-27DAA2	125TRVL	40	78-05-11	1450	4000	8.1	16.0	--
460804103021602	131-099-27DDD2	125TRVL	80	76-06-17	1430	4600	7.8	8.0	--
460712103034901	131-099-33DCD	125TRVL	34	78-05-11	1000	8860	6.8	8.5	--
		125TRVL	30	78-05-11	1300	8000	6.9	10.5	--
		125TRVL	30	81-10-10 1/	1101	4120	7.6	7.1	.1
460738103024402	131-099-34ACC2	125TRVL	40	76-06-17	1700	3800	7.6	7.0	--
		125TRVL	--	81-10-03 1/	1002	--	--	--	--
460754103025801	131-099-34BA	--	--	76-06-28	1000	--	7.6	9.0	--
		125TRVL	35	76-06-28	1500	2400	7.6	9.0	--
460725103021602	131-099-34DAD2	125TRVL	40	76-06-22	1600	2200	7.3	8.5	--
460744103014802	131-099-35BDB2	120TRTR	40	76-06-17	1630	2630	6.8	8.0	--
		120TRTR	29	77-06-28	1000	2680	7.0	9.0	--
460738103005201	131-099-36BCC1	125TRVL	17	77-06-28	1000	20570	7.9	9.1	--
		125TRVL	--	81-10-05 1/	1002	--	--	--	--
460738103005202	131-099-36BCC2	125TRVL	12	78-05-11	1230	16600	7.4	9.5	--
		125TRVL	12	81-10-10 1/	1201	7920	7.5	8.9	--

1/ Analyses performed by J. C. Chemerys, Office of the Regional Hydrologist, Northeastern Region, U.S. Geological Survey, Reston, Va.

SUPPLEMENT 1.—*Quality of waters in the unsaturated zone*—Continued

STATION NUMBER	DATE OF SAMPLE	POTASSIUM, DISSOLVED (MG/L AS K)	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	NITROGEN, NO2+NO3 DISSOLVED (MG/L AS N)	PHOSPHORUS, DISSOLVED (MG/L AS P)	BORON, DISSOLVED (UG/L AS B)
460645103022701	76-06-17	30	8800	39	.6	17	13500	12900	--	--	--
	76-06-17	30	8800	39	.6	17	13400	12900	<.10	<.010	1500
	81-05-28	33	9570	62	.6	19	14400	13800	--	--	1230
461050103010003	77-06-29	19	3000	26	1.1	12	--	4730	--	--	--
	77-07-09	31	6400	49	1.6	6.0	--	9300	--	--	--
	78-08-23	32	8100	39	7.5	24	12250	11800	--	--	--
	81-10-01	33	--	--	--	25	--	--	--	--	--
460553103005301	78-05-10	22	11000	97	.3	17	17500	15800	--	.030	5600
	81-10-01	--	--	--	--	18	--	--	--	--	--
460902103043603	81-10-10	19	1340	5.6	.7	12	2270	2182	--	--	--
460804103010103	78-05-11	46	16000	80	.5	13	24400	24300	--	.710	110
	81-10-02	--	--	--	--	25	--	--	--	--	--
460823103021602	78-05-11	22	830	16	.1	9.6	2010	2140	.03	.010	1100
460804103021602	76-06-17	13	2300	24	1.0	20	3860	3780	<.10	.020	900
460712103034901	78-05-11	26	3200	8.9	.1	27	5210	5020	--	--	--
	78-05-11	26	3200	8.9	.1	27	5630	5030	--	.010	12000
	81-10-10	20	1660	7.8	.2	7.0	--	3350	--	--	--
460738103024402	76-06-17	12	1700	7.0	.7	12	2910	2990	.18	<.010	1700
	81-10-03	--	--	--	--	14	--	--	--	--	--
460754103025801	76-06-28	9.2	820	7.2	1.0	13	--	1670	--	--	--
	76-06-28	9.2	820	7.2	1.0	13	1710	1680	.72	.010	1600
460725103021602	76-06-22	9.6	730	6.7	.9	13	1570	1490	.08	<.010	1300
460744103014802	76-06-17	17	950	6.9	.3	28	2000	2000	.94	.270	1800
	77-06-28	6.8	941	9.0	.6	6.2	1580	1520	--	--	--
460738103005201	77-06-28	26	8160	7.0	3.0	13	12100	11600	--	--	--
	81-10-05	--	--	--	--	16	--	--	--	--	--
460738103005202	78-05-11	30	5200	180	.7	16	19500	11700	--	.660	630
	81-10-10	35	6690	14	1.5	11	--	10300	--	--	--

STATION NUMBER	DATE OF SAMPLE	CARBONATE FET-FLD (MG/L AS CO3)	BICARBONATE FET-FLD (MG/L AS HCO3)	ALKALINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DISSOLVED (MG/L AS CO2)	COLOR (PLATINUM-COBALT UNITS)	HARDNESS (MG/L AS CACO3)	HARDNESS, NONCARBONATE (MG/L CACO3)	CALCIUM DISSOLVED (MG/L AS CA)	MAGNESIUM, DISSOLVED (MG/L AS MG)	SODIUM, DISSOLVED (MG/L AS NA)
460645103022701	76-06-17	--	--	512	63	--	3200	2690	440	510	2800
	76-06-17	0	625	513	56	12	3200	2700	440	510	2800
	81-05-28	1	108	81	18	15	3500	3400	479	555	3050
461050103010003	77-06-29	--	--	472	18	--	1200	696	203	160	1020
	77-07-09	--	--	56	.2	--	890	837	134	135	2510
	78-08-23	--	--	297	11	--	3600	3290	378	640	2370
	81-10-01	--	--	--	--	--	--	--	--	--	--
460553103005301	78-05-10	0	7	6	56	9	5200	5180	460	980	3200
	81-10-01	--	--	--	--	--	5400	--	478	1020	3328
460902103043603	81-10-10	0	448	390	58	--	1500	1070	280	184	103
460804103010103	78-05-11	0	1440	1180	183	1000	3900	2740	100	890	6500
	81-10-02	--	--	--	--	--	4100	--	104	926	7030
460823103021602	78-05-11	0	1040	850	13	1	630	0	95	96	560
460804103021602	76-06-17	0	461	378	13	6	1000	651	230	110	850
460712103034901	78-05-11	--	--	515	158	--	2800	2290	560	340	550
	78-05-11	0	630	520	142	90	2800	2280	560	340	550
	81-10-10	0	1070	931	43	--	560	0	109	71	943
460738103024402	76-06-17	0	612	502	24	18	480	0	87	63	800
	81-10-03	--	--	--	--	--	500	--	90	66	865
460754103025801	76-06-28	--	--	433	21	--	360	0	64	49	450
	76-06-28	0	528	433	20	25	360	0	64	49	450
460725103021602	76-06-22	0	525	431	42	17	670	240	120	90	260
460744103014802	76-06-17	0	711	583	202	18	740	155	150	88	400
	77-06-28	--	--	256	50	--	920	663	174	117	110
460738103005201	77-06-28	--	--	451	11	--	4000	3510	157	866	2130
	81-10-05	--	--	--	--	--	4100	--	163	901	2220
460738103005202	78-05-11	0	920	750	55	45	6500	5780	470	1300	4000
	81-10-10	0	1130	983	63	--	3600	2570	463	580	1960

SUPPLEMENT 1.—*Quality of waters in the unsaturated zone*—Continued

STATION NUMBER	DATE OF SAMPLE	IRON, DIS-SOLVED (UG/L AS FE)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)
460645103022701	76-06-17	--	--	--
	76-06-17	--	--	9500
	81-05-28	1010	80	--
461050103010003	77-06-29	--	--	1400
	77-07-09	--	--	1300
	78-08-23	--	--	9800
	81-10-01	--	--	--
460553103005301	78-05-10	--	--	--
	81-10-01	--	--	--
460902103043603	81-10-10	0	--	3
460804103010103	78-05-11	--	--	--
	81-10-02	--	--	--
460823103021602	78-05-11	--	--	--
460804103021602	76-06-17	--	--	--
460712103034901	78-05-11	--	--	--
	78-05-11	--	--	--
	81-10-10	--	--	--
460738103024402	76-06-17	--	--	--
	81-10-03	--	--	--
460754103025801	76-06-28	--	--	--
	76-06-28	--	--	--
460725103021602	76-06-22	--	--	--
460744103014802	76-06-17	--	--	--
	77-06-28	--	--	2000
460738103005201	77-06-28	--	--	3600
	81-10-05	--	--	--
460738103005202	78-05-11	--	--	--
	81-10-10	--	--	9400

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)	ALKA-LINITY FIELD (MG/L AS CACO3)	HARD-NESS (MG/L AS CACO3)
Unsaturated mine spoils											
460843103032008	131-099-27BBC8	120TRTR	40	81-10-15	1800	6800	7.3	7.6	.0	370	3200

STATION NUMBER	DATE OF SAMPLE	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SILICA, DIS-SOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)
460843103032008	81-10-15	2810	510	460	680	30	3800	140	.4	12	6820	5930

STATION NUMBER	DATE OF SAMPLE	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)	ALUM-INUM, DIS-SOLVED (UG/L AS AL)	ANTI-MONY, DIS-SOLVED (UG/L AS SB)	ARSENIC DIS-SOLVED (UG/L AS AS)	BARIUM, DIS-SOLVED (UG/L AS BA)	CADMIUM DIS-SOLVED (UG/L AS CD)	CHRO-MIUM, DIS-SOLVED (UG/L AS CR)	COBALT, DIS-SOLVED (UG/L AS CO)	COPPER, DIS-SOLVED (UG/L AS CU)	IRON, DIS-SOLVED (UG/L AS FE)
460843103032008	81-10-15	15	10	0	1	100	0	20	0	7	60

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	ZINC, DIS-SOLVED (UG/L AS ZN)
460843103032008	81-10-15	0	310	30	.0	0	7	180	0	12000	90

SUPPLEMENT 2.—*Water quality in the Harmon lignite aquifer*

[Analyses not indicated otherwise were performed by the U.S. Geological Survey National Water-Quality Laboratory, Denver, Colo. "Geologic unit" indicates the aquifer sampled: 125 HRMN = Harmon lignite bed of the Paleocene Bullion Creek Formation of the Fort Union Group. <indicates less than, ND indicates not detected]

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
461034103003301	131-099-13BAB1	125TRVL	260	76-06-28	1000	1920	7.5	8.0	--
		125TRVL	260	76-09-23	--	1700	9.5	8.0	--
461014103044501	131-099-17ADD	125TRVL	147	76-06-22	--	1925	8.6	11.0	--
461533103054801	131-099-17BBB	125HRMN	164	74-05-15	1600	1670	8.8	8.0	--
460852103054401	131-099-20CDC1	125HRMN	35	81-10-15	1500	1760	7.4	7.5	0.0
		125HRMN	35	81-10-15 1/	1501	1760	7.4	7.5	.0
460902103043601	131-099-21CCB	125HRMN	80	76-02-23	1615	1170	8.0	5.5	--
		125HRMN	80	77-07-06	1000	1260	7.7	6.1	--
		125HRMN	80	81-10-09 1/	1701	1260	7.4	6.6	.0
		125HRMN	80	81-10-15	1600	932	7.1	7.5	.0
461355103032802	131-099-21DDD2	125HRMN	60	81-10-22	1430	4300	8.2	7.1	.0
460922103032101	131-099-22BCC	125HRMN	115	81-10-22	1730	1960	8.4	6.8	.0
460856103024401	131-099-22DCC1	125HRMN	76	76-12-20	1440	3600	7.1	7.5	--
		125HRMN	76	77-11-09	1545	3650	9.0	8.0	--
		125HRMN	76	78-11-07	1205	4400	7.5	11.0	--
		125HRMN	76	79-11-14	1530	3550	7.1	10.0	--
		125HRMN	76	80-10-27	1515	4130	7.3	7.7	.0
		125HRMN	76	81-10-22	1530	4190	7.3	7.3	.0
460856103020702	131-099-23CCC2	125TRVL	100	76-09-10	--	2200	8.4	11.0	--
		125TRVL	100	79-06-06	1000	1670	8.0	8.0	--
		125TRVL	100	80-05-27	1000	1810	8.3	7.6	.0
460810103005601	131-099-25CCB	125HRMN	76	81-10-22	1830	2190	8.2	7.2	.0
460801103005502	131-099-25CCC2	125HRMN	80	80-05-27	1000	1760	9.6	9.5	.0
460837103010101	131-099-26ADA	125TRVL	120	75-12-11	1300	2900	8.6	5.0	--
		125TRVL	120	81-05-20	1730	1930	8.2	8.2	.0
		125TRVL	120	81-10-09 1/	1501	2370	7.7	7.5	.0
		125TRVL	120	81-10-21	1800	2850	8.2	6.9	.0

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
461034103003301	76-06-28	--	--	630	39	--	540	0	99	71	210
	76-09-23	18	274	255	.2	90	58	0	15	5.1	340
461014103044501	76-06-22	0	811	665	3.3	--	150	0	1.3	36	430
461533103054801	74-05-15	31	620	560	1.6	200	63	0	14	6.7	360
460852103054401	81-10-15	--	--	380	29	70	480	103	93	60	220
	81-10-15	0	582	506	37	--	480	0	88	62	212
460902103043601	76-02-23	0	418	343	6.7	7	520	180	120	54	51
	77-07-06	--	--	331	13	--	520	194	106	63	51
	81-10-09	0	392	341	24	--	670	328	140	77	53
	81-10-15	--	--	330	51	10	450	116	97	49	32
461355103032802	81-10-22	--	--	540	6.5	--	260	0	48	33	870
460922103032101	81-10-22	--	--	790	6.0	--	51	0	12	4.8	500
460856103024401	76-12-20	0	588	482	75	110	1400	939	270	180	450
	77-11-09	0	580	480	.9	--	1700	1180	300	220	400
	78-11-07	--	--	480	29	--	1500	999	260	200	530
	79-11-14	--	--	370	57	--	790	420	150	100	910
	80-10-27	--	--	450	44	--	1400	946	260	180	470
	81-10-22	--	--	460	45	--	1500	1050	290	190	520
460856103020702	76-09-10	0	550	451	3.5	--	44	0	8.5	5.5	520
	79-06-06	0	364	299	5.8	--	61	0	15	5.9	420
	80-05-27	0	398	326	3.2	--	68	0	14	8.1	400
460810103005601	81-10-22	--	--	330	4.0	--	60	0	14	6.0	470
460801103005502	80-05-27	0	376	308	.2	--	39	0	11	2.8	380
460837103010101	75-12-11	6	486	409	2.0	--	69	0	12	9.5	590
	81-05-20	--	--	310	3.8	--	88	0	23	7.2	380
	81-10-09	0	532	463	19	--	68	0	14	8.0	561
	81-10-21	--	--	420	5.1	--	81	0	16	9.3	580

1/ Analyses performed by J. C. Chemerys, Office of the Regional Hydrologist, Northeastern Region, U.S. Geological Survey, Reston, Va.

SUPPLEMENT 2.—*Water quality in the Harmon lignite aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	ANTI-MONY, DIS-SOLVED (UG/L AS SB)	ARSENIC DIS-SOLVED (UG/L AS AS)	BARIUM, DIS-SOLVED (UG/L AS BA)	BERYL-LIUM, DIS-SOLVED (UG/L AS BE)	BORON, DIS-SOLVED (UG/L AS B)	CADMIUM DIS-SOLVED (UG/L AS CD)	CHRO-MIUM, DIS-SOLVED (UG/L AS CR)	COBALT, DIS-SOLVED (UG/L AS CO)	COPPER, DIS-SOLVED (UG/L AS CU)	IRON, DIS-SOLVED (UG/L AS FE)
461034103003301	76-06-28	--	--	--	--	--	--	--	--	--	--
	76-09-23	--	--	--	--	390	--	--	--	--	--
461014103044501	76-06-22	--	--	--	--	<20	--	--	--	--	3200
461533103054801	74-05-15	--	--	--	--	--	--	--	--	--	60
460852103054401	81-10-15	0	0	74	3	--	2	0	3	0	110
	81-10-15	--	--	--	--	--	--	--	--	--	--
460902103043601	76-02-23	--	--	--	--	230	--	--	--	--	--
	77-07-06	--	--	--	--	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-15	0	0	27	<1	--	<1	0	<3	0	<10
461355103032802	81-10-22	1	1	100	<10	--	0	0	2	1	30
460922103032101	81-10-22	0	1	840	<1	--	<1	0	<3	0	400
460856103024401	76-12-20	--	2	<100	--	500	ND	ND	--	<2	40
	77-11-09	0	3	400	8	520	ND	4	--	<2	40
	78-11-07	1	3	<100	<1	560	ND	ND	--	ND	60
	79-11-14	1	0	200	<1	3700	1	0	--	0	1600
	80-10-27	1	3	200	<1	510	0	0	--	5	140
	81-10-22	0	4	200	0	--	0	0	0	0	220
460856103020702	76-09-10	--	--	--	--	--	--	--	--	--	190
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
460810103005601	81-10-22	0	1	110	<1	--	<1	0	<3	1	160
460801103005502	80-05-27	--	--	--	--	--	--	--	--	--	--
460837103010101	75-12-11	--	--	--	--	840	--	--	--	--	460
	81-05-20	3	3	60	<1	--	1	10	<3	6	90
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-21	1	3	100	<10	--	0	0	1	5	170

STATION NUMBER	DATE OF SAMPLE	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SILICA, DIS-SOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)	PHOS-PHORUS, DIS-SOLVED (MG/L AS P)	ALUM-INUM, DIS-SOLVED (UG/L AS AL)
461034103003301	76-06-28	18	380	4.2	.6	14	1220	1170	--	--	--
	76-09-23	9.8	490	6.1	.9	8.1	1080	1030	.81	.090	--
461014103044501	76-06-22	8.3	420	14	3.6	5.9	1940	1320	--	--	--
461533103054801	74-05-15	5.9	290	11	2.9	13	1110	1070	.04	1.10	--
460852103054401	81-10-15	13	530	5.9	.4	11	1170	1170	.32	--	10
	81-10-15	13	452	5.4	.5	10	1195	1130	--	--	--
460902103043601	76-02-23	9.3	290	4.1	.4	13	766	749	.13	1.20	--
	77-07-06	8.4	326	3.4	.4	11	799	768	--	--	--
	81-10-09	9.2	455	5.6	.5	11	1020	946	--	--	--
	81-10-15	6.6	180	1.8	.4	13	575	579	.15	--	20
461355103032802	81-10-22	15	1700	12	.6	5.6	3060	3010	<.09	--	40
460922103032101	81-10-22	5.7	500	50	2.9	9.0	1610	1560	.19	--	40
460856103024401	76-12-20	11	1800	29	.4	6.7	3310	3040	.15	.010	10
	77-11-09	14	1900	30	.6	7.1	3510	3160	.01	.030	20
	78-11-07	15	2200	65	.4	7.3	3770	3570	.04	.030	<100
	79-11-14	14	2300	8.4	.1	14	3830	3730	.04	.020	0
	80-10-27	12	1800	34	.5	6.6	3120	3040	.00	.030	40
	81-10-22	13	2100	47	.5	5.7	3620	3450	.09	--	0
460856103020702	76-09-10	4.7	660	5.9	2.3	6.6	1550	1490	.19	.190	--
	79-06-06	5.1	338	12	2.2	7.3	1347	985	--	--	--
	80-05-27	5.3	483	34	2.2	6.9	1440	1150	--	--	--
460810103005601	81-10-22	5.6	690	20	2.1	8.6	1370	1420	.14	--	20
460801103005502	80-05-27	5.5	508	64	2.0	8.3	1300	1166	--	--	--
460837103010101	75-12-11	11	910	3.3	1.3	5.4	1800	1790	--	--	--
	81-05-20	8.3	610	3.7	1.0	9.9	1230	1240	2.6	--	0
	81-10-09	6.9	855	3.6	2.2	9.3	1810	1720	--	--	--
	81-10-21	6.7	880	5.8	1.5	6.9	1810	1760	.15	--	40

SUPPLEMENT 2.—*Water quality in the Harmon lignite aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	ZINC, DIS-SOLVED (UG/L AS ZN)
461034103003301	76-06-28	--	--	--	--	--	--	--	--	--	--
	76-09-23	--	--	--	--	--	--	--	--	--	--
461014103044501	76-06-22	--	--	--	--	--	--	--	--	--	--
461533103054801	74-05-15	--	--	<10	--	--	--	--	--	--	--
460852103054401	81-10-15	0	62	180	.2	20	0	0	0	3500	9
	81-10-15	--	--	--	--	--	--	--	--	3100	--
460902103043601	76-02-23	--	--	--	--	--	--	--	--	--	--
	77-07-06	--	--	--	--	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--	--	1800	--
	81-10-15	1	36	120	.0	10	0	0	0	1000	9
461355103032802	81-10-22	2	100	50	.0	1	4	0	0	1800	10
460922103032101	81-10-22	5	41	120	.1	<10	1	0	0	400	24
460856103024401	76-12-20	ND	110	520	<.5	3	--	1	--	4000	20
	77-11-09	ND	110	550	<.1	2	--	<1	--	4200	20
	78-11-07	ND	110	600	<.1	6	--	<1	--	4700	30
	79-11-14	1	280	590	.0	0	--	0	--	2800	120
	80-10-27	3	100	460	.0	11	--	0	--	4000	40
	81-10-22	1	110	550	.0	12	1	0	0	3800	30
460856103020702	76-09-10	--	--	20	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
460810103005601	81-10-22	1	40	82	.0	<10	1	0	0	300	11
460801103005502	80-05-27	--	--	--	--	--	--	--	--	--	--
460837103010101	75-12-11	--	--	120	--	--	--	--	--	--	--
	81-05-20	22	40	40	.1	<10	5	0	0	340	150
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-21	6	50	50	.0	1	1	0	0	2000	20

STATION NUMBER	DATE OF SAMPLE	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	URANIUM NATURAL DIS-SOLVED (UG/L AS U)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
461034103003301	76-06-28	--	--	--	--	--	--
	76-09-23	--	--	--	--	--	--
461014103044501	76-06-22	--	--	--	--	--	--
461533103054801	74-05-15	--	--	--	--	--	--
460852103054401	81-10-15	--	--	--	--	--	--
	81-10-15	--	--	--	--	--	--
460902103043601	76-02-23	--	--	--	--	--	--
	77-07-06	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--
	81-10-15	--	--	--	--	--	--
461355103032802	81-10-22	--	--	--	--	--	--
460922103032101	81-10-22	--	--	--	--	--	--
460856103024401	76-12-20	59	14	11	.40	18	4.4
	77-11-09	51	16	14	.57	18	4.4
	78-11-07	83	18	16	.54	--	7.9
	79-11-14	<88	<19	<17	.37	--	19
	80-10-27	70	<23	<21	.72	28	7.6
	81-10-22	--	--	--	--	--	--
460856103020702	76-09-10	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--
460810103005601	81-10-22	--	--	--	--	--	--
460801103005502	80-05-27	--	--	--	--	--	--
460837103010101	75-12-11	--	--	--	--	--	--
	81-05-20	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--
	81-10-21	--	--	--	--	--	--

SUPPLEMENT 2.—*Water quality in the Harmon lignite aquifer*—Continued

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
460804103010101	131-099-26DDD	125HRMN	76	75-12-11	0915	1500	8.7	5.0	--
		125HRMN	76	76-09-09	--	1250	8.7	9.1	--
		125HRMN	76	76-12-21	1140	1420	8.4	8.5	--
		125HRMN	76	77-11-08	1800	1390	8.3	4.0	--
		125HRMN	76	78-11-06	1600	1430	8.8	8.5	--
		125HRMN	76	79-11-15	1545	1450	8.4	10.0	--
		125HRMN	76	80-10-28	1400	1420	8.6	8.1	.0
		125HRMN	76	81-05-20	1510	1710	7.9	9.4	.0
460825103032601	131-099-27CBB	125HRMN	80	76-05-21	1000	--	--	--	--
		125HRMN	80	81-10-16	1100	2950	7.5	7.7	.0
460804103021603	131-099-27DDD3	125HRMN	--	76-06-16	1000	--	7.7	8.0	--
460830103040801	131-099-28BDD	125HRMN	70	76-05-21	1000	--	--	--	--
460830103044502	131-099-29ADD2	125HRMN	80	81-10-15	1100	15500	8.3	8.6	1.2
460830103044504	131-099-29ADD	125HRMN	82	81-10-09 1/	1601	1620	7.6	8.2	.0
		125HRMN	82	81-10-15	1415	1720	8.3	7.8	.0
460812103053701	131-099-29CDB1	125HRMN	41	81-10-06 1/	1501	1950	8.7	7.9	.0
460804103052301	131-099-29CDD	125HRMN	32	81-10-01	1200	10000	8.4	8.2	.0
		125HRMN	32	81-10-01 1/	1201	10000	8.4	8.2	.0
460804103044401	131-099-32AAA	125HRMN	86	76-05-21	1000	--	8.3	7.1	--
		125HRMN	86	79-06-06	1000	4500	7.5	7.6	--
		125HRMN	86	80-05-27	1000	3670	8.4	8.0	--
460749103054602	131-099-32BBC2	125HRMN	60	81-10-14	1200	2630	10.3	7.6	.0
		125HRMN	60	81-10-14 1/	1201	2630	10.3	7.6	.0

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
460804103010101	75-12-11	27	489	446	1.7	--	24	0	6.3	2.0	350
	76-09-09	18	481	424	1.7	250	20	0	4.7	1.9	320
	76-12-21	5	517	432	3.4	--	18	0	4.2	1.7	330
	77-11-08	0	530	430	4.3	--	59	0	20	2.0	320
	78-11-06	--	--	420	1.1	--	20	0	4.7	1.9	340
	79-11-15	--	--	420	3.2	--	27	0	5.5	3.2	350
	80-10-28	--	--	420	2.0	--	14	0	2.9	1.5	340
	81-05-20	--	--	410	10	--	22	0	4.2	2.8	370
460825103032601	76-05-21	--	304	249	--	--	950	700	--	--	175
	81-10-16	--	--	180	11	150	1100	916	240	120	320
460804103021603	76-06-16	--	--	378	15	--	1000	651	230	110	850
460830103040801	76-05-21	--	254	208	--	--	--	--	--	--	1340
460830103044502	81-10-15	--	--	190	1.8	5	6700	6550	2200	300	71
460830103044504	81-10-09	0	595	518	23	--	130	0	24	17	364
	81-10-15	--	--	460	4.4	--	150	0	28	19	350
460812103053701	81-10-06	0	752	654	2.4	--	25	0	5.4	2.7	461
460804103052301	81-10-01	--	--	810	6.2	7	1600	793	210	260	2100
	81-10-01	0	949	826	6.0	--	1700	850	220	272	2030
460804103044401	76-05-21	0	582	477	4.7	--	310	0	--	--	814
	79-06-06	0	594	487	30	--	370	0	76	43	980
	80-05-27	0	528	433	3.4	--	280	0	68	27	850
460749103054602	81-10-14	--	--	690	.0	--	22	0	4.1	2.8	600
	81-10-14	270	210	453	.1	--	21	0	3.5	2.8	571

SUPPLEMENT 2.—*Water quality in the Harmon lignite aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	POTASSIUM, DISSOLVED (MG/L AS K)	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	NITROGEN, NO2+NO3 DISSOLVED (MG/L AS N)	PHOSPHORUS, DISSOLVED (MG/L AS P)	ALUMINUM, DISSOLVED (UG/L AS AL)
460804103010101	75-12-11	4.4	310	5.0	2.2	8.3	1050	957	.08	.240	--
	76-09-09	3.3	300	5.8	2.2	8.3	980	903	--	.170	130
	76-12-21	2.5	310	6.3	2.6	7.9	964	926	.04	.070	10
	77-11-08	2.9	300	5.5	2.1	8.5	914	924	.01	.150	30
	78-11-06	2.8	300	6.0	2.0	8.8	986	920	.03	.140	40
	79-11-15	3.1	360	6.2	2.2	9.7	960	994	.02	.150	30
	80-10-28	2.9	280	5.1	2.1	8.1	933	897	.00	.210	40
	81-05-20	2.6	350	8.0	2.1	9.1	954	996	.00	--	10
460825103032601	76-05-21	--	1030	12	--	--	1886	--	--	--	--
	81-10-16	8.1	1400	67	.5	8.2	2460	2280	.21	--	10
460804103021603	76-06-16	13	2300	24	1.0	20	3950	3770	--	--	--
460830103040801	76-05-21	--	1060	12	1.1	--	1832	--	--	--	--
460830103044502	81-10-15	68	6450	11	11	12	9606	9237	--	--	--
460830103044504	81-10-09	13	429	4.7	.6	9.5	1220	1160	--	--	--
	81-10-15	13	410	5.5	.5	10	1090	1110	<.10	--	40
460812103053701	81-10-06	5.0	379	6.2	2.2	11	1370	1240	--	--	--
460804103052301	81-10-01	15	5000	42	.5	12	8620	8130	.00	--	100
	81-10-01	28	5270	12	.4	7.9	8670	8343	--	--	--
460804103044401	76-05-21	--	1660	11	--	--	2852	--	--	--	--
	79-06-06	--	1500	12	--	--	3448	--	--	--	--
	80-05-27	--	1712	22	--	--	2960	--	--	--	--
460749103054602	81-10-14	8.3	600	15	1.1	11	1650	1660	.58	--	410
	81-10-14	9.8	653	7.8	1.4	12	1680	1640	--	--	--

STATION NUMBER	DATE OF SAMPLE	ANTIMONY, DISSOLVED (UG/L AS SB)	ARSENIC DISSOLVED (UG/L AS AS)	BARIUM, DISSOLVED (UG/L AS BA)	BERYLLIUM, DISSOLVED (UG/L AS BE)	BORON, DISSOLVED (UG/L AS B)	CADMIUM DISSOLVED (UG/L AS CD)	CHROMIUM, DISSOLVED (UG/L AS CR)	COBALT, DISSOLVED (UG/L AS CO)	COPPER, DISSOLVED (UG/L AS CU)	IRON, DISSOLVED (UG/L AS FE)
460804103010101	75-12-11	--	--	--	--	--	--	--	--	--	90
	76-09-09	--	3	<100	<10	920	ND	ND	ND	6	40
	76-12-21	--	6	<100	--	970	ND	ND	--	2	70
	77-11-08	--	3	500	--	970	ND	4	--	14	50
	78-11-06	--	2	<100	--	980	2	<20	--	ND	80
	79-11-15	--	2	200	--	1000	0	0	--	0	120
	80-10-28	--	1	0	--	910	0	0	--	6	90
	81-05-20	1	5	100	0	--	0	10	0	5	100
460825103032601	76-05-21	--	--	--	--	--	--	--	--	--	--
	81-10-16	0	1	300	<10	--	0	10	2	3	40
460804103021603	76-06-16	--	--	--	--	--	--	--	--	--	--
460830103040801	76-05-21	--	--	--	--	--	--	--	--	--	--
460830103044502	81-10-15	--	--	--	--	--	--	--	--	--	--
460830103044504	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-15	0	1	63	<1	--	<1	0	<3	0	30
460812103053701	81-10-06	--	--	--	--	--	--	--	--	--	--
460804103052301	81-10-01	1	1	200	0	--	0	20	4	4	330
	81-10-01	--	--	--	--	--	--	--	--	--	--
460804103044401	76-05-21	--	--	--	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
460749103054602	81-10-14	0	1	100	0	--	0	0	0	2	40
	81-10-14	--	--	--	--	--	--	--	--	--	--

SUPPLEMENT 2.—*Water quality in the Harmon lignite aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	ZINC, DIS-SOLVED (UG/L AS ZN)
460804103010101	75-12-11	--	--	<10	--	--	--	--	--	--	--
	76-09-09	4	30	<10	<.5	2	7	<1	--	140	<20
	76-12-21	<2	20	<10	<.5	<1	--	<1	--	140	<20
	77-11-08	<2	30	20	.2	<1	--	<1	--	160	60
	78-11-06	7	20	20	<.1	<1	--	<1	--	170	<20
	79-11-15	0	20	0	.2	0	--	0	--	140	0
	80-10-28	5	20	10	.0	0	--	0	--	160	10
	81-05-20	4	30	30	.3	0	2	0	0	180	20
460825103032601	76-05-21	--	--	--	--	--	--	--	--	--	--
	81-10-16	2	60	60	.0	3	3	0	0	1400	90
460804103021603	76-06-16	--	--	--	--	--	--	--	--	--	--
460830103040801	76-05-21	--	--	--	--	--	--	--	--	--	--
460830103044502	81-10-15	--	--	--	--	--	--	--	--	--	--
460830103044504	81-10-09	--	--	--	--	--	--	--	--	1000	--
	81-10-15	1	53	48	.2	<10	0	0	0	1000	5
460812103053701	81-10-06	--	--	--	--	--	--	--	--	100	--
460804103052301	81-10-01	1	100	450	.1	4	10	0	0	6800	40
	81-10-01	--	--	--	--	--	--	--	--	--	--
460804103044401	76-05-21	--	--	--	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
460749103054602	81-10-14	1	50	0	.0	10	2	0	0	260	10
	81-10-14	--	--	--	--	--	--	--	--	270	--

STATION NUMBER	DATE OF SAMPLE	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	URANIUM NATURAL DIS-SOLVED (UG/L AS U)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
460804103010101	75-12-11	--	--	--	--	--	--
	76-09-09	--	--	--	--	--	--
	76-12-21	<11	7.2	5.8	.10	--	.3
	77-11-08	<10	<3.0	<2.7	.13	.6	9.3
	78-11-06	10	<3.6	<3.3	.13	--	6.4
	79-11-15	<18	<5.8	<5.4	.08	--	21
	80-10-28	14	<7.6	<7.3	.14	--	21
	81-05-20	--	--	--	--	--	--
460825103032601	76-05-21	--	--	--	--	--	--
	81-10-16	--	--	--	--	--	--
460804103021603	76-06-16	--	--	--	--	--	--
460830103040801	76-05-21	--	--	--	--	--	--
460830103044502	81-10-15	--	--	--	--	--	--
460830103044504	81-10-09	--	--	--	--	--	--
	81-10-15	--	--	--	--	--	--
460812103053701	81-10-06	--	--	--	--	--	--
460804103052301	81-10-01	--	--	--	--	--	--
	81-10-01	--	--	--	--	--	--
460804103044401	76-05-21	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--
460749103054602	81-10-14	--	--	--	--	--	--
	81-10-14	--	--	--	--	--	--

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*

[Analyses not indicated otherwise were performed by the U.S. Geological Survey National Water-Quality Laboratory, Denver, Colo. "Geologic unit" indicates the aquifer sampled: 125TRVL = basal Bullion Creek-Slope aquifer, 125LDLW = parts of the basal Bullion Creek-Slope aquifer confined to the Paleocene Slope Formation of the Fort Union Group, 125TGRVL = parts of the basal Bullion Creek-Slope aquifer confined to the Paleocene Bullion Creek Formation of the Fort Union Group. < indicates less than, ND indicates not detected]

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
461033103055102	131-099-17BBB2	125TRVL	236	76-09-23	--	1700	8.8	9.0	--
461355103070201	131-099-19CCC	125TRVL	80	74-05-09	1000	3410	7.1	9.0	--
		125TRVL	80	74-11-22	1400	2000	8.7	10.0	--
		125TRVL	80	81-10-15	1130	3150	7.8	9.9	--
		125TRVL	80	81-10-15 1/	1131	3150	7.8	9.9	--
461355103055701	131-099-19DDD	125TRVL	74	74-05-24	--	1860	8.6	10.5	--
		125TRVL	74	74-06-05	1200	1880	8.5	11.0	--
		125TRVL	74	75-05-01 1/	1721	1884	7.9	7.5	--
		125TRVL	74	75-11-07 1/	1031	1690	8.0	10.0	--
		125TRVL	74	76-04-13	1146	1500	8.5	12.0	--
		125TRVL	74	78-08-24	1000	1324	8.6	9.0	.0
		125TRVL	74	79-06-06	1000	1810	7.4	6.2	--
		125TRVL	74	80-05-27 1/	1001	1176	7.9	7.5	--
		125TRVL	74	80-08-16	1030	1760	8.3	7.5	.0
		125TRVL	74	81-10-15	1930	1720	8.4	7.7	.0
		125TRVL	74	81-10-15 1/	1931	1720	8.4	7.7	.0
460852103054402	131-099-20CDC2	125TRVL	94	81-09-30	1230	1590	8.7	7.4	.0
		125TRVL	94	81-10-05 1/	0001	1473	8.6	6.8	.0
461355103043301	131-099-21CCC1	125TRVL	184	74-04-25 2/	1400	1730	8.5	10.1	--
		125TRVL	184	79-06-06	1000	5500	7.5	7.6	--
		125TRVL	184	80-05-27	1000	5530	8.0	7.7	--
		125TRVL	184	81-10-15	1700	1810	8.5	7.7	.0
461355103043303	131-099-21CCC3	125TRVL	152	81-09-30	1100	1860	8.7	8.1	.6
		125TRVL	152	81-09-30 1/	1101	1860	8.2	8.1	.6
		125TRVL	152	81-10-04 1/	0001	1710	8.5	7.8	.0
461355103032801	131-099-21DDD	125TRVL	90	74-05-17	1000	1920	8.4	8.5	--
		125TRVL	90	74-08-28	--	2500	8.4	8.1	--
		125TRVL	90	74-11-21	1000	2350	8.4	8.5	--
		125TRVL	90	74-11-21	1215	2350	8.5	8.5	--
		125TRVL	90	75-05-01	1230	2390	8.8	7.5	--
		125TRVL	90	75-11-10	1530	2300	8.8	8.0	--
		125TRVL	90	76-04-13	1530	2230	8.3	9.5	--
461355103032803	131-099-21DDD3	125TRVL	150	81-09-30	0930	1910	8.3	7.7	.0
		125TRVL	150	81-09-30 1/	0931	1910	8.3	7.7	.0

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
461033103055102	76-09-23	91	863	859	2.6	--	27	0	5.4	3.2	420
461355103070201	74-05-09	0	618	507	79	20	530	19	110	61	620
	74-11-22	0	525	431	2.4	--	31	0	7.0	3.4	440
	81-10-15	--	--	410	14	--	780	370	160	91	570
	81-10-15	--	--	--	13	--	780	347	154	94	559
461355103055701	74-05-24	20	695	603	3.0	--	38	0	9.3	3.6	450
	74-06-05	7	613	514	3.2	1400	30	0	7.0	3.0	420
	75-05-01	0	632	518	13	--	36	0	11	2.1	425
	75-11-07	0	890	730	14	--	62	0	19	3.6	421
	76-04-13	0	480	390	2.4	--	30	0	7.7	2.7	350
	78-08-24	--	--	413	2.1	--	48	0	15	2.5	280
	79-06-06	0	330	271	21	--	270	2	45	39	314
	80-05-27	0	294	241	5.9	--	110	0	31	7.5	210
	80-08-16	--	--	370	3.6	--	50	0	5.8	8.7	385
	81-10-15	--	--	380	2.9	--	--	--	<10	8.1	370
	81-10-15	0	472	387	3.0	--	69	0	13	8.7	358
460852103054402	81-09-30	--	--	600	2.3	--	10	0	2.5	.9	390
	81-10-05	--	--	623	2.6	--	8	0	2.0	.8	375
461355103043301	74-04-25	31	698	616	3.8	2300	44	0	12	3.4	410
	79-06-06	0	442	363	22	--	2700	2330	418	400	580
	80-05-27	0	358	294	5.7	--	2400	2130	205	465	590
	81-10-15	--	--	570	3.4	--	24	0	6.2	1.9	430
461355103043303	81-09-30	--	--	620	2.3	--	34	0	6.2	4.3	460
	81-09-30	--	--	630	7.5	--	35	0	6.4	4.7	443
	81-10-04	5	765	636	3.9	--	33	0	5.5	4.7	420
461355103032801	74-05-17	0	673	556	4.3	--	39	0	5.3	6.1	462
	74-08-28	0	670	550	4.2	--	65	0	4.4	13	510
	74-11-21	4	671	557	4.3	--	35	0	6.9	4.3	500
	74-11-21	0	671	550	3.4	--	33	0	6.2	4.2	500
	75-05-01	11	659	559	1.7	--	26	0	5.3	3.1	530
	75-11-10	8	665	559	1.7	--	24	0	4.8	2.8	510
	76-04-13	0	649	532	5.2	--	23	0	4.6	2.7	460
461355103032803	81-09-30	--	--	560	5.4	--	43	0	9.8	4.4	450
	81-09-30	0	708	581	5.7	--	43	0	9.3	4.8	438

Footnotes at end of table

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	POTASSIUM, DISSOLVED (MG/L AS K)	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	NITROGEN, NO2+NO3 DISSOLVED (MG/L AS N)	PHOSPHORUS, DISSOLVED (MG/L AS P)	ALUMINUM, DISSOLVED (UG/L AS AL)
461033103055102	76-09-23	7.0	93	10	5.4	5.5	1080	1066	1.6	.550	--
461355103070201	74-05-09	15	1300	6.3	.9	12	2590	2430	.03	1.90	--
	74-11-22	3.7	340	48	1.6	7.9	1240	1110	--	--	190
	81-10-15	13	1600	24	.4	7.9	2570	2720	.12	--	0
	81-10-15	42	1520	16	.6	8.0	2698	2660	--	--	--
461355103055701	74-05-24	4.8	390	4.4	1.9	5.7	1380	1250	--	--	--
	74-06-05	3.6	380	29	1.9	8.8	1310	1170	.09	--	--
	75-05-01	1.5	411	9.9	1.1	5.7	1190	1180	--	--	--
	75-11-07	5.1	234	12	1.3	2.6	1150	1140	--	--	--
	76-04-13	9.1	389	1.0	1.1	3.4	1020	1000	--	--	--
	78-08-24	6.3	286	3.9	.6	7.3	902	849	--	--	--
	79-06-06	10	650	12	1.6	--	1250	1235	--	--	--
	80-05-27	5.6	292	16	1.7	--	811	710	--	--	--
	80-08-16	6.8	496	10	.8	12	1179	1150	1.6	--	--
	81-10-15	6.3	460	11	.5	9.5	1080	933	.18	--	10
	81-10-15	7.0	446	6.3	.6	9.2	1070	1080	--	--	--
460852103054402	81-09-30	2.4	240	23	1.7	8.5	1280	1030	.02	--	50
	81-10-05	3.1	185	5.8	1.8	10	1002	971	--	--	--
461355103043301	74-04-25	5.3	300	20	2.7	9.9	1250	1170	.33	2.30	--
	79-06-06	3.8	2625	98	3.1	12	6217	4360	--	--	--
	80-05-27	4.4	1724	145	1.9	13	6620	3340	--	--	--
	81-10-15	2.4	410	29	3.1	8.6	1230	1240	.21	--	70
461355103043303	81-09-30	3.0	470	63	2.9	8.3	1310	1390	.14	--	50
	81-09-30	3.6	339	7.5	3.3	4.4	1350	1210	--	--	--
	81-10-04	5.5	303	7.9	3.2	4.3	1163	1140	--	--	--
461355103032801	74-05-17	5.8	456	8.3	3.0	6.6	1308	1290	--	--	--
	74-08-28	11	600	8.5	2.7	6.4	1700	1490	--	--	--
	74-11-21	4.3	550	13	1.9	7.4	1490	1430	--	--	50
	74-11-21	4.6	560	58	1.9	7.5	1490	1470	--	--	50
	75-05-01	4.4	510	37	2.4	7.5	1480	1450	--	--	70
	75-11-10	4.2	520	12	2.4	6.3	1420	1410	--	--	90
	76-04-13	4.7	490	12	2.5	5.4	1350	1300	--	--	120
461355103032803	81-09-30	3.1	490	34	3.7	7.9	1330	1340	.13	--	50
	81-09-30	4.0	389	9.9	4.1	4.1	4403	1210	--	--	--

STATION NUMBER	DATE OF SAMPLE	ANTIMONY, DISSOLVED (UG/L AS SB)	ARSENIC DISSOLVED (UG/L AS AS)	BARIUM, DISSOLVED (UG/L AS BA)	BERYLLIUM, DISSOLVED (UG/L AS BE)	BORON, DISSOLVED (UG/L AS B)	CADMIUM DISSOLVED (UG/L AS CD)	CHROMIUM, DISSOLVED (UG/L AS CR)	COBALT, DISSOLVED (UG/L AS CO)	COPPER, DISSOLVED (UG/L AS CU)	IRON, DISSOLVED (UG/L AS FE)
461033103055102	76-09-23	--	--	--	--	1300	--	--	--	--	--
461355103070201	74-05-09	--	--	--	--	--	--	--	--	--	110
	74-11-22	--	<1	--	<10	--	ND	<20	--	7	90
	81-10-15	0	0	100	0	--	0	0	0	0	1400
	81-10-15	--	--	--	--	--	--	--	--	--	--
461355103055701	74-05-24	--	--	--	--	220	--	--	--	--	630
	74-06-05	--	--	--	<10	1300	<2	ND	--	24	100
	75-05-01	--	--	0	--	0	--	--	--	--	30
	75-11-07	--	--	100	--	50	--	--	--	--	--
	76-04-13	--	--	100	--	20	--	--	--	--	170
	78-08-24	--	--	--	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
	80-08-16	--	1	--	--	--	0	10	--	--	--
	81-10-15	0	1	50	<1	--	<1	0	<3	2	240
	81-10-15	--	--	--	--	--	--	--	--	--	--
460852103054402	81-09-30	1	1	23	<1	--	<1	0	<3	30	74
	81-10-05	--	--	--	--	--	--	--	--	--	--
461355103043301	74-04-25	--	--	--	--	--	--	--	--	--	850
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	1970
	81-10-15	0	2	200	<1	--	<1	0	9	8	410
461355103043303	81-09-30	0	6	150	4	--	3	10	14	13	390
	81-09-30	--	--	--	--	--	--	--	--	--	--
	81-10-04	--	--	--	--	--	--	--	--	--	--
461355103032801	74-05-17	--	--	--	<10	1100	2	ND	--	6	--
	74-08-28	--	--	--	--	--	--	--	--	--	--
	74-11-21	--	<1	--	<10	--	2	<20	--	<20	90
	74-11-21	--	1	--	<10	--	<2	<20	--	<20	40
	75-05-01	--	1	<100	<10	1100	<2	ND	--	4	40
	75-11-10	--	2	<100	<10	980	ND	<20	--	11	<10
	76-04-13	--	1	<100	<10	230	<2	<20	--	28	260
461355103032803	81-09-30	0	3	150	1	--	<1	10	5	7	300
	81-09-30	--	--	--	--	--	--	--	--	--	--

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	VANA-DIUM, DIS-SOLVED (UG/L AS V)
461033103055102	76-09-23	--	--	--	--	--	--	--	--	--	--
461355103070201	74-05-09	--	--	60	--	--	--	--	--	--	--
	74-11-22	5	<10	50	<.1	2	8	<1	--	--	--
	81-10-15	0	90	410	.0	1	0	0	0	4600	--
	81-10-15	--	--	--	--	--	--	--	--	4900	--
461355103055701	74-05-24	--	--	80	--	--	--	--	--	--	--
	74-06-05	45	30	80	<.5	2	14	2	ND	--	24
	75-05-01	4	--	50	--	--	--	--	--	--	--
	75-11-07	0	--	110	--	--	--	--	--	--	--
	76-04-13	16	--	110	--	--	--	--	--	--	--
	78-08-24	--	--	--	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
	80-08-16	0	--	--	--	--	--	0	--	--	--
	81-10-15	3	33	98	.0	<10	1	1	0	250	--
	81-10-15	--	--	--	--	--	--	--	--	230	--
460852103054402	81-09-30	1	21	14	.0	<10	1	0	0	73	22
	81-10-05	--	--	--	--	--	--	--	--	100	--
461355103043301	74-04-25	--	--	50	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
	81-10-15	15	22	57	.0	10	15	0	0	160	--
461355103043303	81-09-30	12	32	49	.0	20	19	0	0	200	--
	81-09-30	--	--	--	--	--	--	--	--	--	--
	81-10-04	--	--	--	--	--	--	--	--	300	--
461355103032801	74-05-17	12	30	--	<.5	<1	4	1	ND	--	4.0
	74-08-28	--	--	--	--	--	--	--	--	--	--
	74-11-21	4	<10	30	<.1	<1	4	<1	--	--	--
	74-11-21	8	20	20	<.1	1	9	<1	--	--	--
	75-05-01	ND	30	30	<.5	<1	<2	<1	--	220	14
	75-11-10	4	20	30	<.5	<1	13	<1	--	200	--
	76-04-13	4	30	20	<.5	<1	29	<1	--	210	.2
461355103032803	81-09-30	13	30	52	.0	<10	14	1	0	250	--
	81-09-30	--	--	--	--	--	--	--	--	300	--

STATION NUMBER	DATE OF SAMPLE	ZINC, DIS-SOLVED (UG/L AS ZN)	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	URANIUM NATURAL DIS-SOLVED (UG/L AS U)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
461033103055102	76-09-23	--	--	--	--	--	--	--
461355103070201	74-05-09	--	--	--	--	--	--	--
	74-11-22	240	--	--	--	--	--	17
	81-10-15	30	--	--	--	--	--	--
	81-10-15	--	--	--	--	--	--	--
461355103055701	74-05-24	--	--	--	--	--	--	--
	74-06-05	310	--	--	--	--	--	--
	75-05-01	--	--	--	--	--	--	--
	75-11-07	--	--	--	--	--	--	--
	76-04-13	--	--	--	--	--	--	--
	78-08-24	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--
	80-08-16	--	--	--	--	--	--	--
	81-10-15	79	--	--	--	--	--	--
	81-10-15	--	--	--	--	--	--	--
460852103054402	81-09-30	5	--	--	--	--	--	--
	81-10-05	--	--	--	--	--	--	--
461355103043301	74-04-25	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--
	81-10-15	610	--	--	--	--	--	--
461355103043303	81-09-30	34	--	--	--	--	--	--
	81-09-30	--	--	--	--	--	--	--
	81-10-04	--	--	--	--	--	--	--
461355103032801	74-05-17	220	--	--	--	--	--	--
	74-08-28	--	--	--	--	--	--	--
	74-11-21	30	--	--	--	--	--	17
	74-11-21	40	--	--	--	--	--	9.7
	75-05-01	20	--	--	--	--	--	23
	75-11-10	30	<21	9.6	7.6	.93	--	.2
	76-04-13	40	--	--	--	--	--	17
461355103032803	81-09-30	48	--	--	--	--	--	--
	81-09-30	--	--	--	--	--	--	--

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
461402103031801	131-099-22CCB	125TRVL	167	74-04-25	1600	1860	8.7	9.5	--
		125TRVL	167	74-11-25	1430	2340	9.0	5.0	--
		125TRVL	167	75-05-01	1000	3100	8.7	7.5	--
		125TRVL	167	75-11-10	1230	2800	8.7	7.0	--
		125TRVL	167	76-04-14	1005	1880	8.8	7.5	--
460856103024403	131-099-22DCC3	125TRVL	118	81-09-29	1830	2390	9.5	8.2	.1
		125TRVL	118	81-10-09 1/	1301	3610	7.0	7.3	.0
460856103020701	131-099-23CCC1	125TRVL	170	75-12-10	1230	3200	8.4	5.0	--
		125TRVL	170	78-10-27	1000	2340	8.1	6.0	--
		125TRVL	170	79-06-06	1000	2330	8.3	6.3	--
		125TRVL	170	80-05-27	1000	2330	8.3	6.8	.0
		125TRVL	170	81-10-22	1600	1470	9.0	7.1	.0
461349103004901	131-099-25BBB1	125LDLW	417	74-05-09	--	1640	--	19.0	--
461349103004902	131-099-25BBB2	125TRVL	200	74-04-23	1400	1280	8.5	9.5	--
460801103005501	131-099-25CCC1	125TRVL	158	74-04-23	1000	1290	8.5	9.5	--
		125TRVL	158	74-11-27	1000	1580	8.9	8.0	--
		125TRVL	158	75-04-30	1000	1530	9.0	8.5	--
		125TRVL	158	75-11-11	1000	1450	8.8	7.0	--
		125TRVL	158	76-04-14	1000	1500	8.8	10.0	--
		125TRVL	158	79-06-06	1000	1610	9.9	8.0	--
460830103021601	131-099-27ADD	125TRVL	120	76-09-16	--	1600	--	10.5	--
		125TRVL	120	81-05-21	1245	1625	8.2	8.6	.0
		125TRVL	120	81-10-21	1000	1590	8.5	5.6	.0
		125TRVL	120	81-10-21 1/	1001	1590	8.5	5.6	.0
460830103021602	131-099-27ADD2	125TRVL	112	81-10-04	1900	1560	8.4	7.7	.0
		125TRVL	112	81-10-04 1/	1901	1560	8.4	7.7	.0
460843103032003	131-099-27BBC3	125TRVL	160	81-10-14	1430	1680	8.5	5.6	.0
		125TRVL	160	81-10-14 1/	1431	1680	8.5	5.6	.0
460823103021601	131-099-27DAA	125TRVL	--	76-09-16	--	4000	--	6.2	--
460804103021601	131-099-27DDD1	125TRVL	112	76-06-17	1130	1580	8.6	7.5	--
		125TRVL	112	76-09-08	--	1500	8.8	10.8	--
		125TRVL	112	76-12-21	1035	1400	8.7	9.0	--
		125TRVL	112	77-11-09	1300	1390	8.3	9.5	--
460804103033101	131-099-28DDD	125TRVL	130	76-09-29	--	2300	--	8.2	--
		125TRVL	130	81-10-16	1000	1330	8.0	7.8	.0

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
461402103031801	74-04-25	98	788	809	3.0	4000	92	0	24	7.8	430
	74-11-25	72	914	870	1.7	--	130	0	24	18	500
	75-05-01	41	847	763	3.0	--	330	0	49	49	600
	75-11-10	56	853	793	3.1	--	340	0	57	47	520
	76-04-14	47	934	844	2.6	--	28	0	7.7	2.0	420
460856103024403	81-09-29	--	--	560	.3	--	24	0	5.8	2.1	480
	81-10-09	0	560	459	98	--	1400	940	258	183	482
460856103020701	75-12-10	44	634	593	4.6	--	180	0	15	35	630
	78-10-27	0	480	394	6.1	--	190	0	15	36	451
	79-06-06	0	472	387	3.8	--	250	0	12	53	424
	80-05-27	0	396	325	3.2	--	270	0	12	57	414
	81-10-22	--	--	620	1.1	--	51	0	13	4.4	330
461349103004901	74-05-09	45	968	869	--	--	36	0	5.1	5.7	420
461349103004902	74-04-23	28	647	577	3.3	2300	16	0	4.1	1.3	320
460801103005501	74-04-23	16	679	584	3.6	--	25	0	7.4	1.7	320
	74-11-27	24	696	611	1.5	--	19	0	5.8	1.1	370
	75-04-30	23	653	574	1.1	--	21	0	6.0	1.4	340
	75-11-11	22	635	557	1.7	--	25	0	6.6	2.1	370
	76-04-14	21	629	551	1.7	--	22	0	5.9	1.8	330
	79-06-06	0	252	207	.1	--	50	0	16	2.3	445
460830103021601	76-09-16	0	709	582	--	--	1300	729	310	130	370
	81-05-21	4	673	538	6.8	--	26	0	5.1	3.1	422
	81-10-21	--	--	540	3.3	--	26	0	5.1	3.1	390
	81-10-21	5	675	562	3.5	--	27	0	5.0	3.4	370
460830103021602	81-10-04	--	--	540	4.1	--	32	0	6.4	3.9	400
	81-10-04	0	680	558	4.3	--	37	0	6.6	4.8	392
460843103032003	81-10-14	--	--	690	4.2	--	22	0	5.8	1.7	420
	81-10-14	0	880	722	4.5	--	22	0	5.2	2.1	410
460823103021601	76-09-16	0	685	562	--	--	440	0	74	63	860
460804103021601	76-06-17	17	713	613	3.0	3000	63	0	17	4.9	390
	76-09-08	26	723	636	2.0	7000	34	0	8.4	3.0	370
	76-12-21	11	753	636	2.5	--	28	0	7.6	2.2	360
	77-11-09	0	780	640	6.3	--	27	0	6.6	2.3	370
460804103033101	76-09-29	0	805	660	--	--	41	0	9.2	4.3	540
	81-10-16	--	--	300	5.8	--	88	0	26	5.6	210

Footnotes at end of table

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	POTASSIUM, DISSOLVED (MG/L AS K)	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	NITROGEN, NO2+NO3 DISSOLVED (MG/L AS N)	PHOSPHORUS, DISSOLVED (MG/L AS P)	ALUMINUM, DISSOLVED (UG/L AS AL)
461402103031801	74-04-25	4.6	98	66	5.2	10	1440	1230	--	1.60	--
	74-11-25	5.5	350	68	3.9	13	1520	1580	--	--	40
	75-05-01	6.7	750	17	3.8	11	2070	1990	--	--	40
	75-11-10	4.7	710	18	4.7	7.7	1840	1910	--	--	70
	76-04-14	2.5	100	19	3.9	9.6	1140	1120	--	--	100
460856103024403	81-09-29	4.8	530	21	2.5	10	1390	1390	.08	--	150
	81-10-09	16	1990	36	1.5	6.8	3260	3250	--	--	--
460856103020701	75-12-10	8.3	890	13	2.0	8.8	1512	2000	.15	.350	--
	78-10-27	7.7	800	16	2.6	7.9	1592	1570	--	--	--
	79-06-06	8.7	810	13	1.9	9.1	1582	1560	--	--	--
	80-05-27	7.9	845	20	1.8	6.9	1585	1560	--	--	--
	81-10-22	2.4	290	40	4.9	5.4	1070	1060	<.09	--	30
461349103004901	74-05-09	5.4	63	6.3	6.5	3.3	1150	1090	--	--	--
461349103004902	74-04-23	2.1	140	24	4.2	9.3	926	881	.25	.890	--
460801103005501	74-04-23	3.0	150	33	5.2	10	1040	897	--	--	--
	74-11-27	2.9	130	91	6.8	8.6	1050	1010	--	--	--
	75-04-30	2.9	170	49	3.5	7.6	1000	949	--	--	--
	75-11-11	2.8	190	20	4.2	5.8	983	960	--	--	--
	76-04-14	2.3	200	20	3.8	6.3	976	923	--	--	--
	79-06-06	1.6	350	32	4.0	7.5	1322	983	--	--	--
460830103021601	76-09-16	5.7	320	67	2.2	7.8	1671	1640	.18	.390	--
	81-05-21	6.2	356	22	3.9	8.1	1176	1170	--	--	--
	81-10-21	3.2	320	24	4.0	8.9	1070	1080	<.09	--	30
	81-10-21	3.1	259	9.0	4.3	3.9	1010	1000	--	--	--
460830103021602	81-10-04	3.0	370	25	3.6	8.0	1120	1150	.13	--	70
	81-10-04	3.6	318	9.1	4.0	4.0	1100	1080	--	--	--
460843103032003	81-10-14	2.0	290	34	4.2	8.7	1200	1180	.18	--	70
	81-10-14	3.7	177	10	4.7	4.4	1083	1050	--	--	--
460823103021601	76-09-16	14	1800	5.9	.9	7.6	3191	3170	.84	.110	--
460804103021601	76-06-17	2.9	300	67	3.7	8.9	1350	1180	.09	.660	--
	76-09-08	2.3	170	7.2	2.5	8.8	991	985	--	.680	310
	76-12-21	2.0	130	80	4.2	8.1	1190	990	.20	.330	130
	77-11-09	2.2	160	12	4.1	3.5	1180	948	.23	.650	160
460804103033101	76-09-29	5.4	520	36	2.4	4.7	1532	1520	.21	.450	--
	81-10-16	3.4	200	17	1.6	4.8	653	669	4.4	--	40

STATION NUMBER	DATE OF SAMPLE	ANTIMONY, DISSOLVED (UG/L AS SB)	ARSENIC DISSOLVED (UG/L AS AS)	BARIUM, DISSOLVED (UG/L AS BA)	BERYLLIUM, DISSOLVED (UG/L AS BE)	BORON, DISSOLVED (UG/L AS B)	CADMIUM DISSOLVED (UG/L AS CD)	CHROMIUM, DISSOLVED (UG/L AS CR)	COBALT, DISSOLVED (UG/L AS CO)	COPPER, DISSOLVED (UG/L AS CU)	IRON, DISSOLVED (UG/L AS FE)
461402103031801	74-04-25	--	--	--	--	--	--	--	--	--	770
	74-11-25	--	5	--	<10	--	2	<20	--	7	140
	75-05-01	--	2	<100	<10	1300	<2	ND	--	3	250
	75-11-10	--	4	<100	10	820	ND	2	--	8	600
	76-04-14	--	6	<100	<10	270	ND	--	--	7	660
460856103024403	81-09-29	0	2	100	0	--	0	10	2	4	210
	81-10-09	--	--	--	--	--	--	--	--	--	--
460856103020701	75-12-10	--	--	--	--	--	--	--	--	--	320
	78-10-27	--	--	--	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
	81-10-22	0	1	140	3	--	<1	0	<3	1	2100
461349103004901	74-05-09	--	--	--	--	1300	--	--	--	--	40
461349103004902	74-04-23	--	--	--	--	--	--	--	--	--	690
460801103005501	74-04-23	--	--	--	--	--	--	--	--	--	--
	74-11-27	--	--	--	--	--	--	--	--	--	310
	75-04-30	--	--	0	--	240	--	--	--	--	380
	75-11-11	--	--	100	--	1100	--	--	--	--	3
	76-04-14	--	--	100	--	200	--	--	--	--	590
	79-06-06	--	--	--	--	--	--	--	--	--	--
460830103021601	76-09-16	--	--	--	--	--	--	--	--	--	77000
	81-05-21	--	--	--	--	--	--	--	--	--	--
	81-10-21	0	2	82	1	--	<1	0	<3	2	270
	81-10-21	--	--	--	--	--	--	--	--	--	--
460830103021602	81-10-04	0	2	78	1	--	<1	0	5	6	180
	81-10-04	--	--	--	--	--	--	--	--	--	--
460843103032003	81-10-14	0	4	200	1	--	<1	0	20	11	370
	81-10-14	--	--	--	--	--	--	--	--	--	--
460823103021601	76-09-16	--	--	--	--	--	--	--	--	--	602
460804103021601	76-06-17	--	--	--	--	1500	--	--	--	--	--
	76-09-08	--	18	<100	10	3400	ND	<20	6	12	550
	76-12-21	--	50	200	--	2500	ND	ND	--	3	570
	77-11-09	--	2	500	--	2000	ND	8	--	8	570
460804103033101	76-09-29	--	--	--	--	--	--	--	--	--	1900
	81-10-16	8	4	130	<1	--	<1	0	<3	13	190

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	VANA-DIUM, DIS-SOLVED (UG/L AS V)
461402103031801	74-04-25	--	--	60	--	--	--	--	--	--	--
	74-11-25	12	30	110	<.5	3	<2	<1	--	--	--
	75-05-01	6	50	230	<.5	6	4	<1	--	1400	24
	75-11-10	5	20	130	1.6	9	13	<1	--	780	--
	76-04-14	16	20	90	<.5	7	38	<1	--	160	1.4
460856103024403	81-09-29	4	20	30	.3	5	6	0	0	270	--
	81-10-09	--	--	--	--	--	--	--	--	--	--
460856103020701	75-12-10	--	--	100	--	--	--	--	--	--	--
	78-10-27	--	--	--	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
	81-10-22	5	29	62	.0	<10	1	0	0	180	--
461349103004901	74-05-09	--	--	400	--	--	--	--	--	--	--
461349103004902	74-04-23	--	--	50	--	--	--	--	--	--	--
460801103005501	74-04-23	--	--	--	--	--	--	--	--	--	--
	74-11-27	9	--	80	--	--	--	--	--	--	--
	75-04-30	8	--	80	--	--	--	--	--	--	--
	75-11-11	0	--	130	--	--	--	--	--	--	--
	76-04-14	0	--	80	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
460830103021601	76-09-16	--	--	2000	--	--	--	--	--	--	--
	81-05-21	--	--	--	--	--	--	--	--	--	--
	81-10-21	3	30	55	.0	<10	2	0	0	160	--
	81-10-21	--	--	--	--	--	--	--	--	200	--
460830103021602	81-10-04	8	25	35	.0	20	3	0	0	200	--
	81-10-04	--	--	--	--	--	--	--	--	300	--
460843103032003	81-10-14	17	20	40	.0	<10	26	0	0	190	--
	81-10-14	--	--	--	--	--	--	--	--	200	--
460823103021601	76-09-16	--	--	100	--	--	--	--	--	--	--
460804103021601	76-06-17	--	--	--	--	--	--	--	--	--	--
	76-09-08	26	20	150	<.5	3	24	<1	--	200	--
	76-12-21	5	20	80	<.5	<1	--	<1	--	230	--
	77-11-09	8	20	110	<.1	2	--	<1	--	240	--
460804103033101	76-09-29	--	--	60	--	--	--	--	--	--	--
	81-10-16	81	14	76	.0	10	12	1	0	230	--

STATION NUMBER	DATE OF SAMPLE	ZINC, DIS-SOLVED (UG/L AS ZN)	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	URANIUM NATURAL DIS-SOLVED (UG/L AS U)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
461402103031801	74-04-25	--	--	--	--	--	--	--
	74-11-25	450	--	--	--	--	--	38
	75-05-01	270	--	--	--	--	--	23
	75-11-10	390	--	--	--	--	--	.1
	76-04-14	550	--	--	--	--	--	46
460856103024403	81-09-29	20	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--
460856103020701	75-12-10	--	--	--	--	--	--	--
	78-10-27	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--
	81-10-22	49	--	--	--	--	--	--
461349103004901	74-05-09	--	--	--	--	--	--	--
461349103004902	74-04-23	--	--	--	--	--	--	--
460801103005501	74-04-23	--	--	--	--	--	--	--
	74-11-27	--	--	--	--	--	--	--
	75-04-30	--	--	--	--	--	--	--
	75-11-11	--	--	--	--	--	--	--
	76-04-14	--	--	--	--	--	--	--
	79-06-06	--	--	--	--	--	--	--
460830103021601	76-09-16	--	--	--	--	--	--	--
	81-05-21	--	--	--	--	--	--	--
	81-10-21	31	--	--	--	--	--	--
	81-10-21	--	--	--	--	--	--	--
460830103021602	81-10-04	32	--	--	--	--	--	--
	81-10-04	--	--	--	--	--	--	--
460843103032003	81-10-14	88	--	--	--	--	--	--
	81-10-14	--	--	--	--	--	--	--
460823103021601	76-09-16	--	--	--	--	--	--	--
460804103021601	76-06-17	--	--	--	--	--	--	--
	76-09-08	40	--	--	--	--	--	--
	76-12-21	<20	430	40	33	.34	6.5	150
	77-11-09	20	380	47	- 41	.39	6.4	170
460804103033101	76-09-29	--	--	--	--	--	--	--
	81-10-16	67	--	--	--	--	--	--

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
460830103044501	131-099-29ADD1	125TRVL	118	75-12-10	1330	2000	8.5	4.0	--
		125TRVL	118	76-09-10	1000	2100	8.7	12.5	--
		125TRVL	118	80-08-15	1500	1750	8.3	7.1	.0
		125TRVL	118	81-10-09 1/	1201	2220	8.2	7.3	.0
		125TRVL	118	81-10-15	1230	2160	8.7	7.7	.1
461349103054801	131-099-29BBB	125TRVL	136	74-05-01	1600	1620	8.5	9.8	--
		125TRVL	136	74-11-22	1000	1800	8.8	8.5	--
		125TRVL	136	75-05-01	1520	1900	9.0	9.5	--
		125TRVL	136	75-11-07	1240	1730	8.8	10.0	--
		125TRVL	136	76-04-13	0945	1970	8.8	10.5	--
		125TRVL	136	81-10-15	1400	1720	8.7	14.4	.0
		125TRVL	136	81-10-15 1/	1401	1720	8.7	14.4	.0
460834103055501	131-099-29BCC	125TGRVL	53	81-10-06	1700	1920	9.0	8.1	.0
		125TGRVL	53	81-10-06 1/	1701	1920	9.0	8.1	.0
460812103053702	131-099-29CDB2	125TGRVL	61	81-10-06	1500	1950	8.7	7.9	.0
461257103051001	131-099-32AAB	125TRVL	39	74-05-01	1800	2720	9.1	7.1	--
460749103054601	131-099-32BBC1	125TRVL	114	81-10-14	0930	2510	11.3	8.6	.0
460747103032903	131-099-33ADA3	125TRVL	76	81-09-30	1430	3100	8.7	8.1	.8
460757103040801	131-099-33BAA1	125TRVL	150	76-02-24	1010	1850	11.5	6.0	--
		125TRVL	150	81-10-09 1/	1001	1010	10.4	6.4	.0
		125TRVL	150	81-10-16	1330	2590	8.5	7.7	.0
460757103040802	131-099-33BAA2	125TRVL	90	76-02-24	0900	3950	11.4	6.0	--
		125TRVL	90	76-09-10	--	3200	10.9	--	--
		125TRVL	90	81-10-09 1/	1101	2220	8.2	7.1	.0
		125TRVL	90	81-10-16	1400	1160	10.8	7.8	.2
460709103032802	131-099-33DDD2	125TRVL	28	81-10-01	1030	7120	8.1	8.1	.5
460759103030601	131-099-34BAB	125TRVL	--	81-10-16	1545	1750	8.6	7.8	.0
460759103015001	131-099-35BAB1	125TRVL	79	81-10-21	0900	1460	8.6	7.6	.0
460744103014801	131-099-35BDB	125TRVL	78	75-12-10	1600	1450	8.9	6.0	--
460710103012702	131-099-35DCC2	125TRVL	165	81-09-29	1400	2620	8.4	8.9	.0

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
460830103044501	75-12-10	0	715	586	3.6	--	36	0	8.0	3.8	530
	76-09-10	49	622	592	2.3	1400	25	0	5.0	3.0	490
	80-08-15	--	--	462	4.4	--	150	0	27	20	345
	81-10-09	7	692	568	6.5	--	22	0	4.4	2.5	498
	81-10-15	--	--	570	2.1	--	25	0	5.3	2.7	530
461349103054801	74-05-01	32	666	599	3.7	500	35	0	9.2	2.8	380
	74-11-22	22	689	602	1.9	--	25	0	5.5	2.8	400
	75-05-01	30	678	606	1.2	--	130	0	49	1.1	380
	75-11-07	37	673	614	1.9	--	9	0	2.2	.8	390
	76-04-13	31	682	611	1.9	--	45	0	3.0	9.0	410
	81-10-15	--	--	590	2.2	--	10	0	2.6	.8	420
	81-10-15	15	710	625	2.4	--	10	0	2.4	.9	403
460834103055501	81-10-06	--	--	600	1.1	--	15	0	4.3	1.0	460
	81-10-06	57	650	572	1.2	--	17	0	4.1	1.5	427
460812103053702	81-10-06	--	--	590	2.2	--	23	0	5.5	2.2	480
461257103051001	74-05-01	150	513	671	1.0	700	140	0	31	14	600
460749103054601	81-10-14	--	--	480	.0	--	5	0	1.8	.1	460
460747103032903	81-09-30	--	--	490	1.8	--	47	0	10	5.1	700
460757103040801	76-02-24	200	0	409	.0	50	29	0	5.9	3.4	370
	81-10-09	176	0	360	.0	--	8	0	2.6	.4	--
	81-10-16	--	--	530	3.2	--	49	0	10	5.6	620
460757103040802	76-02-24	77	0	243	.0	35	140	0	52	1.8	730
	76-09-10	88	0	176	.0	170	51	0	20	.1	670
	81-10-09	0	632	556	5.8	--	39	0	8.0	4.6	555
	81-10-16	--	--	320	.0	--	8	0	2.6	.3	240
460709103032802	81-10-01	--	--	370	5.7	32	1400	1030	260	180	1300
460759103030601	81-10-16	--	--	590	2.8	--	120	0	24	14	360
460759103015001	81-10-21	--	--	500	2.4	--	29	0	7.2	2.6	350
460744103014801	75-12-10	55	588	574	1.4	--	31	0	9.3	2.0	320
460710103012702	81-09-29	--	--	620	4.7	--	53	0	11	6.0	540

Footnotes at end of table

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	POTASSIUM, DISSOLVED (MG/L AS K)	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	NITROGEN, NO2+NO3 DISSOLVED (MG/L AS N)	PHOSPHORUS, DISSOLVED (MG/L AS P)	ALUMINUM, DISSOLVED (UG/L AS AL)
460830103044501	75-12-10	4.2	490	17	1.7	9.1	1432	1420	.04	1.10	--
	76-09-10	4.1	420	65	1.4	8.1	1381	1400	--	.360	110
	80-08-15	13	410	5.8	.6	9.0	1130	1110	.10	--	45
	81-10-09	3.7	509	6.8	2.2	3.8	1403	1390	--	--	--
	81-10-15	3.1	540	16	2.1	8.0	1450	1450	.11	--	30
461349103054801	74-05-01	4.2	290	8.6	1.3	9.7	1080	1100	.09	1.90	--
	74-11-22	3.6	260	51	.9	9.8	1100	1120	--	--	70
	75-05-01	2.7	290	31	1.3	9.1	1100	1160	--	--	20
	75-11-07	1.7	280	7.4	1.2	7.3	1070	1100	--	--	40
	76-04-13	2.4	310	6.2	1.3	8.3	1090	1150	--	--	60
	81-10-15	2.0	310	15	1.4	8.3	1090	1120	.12	--	30
	81-10-15	2.8	271	4.8	1.4	8.0	1100	1070	--	--	--
460834103055501	81-10-06	4.8	350	8.2	1.6	9.2	1180	1200	.12	--	190
	81-10-06	6.2	337	6.5	1.5	9.8	1170	1230	--	--	--
460812103053702	81-10-06	3.6	410	9.3	2.2	10	1280	1280	.12	--	100
461257103051001	74-05-01	9.0	770	13	2.0	--	1910	1840	--	1.10	--
460749103054601	81-10-14	2.9	480	12	2.3	34	1280	1280	.11	--	140
460747103032903	81-09-30	3.9	1000	15	1.9	8.5	2090	2040	.03	--	190
460757103040801	76-02-24	4.5	410	9.3	1.3	34	1110	1270	.15	.350	--
	81-10-09	--	135	9.8	--	116	730	699	--	--	--
	81-10-16	3.0	770	76	2.1	9.9	1700	1820	.22	--	40
460757103040802	76-02-24	11	1400	7.6	1.9	32	2520	2430	.14	.100	--
	76-09-10	7.5	1300	7.2	2.2	36	2230	2230	--	.090	150
	81-10-09	4.3	703	6.1	2.3	5.0	1690	1622	--	--	--
	81-10-16	1.9	160	23	2.1	57	644	681	.33	--	200
460709103032802	81-10-01	14	3700	32	.2	12	5900	5730	.00	--	30
460759103030601	81-10-16	3.0	190	59	3.6	15	1080	1020	.22	--	30
460759103015001	81-10-21	2.5	380	35	3.5	9.1	1090	1100	.20	--	30
460744103014801	75-12-10	3.2	160	18	3.0	14	920	935	.08	.810	--
460710103012702	81-09-29	3.4	710	41	.4	8.4	1680	1690	.14	--	100

STATION NUMBER	DATE OF SAMPLE	ANTIMONY, DISSOLVED (UG/L AS SB)	ARSENIC DISSOLVED (UG/L AS AS)	BARIUM, DISSOLVED (UG/L AS BA)	BERYLLIUM, DISSOLVED (UG/L AS BE)	BORON, DISSOLVED (UG/L AS B)	CADMIUM DISSOLVED (UG/L AS CD)	CHROMIUM, DISSOLVED (UG/L AS CR)	COBALT, DISSOLVED (UG/L AS CO)	COPPER, DISSOLVED (UG/L AS CU)	IRON, DISSOLVED (UG/L AS FE)
460830103044501	75-12-10	--	--	--	--	--	--	--	--	--	820
	76-09-10	--	8	<100	10	1400	ND	ND	8	9	90
	80-08-15	0	1	65	<1	--	<1	1	<3	1	45
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-15	0	2	100	<10	--	0	10	6	5	650
461349103054801	74-05-01	--	--	--	--	--	--	--	--	--	190
	74-11-22	--	3	--	<10	--	<2	<20	--	7	60
	75-05-01	--	3	<100	<10	230	<2	ND	--	14	60
	75-11-07	--	2	<100	10	610	<2	2	--	5	300
	76-04-13	--	2	<100	<10	250	<2	<20	--	7	200
	81-10-15	0	1	100	3	--	2	0	4	1	270
	81-10-15	--	--	--	--	--	--	--	--	--	--
460834103055501	81-10-06	0	2	82	<1	--	<1	10	<3	16	100
	81-10-06	--	--	--	--	--	--	--	--	--	--
460812103053702	81-10-06	0	2	97	<1	--	<1	10	<3	27	150
461257103051001	74-05-01	--	--	--	--	--	--	--	--	--	170
460749103054601	81-10-14	0	5	<100	<10	--	0	10	0	4	80
460747103032903	81-09-30	0	2	200	0	--	1	10	4	2	100
460757103040801	76-02-24	--	--	--	--	560	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-16	0	1	100	<10	--	0	10	0	1	80
460757103040802	76-02-24	--	--	--	--	680	--	--	--	--	--
	76-09-10	--	25	<100	10	820	ND	ND	ND	8	<10
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-16	1	16	75	<1	--	<1	0	<3	9	85
460709103032802	81-10-01	0	0	100	0	--	0	10	1	1	870
460759103030601	81-10-16	0	1	120	<1	--	<1	0	<3	4	53
460759103015001	81-10-21	0	5	190	3	--	<1	0	5	1	350
460744103014801	75-12-10	--	--	--	--	--	--	--	--	--	420
460710103012702	81-09-29	0	4	100	0	--	0	0	4	10	570

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	VANA-DIUM, DIS-SOLVED (UG/L AS V)
460830103044501	75-12-10	--	--	100	--	--	--	--	--	--	--
	76-09-10	10	30	20	<.5	2	21	<1	--	200	--
	80-08-15	1	63	58	.2	<10	0	0	0	690	--
	81-10-09	--	--	--	--	--	--	--	--	200	--
	81-10-15	5	30	30	.0	0	11	0	0	240	--
461349103054801	74-05-01	--	--	40	--	--	--	--	--	--	--
	74-11-22	11	<10	60	<.5	4	10	<1	--	--	--
	75-05-01	5	20	50	<.5	2	3	<1	--	90	26
	75-11-07	4	<10	40	.6	3	10	<1	--	50	--
	76-04-13	6	20	50	1.0	3	32	<1	--	100	1.3
	81-10-15	3	24	25	.0	10	1	0	0	93	--
	81-10-15	--	--	--	--	--	--	--	--	100	--
460834103055501	81-10-06	13	23	9	.0	<10	7	0	0	120	--
	81-10-06	--	--	--	--	--	--	--	--	100	--
460812103053702	81-10-06	20	24	13	.0	<10	8	0	0	140	--
461257103051001	74-05-01	--	--	40	--	--	--	--	--	--	--
460749103054601	81-10-14	4	30	0	.0	8	0	1	0	70	--
460747103032903	81-09-30	4	40	30	.0	10	6	0	0	430	--
460757103040801	76-02-24	--	--	--	--	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-16	2	40	70	.0	0	0	0	0	390	--
460757103040802	76-02-24	--	--	--	--	--	--	--	--	--	--
	76-09-10	10	<10	<10	<.5	9	7	<1	--	280	--
	81-10-09	--	--	--	--	--	--	--	--	300	--
	81-10-16	14	6	5	.0	20	5	0	0	37	--
460709103032802	81-10-01	1	230	940	.3	1	8	0	0	6600	--
460759103030601	81-10-16	2	<4	60	.1	20	2	0	0	280	--
460759103015001	81-10-21	3	5	68	.0	10	3	0	0	190	--
460744103014801	75-12-10	--	--	40	--	--	--	--	--	--	--
460710103012702	81-09-29	10	40	50	.0	5	12	0	0	350	--

STATION NUMBER	DATE OF SAMPLE	ZINC, DIS-SOLVED (UG/L AS ZN)	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	URANIUM NATURAL DIS-SOLVED (UG/L AS U)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
460830103044501	75-12-10	--	--	--	--	--	--	--
	76-09-10	ND	--	--	--	--	--	--
	80-08-15	8	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--
	81-10-15	10	--	--	--	--	--	--
461349103054801	74-05-01	--	--	--	--	--	--	--
	74-11-22	290	--	--	--	--	--	19
	75-05-01	80	--	--	--	--	--	16
	75-11-07	110	45	58	49	.14	--	.9
	76-04-13	80	--	--	--	--	--	38
	81-10-15	40	--	--	--	--	--	--
	81-10-15	--	--	--	--	--	--	--
460834103055501	81-10-06	43	--	--	--	--	--	--
	81-10-06	--	--	--	--	--	--	--
460812103053702	81-10-06	60	--	--	--	--	--	--
461257103051001	74-05-01	--	--	--	--	--	--	--
460749103054601	81-10-14	40	--	--	--	--	--	--
460747103032903	81-09-30	10	--	--	--	--	--	--
460757103040801	76-02-24	--	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--
	81-10-16	10	--	--	--	--	--	--
460757103040802	76-02-24	--	--	--	--	--	--	--
	76-09-10	ND	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--
	81-10-16	12	--	--	--	--	--	--
460709103032802	81-10-01	80	--	--	--	--	--	--
460759103030601	81-10-16	3	--	--	--	--	--	--
460759103015001	81-10-21	28	--	--	--	--	--	--
460744103014801	75-12-10	--	--	--	--	--	--	--
460710103012702	81-09-29	50	--	--	--	--	--	--

SUPPLEMENT 3.—*Water quality in the confined basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
461257103004901	131-099-36BBB1	125TRVL	155	74-04-23	1600	1290	8.5	9.5	--
		125TRVL	155	74-11-27	1100	1580	8.9	8.0	--
		125TRVL	155	75-04-30	1400	1530	9.0	8.5	--
		125TRVL	155	75-11-11	1325	1450	8.8	7.0	--
		125TRVL	155	76-04-14	1230	1500	8.8	10.0	--

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
461257103004901	74-04-23	16	679	584	3.6	3000	25	0	7.4	1.7	320
	74-11-27	24	696	611	1.4	--	19	0	5.8	1.1	370
	75-04-30	23	653	574	1.1	--	21	0	6.0	1.4	340
	75-11-11	22	635	557	1.7	--	25	0	6.6	2.1	370
	76-04-14	21	629	551	1.7	--	22	0	5.9	1.8	330

STATION NUMBER	DATE OF SAMPLE	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SILICA, DIS-SOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)	PHOS-PHORUS, DIS-SOLVED (MG/L AS P)	ALUM-INUM, DIS-SOLVED (UG/L AS AL)
461257103004901	74-04-23	3.0	150	33	5.2	10	1040	897	.05	.900	--
	74-11-27	2.9	130	91	6.8	8.6	1050	1010	--	--	200
	75-04-30	2.9	170	49	3.5	7.6	1000	952	--	--	150
	75-11-11	2.8	190	20	4.2	5.8	983	961	--	--	420
	76-04-14	2.3	200	20	4.6	6.9	976	925	--	--	180

STATION NUMBER	DATE OF SAMPLE	ANTI-MONY, DIS-SOLVED (UG/L AS SB)	ARSENIC DIS-SOLVED (UG/L AS AS)	BARIUM, DIS-SOLVED (UG/L AS BA)	BERYL-LIUM, DIS-SOLVED (UG/L AS BE)	BORON, DIS-SOLVED (UG/L AS B)	CADMIUM DIS-SOLVED (UG/L AS CD)	CHRO-MIUM, DIS-SOLVED (UG/L AS CR)	COBALT, DIS-SOLVED (UG/L AS CO)	COPPER, DIS-SOLVED (UG/L AS CU)	IRON, DIS-SOLVED (UG/L AS FE)
461257103004901	74-04-23	--	--	--	--	--	--	--	--	--	530
	74-11-27	--	5	--	<10	--	<2	<20	--	<2	310
	75-04-30	--	4	<10	<10	240	3	ND	--	8	380
	75-11-11	--	7	<10	<10	1100	ND	20	--	17	<10
	76-04-14	--	6	<10	<10	280	ND	<20	--	5	590

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	VANA-DIUM, DIS-SOLVED (UG/L AS V)
461257103004901	74-04-23	--	--	70	--	--	--	--	--	--	--
	74-11-27	9	<10	80	<.5	28	ND	<1	--	--	--
	75-04-30	8	20	80	<.5	13	6	<1	--	100	80
	75-11-11	3	20	130	<.5	14	20	<1	--	100	--
	76-04-14	ND	20	80	<.5	25	10	<1	--	110	4.5

STATION NUMBER	DATE OF SAMPLE	ZINC, DIS-SOLVED (UG/L AS ZN)	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	URANIUM NATURAL DIS-SOLVED (UG/L AS U)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
461257103004901	74-04-23	--	--	--	--	--	--	--
	74-11-27	300	--	--	--	--	--	48
	75-04-30	200	--	--	--	--	--	37
	75-11-11	320	120	22	18	.10	--	.9
	76-04-14	150	--	--	--	--	--	98

1/ Analyses performed by J. C. Chemerys, Office of the Regional Hydrologist, Northeastern Region, U.S. Geological Survey, Reston, Va.
2/ Analyses performed by the North Dakota State Water Commission, Bismarck, N. Dak.

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*

[Analyses not indicated otherwise were performed by the U.S. Geological Survey National Water-Quality Laboratory, Denver, Colo. "Geologic unit" indicates the aquifer sampled: 125TRVL = basal Bullion Creek-Slope aquifer, 125TGRV = parts of the basal Bullion Creek-Slope aquifer confined to the Paleocene Bullion Creek Formation of the Fort Union Group. <indicates less than, ND indicates not detected]

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
461202103005001	130-099-01BBB	125TRVL	60	74-05-25 1/	--	2470	8.3	10.5	--
		125TRVL	60	74-05-25	1000	--	--	--	--
		125TRVL	60	74-06-05	1200	2230	8.0	11.0	--
		125TRVL	60	74-11-20	1730	2200	8.3	8.5	--
		125TRVL	60	74-11-21	1600	4450	8.4	8.5	--
		125TRVL	60	75-04-30	1130	4100	8.7	8.0	--
		125TRVL	60	75-11-05	1400	3700	8.6	12.0	--
		125TRVL	60	76-04-12	1540	3750	8.6	14.0	--
		125TRVL	60	79-06-13	1000	2200	8.5	6.6	--
		125TRVL	60	81-05-28	1230	3600	8.3	6.2	.0
		125TRVL	60	81-10-21	1200	2790	8.5	8.0	.3
460707103005801	131-099-02AAA	125TRVL	72	81-05-28	1130	3500	8.3	6.3	.0
		125TRVL	70	81-10-22	1200	1780	10.5	7.0	--
460705103013101	130-099-02ABB	125TRVL	76	76-05-06	1500	3200	11.9	4.0	--
		125TRVL	76	76-09-23	0900	1600	10.1	8.0	--
		125TRVL	76	81-05-28	1030	2080	11.8	6.5	.0
		125TRVL	76	81-10-09 2/	0801	--	--	--	.1
		125TRVL	76	81-10-22	1100	1160	10.0	--	.6
460707103015001	130-099-02BAB	125TRVL	59	81-10-22	1130	2260	8.8	--	.0
461116103020602	130-099-02CCC2	125TRVL	56	76-05-07	0830	2800	8.8	5.5	--
		125TRVL	56	76-09-22	--	3000	8.7	--	--
		125TRVL	56	77-07-07	1000	--	8.6	6.3	.0
		125TRVL	56	81-05-28	0930	3340	8.2	6.2	.1
		125TRVL	56	81-10-10 2/	0701	--	--	--	.4
		125TRVL	56	81-10-21	1130	3380	8.1	7.2	.0
		125TRVL	56	81-10-21 2/	1131	3380	8.1	--	.6
460705103022701	130-099-03AAB1	125TRVL	96	75-12-10	1530	3200	12.4	6.0	--
		125TRVL	96	76-09-23	0930	1350	10.5	--	--
		125TRVL	96	80-05-27	1000	3940	8.4	6.3	--
		125TRVL	89	81-05-28	0820	1430	10.4	6.2	.0
		125TRVL	96	81-10-10 2/	0801	--	--	--	.3
		125TRVL	96	81-10-22	1030	1220	10.6	6.8	.0
461202103024301	130-099-03ABB	125TRVL	89	74-05-22	1530	6390	9.7	8.0	--
		125TRVL	89	74-07-07	1000	--	9.8	--	.0
		125TRVL	89	74-08-20	--	5240	10.0	--	--
		125TRVL	96	81-05-28	1345	7500	9.7	6.2	.1

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
461202103005001	74-05-25	7	689	577	5.6	--	59	0	13	6.4	580
	74-05-25	--	--	--	--	--	--	0	--	--	--
	74-06-05	0	689	565	11	80	62	0	13	7.2	530
	74-11-20	7	689	568	5.5	78	85	0	16	11	470
	74-11-21	7	608	510	4.0	84	450	0	88	55	820
	75-04-30	7	585	491	1.9	85	150	0	30	18	710
	75-11-05	7	603	506	2.5	60	100	0	21	12	750
	76-04-12	40	539	509	2.5	82	81	0	16	9.8	720
	79-06-13	0	390	320	2.0	--	42	0	8.9	4.8	555
	81-05-28	28	558	504	4.9	--	77	0	15	9.6	690
	81-10-21	--	--	480	2.9	76	43	0	9.0	5.0	560
460707103005801	81-05-28	36	592	471	5.3	--	81	0	16	10	701
	81-10-22	--	--	500	.0	--	18	0	5.5	1.0	400
460705103013101	76-05-06	165	0	775	.0	280	65	0	26	.1	370
	76-09-23	292	254	695	.1	700	15	0	5.7	.1	380
	81-05-28	171	300	353	.0	--	93	0	32	3.2	410
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-22	--	--	400	.0	520	13	0	4.0	.7	260
460707103015001	81-10-22	--	--	560	1.7	--	41	0	8.4	4.8	520
461116103020602	76-05-07	30	723	643	2.2	18	56	0	13	5.8	610
	76-09-22	188	413	652	2.5	32	52	0	12	5.4	650
	77-07-07	--	--	621	3.0	--	32	0	4.2	5.2	670
	81-05-28	24	524	490	5.8	--	67	0	14	7.9	690
	81-10-10	--	--	--	--	46	--	--	--	--	--
	81-10-21	--	--	510	7.8	--	64	0	13	7.4	740
	81-10-21	--	--	--	8.3	36	59	0	12	7.0	753
460705103022701	75-12-10	306	0	862	.0	18	32	0	12	.4	400
	76-09-23	283	82	538	.0	17	7	0	2.5	.2	300
	80-05-27	--	582	477	3.7	--	270	0	65	27	895
	81-05-28	157	96	341	.0	--	16	0	3.3	1.9	281
	81-10-10	--	--	--	--	--	--	--	--	--	--
	81-10-22	--	--	260	.0	--	18	0	3.9	2.0	250
461202103024301	74-05-22	56	40	126	.1	10	430	306	170	1.6	1400
	74-07-07	--	--	149	.0	--	350	197	135	2.0	1300
	74-08-20	100	6	171	.0	11	260	89	100	2.4	1200
	81-05-28	61	74	55	.0	--	490	433	192	1.8	1600

Footnotes at end of table

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	POTASSIUM, DISSOLVED (MG/L AS K)	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	NITROGEN, NO2+NO3 DISSOLVED (MG/L AS N)	PHOSPHORUS, DISSOLVED (MG/L AS P)	ALUMINUM, DISSOLVED (UG/L AS AL)
461202103005001	74-05-25	4.4	570	110	1.1	9.1	1600	1650	--	--	--
	74-05-25	--	--	--	--	--	--	--	--	--	--
	74-06-05	5.1	530	81	1.4	9.4	1620	1520	.02	.060	--
	74-11-20	5.9	470	40	1.3	8.0	1420	1380	--	--	40
	74-11-21	11	1600	45	.8	10	3100	2940	--	--	30
	75-04-30	6.5	1100	49	1.3	6.9	2570	2230	--	--	<10
	75-11-05	6.4	1200	39	1.5	6.1	2270	2350	--	--	20
	76-04-12	6.2	1100	26	1.5	6.7	2210	2240	--	--	10
	79-06-13	6.2	713	20	1.4	7.0	1720	1510	--	--	--
	81-05-28	6.3	996	21	1.1	6.2	2340	2080	--	--	--
	81-10-21	5.0	780	18	2.1	4.7	1750	1670	<.09	--	10
460707103005801	81-05-28	5.8	987	18	1.3	5.8	2380	2110	--	--	--
	81-10-22	4.9	390	45	4.2	16	1150	1170	.20	--	40
460705103013101	76-05-06	7.7	120	16	2.2	16	904	1060	.02	<.010	--
	76-09-23	2.9	130	37	3.0	25	1000	1300	.19	.340	--
	81-05-28	8.2	420	13	1.8	12	1410	1400	--	--	--
	81-10-09	--	104	15	--	12	--	--	--	--	--
	81-10-22	2.1	160	22	3.7	27	730	720	.79	--	80
460707103015001	81-10-22	4.1	600	20	3.5	7.4	1530	1500	<.09	--	10
461116103020602	76-05-07	4.7	690	21	2.9	10	1800	1780	.01	.210	--
	76-09-22	5.4	740	17	2.8	9.2	1870	2030	2.6	.200	--
	77-07-07	5.5	830	16	3.3	8.7	--	1920	--	--	--
	81-05-28	4.6	1030	26	2.4	7.7	2400	2090	--	--	--
	81-10-10	--	1130	14	--	9.8	--	--	--	--	--
	81-10-21	5.3	1100	21	2.3	7.1	2250	2200	.12	--	0
	81-10-21	5.6	1130	16	2.2	9.8	--	2260	--	--	--
460705103022701	75-12-10	5.6	50	9.4	2.9	39	--	1260	.11	.290	--
	76-09-23	2.5	120	7.6	2.5	28	747	1080	.08	.250	--
	80-05-27	--	916	26	--	--	3340	--	--	--	--
	81-05-28	2.6	257	16	1.7	56	917	986	--	--	--
	81-10-10	--	258	11	--	55	--	--	--	--	--
	81-10-22	2.3	250	14	2.6	54	781	735	.14	--	120
461202103024301	74-05-22	17	3200	17	.8	28	5060	4970	.06	.230	--
	74-07-07	13	2800	16	1.1	28	--	4380	--	--	--
	74-08-20	7.5	2500	15	1.7	29	4050	4070	--	--	--
	81-05-28	19	3610	19	.9	27	5760	5610	--	--	--

STATION NUMBER	DATE OF SAMPLE	ANTIMONY, DISSOLVED (UG/L AS SB)	ARSENIC DISSOLVED (UG/L AS AS)	BARIUM, DISSOLVED (UG/L AS BA)	BERYLLIUM, DISSOLVED (UG/L AS BE)	BORON, DISSOLVED (UG/L AS B)	CADMIUM DISSOLVED (UG/L AS CD)	CHROMIUM, DISSOLVED (UG/L AS CR)	COBALT, DISSOLVED (UG/L AS CO)	COPPER, DISSOLVED (UG/L AS CU)	IRON, DISSOLVED (UG/L AS FE)
461202103005001	74-05-25	--	--	--	--	780	--	--	--	--	100
	74-05-25	--	--	--	--	--	--	--	--	--	--
	74-06-05	--	--	--	<10	980	2	ND	--	12	160
	74-11-20	--	1	--	<10	--	<2	<20	--	150	370
	74-11-21	--	1	--	<10	--	<2	<20	--	<20	30
	75-04-30	--	1	<100	<10	1100	<2	ND	--	42	50
	75-11-05	--	1	<100	<10	1000	<2	4	--	60	30
	76-04-12	--	1	200	10	970	<2	<20	--	120	130
	79-06-13	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	--	--	970	--	--	--	--	96
	81-10-21	0	1	200	10	--	0	0	0	3	500
460707103005801	81-05-28	--	--	--	--	1010	--	--	--	--	91
	81-10-22	1	4	130	1	--	<1	0	3	5	5
460705103013101	76-05-06	--	--	--	--	470	--	--	--	--	--
	76-09-23	--	--	--	--	1200	--	--	--	--	--
	81-05-28	--	--	--	--	520	--	--	--	--	28
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-22	0	5	110	<1	--	<1	0	<3	5	300
460707103015001	81-10-22	0	2	<100	<10	--	0	0	1	2	330
461116103020602	76-05-07	--	--	--	--	1100	--	--	--	--	--
	76-09-22	--	--	--	--	1100	--	--	--	--	--
	77-07-07	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	--	--	1100	--	--	--	--	34
	81-10-10	--	--	--	--	--	--	--	--	--	--
	81-10-21	0	2	200	0	--	0	0	0		40
	81-10-21	--	--	--	--	--	--	--	--	--	--
460705103022701	75-12-10	--	--	--	--	--	--	--	--	--	70
	76-09-23	--	--	--	--	450	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	--	--	420	--	--	--	--	62
	81-10-10	--	--	--	--	--	--	--	--	--	--
	81-10-22	1	10	45	4	--	1	0	<3	8	56
461202103024301	74-05-22	--	--	--	--	--	--	--	--	--	960
	74-07-07	--	--	--	--	--	--	--	--	--	--
	74-08-20	--	--	--	--	1400	--	--	--	--	920
	81-05-28	--	--	--	--	--	--	--	--	--	1080

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	VANA-DIUM, DIS-SOLVED (UG/L AS V)
461202103005001	74-05-25	--	--	60	--	--	--	--	--	--	--
	74-05-25	--	--	--	--	--	--	--	--	--	--
	74-06-05	--	50	30	<.5	26	12	2	ND	--	.7
	74-11-20	70	30	70	<.1	18	3	<1	--	--	6.4
	74-11-21	5	70	250	<.1	17	5	<1	--	--	4.0
	75-04-30	3	50	240	<.5	33	5	<1	--	590	.0
	75-11-05	2	50	210	2.4	30	2	<1	--	390	1.1
	76-04-12	8	50	140	<.5	37	2	<1	--	350	1.7
	79-06-13	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	160	--	--	--	--	--	--	--
	81-10-21	1	40	120	.0	44	2	0	0	220	--
460707103005801	81-05-28	--	--	140	--	--	--	--	--	--	--
	81-10-22	21	22	18	.0	<10	16	1	0	180	--
460705103013101	76-05-06	--	--	--	--	--	--	--	--	--	--
	76-09-23	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	120	--	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-22	29	11	15	.0	<10	9	0	0	97	--
460707103015001	81-10-22	6	30	30	.0	1	3	0	0	270	--
461116103020602	76-05-07	--	--	--	--	--	--	--	--	--	--
	76-09-22	--	--	--	--	--	--	--	--	--	--
	77-07-07	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	97	--	--	--	--	--	--	--
	81-10-10	--	--	--	--	--	--	--	--	--	--
	81-10-21	1	50	120	.0	10	2	0	0	410	--
	81-10-21	--	--	--	--	--	--	--	--	480	--
460705103022701	75-12-10	--	--	<10	--	--	--	--	--	--	--
	76-09-23	--	--	--	--	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	16	--	--	--	--	--	--	--
	81-10-10	--	--	--	--	--	--	--	--	--	--
	81-10-22	7	12	7	.0	20	10	0	0	94	--
461202103024301	74-05-22	--	--	40	--	--	--	--	--	--	--
	74-07-07	--	--	--	--	--	--	--	--	--	--
	74-08-20	--	--	40	--	--	--	--	--	--	--
	81-05-28	--	--	48	--	--	--	--	--	--	--

STATION NUMBER	DATE OF SAMPLE	ZINC, DIS-SOLVED (UG/L AS ZN)	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
461202103005001	74-05-25	--	--	--	--	--	--
	74-05-25	--	--	--	--	--	--
	74-06-05	1300	--	--	--	--	--
	74-11-20	1400	--	--	--	--	30
	74-11-21	500	--	--	--	--	16
	75-04-30	530	--	--	--	--	26
	75-11-05	580	<19	<5.2	<4.3	.11	22
	76-04-12	350	--	--	--	--	--
	79-06-13	--	--	--	--	--	--
	81-05-28	--	--	--	--	--	--
	81-10-21	250	--	--	--	--	--
460707103005801	81-05-28	--	--	--	--	--	--
	81-10-22	11	--	--	--	--	--
460705103013101	76-05-06	--	--	--	--	--	--
	76-09-23	--	--	--	--	--	--
	81-05-28	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--
	81-10-22	24	--	--	--	--	--
460707103015001	81-10-22	30	--	--	--	--	--
461116103020602	76-05-07	--	--	--	--	--	--
	76-09-22	--	--	--	--	--	--
	77-07-07	--	--	--	--	--	--
	81-05-28	--	--	--	--	--	--
	81-10-10	--	--	--	--	--	--
	81-10-21	20	--	--	--	--	--
	81-10-21	--	--	--	--	--	--
460705103022701	75-12-10	--	--	--	--	--	--
	76-09-23	--	--	--	--	--	--
	80-05-27	--	--	--	--	--	--
	81-05-28	--	--	--	--	--	--
	81-10-10	--	--	--	--	--	--
	81-10-22	16	--	--	--	--	--
461202103024301	74-05-22	--	--	--	--	--	--
	74-07-07	--	--	--	--	--	--
	74-08-20	--	--	--	--	--	--
	81-05-28	--	--	--	--	--	--

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
460645103021801	130-099-03ADD	125TRVL	67	76-05-06	1410	7000	9.2	9.5	--
		125TRVL	67	76-09-08	1000	--	9.0	11.6	--
		125TRVL	67	78-08-27	1000	--	7.8	8.1	.0
		125TRVL	67	81-05-28	1705	7500	8.0	6.2	.0
		125TRVL	67	81-10-09 2/	1801	6200	7.8	7.0	.0
		125TRVL	67	81-10-21	1400	6700	8.2	6.8	.0
460705103025601	130-099-03BAA	125TRVL	70	75-12-10	1700	7500	9.6	6.5	--
		125TRVL	70	81-05-26	1000	13000	7.8	6.3	1.3
		125TRVL	70	81-10-22	1000	8800	7.9	6.9	.0
		125TRVL	70	81-10-22 2/	1001	8800	7.9	7.0	.8
460659103032701	130-099-04AAA	125TRVL	65	81-10-06	1900	5350	11.2	8.6	--
		125TRVL	65	81-10-06 2/	1901	5350	11.2	8.6	.7
460645103033301	130-099-04ADD	125TRVL	80	81-05-27	0730	12500	7.0	6.2	1.2
		125TRVL	--	81-10-22	0930	8700	6.9	7.1	.0
460705103041101	130-099-04BAA	125TRVL	47	76-09-16	--	4500	--	15.0	--
		125TRVL	47	77-07-06	1000	--	7.4	6.8	.8
		125TRVL	47	78-08-25	1000	--	7.3	7.9	--
		125TRVL	47	78-11-06	1330	5900	7.3	9.0	--
		125TRVL	47	79-06-06	1000	4100	7.4	6.7	--
		125TRVL	47	79-11-15	1400	4500	7.4	12.0	--
		125TRVL	47	80-10-28	1100	4600	7.1	7.5	.0
		125TRVL	47	81-05-26	1130	6450	7.1	6.2	.1
		125TRVL	47	81-06-01	1210	4200	7.2	7.5	2.1
		125TRVL	47	81-06-01	1305	4200	7.2	7.5	3.1
		125TRVL	47	81-06-01	1400	4500	7.8	9.5	10.0
		125TRVL	47	81-06-01	1450	4200	7.2	7.5	2.3
		125TRVL	47	81-06-01	1520	4400	7.3	8.0	1.0
		125TRVL	47	81-07-08	1100	5140	7.1	7.5	2.0
		125TRVL	47	81-07-08	1130	5110	7.0	7.5	4.0
		125TRVL	47	81-07-08	1245	5060	7.0	8.0	1.4
		125TRVL	47	81-07-08	1300	5400	7.8	10.0	11.0
		125TRVL	47	81-07-08	1350	5140	7.1	7.5	2.2
		125TRVL	47	81-10-21	1645	4700	7.1	7.5	.0
460645103033302	130-099-04ADD2	125TRVL	50	81-10-09 2/	0701	7200	7.3	7.0	.0
461050103010001	130-099-11ADD	125TRVL	79	74-05-16 1/	1400	3790	9.3	8.0	--
460731103021601	131-099-34DAA	--	1254	76-02-24	1400	1750	8.6	9.0	--

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
460645103021801	76-05-06	0	407	334	.4	18	150	0	11	30	1800
	76-09-08	7	238	207	.4	17	160	0	13	31	1600
	78-08-27	--	--	320	9.4	--	600	285	97	88	560
	81-05-28	0	1020	837	16	--	220	0	29	35	1690
	81-10-09	--	--	--	12	--	--	--	--	--	--
	81-10-21	--	--	390	4.7	--	240	0	34	36	1500
460705103025601	75-12-10	46	181	225	.1	--	87	0	10	15	1500
	81-05-26	0	592	486	15	--	1000	563	85	203	2020
	81-10-22	--	--	520	13	--	1100	597	100	210	1800
	81-10-22	--	--	--	14	--	990	439	90	186	1880
460659103032701	81-10-06	--	--	140	.0	--	860	722	320	14	950
	81-10-06	--	--	--	--	--	730	--	279	7.8	1000
460645103033301	81-05-27	0	437	358	70	--	2100	1770	212	387	1570
	81-10-22	--	--	230	56	--	2300	2050	250	400	1400
460705103041101	76-09-16	--	485	398	--	--	710	314	130	94	890
	77-07-06	--	--	394	30	--	670	275	111	95	840
	78-08-25	--	--	377	41	--	690	315	122	94	880
	78-11-06	--	--	380	37	--	680	303	110	98	970
	79-06-06	--	380	312	24	--	680	369	129	87	680
	79-11-15	--	--	490	38	--	1600	1060	290	200	540
	80-10-28	--	--	390	--	--	740	350	130	100	870
	81-05-26	0	792	652	101	--	600	0	85	95	960
	81-06-01	0	492	403	72	--	790	335	160	90	850
	81-06-01	0	493	404	69	--	770	356	150	96	840
	81-06-01	0	487	399	.0	--	750	357	150	91	840
	81-06-01	0	488	400	55	--	790	335	140	100	840
	81-06-01	0	485	398	53	--	760	359	150	94	840
	81-07-08	0	492	403	70	--	830	465	150	110	860
	81-07-08	0	487	399	76	--	830	485	150	110	850
	81-07-08	0	490	402	85	--	790	490	150	100	850
	81-07-08	0	483	396	12	--	820	708	160	100	900
	81-07-08	0	482	395	57	--	830	464	140	100	860
	81-10-21	--	--	400	62	--	660	257	100	98	850
460645103033302	81-10-09	--	--	--	23	--	--	--	--	--	--
461050103010001	74-05-16	180	727	896	.9	10	100	0	32	5.4	880
460731103021601	76-02-24	40	850	764	3.7	--	9	0	1.6	1.1	460

Footnotes at end of table

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	POTASSIUM, DISSOLVED (MG/L AS K)	SULFATE DISSOLVED (MG/L AS SO4)	CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	SILICA, DISSOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	NITROGEN, NO2+NO3 DISSOLVED (MG/L AS N)	PHOSPHORUS, DISSOLVED (MG/L AS P)	ALUMINUM, DISSOLVED (UG/L AS AL)
460645103021801	76-05-06	19	3500	18	.7	10	5640	5590	.01	.060	--
	76-09-08	17	3400	16	1.1	10	5340	5220	--	.080	10
	78-08-27	18	1530	11	1.6	.1	--	2500	--	--	--
	81-05-28	12	2880	54	.8	8.8	6020	5210	--	--	--
	81-10-09	--	3010	17	--	13	--	--	--	--	--
	81-10-21	11	2800	48	1.2	8.8	4960	4680	<.09	--	0
460705103025601	75-12-10	15	3000	16	1.0	14	--	4750	.02	.130	--
	81-05-26	17	4730	42	.5	7.8	8080	7400	--	--	--
	81-10-22	15	4600	37	.8	7.7	7060	7090	<.09	--	0
	81-10-22	22	4410	24	1.4	10	7070	6960	--	--	--
460659103032701	81-10-06	87	2700	28	.2	1.2	4400	4190	.21	--	100
	81-10-06	105	2750	19	.2	1.6	--	--	--	--	--
460645103033301	81-05-27	15	4940	28	.4	6.7	7970	7370	--	--	--
	81-10-22	13	4800	25	.7	6.6	7790	7060	<.09	--	20
460705103041101	76-09-16	16	2100	8.0	.2	14	--	3490	.09	<.010	--
	77-07-06	15	2200	5.6	.9	12	--	3520	--	--	--
	78-08-25	19	2200	7.0	1.1	13	--	3560	--	--	--
	78-11-06	15	2400	7.5	.1	14	3700	3850	.02	.050	<100
	79-06-06	--	1563	12	--	--	3311	--	--	--	--
	79-11-15	14	2200	34	.4	7.7	3560	3580	.03	.010	0
	80-10-28	14	2200	9.0	.2	14	3640	3580	.00	.060	20
	81-05-26	16	1950	14	.1	10	4120	3520	--	--	--
	81-06-01	14	2100	8.8	.1	14	3490	3510	--	--	--
	81-06-01	14	2100	8.7	.1	14	3450	3480	--	--	--
	81-06-01	14	2100	9.2	.1	13	3430	3460	--	--	--
	81-06-01	14	2100	8.8	.1	14	3490	3510	--	--	--
	81-06-01	14	2100	10	.1	15	3450	3470	--	--	--
	81-07-08	15	2200	40	.1	14	3600	3620	.06	--	60
	81-07-08	15	2200	39	.1	14	3580	3600	.06	--	20
	81-07-08	14	2200	42	.1	13	3540	3560	.07	--	20
	81-07-08	14	2500	52	.1	13	3780	3810	.08	--	10
	81-07-08	15	2200	40	.1	13	3600	3620	.06	--	60
	81-10-21	14	1900	12	.2	9.9	3560	3230	<.09	--	0
460645103033302	81-10-09	--	5070	11	--	3.3	--	--	--	--	--
461050103010001	74-05-16	11	1000	11	1.2	28	2650	2690	.03	4.90	--
460731103021601	76-02-24	1.2	14	130	4.4	7.1	1050	1120	--	--	--

STATION NUMBER	DATE OF SAMPLE	ANTIMONY, DISSOLVED (UG/L AS SB)	ARSENIC DISSOLVED (UG/L AS AS)	BARIUM, DISSOLVED (UG/L AS BA)	BERYLLIUM, DISSOLVED (UG/L AS BE)	BORON, DISSOLVED (UG/L AS B)	CADMIUM DISSOLVED (UG/L AS CD)	CHROMIUM, DISSOLVED (UG/L AS CR)	COBALT, DISSOLVED (UG/L AS CO)	COPPER, DISSOLVED (UG/L AS CU)	IRON, DISSOLVED (UG/L AS FE)
460645103021801	76-05-06	--	--	--	--	990	--	--	--	--	--
	76-09-08	--	6	<100	<10	950	ND	<20	ND	9	20
	78-08-27	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	--	--	1000	--	--	--	--	72
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-21	0	3	200	0	--	0	0	0	0	60
460705103025601	75-12-10	--	--	--	--	--	--	--	--	--	40
	81-05-26	--	--	--	--	820	--	--	--	--	410
	81-10-22	0	5	100	0	--	0	10	1	0	360
	81-10-22	--	--	--	--	--	--	--	--	--	--
460659103032701	81-10-06	0	2	100	0	--	0	20	0	10	50
	81-10-06	--	--	--	--	--	--	--	--	--	--
460645103033301	81-05-27	--	--	--	--	--	--	--	--	--	--
	81-10-22	0	0	<100	<10	--	0	20	42	4	18000
460705103041101	76-09-16	--	--	--	--	--	--	--	--	--	410
	77-07-06	--	--	--	--	--	--	--	--	--	--
	78-08-25	--	--	--	--	--	--	--	--	--	--
	78-11-06	--	1	<100	--	3800	ND	ND	--	ND	1900
	79-06-06	--	--	--	--	--	--	--	--	--	--
	79-11-15	--	3	300	--	580	0	0	--	0	80
	80-10-28	--	1	100	--	3600	1	0	--	7	1500
	81-05-26	--	--	--	--	1320	--	--	--	--	1400
	81-06-01	--	--	--	--	2000	--	--	--	--	2000
	81-06-01	--	--	--	--	2100	--	--	--	--	2000
	81-06-01	--	--	--	--	2100	--	--	--	--	1600
	81-06-01	--	--	--	--	2100	--	--	--	--	2000
	81-06-01	--	--	--	--	2100	--	--	--	--	1900
	81-07-08	--	1	0	--	3100	1	10	--	6	0
	81-07-08	--	0	100	--	2900	2	10	--	10	1300
	81-07-08	--	0	0	--	2700	0	10	--	1	1300
	81-07-08	--	0	0	--	2900	0	10	--	0	440
	81-07-08	--	1	0	--	2900	1	10	--	6	1100
	81-10-21	0	1	100	0	--	0	0	0	0	1300
460645103033302	81-10-09	--	--	--	--	--	--	--	--	--	--
461050103010001	74-05-16	--	--	--	--	--	--	--	--	--	30
460731103021601	76-02-24	--	--	--	--	1700	--	--	--	--	60

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	VANA-DIUM, DIS-SOLVED (UG/L AS V)
460645103021801	76-05-06	--	--	--	--	--	--	--	--	--	--
	76-09-08	2	100	90	<.5	7	5	<1	--	1600	2.6
	78-08-27	--	--	--	--	--	--	--	--	--	--
	81-05-28	--	--	310	--	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--	--	--	--	--
	81-10-21	0	100	280	.0	5	2	0	0	1900	--
460705103025601	75-12-10	--	--	<10	--	--	--	--	--	--	--
	81-05-26	--	--	250	--	--	--	--	--	--	--
	81-10-22	2	190	240	.4	2	5	0	0	2300	--
	81-10-22	--	--	--	--	--	--	--	--	1800	--
460659103032701	81-10-06	4	140	10	.0	91	53	1	0	3600	--
	81-10-06	--	--	--	--	--	--	--	--	4000	--
460645103033301	81-05-27	--	--	--	--	--	--	--	--	--	--
	81-10-22	0	540	4500	.0	<1	110	0	0	6700	--
460705103041101	76-09-16	--	--	670	--	--	--	--	--	--	--
	77-07-06	--	--	--	--	--	--	--	--	--	--
	78-08-25	--	--	--	--	--	--	--	--	--	--
	78-11-06	ND	290	700	<.1	<1	--	<1	--	4000	--
	79-06-06	--	--	--	--	--	--	--	--	--	--
	79-11-15	0	100	390	.2	5	--	0	--	3200	--
	80-10-28	5	270	640	.0	0	--	0	--	4300	--
	81-05-26	--	--	710	--	--	--	--	--	--	--
	81-06-01	--	--	810	--	--	--	--	--	--	--
	81-06-01	--	--	830	--	--	--	--	--	--	--
	81-06-01	--	--	770	--	--	--	--	--	--	--
	81-06-01	--	--	790	--	--	--	--	--	--	--
	81-06-01	--	--	780	--	--	--	--	--	--	--
	81-07-08	7	300	690	.0	<1	--	<1	--	4100	--
	81-07-08	7	290	730	.1	0	--	0	--	4200	--
	81-07-08	4	280	690	.0	0	--	0	--	4100	--
	81-07-08	5	280	620	.0	0	--	0	--	4000	--
	81-07-08	7	290	690	.1	0	--	0	--	4100	--
	81-10-21	1	270	670	.0	1	1	0	0	3300	--
460645103033302	81-10-09	--	--	--	--	--	--	--	--	--	--
461050103010001	74-05-16	--	--	20	--	--	--	--	--	--	--
460731103021601	76-02-24	--	--	<10	--	--	--	--	--	--	--

STATION NUMBER	DATE OF SAMPLE	ZINC, DIS-SOLVED (UG/L AS ZN)	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
460645103021801	76-05-06	--	--	--	--	--	--
	76-09-08	180	--	--	--	--	--
	78-08-27	--	--	--	--	--	--
	81-05-28	--	--	--	--	--	--
	81-10-09	--	--	--	--	--	--
	81-10-21	20	--	--	--	--	--
460705103025601	75-12-10	--	--	--	--	--	--
	81-05-26	--	--	--	--	--	--
	81-10-22	30	--	--	--	--	--
	81-10-22	--	--	--	--	--	--
460659103032701	81-10-06	10	--	--	--	--	--
	81-10-06	--	--	--	--	--	--
460645103033301	81-05-27	--	--	--	--	--	--
	81-10-22	100	--	--	--	--	--
460705103041101	76-09-16	--	--	--	--	--	--
	77-07-06	--	--	--	--	--	--
	78-08-25	--	--	--	--	--	--
	78-11-06	30	<30	20	19	.38	8.1
	79-06-06	--	--	--	--	--	--
	79-11-15	30	<75	22	20	.15	38
	80-10-28	10	<53	<28	<27	.37	15
	81-05-26	--	--	--	--	--	--
	81-06-01	--	--	--	--	--	--
	81-06-01	--	--	--	--	--	--
	81-06-01	--	--	--	--	--	--
	81-06-01	--	--	--	--	--	--
	81-06-01	--	--	--	--	--	--
	81-07-08	80	--	--	--	--	6.0
	81-07-08	50	--	--	--	--	13
	81-07-08	40	--	--	--	--	7.2
	81-07-08	10	--	--	--	--	9.3
	81-07-08	100	--	--	--	--	6.8
	81-10-21	20	--	--	--	--	--
460645103033302	81-10-09	--	--	--	--	--	--
461050103010001	74-05-16	--	--	--	--	--	--
460731103021601	76-02-24	--	--	--	--	--	--

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
460826103044404	131-099-29DAA4	125TGRV	--	80-08-15	1630	1340	8.6	8.6	--
460853103054501	131-099-20CCD	125TGRV	--	80-08-15	1610	1360	8.7	9.6	--
461625103004901	131-099-12BBB	125TRVL	169	74-05-16	1200	2350	8.4	8.0	--
		125TRVL	169	76-09-29	--	--	--	--	--
461034103003302	131-099-13BAB2	125TRVL	120	76-06-28	1430	1750	7.5	8.0	--
		125TRVL	--	81-10-02	1002	--	--	--	--
461211103043301	131-099-33CCC	125TRVL	58	74-04-30 1/	1400	3730	7.5	8.8	--
		125TRVL	58	74-11-20	1430	3800	7.8	7.0	--
		125TRVL	58	75-04-28	1600	3900	7.8	7.5	--
		125TRVL	58	75-11-11	1115	4000	7.7	8.0	--
		125TRVL	58	76-04-15	0945	4350	7.6	8.5	--
460709103032806	131-099-33DDD6	125TRVL	65	81-10-01 2/	1031	5490	8.1	8.1	.1

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	COLOR (PLAT-INUM-COBALT UNITS)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)
460826103044404	80-08-15	--	--	490	2.3	--	110	0	21	14	380
460853103054501	80-08-15	--	--	470	1.8	--	550	81	110	67	210
461625103004901	74-05-16	5	450	377	2.8	1	160	0	39	16	470
	76-09-29	0	550	451	--	--	110	0	20	15	480
461034103003302	76-06-28	0	769	631	39	3	540	0	99	71	210
	81-10-02	--	--	--	--	--	560	--	103	74	278
461211103043301	74-04-30	0	629	516	36	20	740	221	130	100	630
	74-11-20	0	655	537	17	--	740	200	130	100	670
	75-04-28	0	631	518	16	30	720	199	120	100	670
	75-11-11	0	607	498	19	30	770	268	140	100	660
	76-04-15	0	618	507	25	30	780	275	130	110	670
460709103032806	81-10-01	0	918	799	13	--	1400	595	264	178	1310

STATION NUMBER	DATE OF SAMPLE	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SILICA, DIS-SOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)	PHOS-PHORUS, DIS-SOLVED (MG/L AS P)	ALUM-INUM, DIS-SOLVED (UG/L AS AL)
460826103044404	80-08-15	12	390	7.8	.4	9.4	1150	1130	.00	--	10
460853103054501	80-08-15	17	480	7.4	.4	10	1230	1190	.26	--	10
461625103004901	74-05-16	10	790	10	1.1	8.6	1600	1580	.03	.380	--
	76-09-29	9.7	650	5.3	2.2	5.5	1480	1460	.56	.130	--
461034103003302	76-06-28	18	380	4.2	.6	14	1040	1180	.08	.500	--
	81-10-02	--	--	--	--	18	--	--	--	--	--
461211103043301	74-04-30	18	1600	8.0	.4	13	2940	2810	.17	.340	--
	74-11-20	15	1500	6.0	.2	12	2980	2760	--	--	<100
	75-04-28	15	1600	6.3	.2	11	2940	2850	--	--	30
	75-11-11	17	1700	6.5	.3	10	3030	2950	--	--	<100
	76-04-15	17	1600	5.9	.2	11	2990	2860	--	--	<100
460709103032806	81-10-01	20	3680	16	1.0	13	6140	5930	--	--	--

STATION NUMBER	DATE OF SAMPLE	ANTI-MONY, DIS-SOLVED (UG/L AS SB)	ARSENIC DIS-SOLVED (UG/L AS AS)	BARIUM, DIS-SOLVED (UG/L AS BA)	BERYL-LIUM, DIS-SOLVED (UG/L AS BE)	BORON, DIS-SOLVED (UG/L AS B)	CADMIUM DIS-SOLVED (UG/L AS CD)	CHRO-MIUM, DIS-SOLVED (UG/L AS CR)	COBALT, DIS-SOLVED (UG/L AS CO)	COPPER, DIS-SOLVED (UG/L AS CU)	IRON, DIS-SOLVED (UG/L AS FE)
460826103044404	80-08-15	--	1	--	<1	1200	<1	10	--	0	10
460853103054501	80-08-15	--	1	--	<1	1600	<1	0	--	0	<10
461625103004901	74-05-16	--	--	--	--	--	--	--	--	--	20
	76-09-29	--	--	--	--	--	--	--	--	--	1800
461034103003302	76-06-28	--	--	--	--	400	--	--	--	--	--
	81-10-02	--	--	--	--	--	--	--	--	--	--
461211103043301	74-04-30	--	--	--	--	--	--	--	--	--	590
	74-11-20	--	<1	--	<10	--	<2	<20	--	2	<10
	75-04-28	--	<1	<100	<10	7200	<2	ND	--	8	280
	75-11-11	--	<1	<100	<10	7700	ND	<20	--	ND	2000
	76-04-15	--	<1	<100	<10	1900	<2	ND	--	<2	1800
460709103032806	81-10-01	--	--	--	--	--	--	--	--	--	--

Footnotes at end of table

SUPPLEMENT 4.—*Water quality in the unconfined (and transitional) basal Bullion Creek-Slope aquifer*—Continued

STATION NUMBER	DATE OF SAMPLE	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	VANA-DIUM, DIS-SOLVED (UG/L AS V)
460826103044404	80-08-15	3	50	20	--	<10	0	0	--	--	--
460853103054501	80-08-15	2	60	190	--	<10	0	0	--	--	--
461625103004901	74-05-16	--	--	<10	--	--	--	--	--	--	--
	76-09-29	--	--	90	--	--	--	--	--	--	--
461034103003302	76-06-28	--	--	--	--	--	--	--	--	--	--
	81-10-02	--	--	--	--	--	--	--	--	--	--
461211103043301	74-04-30	--	--	280	--	--	--	--	--	--	--
	74-11-20	<2	230	500	<.1	<1	3	<1	--	--	.0
	75-04-28	2	230	400	<.5	<1	<2	<1	--	4400	1.6
	75-11-11	<2	230	430	<.5	<1	2	1	--	4300	.2
	76-04-15	<2	230	330	<.5	<1	2	<1	--	4000	.6
460709103032806	81-10-01	--	--	--	--	--	--	--	--	730	--

STATION NUMBER	DATE OF SAMPLE	ZINC, DIS-SOLVED (UG/L AS ZN)	GROSS ALPHA, DIS-SOLVED (UG/L AS U-NAT)	GROSS BETA, DIS-SOLVED (PCI/L AS CS-137)	GROSS BETA, DIS-SOLVED (PCI/L AS SR/YT-90)	RADIUM 226, DIS-SOLVED, RADON METHOD (PCI/L)	CARBON, ORGANIC DIS-SOLVED (MG/L AS C)
460826103044404	80-08-15	<3	--	--	--	--	--
460853103054501	80-08-15	<3	--	--	--	--	--
461625103004901	74-05-16	--	--	--	--	--	--
	76-09-29	--	--	--	--	--	--
461034103003302	76-06-28	--	--	--	--	--	--
	81-10-02	--	--	--	--	--	--
461211103043301	74-04-30	--	--	--	--	--	--
	74-11-20	750	--	--	--	--	20
	75-04-28	70	--	--	--	--	40
	75-11-11	30	<41	81	64	.08	24
	76-04-15	30	--	--	--	--	16
460709103032806	81-10-01	--	--	--	--	--	--

1/ Analyses performed by the North Dakota State Water Commission Laboratory, Bismarck, N. Dak.
2/ Analyses performed by J. C. Chemerys, Office of the Regional Hydrologist, Northeastern Region, U.S. Geological Survey, Reston, Va.

SUPPLEMENT 5.—*Water quality in saturated spoils*

[Analyses not indicated otherwise were performed by the U.S. Geological Survey National Water-Quality Laboratory, Denver, Colo. "Geologic unit" indicates the aquifer sampled: 120TRTR = spoils from mining the basal sandstone ofthe Paleocene Bullion Creek Formation of the Fort Union Group; <indicates less than]

STATION NUMBER	LOCAL IDENT-I-FIER	GEO-LOGIC UNIT	DEPTH OF WELL, TOTAL (FEET)	DATE OF SAMPLE	TIME	SPE-CIFIC CON-DUCT-ANCE (UMHOS)	PH (STAND-ARD UNITS)	TEMPER-ATURE (DEG C)	OXYGEN, DIS-SOLVED (MG/L)
460843103032001	131-099-27BBC1	120TRTR	86	81-10-14	1600	7500	6.9	5.4	1.0
		120TRTR	86	81-10-14 1/	1601	7500	6.9	5.4	.1
460747103032901	131-099-33ADA1	120TRTR	5	81-10-16	1500	6500	6.8	7.8	.1
460747103032902	131-099-33ADA2	120TRTR	38	81-10-02 2/	0002	2740	8.5	6.1	.0
460737103032901	131-099-33ADD	120TRTR	38	81-10-16	1630	2120	7.4	7.9	.0

STATION NUMBER	DATE OF SAMPLE	CAR-BONATE FET-FLD (MG/L AS CO3)	BICAR-BONATE FET-FLD (MG/L AS HCO3)	ALKA-LINITY FIELD (MG/L AS CACO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	HARD-NESS (MG/L AS CACO3)	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)
460843103032001	81-10-14	--	--	570	139	1200	629	230	150	1500	70
	81-10-14	0	895	734	180	1200	432	232	142	1490	72
460747103032901	81-10-16	--	--	290	89	3200	2870	390	530	730	17
460747103032902	81-10-02	32	1190	1030	6.0	210	0	9.6	46	738	16
460737103032901	81-10-16	--	--	349	27	520	170	98	66	250	17

STATION NUMBER	DATE OF SAMPLE	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SILICA, DIS-SOLVED (MG/L AS SIO2)	SOLIDS, RESIDUE AT 180 DEG. C DIS-SOLVED (MG/L)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	NITRO-GEN, NO2+NO3 DIS-SOLVED (MG/L AS N)	ALUM-INUM, DIS-SOLVED (UG/L AS AL)	ANTI-MONY, DIS-SOLVED (UG/L AS SB)	ARSENIC DIS-SOLVED (UG/L AS AS)
460843103032001	81-10-14	3700	56	.7	17	6220	6070	<.10	0	0	6
	81-10-14	3750	24	1.3	19	6230	6170	--	--	--	--
460747103032901	81-10-16	4200	93	.3	9.7	6660	6150	5.2	30	0	2
460747103032902	81-10-02	758	18	1.5	9.1	--	2250	--	--	--	--
460737103032901	81-10-16	720	14	.4	11	1430	1390	.21	30	0	4

STATION NUMBER	DATE OF SAMPLE	BARIUM, DIS-SOLVED (UG/L AS BA)	BERYL-LIUM, DIS-SOLVED (UG/L AS BE)	CADMIUM DIS-SOLVED (UG/L AS CD)	CHRO-MIUM, DIS-SOLVED (UG/L AS CR)	COBALT, DIS-SOLVED (UG/L AS CO)	COPPER, DIS-SOLVED (UG/L AS CU)	IRON, DIS-SOLVED (UG/L AS FE)	LEAD, DIS-SOLVED (UG/L AS PB)	LITHIUM DIS-SOLVED (UG/L AS LI)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)
460843103032001	81-10-14	<100	<10	0	10	1	1	50	0	150	730
	81-10-14	--	--	--	--	--	--	--	--	--	--
460747103032901	81-10-16	100	<10	0	20	8	3	70	0	130	310
460747103032902	81-10-02	--	--	--	--	--	--	--	--	--	--
460737103032901	81-10-16	100	<10	0	0	1	0	240	1	40	230

STATION NUMBER	DATE OF SAMPLE	MERCURY DIS-SOLVED (UG/L AS HG)	MOLYB-DENUM, DIS-SOLVED (UG/L AS MO)	NICKEL, DIS-SOLVED (UG/L AS NI)	SELE-NIUM, DIS-SOLVED (UG/L AS SE)	SILVER, DIS-SOLVED (UG/L AS AG)	STRON-TIUM, DIS-SOLVED (UG/L AS SR)	ZINC, DIS-SOLVED (UG/L AS ZN)
460843103032001	81-10-14	.0	2	1	0	0	5500	120
	81-10-14	--	--	--	--	--	500	--
460747103032901	81-10-16	.0	2	13	13	0	3700	90
460747103032902	81-10-02	--	--	--	--	--	680	--
460737103032901	81-10-16	.5	0	2	0	0	1800	50

1/ Analyses performed by J. C. Chemerys, Office of the Regional Hydrologist, Northeastern Region, U.S. Geological Survey, Reston, Va.

2/ Analyses performed by the North Dakota State Water Commission Laboratory, Bismarck, N. Dak.

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