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Thomas M. Hamilton
University of North Dakota

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GROUNDWATER FLOW IN PART OF THE LITTLE MISSOURI RIVER BASIN, NORTH DAKOTA

by

Thomas M Hamilton

B. S. in Geology, Capital University, 1965

M. S. in Geology, University of North Dakota, 1967

A Dissertation
Submitted to the Faculty
of the
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in partial fulfillment of the requirements
for the Degree of
Doctor of Philosophy

Grand Forks, North Dakota

June
1970

This dissertation submitted by Thomas M Hamilton in partial fulfillment of the requirements for the Degree of Doctor of Philosophy from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

(Chairman)

Walter L Moore

Vera Facey

Dean of the Graduate School

Permission

Title Groundwater Flow in Part of the
Little Missouri River Basin, North Dakota

Department Geology

Degree Doctor of Philosophy

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Date 5/27/78

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ABSTRACT

The Little Missouri valley in western North Dakota is deeply incised into slightly permeable Mesozoic and Cenozoic sediments. An evaluation of the groundwater flow in part of this valley was based on the present groundwater flow-system models. Abrupt changes in the hydrochemical facies have been explained relative to a continuous flow system.

The Little Missouri valley is the discharge area of a regional groundwater flow system; it affects the potential distribution of the flow system for a minimum of 1,000 feet below the valley floor. The discharge area is approximately the same width as the valley floor and has a ratio of the vertical to longitudinal flow component (in terms of gradient) of at least 100.

The groundwater divides in the center of the study area are asymmetrically spaced relative to the discharge area and underlie the surface-water divides. The recharge area to the west of the valley has a higher potential and steeper gradient than the eastern recharge area as a result of its higher elevation and overall lower permeability.

Lithology strongly controls the groundwater chemistry. The highest concentrations of dissolved solids are associated with some of the shortest groundwater flow paths; this water usually contains abundant sulfate.

Sodium is the dominant cation (comprising 90 to 99 percent of the total cations) in the discharge area and below a depth of about 200 feet in the recharge areas. This sodium facies is the result of the exchange of sodium for calcium by cation exchange minerals in the sediment. Groundwater rich in calcium and magnesium occurs where much of the calcium and magnesium exchange capacity of the sediment has probably been exhausted.

Repeating anion facies occur in a vertical section of the flow system. Bicarbonate facies, occurring at depths of several hundred feet are attributable to a sequence of reactions initiated by the reduction of sulfate. The total change of the groundwater chemistry as a result of this reduction is (1) a decrease in the absolute amount of sulfate, (2) an increase in the amount of bicarbonate, (3) an indirect increase in sodium, and (4) an increase in the total dissolved solids.

The highly-permeable valley-fill sediment receives seepage contributions related to three separate sources. The probable order of relative importance of these contributions is (1) seepage from the regional groundwater flow system, (2) seepage through the beds of ephemeral streams during runoff, and (3) seepage through the river banks at high stream stage. Much of the groundwater in the valley-fill sediment probably leaves the basin as underflow.

The cations in the groundwater of the valley-fill sediment are composed of as much as 50 percent calcium and magnesium. This high percentage may be explained as a reversal of the cation-exchange equilibrium when calcium-rich clays, that were eroded from the recharge areas, are brought into contact with the sodium-rich groundwater of the regional discharge area.

INTRODUCTION

Most appraisals of the quantity and availability of groundwater are presently directed toward the short-term economics of its withdrawal and consider a groundwater system only in terms of discrete aquifers. Water contributed from other parts of the system is often considered in such terms as "leakage", which if taken literally, imply the existence of a defect or abnormality in the system. This water is "abnormal" only as a result of assumptions and limitations placed on the system for purposes of evaluation. The permeable units of a groundwater flow system may be the least important or only of proportionally equal importance in many types of studies.

The importance of evaluating groundwater in terms of quantity, quality, and flow-rate and direction of movement is not confined to hydrological studies. Pollution studies of the movement of contaminants, geological studies of diagenesis, botanical studies of certain plant communities, and engineering evaluations of slope stability are affected by one or more aspects of groundwater. The necessity of considering all aspects of groundwater in terms of a continuous system is obvious.

The microscopic (intergranular) aspects of groundwater flow under natural conditions cannot be described at present because there is no means of describing the infinitesimal nature of the medium through which it moves. However, boundary-valued models that describe the large-scale movement and chemistry of groundwater in terms of continuous flow systems have been proposed. The general applicability of existing models has been demonstrated for areas ranging in size from thousands of square miles (Maxey, 1968; Hitchon, 1969a and 1969b) to a few square miles or less (Meyboom, 1967a; Williams, 1968). The models are constantly being improved. Testing is essential on all scales and under varying conditions of climate, geology, and topography in evaluation of their total usefulness (or uselessness) in groundwater studies.

Purpose

The purpose of this report is to present a preliminary evaluation of the groundwater flow system of part of the Little Missouri River basin in western North Dakota. Specific considerations include (1) the lateral extent of the regional discharge area, (2) the minimum depth effects of the river valley on the flow system, (3) the distribution and possible controls of groundwater-chemical facies, and (4) a first order approximation of the importance of separable sources of groundwater seepage to the valley fill sediment.

General Setting and Climate

The study area is located in part of the Little Missouri River basin in western North Dakota (fig. 1). The area is sparsely populated; for example, Billings County has a population density of about one person per square mile, and much of the area is not easily accessible.

The climate of the study area is typical of most of the semiarid Great Plains. The average annual rainfall is 14 to 15 inches; extreme variation from this average occurs locally. Most of the precipitation falls during thunderstorms of short duration and high intensity between April and September. The mean potential evaporation is about 3 to 4 times the mean annual precipitation. The temperature averages about 40 to 42 degrees Fahreheit.

Terminology and Concepts

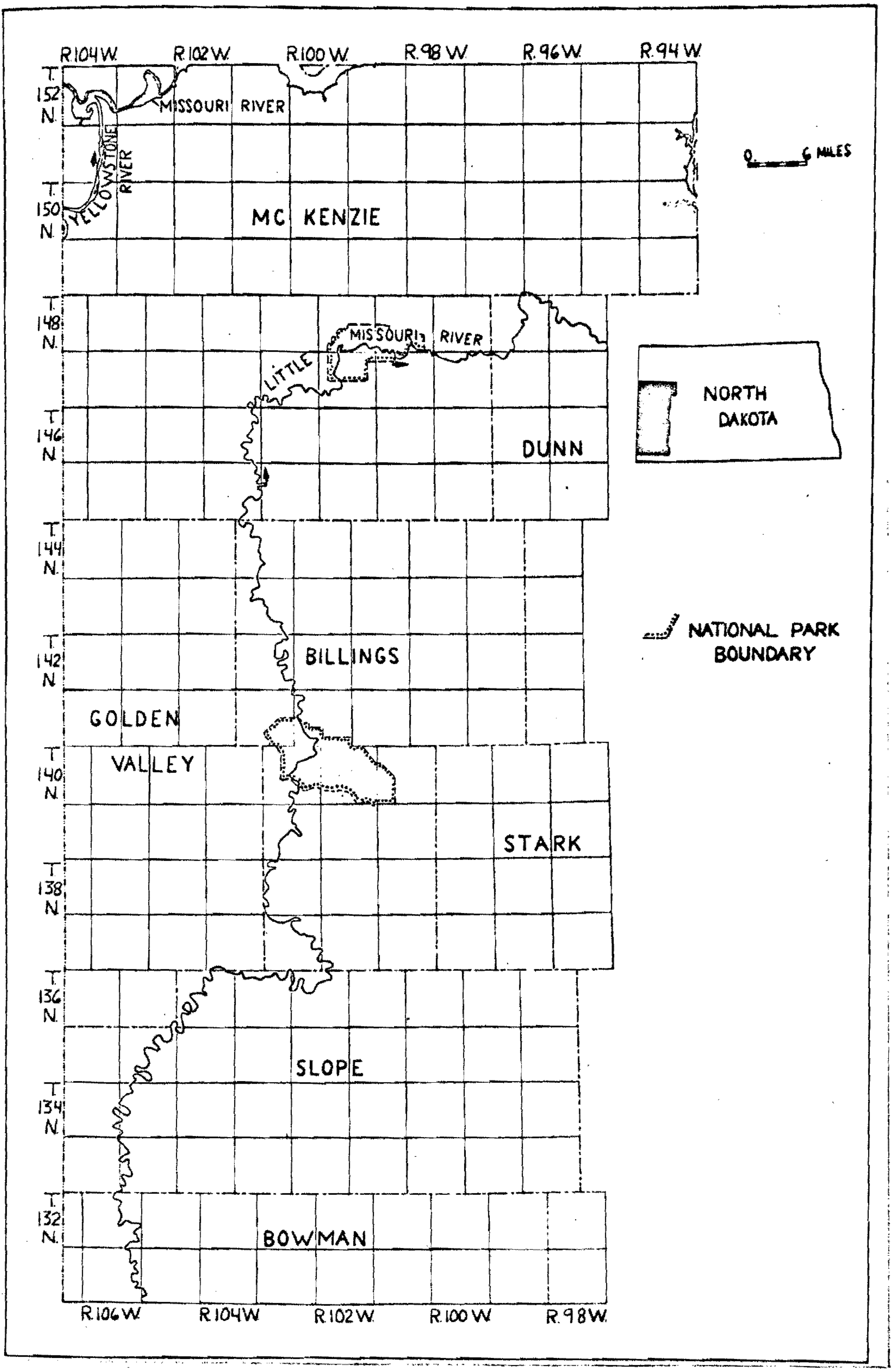
The purpose of this section is to define terms and concepts which are used in this report and not specifically described elsewhere.

Terms and concepts pertaining to the flow system

A flow system as defined by Tóth (1963, p. 4806) is

> . . . a set of flow lines in which any two flow lines adjacent at one point of the flow region

Figure 1.--Location map of the part of North Dakota considered in this study. The North and South Units of Theodore Roosevelt National Memorial Park are outlined.


R.104 W.
R.102 W.
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R.98 W.
R.96 W.
R.94 W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
MISSOURI RIVER
YELLOWSTONE RIVER
MC KENZIE
0 6 MILES
LITTLE MISSOURI RIVER
NORTH DAKOTA
DUNN
BILLINGS
NATIONAL PARK BOUNDARY
GOLDEN VALLEY
STARK
SLOPE
BOWMAN
R.106 W.
R.104 W.
R.102 W.
R.100 W.
R.98 W.

> remain adjacent through the whole region; they can be intersected anywhere by an uninterrupted surface across which flow takes place in one direction.

Three types of flow systems are recognized, depending on the relationship to topography and the flow path lengths involved. (1) A local flow system is developed between an adjacent topographic high and low and has flow path lengths ranging from a few feet to a few thousand feet. (2) An intermediate flow system is developed between intermediate topographic highs and lows in the basin and generally has flow path lengths ranging from a few to several thousand feet. (3) A regional flow system is developed between the highest and lowest regionally significant topographic features in a basin and generally has flow path lengths measured in miles.

Groundwater flow is three-dimensional and can be resolved into components and resultants. The components (fig. 2) are the longitudinal component which is parallel to a river or divide, the vertical component (either up or down), and the lateral component which is normal to the

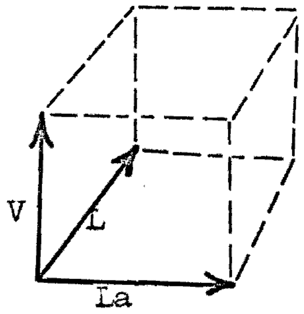

Figure 2.--The vertical (V), lateral (La), and longitudinal (L) components of groundwater flow.

plane of the longitudinal and vertical components (parallel to the direction of maximum basin slope). These three components can be resolved into a flow resultant, a horizontal component and a total flow vector (Meyboom, van Everdingen, and Freeze, 1966) as shown in figure 3.

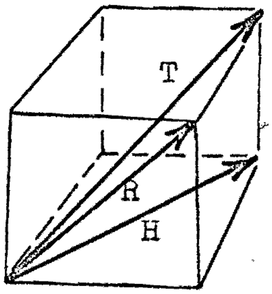

Figure 3.--The horizontal component (H), the flow resultant (R), and the total flow vector (T) of groundwater flow.

The horizontal flow component is approximated by maps of the piezometric surface or water table and the flow resultant is approximated by cross sections of the flow field.

A flow-system cross section is constructed by contouring values of potential in the plane of the section and by drawing flow resultants at right angles to the equipotential lines (for homogeneous isotropic conditions). An equipotential line can only be terminated at right angles on an impermeable boundary of the flow field. Most cross sections representing field conditions must be constructed with a consideration of anisotropic conditions in the sediment and vertical exaggeration of the section. Under these conditions, (1) equipotential lines and flow resultants are refracted at a permeability interface according to the tangent law (Hubbert, 1940, p. 943), and (2) flow resultants constructed on a vertically exaggerated section can no longer be drawn normal to equipotential lines but must be corrected for the distortion (van Everdingen, 1963).

A recharge area is an area in which the groundwater potential decreases with depth. A discharge area is one in which the potential increases with depth. The direction of potential change at depth may, in some cases, be reversed if the boundary between two flow systems is exceeded.

The water table is defined as a surface of a flow system at atmospheric pressure.

Terms and concepts pertaining to the water chemistry

The concentration of chemical constituents in water may be expressed in various ways. Two units for expressing concentration are used in this report. They are (1) parts per million(ppm), which expresses the parts by weight of dissolved matter in a million parts by weight of solution and (2) equivalents per million (epm), which is the normality X 10^3.

A hydrochemical facies is a lateral or vertical subdivision of a body of water which is distinguishable from other parts of the same system on the basis of its chemical character. The classification that is used to designate various facies follows that of Back (1960), and is expressed in terms of the percentage (based on equivalents per million) are refracted at a permeability interface according to the tangent law (Hubbert, 1940, p. 943), and (2) flow resultants constructed on a vertically exaggerated section can no longer be drawn normal to equipotential lines but must be corrected for the distortion (van Everdingen, 1963).

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A facies term which stands alone (either cation or anion or a combination) indicates that the ion content of the water is composed of at least 90 percent of that member (for example, bicarbonate water indicates that the anions are composed of at least 90 percent bicarbonate). Double anion terms (for example bicarbonate-sulfate) describe water that is composed of at least 50 percent but less than 90 percent of the first named member (bicarbonate); the second member is greater than 10 but less than 50 percent of the total anions. A calcium-magnesium facies indicates that the cations are composed of at least 90 percent calcium and magnesium. But, a calcium-sodium facies represents water in which the calcium and magnesium comprise at least 50 percent of the total cations. These few examples represent the general scheme of the classification.

Previous and Present Studies

No formal studies of the groundwater movement in the study area had been made prior to 1967, but reference to the occurrence and general chemical character of the groundwater was included in reports of regional and statewide surveys (Riffenburg, 1925; Simpson, 1929; Abbott and Voedisch, 1938; North Dakota State Dept. of Health, 1964). Tables of well schedules for individual counties were compiled during the 1930's as a part of a project of the Works Progress Administration. Data from a few, shallow observation wells in the area are included in various U. S. Geological Survey reports.

At the present time the U. S. Geological Survey is completing a groundwater resource evaluation of Stark and Hettinger Counties, which adjoin and partially overlap the eastern side of the study area.

Evaluation of Recent Work

General theoretical background of groundwater flow

The movement of groundwater has long been known to proceed in the direction of decreasing head, and this concept formed the basis for depicting and interpreting directions of movement of groundwater by constructing piezometric maps. No satisfactory mathematical expression of this condition was available until Hubbert's (1940) work in which he described the energy potential (Φ) at any point in the system in terms of the measurable physical properties of the system. This relationship, for general three dimensional flow, was expressed as a generalization of the Bernoulli equation in the form

$$\Phi = gZ + \int_{P_0}^{P} \frac{dP}{\rho} + \frac{V^2}{2}, \tag{1}$$

where g is the acceleration due to gravity, Z is the height above a datum, P is pressure, ρ is the density of the fluid, and V is the velocity of the fluid. The elements of the equation can be considered as potential energy (gZ), flow energy ($\frac{dP}{\rho}$), and kinetic energy ($\frac{V^2}{2}$). If the density is constant or if its functional relationship to P is known, then integration yields a constant, provided four conditions hold: (1) flow is along a streamline, (2) the fluid is incompressible, (3) the fluid is frictionless, and (4) the system is in a steady state. Condition (3) holds only for ideal fluid flow; therefore, the relationship would not be constant on a given groundwater flow line but would decrease in the direction of flow.

The expression of kinetic energy can be eliminated from the equation in its application to groundwater flow because of the extremely low velocities involved, reducing the equation to the form

$$\Phi = gZ + \int_{P_o}^{P} \frac{dP}{\rho}. \qquad (2)$$

Integration yields

$$\Phi = gZ + \frac{P-P_o}{\rho}, \qquad (3)$$

which can be further simplified (Hubbert, 1940, p. 802) to

$$\Phi = gh, \qquad (4)$$

where h is elevation to which water rises in a piezometer inserted to some point in the system. The result in this form is energy per unit mass with dimensions, in terms of length (L), time (T), and mass (M), of $(L/T)^2$. A different form of this expression can be derived by dividing equation 4 by gravity (g) to yield

$$\Phi = Z + \frac{P-P_o}{\gamma} = h, \qquad (5)$$

where γ is the specific weight (ρg). The potential in this form can be interpreted as energy per unit weight (ft-lb/lb). The dimensions are

$$L + ML^{-1}T^{-2}/ML^{-2}T^{-2} = L.$$

This form is convenient because the measurement of Φ in terms of h can be made from the free surface in a piezometer and reported as feet of water. The magnitude of Φ in this form is generally referred to as the piezometric or total head.

Another important concept in evaluating a flow system is the relationship expressed by Darcy's law. A general form for this law is given as

$$V = -K \frac{dh}{dl}, \qquad (6)$$

where V is velocity of flow, dh/dl is the differential change of head (h) with length of flow (l) and is referred to as the hydraulic gradient, and K is a proportionality constant (hydraulic conductivity). The negative sign indicates that flow is in the direction of decreasing potential. Much recent research has been devoted to the validity of Darcy's law as it is related to both rate of flow and the intergranular forces of fine-grained sediment (non-Darcy flow). Meyboom (1966a) summarizes the literature in a general discussion of these concepts. These aspects are not considered here.

Application and expansion of flow theory

Following the publication of Hubbert's paper, little work was done with the application of basic flow theory to stratified media on a large scale. Much research was devoted to developing and improving pump-test theory in search of a means for evaluating the permeability (hydraulic conductivity) of aquifers. A general model (one which uses botanic, geologic, pedologic, and hydrologic conditions) for predicting basin-wide and interbasin groundwater flow was not developed until the early 1960's. Meinzer (1927) had earlier described the occurrence of phreatophytes and the usefulness of such observations in groundwater studies. Meyboom (1963) described the groundwater flow conditions in the semiarid prairie of Saskatchewan, Canada. The resulting model, based on field observations, was referred to as the Prairie Profile. At about the same time Tóth (1963) presented a theoretical treatment of groundwater flow in small basins. The conclusions obtained from these two approaches will be compared later. The concept of qualitative and quantitative applications in the form of digital modeling of regional groundwater flow systems was treated by Freeze and Witherspoon (1966, 1967, and 1968). They presented mathematical models (1966) for nonhomogeneous anisotropic conditions that have steady state solutions obtainable by digital computer. These models were tested under varying conditions of water table and permeability configuration (1967) and resulted in several conclusions pertaining to the properties of regional flow systems. Two of those conclusions are of particular interest: (1) recharge areas are consistently larger than discharge areas (p. 623) and (2) discontinuites in permeability associated with stratigraphic pinchouts can create unanticipated recharge and discharge areas (p. 634). The third of this series of papers (1968) considered quantitative evaluation of theoretical flow nets and their comparison with field examples.

Hitchon (1969a and 1969b) applied concepts of fluid flow in an analysis of the effects of geology and topography on fluid migration in a large sedimentary basin. He concluded that the effect of large river valleys on fluid potential distributions was observable to depths of at least 5,000 ft (1969a, p. 193), and that the flow system was affected significantly by high permeability zones at depth, even if they were not of basin-wide extent (1969b, p. 468).

The Prairie Profile.-Meyboom (1963) combined the observations of several workers with his own and presented a model which he felt made mapping of the flow system possible using information from many scientific disciplines. He felt that this model was particularly well suited to conditions in western Canada, hence the name Prairie

Profile. The flow conditions of the model were established on the basis of topography and geology (p. 9).

> By definition the Prairie Profile consists of a central topographic high bounded at either side by an area of lower elevation. Geologically the profile is made up of two layers of different permeability, the upper layer having the lower permeability. Through the profile is a steady flow of groundwater from the area of recharge to the area of discharge. The ratio of permeabilities is such that groundwater flow is essentially downward through the material of low permeability and lateral and upward through the underlying more permeable layer. The potential distribution in the profile is governed by the differential equation of Laplace.

The model (fig. 4) depicts a large-scale flow system bounded by topographically significant lows on which is superimposed local flow systems. The Prairie Profile differs from the classical model of an artesian system in that it does not require outcrop of the aquifer updip from the artesian area and it does not limit recharge to the outcrop area, thereby, greatly increasing the area of recharge. The model also presents the possibility that in a local flow system one could drill a well that shows an increase in head with depth followed by a decrease with depth when the basal limit of the local system has been exceeded.

The recharge area may contain fresh-water phreatophytes. The discharge areas of the model are characterized by accumulations of sodium salts, alkali soils, and vegetation that is both alkali tolerant and phreatophytic.

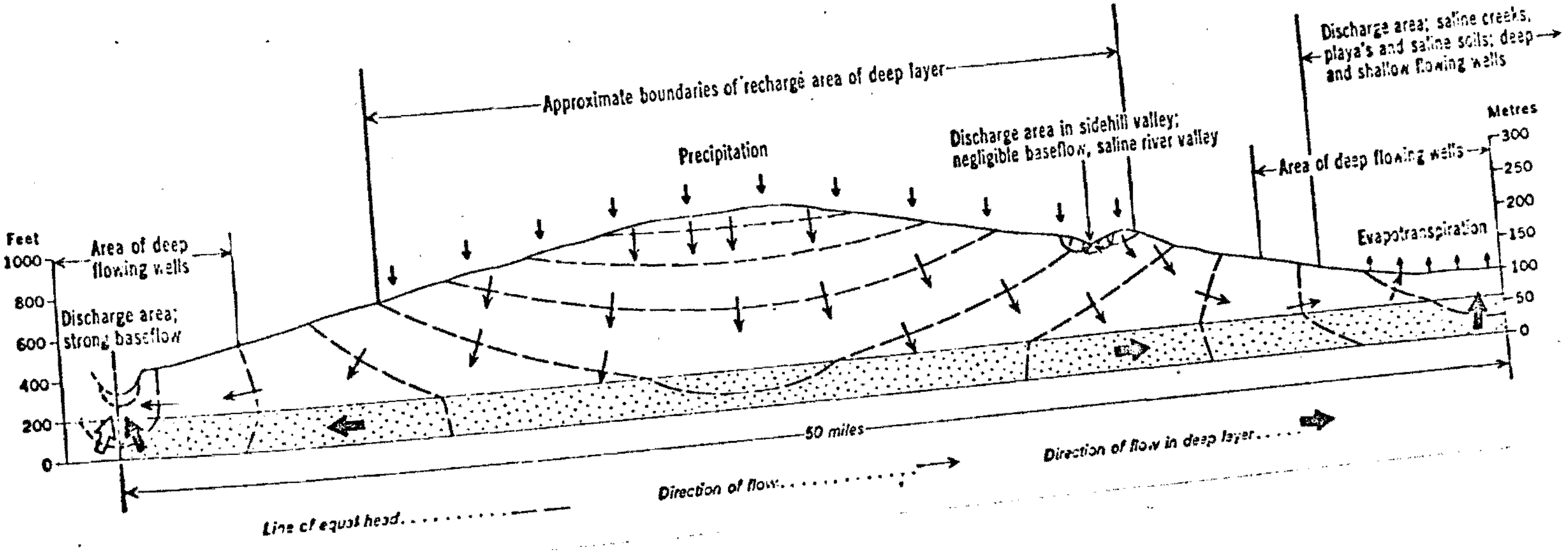


Figure 4.--The Prairie Profile, from Meyboom (1966, p. 27).

Small-basin flow system.-Tóth (1963) developed a mathematical model for groundwater flow with specified boundary conditions starting with Hubbert's (1940) equation for potential distribution. The model is for small basins (upper limit of several hundred square miles, p. 4797) underlain by isotropic homogeneous material and bounded by symmetrical divides. The water table was represented as a horizontal surface under assumed sinusoidal topography. The half width of the theoretical basin was taken to be 20,000 feet, and values for depth to the horizontal impermeable boundary ranged from 1,000 to 10,000 feet.

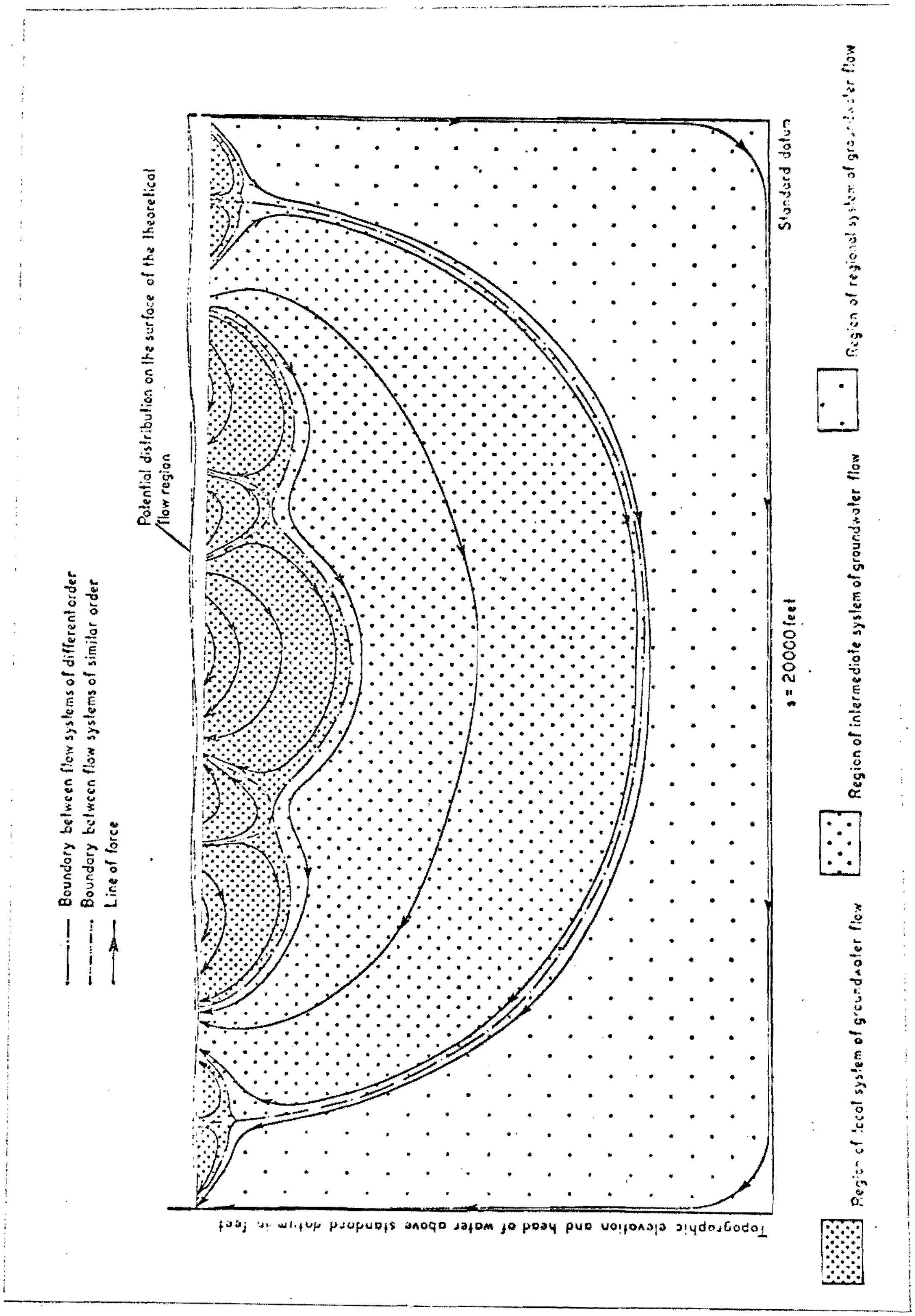
Inspection of flow systems derived from this model (fig. 5) indicates the existence of three different magnitudes of groundwater flow systems, (1) local, (2) intermediate, and (3) regional.

Discussion and comparison of the models.-The models are different in approach, one theoretical and one practical. The situation they depict is in all major aspects the same. The applicability of some assumptions in Tóth's model, particularly homogeneous isotropic conditions, and to some extent symmetrical drainage divides, may not seem consistent with actual conditions. But Tóth states (p. 4811)

> . . . in drainage basins, down to depths at which basin-wide extended layers of contrasting low permeability are found, groundwater motion may be treated as an unconfined flow through a homogeneous medium.

This neglects, by definition, stratigraphic discontinuities

Figure 5.--Small-basin flow systems determined by a mathematical model, from Tóth (1963, p. 4807).


Boundary between flow systems of different order
Boundary between flow systems of similar order
Line of force
Potential distribution on the surface of the theoretical flow region
s = 20000 feet
Standard datum
Topographic elevation and head of water above standard datum in feet
Region of local system of groundwater flow
Region of intermediate system of groundwater flow
Region of regional system of groundwater flow

which might cause significant change in the flow system (Freeze and Witherspoon, 1967). Tóth, however, considered this condition theoretically in an earlier paper (1962). Variation from the assumed conditions could be expected to occur, but can be handled mathematically by determination of the proper functional relationship; it does increase the complexity of the analysis.

Apparently the major point of disagreement between the two authors is the scale to which a flow system can develop. Tóth maintains that no large scale systems (several tens of miles) can be established in any area except one having a gentle continuous slope and no local relief (p. 4808). Meyboom notes (1963, p. 27) field evidence indicating that large scale systems are possible, even in areas of significant local relief.

Groundwater chemistry

Groundwater chemistry has important practical aspects, particularly in terms of its quality for consumption and irrigation and as it is used in oil exploration. Some chemical constituents have been used in studies of groundwater occurrence. For example, bromide concentrations have been used to differentiate salinity sources (Piper, Garrett, and others, 1953).

The first extensive treatment of changes in water chemistry with respect to position and time was given by Chebotarev (1955). His data was from several thousand water samples which ranged in composition from brine to fresh. Based on an analysis of this data he proposed the following groundwater chemical sequence and stated:

> Because of the different mobility of the chemical elements and the nature of the physical-chemical processes in the subsurface reservoir, the geochemical types of water change with the increase of the total salinity as well as with increasing depth, and the following series hold good:
>
> $$HCO_3^- \rightarrow HCO_3^- + Cl^- \rightarrow Cl^- + HCO_3^- \rightarrow$$
>
> $$Cl^- + SO_4^{--} \text{ or } SO_4^{--} + Cl^- \rightarrow Cl^-.$$

Simply stated, the sequence means that the most soluble products remain in solution, or the greater the length of time that water has been in contact with the sediment, the greater the concentration of chloride and total dissolved solids.

Water chemistry reflects residence in the sediment and should therefore be a qualitative tool in studies of direction of groundwater flow. Brown (1963) elaborated on this concept. Others have employed it as either a primary means of evaluating direction of flow (Charron, 1965; Back, 1960) or as a secondary indicator (Meyboom 1966b; Tóth, 1968).

Variations of Chebotarev's sequence have been cited in studies of groundwater flow systems, but deviation is usually explained as occurring in a system of insufficient magnitude to produce the complete sequence, or as a result of "unusual" lithologic effects.

An Approach to Defining the Little Missouri River Flow System

A general model of the Little Missouri River flow system was conceived early in the study to serve as a guide for data collection. The valley bottom was assumed to be a discharge area because of its low topographic position and because the stream flows during most extended dry periods. Evidence supporting the existence of a discharge area in the Little Missouri valley is the presence of phreatophytes (Meinzer, 1927) on the valley floor, the presence of springs and seeps, and localized accumulations of alkali salts along the base of the valley wall (Meyboom, 1966b). The most common phreatophyte is Populus sargentii (plains cottonwood), which in a semiarid environment is a definite phreatophyte (Meyboom, 1967, p. 32). The valley-bottom soils are not good flow-system indicators because they are immature as a result of much recent alluviation (Hamilton, 1967; Everitt, 1968).

The valley is a groundwater discharge area; however, the magnitude of the flow system (the vertical and lateral extent) could not be determined without examining the physical and chemical properties of the system.

Most of the data came from the discharge end of the regional flow system because the majority of wells tapping this system are located there. Very few deep wells exist outside the valley. The private wells drilled in the uplands are shallow and most are probably related to the discharge ends of locally controlled groundwater flow systems. The local groundwater systems are an important part of the total system but they could not be individually evaluated on the scale of this study. A few deep municipal wells do exist in the recharge area and they furnished the few data points at the end of the system.

It was necessary to locate groups of wells that would yield accurate data (See appendix A) and would be aligned at nearly right angles to the valley axis so they could be used to construct flow-system cross sections.

Although deep wells have been drilled in the Little Missouri River valley for many years the area is not highly developed, and it was difficult to find closely spaced wells penetrating to similar depths in some areas. Many of the older wells are of unknown depth and in some instances the casings are badly corroded. No measurements or samples were collected from the latter wells.

OBSERVATIONS

Topography and Stratigraphy

The establishment and maintenance of a groundwater flow system is primarily controlled by two factors: (1) topography, which provides the relief that drives the system, and (2) the permeability (vertical and lateral) of the material which influences the rate and direction of movement. It follows then, that the more that is known about both of these factors, the more easily definable the flow system should be.

Topography

The major topographic feature of the study area is the Little Missouri River valley. The valley imposes a significant steepening on the regional eastward slope of the land surface. This local steepening averages slightly less than five times the regional slope in the southern part of the study area, about five times the regional slope in the center, and more than five times in the northern part.

The Little Missouri River is bounded by an area of badlands several miles wide (fig. 6). Only a few tributaries sustain a measurable flow throughout most of the

Figure 6.--General view of the badlands bordering the Little Missouri River, North Dakota.

year; the vast majority are ephemeral. The drainage pattern is dendritic and completely integrated.

The land surface is broken by isolated buttes, some rising several hundred feet above the regional surface (fig. 7). Many of these buttes are imposing features, but because of their isolation their total affect on the regional topography is small when compared to the Little Missouri valley.

The Little Missouri valley is topographically bounded to the west and northwest by the deep Yellowstone River valley, to the north by the Missouri River trench (now Lake Sakakawea), and less abruptly to the east by several east-sloping valleys.

Stratigraphy

The study area is entirely contained within the Williston basin (fig. 8). The basin contains significant sedimentary deposits ranging in age from Cambrian to Quaternary. The sediments of primary concern in this report range from late Cretaceous to early Tertiary in age.

The stratigraphic units considered in this report include the section from the Cretaceous Pierre Shale through the Paleocene Sentinel Butte Formation. Younger strata crop out, but they occur as isolated exposures on butte tops, and are not considered significant in the flow-system evaluations. The included discussions of the stratigraphy draw most heavily on two sources, Frye (1969)

igure 7.--General view of isolated buttes on the regional eastward-sloping surface. The picture was taken looking west from the South Unit of Theodore Roosevelt National Memorial Park.

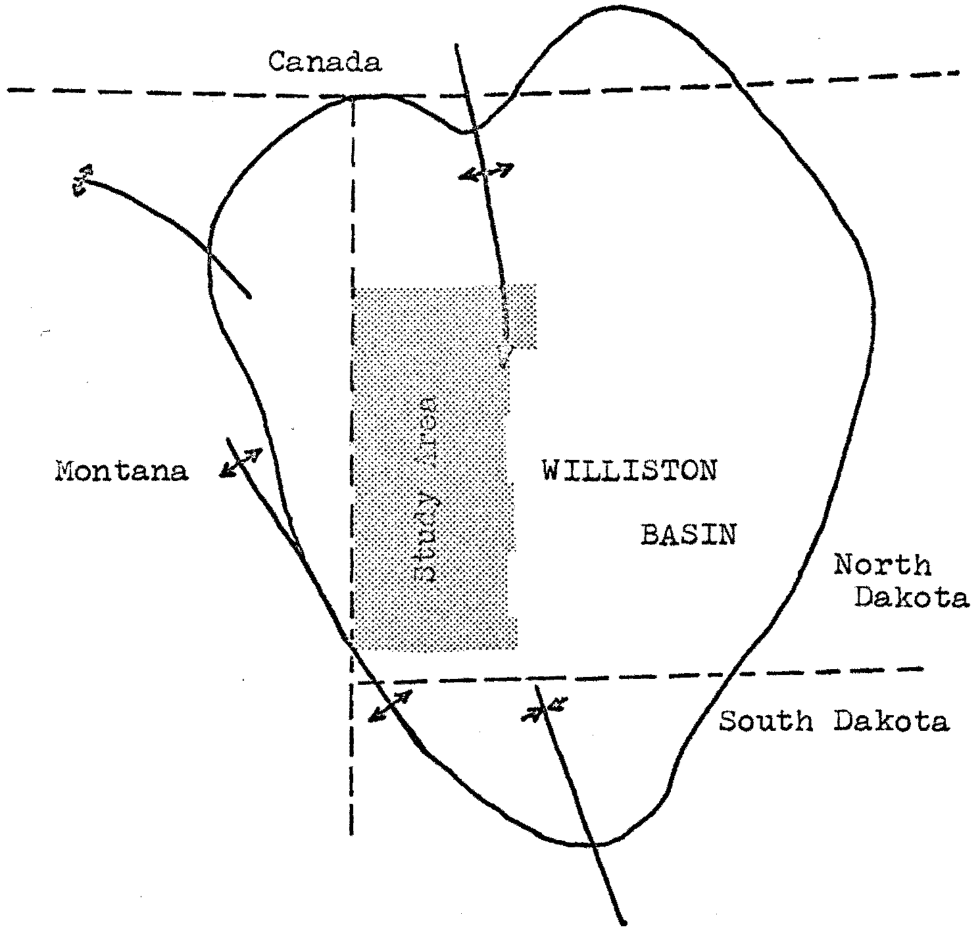


Figure 8.--Generalized map showing the approximate boundary of the Williston basin and some major structural trends within the basin.

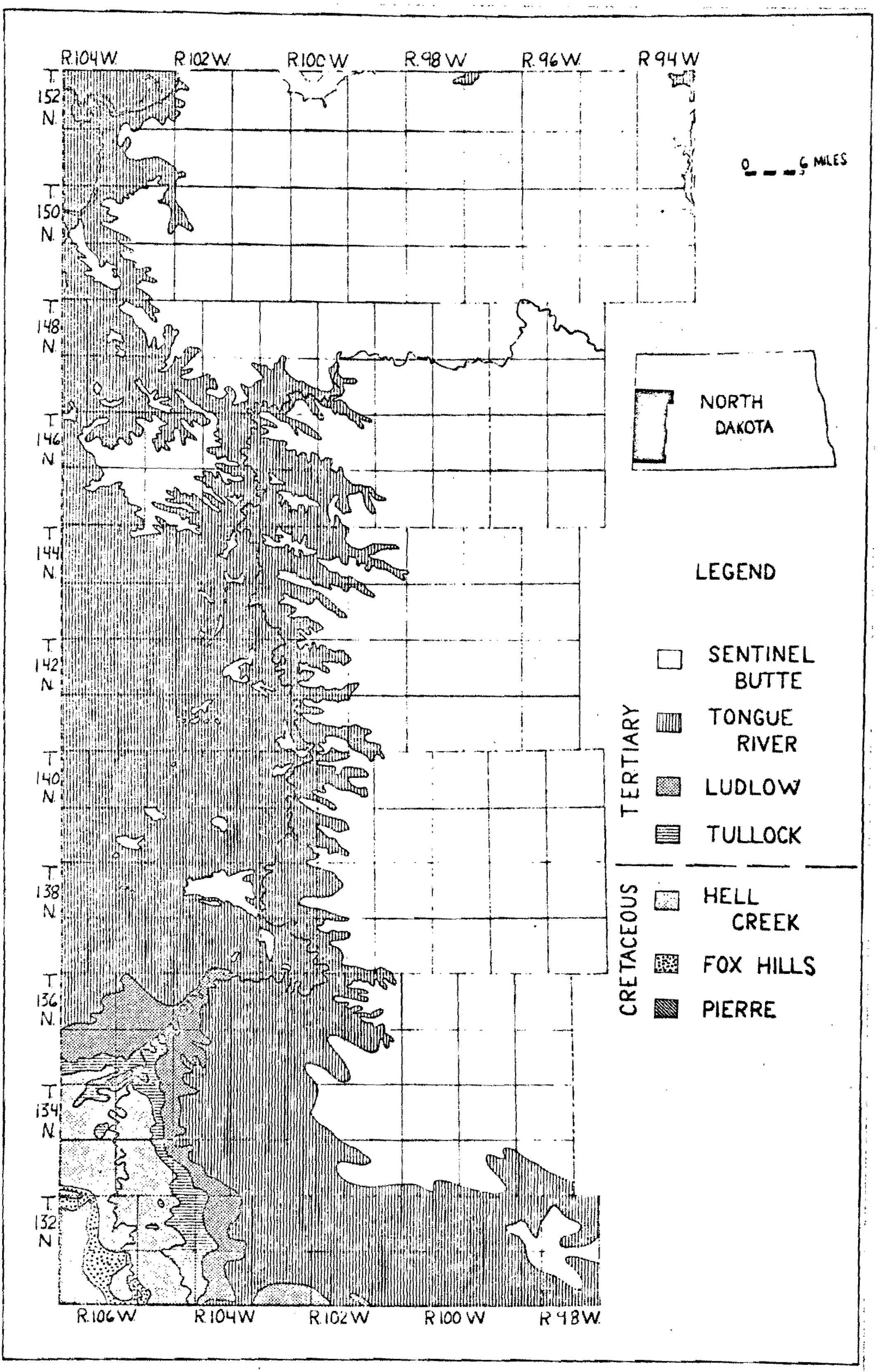
and Royse (1967), who conducted field and laboratory investigations of the surficial exposures of much of this section and compiled the literature. Hennen (1943) constructed a west-east surface and subsurface cross section of the Tertiary and upper Cretaceous deposits. No other subsurface studies of these formations were found.

A map of the outcropping stratigraphic units of the study area is shown in figure 9. The beds dip northward and eastward. Because of the importance of the relative permeabilities on the flow system, a brief description of the formations follows.

Pierre Shale.-The oldest formation considered is the Cretaceous Pierre Shale. It is significant to the study because it is considered to be the basal impermeable boundary of the regional flow systems that are established in overlying units. The Pierre crops out in the southern part of the study area, along the crest of the Cedar Creek anticline. The formation is composed of predominantely blue-gray marine shales that are as much as 2,000 feet thick.

The contact between the Pierre Shale and the overlying Fox Hills Formation is gradational (Feldman, 1967, p. 37). Feldman describes the contact in outcrop (p. 41) in Bowman County (sec. 4, T. 131 N., R. 106 W.) as being gradational through about 10 feet, with a change from dark blue shale, containing gypsum, jarosite, and scattered concretions, to buff or yellow fine grained sand.

Figure 9.--Geologic map of the study area, after Carlson (1969), Frye (1969), and Royse (1967).


R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T 152 N.
T 150 N.
T 148 N.
T 146 N.
T 144 N.
T 142 N.
T 140 N.
T 138 N.
T 136 N.
T 134 N.
T 132 N.
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.
0 6 MILES
NORTH DAKOTA
LEGEND
TERTIARY
SENTINEL BUTTE
TONGUE RIVER
LUDLOW
TULLOCK
CRETACEOUS
HELL CREEK
FOX HILLS
PIERRE

Fox Hills Formation.-The Cretaceous Fox Hills Formation consists of near-shore and shoreline marine sand, silt, and clay. The formation is about 100 feet thick in outcrop along the Cedar Creek anticline, but thickens basinward to more than 250 feet in the subsurface of the study area. The upper part of the formation contains a light gray sand unit called the Colgate Member. This sand has a wide lateral extent and occurs in the subsurface throughout the study area.

Hell Creek Formation.-The Hell Creek Formation is of late Cretaceous age and is composed of nonmarine and brackish-water clay, silt, and sand with some lignite. Frye (1969) measured stratigraphic sections and indicated that laterally persistent sands occur near the top and bottom of the formation in the southern parts of the study area.

The contact between the Hell Creek and Fox Hills Formations varies from gradational to unconformable (Frye, 1969, p. 22). Taylor (1965, p. 4) described a basal Hell Creek sand in eastern Montana which was medium to coarse grained. This sand pinches out between eastern Montana and western North Dakota, where the contact is generally marked by a basal Hell Creek lignite, lignitic clay, or bentonite (Frye, 1969).

The thickness of the Hell Creek may exceed 450 feet in places, though an average of 350 feet is probably more typical.

Tullock, Ludlow, and Cannonball Formations.-Overlying the Hell Creek Formation is a sequence of Paleocene sediments, the Tullock, Ludlow, and Cannonball Formations, which because of complex facies relationships, are treated as a composite interval.

The westerly Tullock and Ludlow Formations are of nonmarine and brackish-water origin and are time equivalents of the more easterly marine Cannonball Formation. The Tullock Formation is not recognized in the subsurface of the study area because of a lack of sufficient criteria and control and the following discussion refers only to the Ludlow and Cannonball Formations.

The Ludlow Formation is composed predominately of clay, lignite, and some sand lenses. The Cannonball Formation is composed of sand, silt, and clay. Two tongues of the Cannonball separated by about 150 feet of Ludlow Formation were recognized in western North Dakota by Brown (1962, p. 8), based on marine fossils recovered from the exposures.

The Ludlow-Cannonball interval varies greatly in thickness from west to east, but 200 to 300 feet is believed to be typical in the study area.

Tongue River Formation.-The Paleocene Tongue River Formation is generally a buff to light gray (in outcrop) sequence of nonmarine sediments that were deposited as the Cannonball Sea retreated from North Dakota. The sediments are primarily clay, silt, and some sand and lignite. A widespread sand lies at the base of the formation and may attain a thickness of more than 40 feet. Two relatively continuous thick lignite beds or lignitic shale beds are present, the Harmon lignite about 150 feet above the base and the HT Butte bed in the uppermost part of the formation.

The bright Tongue River conformably overlies the somber Ludlow Formation in the study area. The thickness of the Tongue River Formation is generally between 300 and 500 feet.

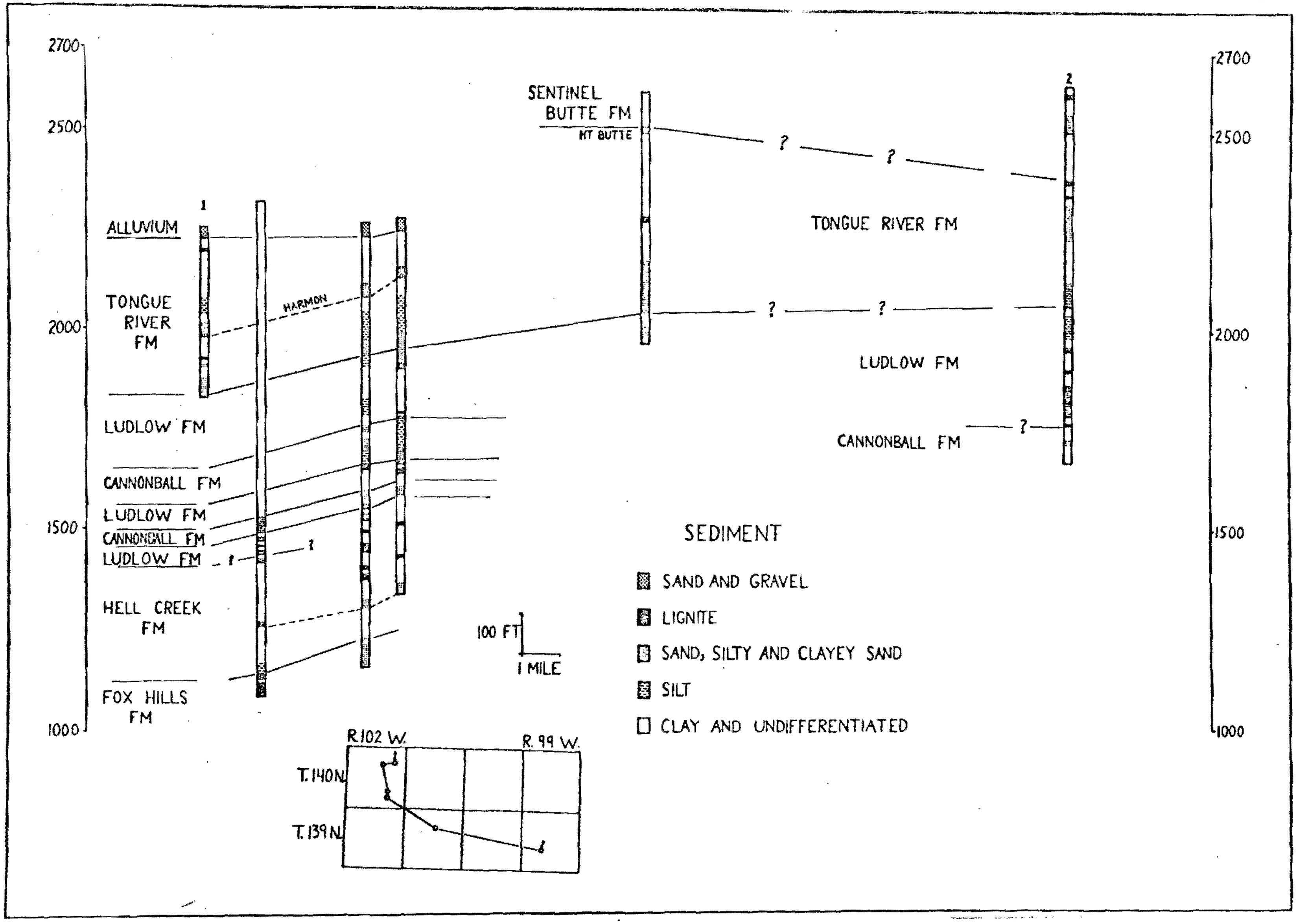
Sentinel Butte Formation.-The Sentinel Butte Formation, of late Paleocene age, is the uppermost stratigraphic unit considered in this study. It overlies the Tongue River Formation and differs from it by the presence of more somber-colored beds. Royse (1967, p. 5) indicated that this color difference is predominantely a weathering phenomenon which cannot be used to distinguish the formations in the subsurface. The two formations have similar lithologies, but the Sentinel Butte is more sandy. The contact between the Sentinel Butte and Tongue River Formations was found by Royse (1967, p. 3) to be distinguishable on the basis of three criteria: a marked change in color in outcrop, a persistent lignitic horizon in the uppermost Tongue River (HT Butte), and the presence of a sandy unit in the base of the Sentinel Butte.

The greatest thickness of the Sentinel Butte Formation is in the northern part of the study area where it may exceed 600 feet.

Summary of bedrock stratigraphy.-The strata overlying the Pierre Shale are predominately fine grained. Some persistent lignites are present in the Tongue River Formation, and sand beds of significant lateral persistence occur in the uppermost Fox Hills, Cannonball, and basal Tongue River and Sentinel Butte Formations. Numerous local lenses of sand occur throughout the section. A cross section of the subsurface stratigraphy in the area of the South Unit of Roosevelt Park is shown in figure 10. The data for this cross section came from logs of water wells in the area (appendix B). Two of the logs have been published (Simpson, 1929) and one is from a North Dakota State Water Commission test hole in Stark County. The remaining logs were obtained from the files of the U. S. Geological Survey in Bismarck, North Dakota, and through personal contact with private well drillers.

River alluvium.-The recent alluvial fill in the Little Missouri valley is a significant deposit in connection with discussions of groundwater flow because of its relatively high permeability. The alluvial fill averages three-fourths of a mile wide. At the surface it is clayey, sandy silt. Samples from seven test holes drilled by the North Dakota State Water Commission in the South Unit of Roosevelt Park in 1963 (Project No. 1326) are unconsolidated sand and gravel consisting mostly of quartz, clinker, li~~g~~gnite, and limestone, with occasional igneous and metamorphic pebbles. The thickness is about 20 to

Figure 10.--Subsurface cross section in the center of the study area.


2700
2500
2000
1500
1000
SENTINEL BUTTE FM
HT BUTTE
ALLUVIUM
TONGUE RIVER FM
HARMON
LUDLOW FM
CANNONBALL FM
LUDLOW FM
CANNONBALL FM
LUDLOW FM
HELL CREEK FM
FOX HILLS FM
1
2
?
TONGUE RIVER FM
LUDLOW FM
CANNONBALL FM
100 FT
1 MILE
R.102 W.
R. 99 W.
T.140N.
T.139N.
SEDIMENT
▨ SAND AND GRAVEL
▨ LIGNITE
▨ SAND, SILTY AND CLAYEY SAND
▨ SILT
☐ CLAY AND UNDIFFERENTIATED
2700
2500
2000
1500
1000

30 feet.

Structure contour map on the Pierre Shale.-Electric and radiation logs from oil wells (fig. 11) were used to draw a contour map on the top of the Pierre Shale (fig. 12). The elevation of tops in individual wells is given in appendix C. The Pierre Shale is assumed to be the basal impermeable boundary of the regional flow system in the area; therefore, the Pierre can be viewed as a flow system "basement".

The map indicates that several structural features are present in the area. The structural feature in the southwestern corner is the Cedar Creek anticline which trends from northwest to southeast. In the northeastern corner of the study area the southern end of Nesson anticline is apparent. The primary center of deposition throughout much of the history of the Williston basin is just to the north of the study area on the western flank of the Nesson anticline. The trends of several minor structural elements are conspicuous as flattening or noses on the regional dip.

This map also shows the rather low dips within the area. The dip of the Pierre Shale is greatest on the northeastern flank of the Cedar Creek anticline, but there it is only about 50 ft/mi (about $\frac{1}{2}$ degree). Farther to the north the dip is considerably less. Because of its low permeability, as a result of its fine-grained character,

Figure 11.--Location of oil wells used in constructing a structure contour map.

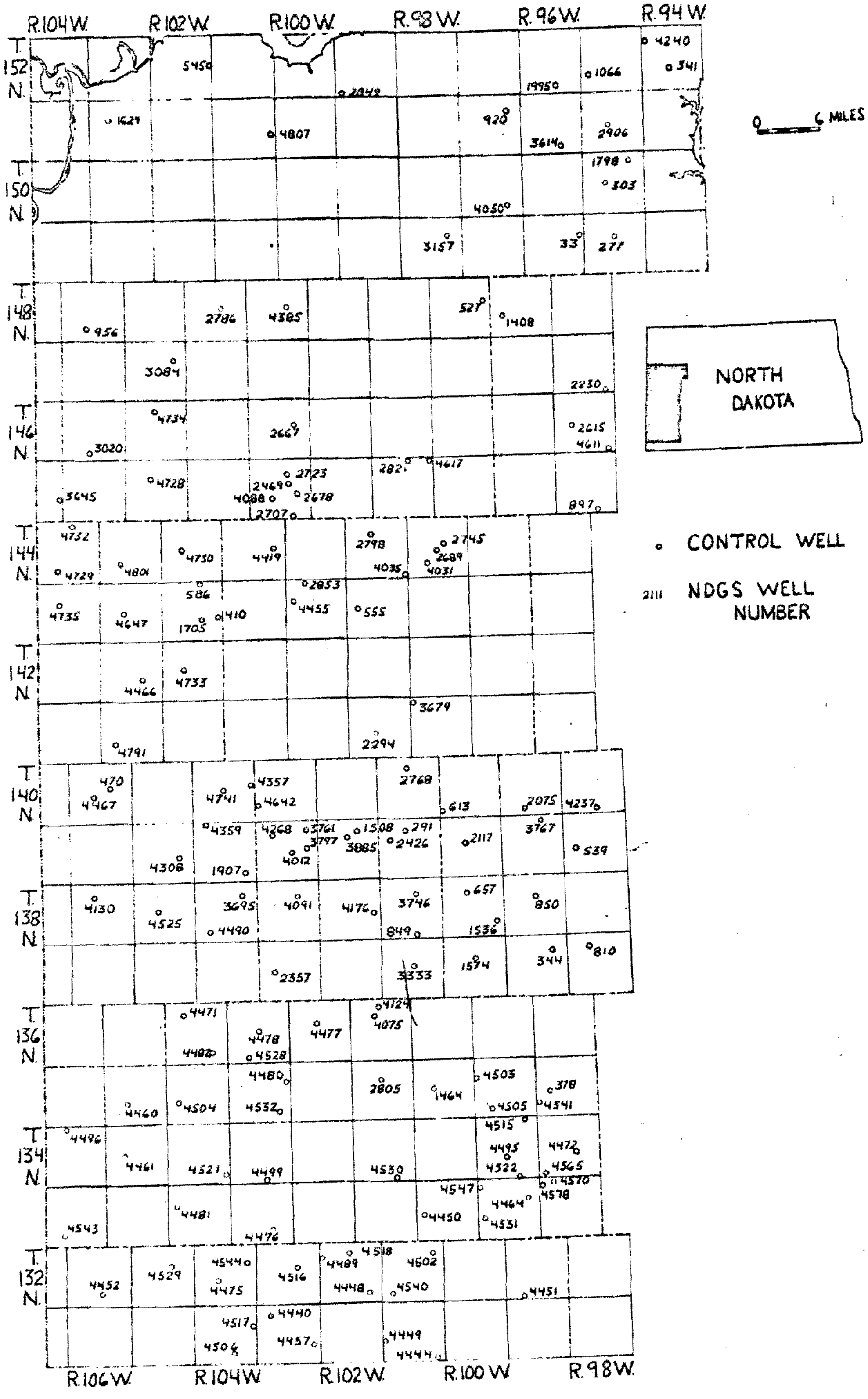
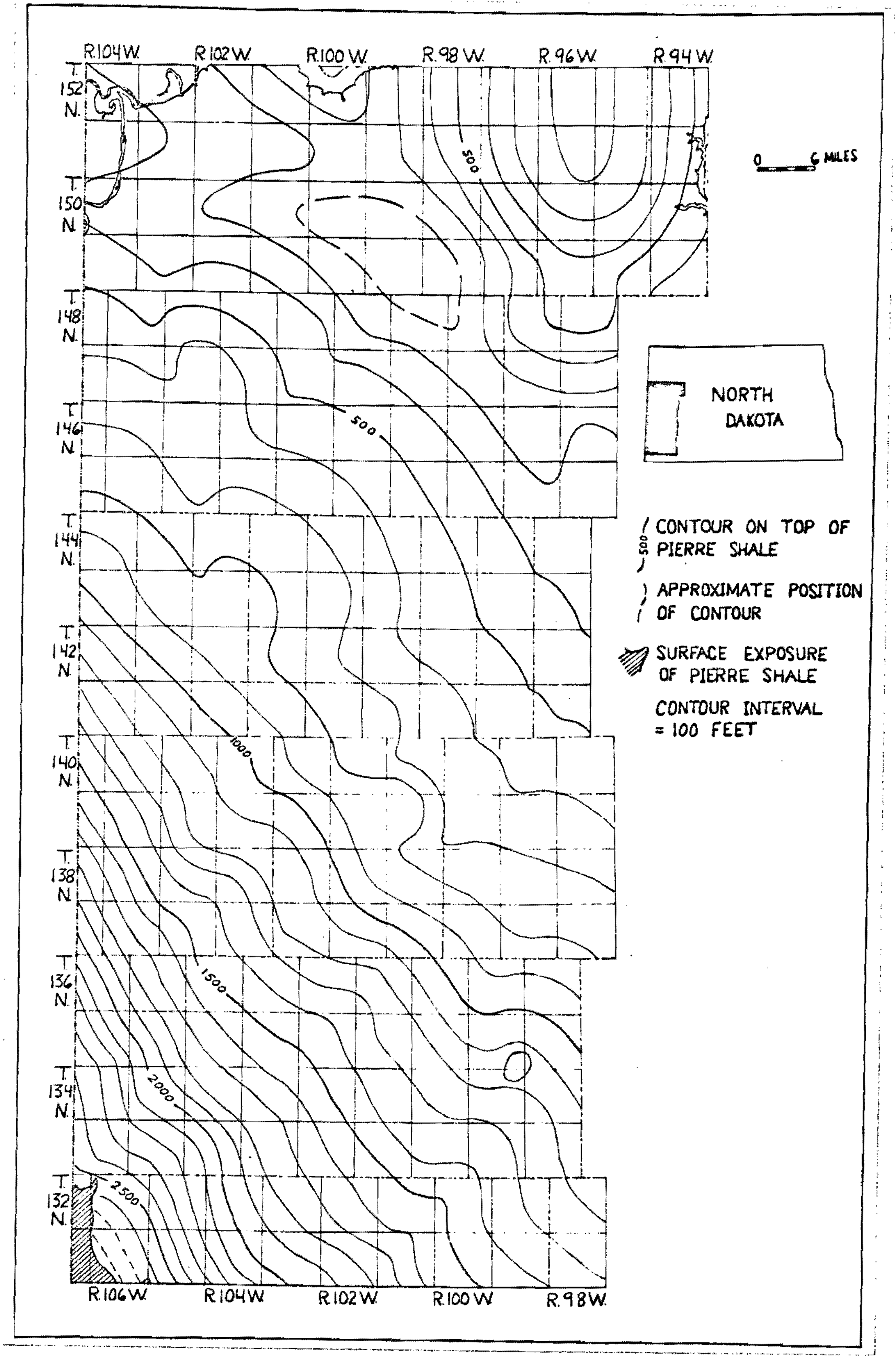

R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
0 6 MILES
NORTH DAKOTA
CONTROL WELL
2111 NDGS WELL NUMBER
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.
4240
341
5450
1066
1995
2849
1627
4807
920
3614
2906
1798
303
4050
3157
33
277
956
2786
4385
527
1408
3084
2230
4734
2667
2615
4611
3020
4728
2469
2723
282
4617
3645
4088
2678
2707
897
4732
2798
2745
4730
4419
2689
4031
4035
4729
4801
2853
586
4735
4647
1705
1410
4455
555
4466
4733
3679
2294
4791
470
4467
4741
4357
4642
2768
613
2075
4237
4359
4268
3761
3797
1508
3885
291
2426
2117
3767
539
4012
4308
1907
4130
4525
3695
4490
4091
4176
3746
657
850
849
1536
2357
3333
1574
344
810
4471
4124
4075
4482
4478
4528
4477
4480
2805
4503
378
4460
4504
4532
1464
4505
4541
4496
4515
4495
4472
4461
4521
4499
4530
4522
4565
4570
4547
4578
4481
4450
4464
4543
4476
4531
4518
4544
4489
4602
4452
4529
4475
4516
4448
4540
4451
4517
4440
4449
4506
4457
4444

Figure 12.--Structure contour map on the top of the Pierre Shale. The contours are in feet above mean sea level.


R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.
500
500
1000
1500
2000
2500
0 6 MILES
NORTH DAKOTA
CONTOUR ON TOP OF PIERRE SHALE
500
APPROXIMATE POSITION OF CONTOUR
SURFACE EXPOSURE OF PIERRE SHALE
CONTOUR INTERVAL = 100 FEET

and because of its very low dip the Pierre Shale qualifies as a nearly impermeable and horizontal basal flow system boundary.

Hydrogeology

In the following brief description of the general hydrogeologic conditions a distinction is made between shallow and deep groundwater on the basis of physical and chemical data. The relationship of the two will be demonstrated later.

Shallow groundwater

In this study, shallow groundwater is defined as that which occurs in Quaternary alluvial sediment. The base flow of the Little Missouri River is maintained by water discharged from the alluvium, therefore, the water at base-flow stage is assumed to have a chemical character similar to the shallow groundwater. Data were obtained from pits, shallow domestic and test wells, and surface water observations.

The shallow groundwater is maintained primarily by contributions from three sources: (1) the deep groundwater (bedrock flow systems), (2) recharge through the channel banks during periods when the stream stage is higher than the groundwater table (this increment contributed to the shallow groundwater is called bank storage (Linsley, et. al., 1958) and is discharged to the stream during the recessional stage), and (3) infiltration through the bed of ephemeral tributaries during runoff.

Infiltration through the surface of the alluvial fill is not considered a significant source of recharge. Most precipitation in western North Dakota occurs as rain during the late spring and summer months. The soil probably has a high moisture deficiency (no figures are available) and therefore most water falling on the valley fill surface goes to replenish the deficiency. This condition was observed during the summer of 1969 when an abnormally large amount of precipitation fell during a period of a few weeks. Even after one week of rain, which exceeded 7 inches, the wetted front did not exceed a depth of 3 to 4 feet. Recharge through the surface of the valley fill might occur during periods of very intense rainfall (several inches per day) or in areas of abundant drying cracks. Rainfall of extreme intensity does occur infrequently. However, the amount of recharge resulting from a storm of extreme intensity is probably not significant in comparison to the total yearly recharge from all sources. No observations have been made of the possible recharge from snow and frost melt. Drying cracks have been observed but no quantitative data as to their extent or significance to recharge are available.

The transverse gradient of the shallow groundwater is very low, probably on the order of 1 ft/mi. The gradient was so low that it could not be measured within the limits of precision of the instruments being used. The longitudinal gradient averages 5 to 6 ft/mi.

High transverse gradients were associated with special recharge conditions, such as the release of bank storage, or infiltration through excavations on or along the valley fill. An example of localized infiltration was associated with an excavation about 1 mile south of the South Unit of Roosevelt Park. The site is a road-bed aggregate pit in bedrock abutting river terrace sediment. The pit acted as a collecting basin and impounded water running off an adjoining hillside. The stream channel was approximately 500 feet west of and 30 feet below the excavation. During periods of high rainfall (such as the summer of 1969) a large amount of infiltration was induced through this excavation. The effect on the stream channel was apparent. The stream bank opposite the excavation underwent mass movement apparently in response to increased hydrodynamic pressure. The channel bottom at this location was very soft (almost quick) shortly after the heavy rains. This condition persisted for several days. Isolated conditions of a similar nature were observed in other areas along the Little Missouri River.

As a result of groundwater contributions from several sources, some of which are transient, the alluvial water chemistry may show considerable local variation. However, with the establishment of base-flow conditions in the river, the water chemistry soon reaches an equilibrium and does not show significant variation over a distance of several tens of miles. The water can be generally classified according to the dominant ions present as sodium-calcium sulfate-bicarbonate water.

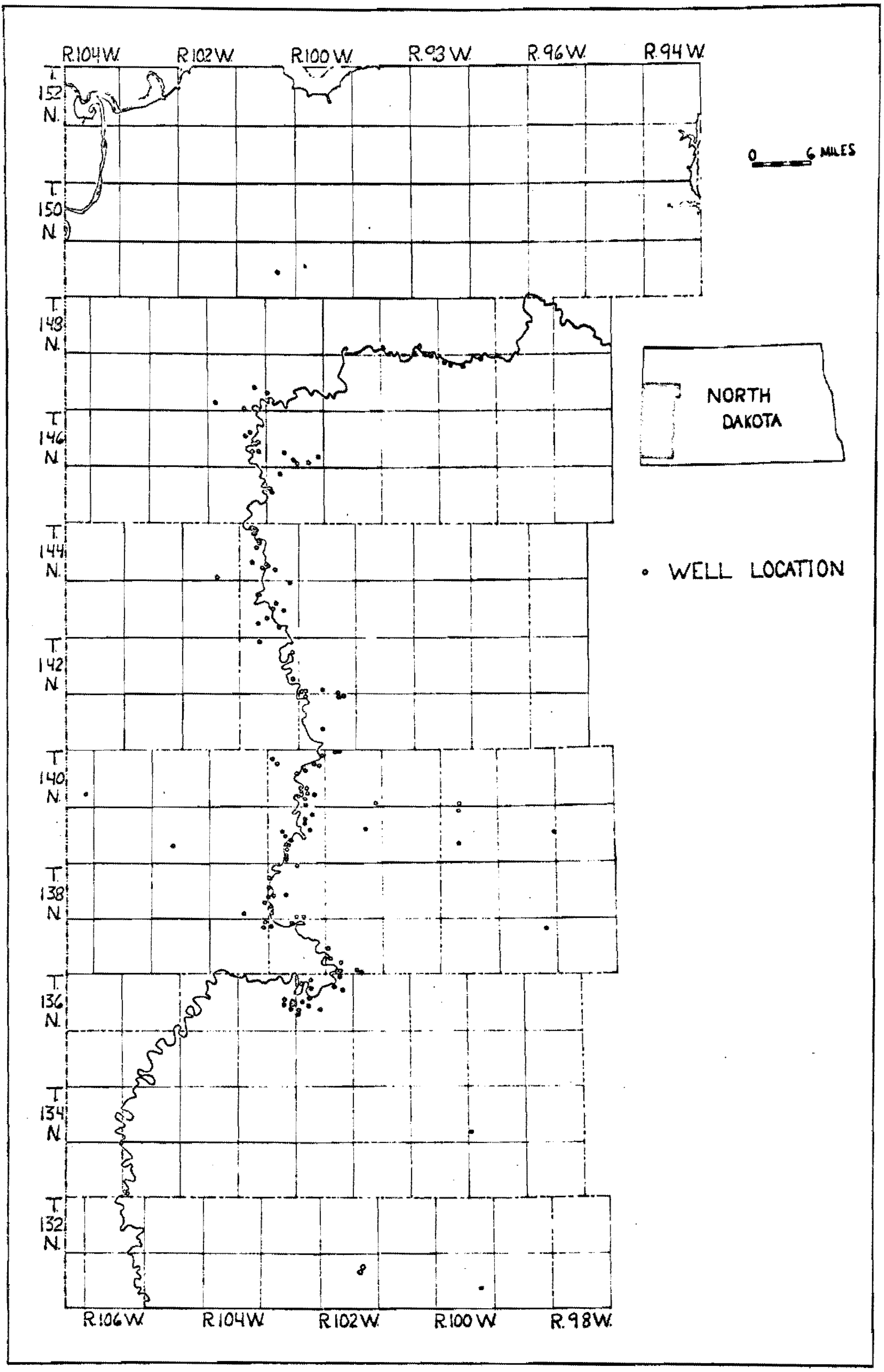
Deep groundwater

In this study, deep groundwater is defined as that which occurs in sediment older than Quaternary; more specifically, it is water occurring in the Fox Hills through Sentinel Butte Formations. The type of the groundwater flow system involved ranges from regional to local. Data were obtained from wells (fig. 13) and springs.

A plot of static water level (measured from the land surface) against well depth is shown in figure 14. The plotted data shows two diverging trends. The trend above the zero-line shows an increase in water level with depth indicating that these wells are in a discharge area. All data which plotted above the zero-line were from wells located on the valley floor of the Little Missouri River. The trend below the zero-line shows a decrease in water level with depth indicating that these wells are in a recharge area (these data were from wells located 15 to 25 miles east and west of the Little Missouri valley). This qualitative evaluation substantiates the earlier assumption that the valley is a discharge area.

The water chemistry (excluding springs and samples from local flow systems) shows both vertical and lateral variation. One invariant throughout the discharge area

Figure 13.--Location map of deep-groundwater wells from which data was obtained.


R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.
0 6 MILES
NORTH DAKOTA
• WELL LOCATION

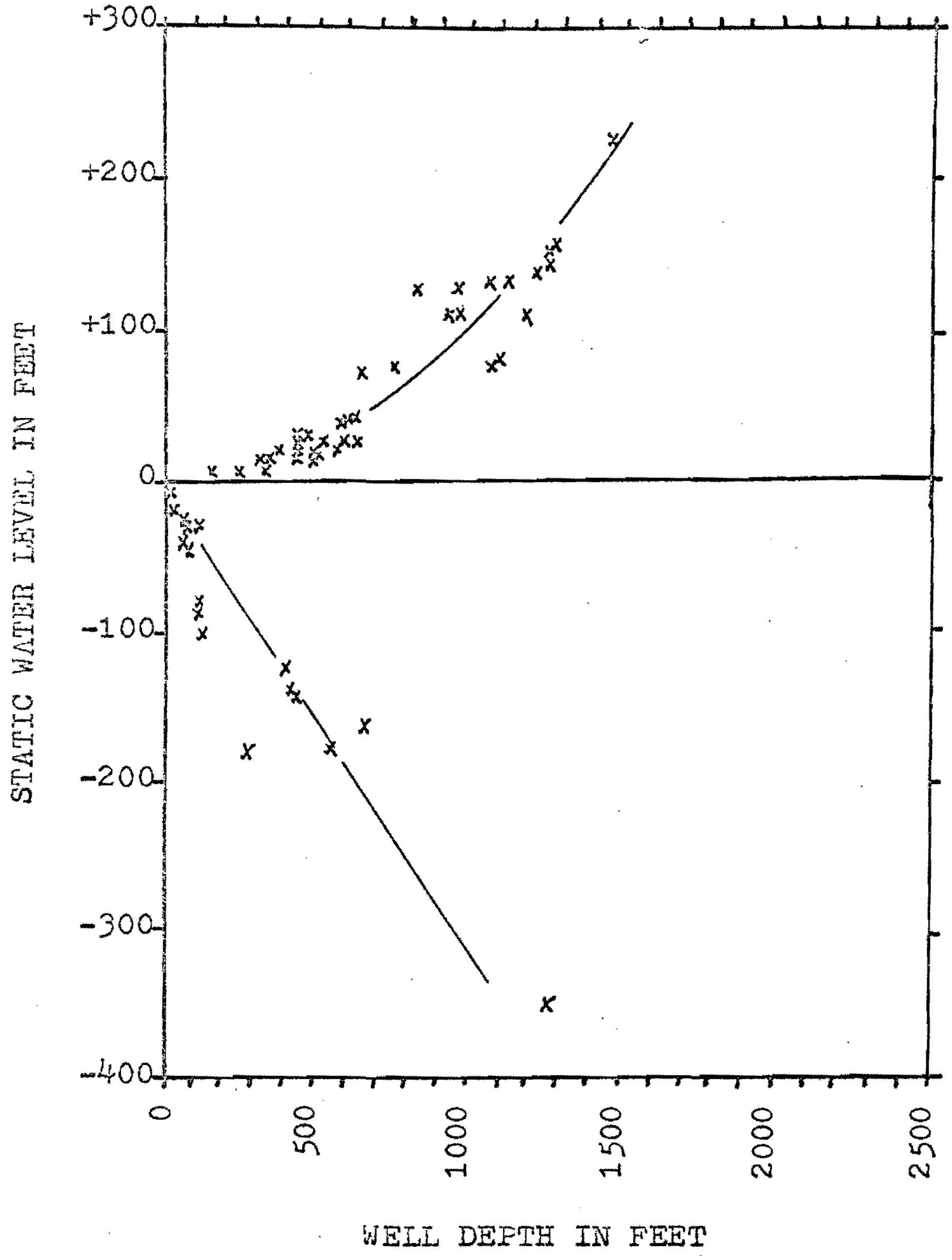


Figure 14.--Relationship of well depth and static water level.

and below a depth of a few hundred feet in the recharge areas is the almost complete absence of calcium and magnesium. The waters in a broad sense can be classified according to the dominant ions present as sodium bicarbonate-sulfate grading to sodium bicarbonate from south to north.

Water from springs and a few of the wells sampled is derived from local flow systems. Many of the springs sampled were associated with lignites and were located near the base of isolated hills. The source of recharge was through the hill, and the flow path lengths ranged from a few hundred to a few thousand feet. Chemical analyses from separate local flow systems indicate high variation in quality, with most analyses yielding values of total dissolved solids greatly in excess of samples from larger flow systems with flow paths at least a few miles in length. This is in opposition to the commonly accepted generalization that the concentration of total dissolved solids varies directly with the length of flow path (Chebotarev, 1955). Obviously more than just flow-path length needs to be considered in western North Dakota.

FLOW-SYSTEM EVALUATION

Potential Distribution

The potential distribution of the flow system is represented by three vertical cross sections (figs. 15, 16, 17) constructed at nearly right angles to the axis of the Little Missouri valley. In constructing these cross sections it was assumed that steady-state flow exists. This assumption is justifiable because drillers indicate that present values of total head are not significantly different from original values; in some cases the period of time involved is several tens of years. A variation in total head of a few feet is considered insignificant in comparison with a total saturated thickness of more than 1,000 feet. Some reports of significant decline in total head can be attributed to either faulty well completion or casing failure. The angle of intersection of the flow resultants and equipotential lines in these sections were corrected for vertical exaggeration using the procedure developed by van Everdingen (1963).

The cross sections (figs. 15, 16, 17) depict several important features of the flow system. (1) The potential

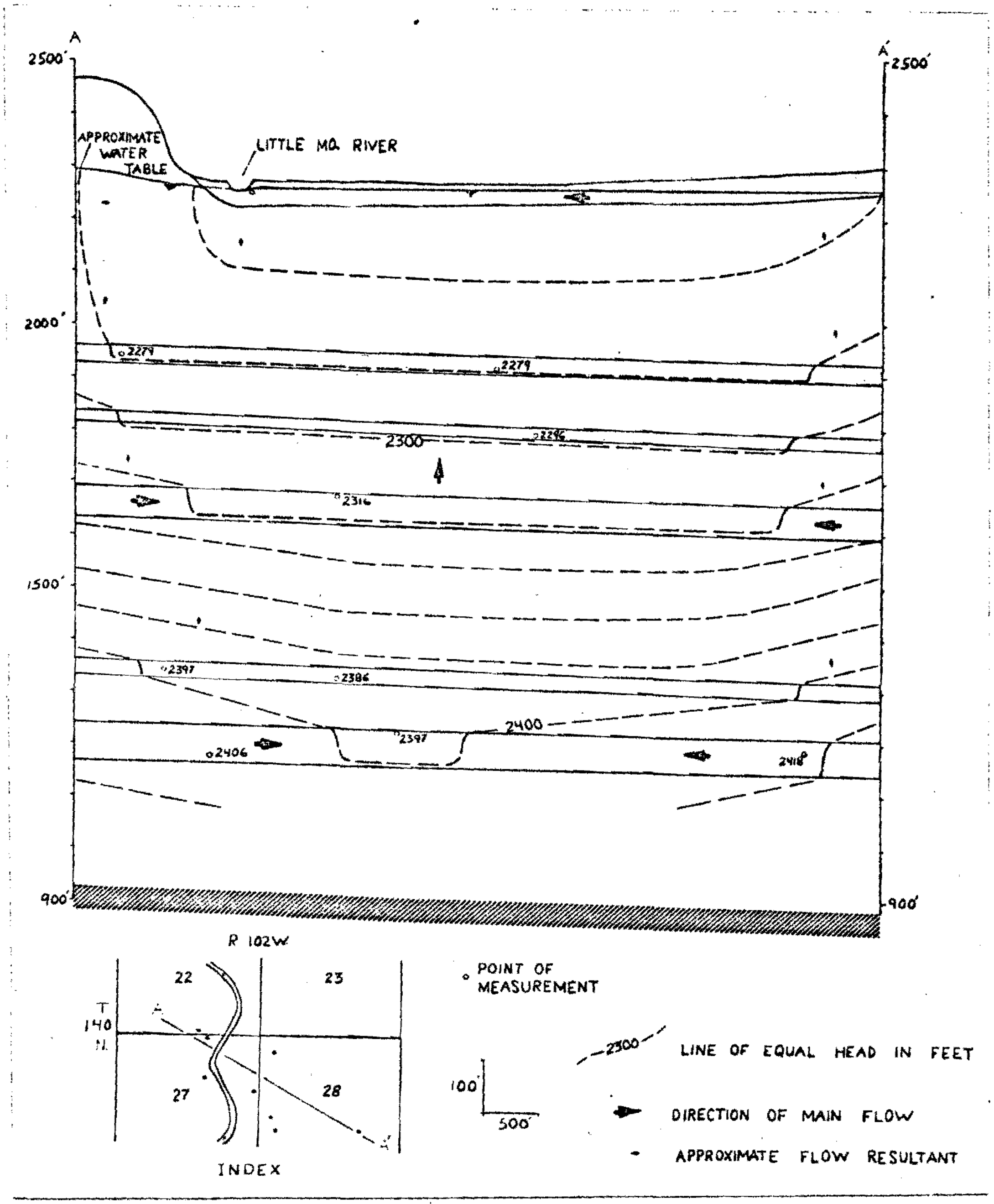


Figure 15.--Pattern of groundwater flow in the Little Missouri valley, North Dakota. The diagonal pattern indicates the approximate top of the Pierre Shale.

Figure 16.--Pattern of groundwater flow in the Little Missouri valley, North Dakota. The diagonal pattern indicates the approximate top of the Pierre Shale.

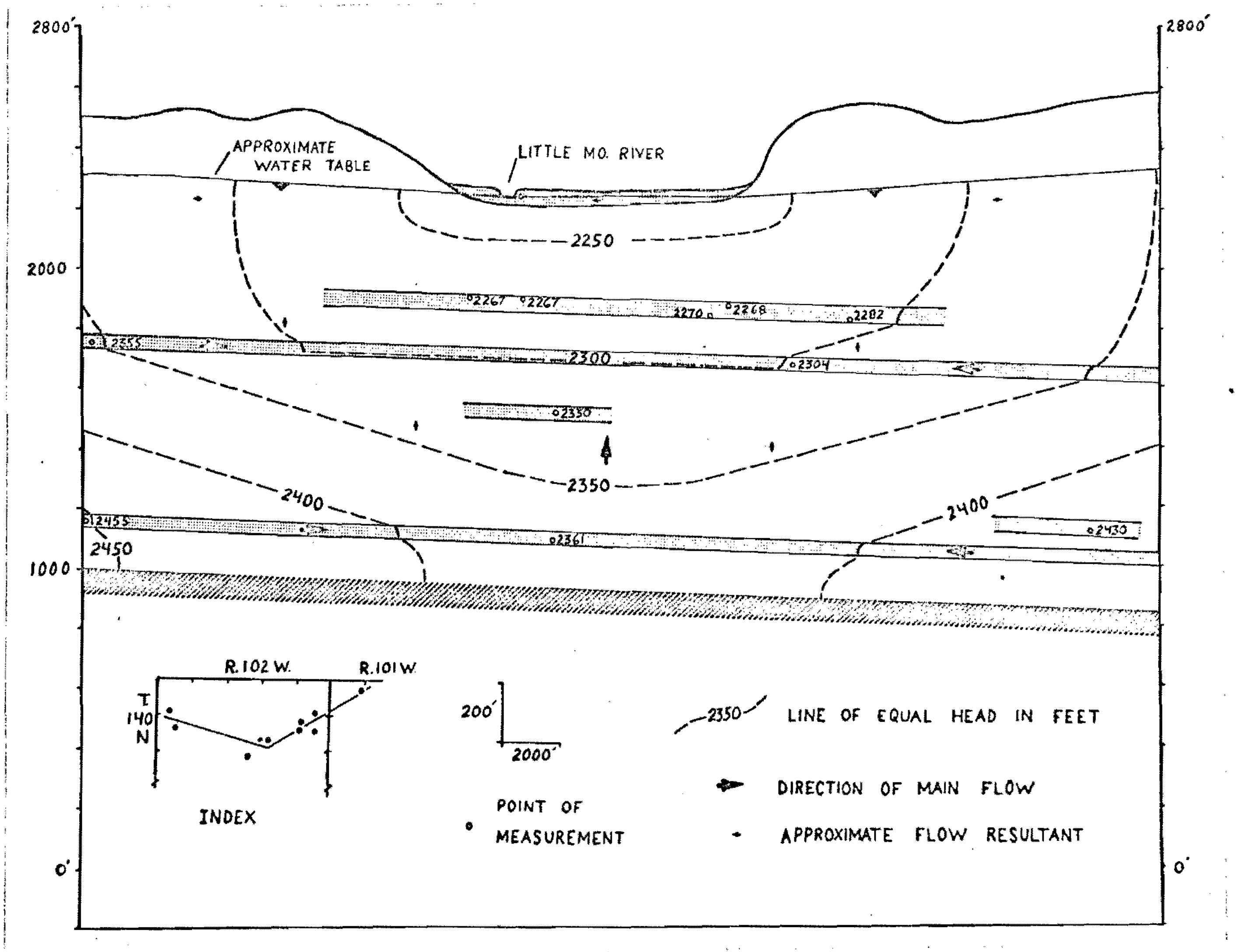
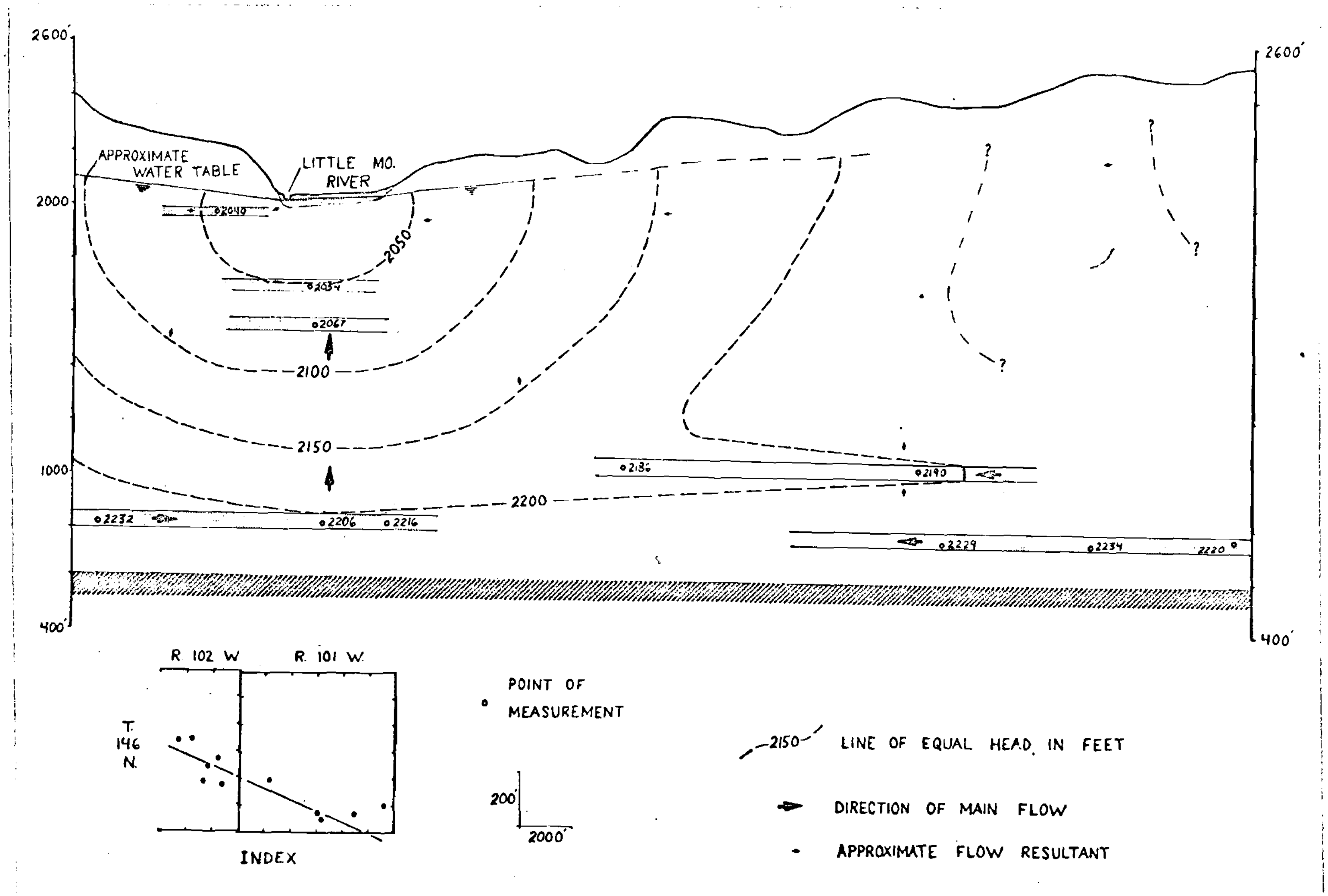

2800'
2800'
APPROXIMATE WATER TABLE
LITTLE MO. RIVER
2250
2000
2267
2267
2270
2268
2282
2255
2300
2304
2330
2350
2400
2455
2450
2361
2400
2430
1000
R.102 W.
R.101 W.
T 140 N
INDEX
200'
2000'
POINT OF MEASUREMENT
2350
LINE OF EQUAL HEAD IN FEET
DIRECTION OF MAIN FLOW
APPROXIMATE FLOW RESULTANT
0'
0'

Figure 17.--Pattern of groundwater flow in the Little Missouri valley, North Dakota. The diagonal pattern indicates the approximate top of the Pierre Shale.



2600'
2000
1000
400'
2600'
400'
APPROXIMATE WATER TABLE
LITTLE MO. RIVER
2040
2050
2034
2067
2100
2150
2200
2136
2190
2232
2206
2216
2229
2234
2220
?
R. 102 W
R. 101 W.
T. 146 N.
INDEX
POINT OF MEASUREMENT
200'
2000'
2150
LINE OF EQUAL HEAD IN FEET
DIRECTION OF MAIN FLOW
APPROXIMATE FLOW RESULTANT

distribution is focused around a groundwater sink that coincides with the trench of the Little Missouri River. The potential decreases upward, indicating that the valley is a discharge area. (2) The movement of groundwater is affected by the Little Missouri trench down to at least the top of the Pierre Shale. No evaluation of oil-well drill-stem tests below the Pierre Shale has been made; therefore, no conclusions can be reached as to the maximum depth effect of the trench. (3) The flow components of largest magnitude (lateral and vertical) are contained in the plane of the cross section. Typical values, in terms of the gradient of the three components in the discharge area, are given in table 1. The values indicate that the longitudinal component is at most about 1 percent of the vertical. (4) The groundwater flow

Table 1.--Values of gradient in the discharge area with respect to the flow components.

	Range of values (ft/ft)
Lateral Component	1×10^{-2} to 7×10^{-3}
Longitudinal Component	1×10^{-3} to 6×10^{-4}
Vertical Component	2×10^{-1} to 1×10^{-1}

lines are directed toward the river from opposite sides of the regional system. The flow lines converge in the discharge area, which is approximately the same width as the valley bottom.

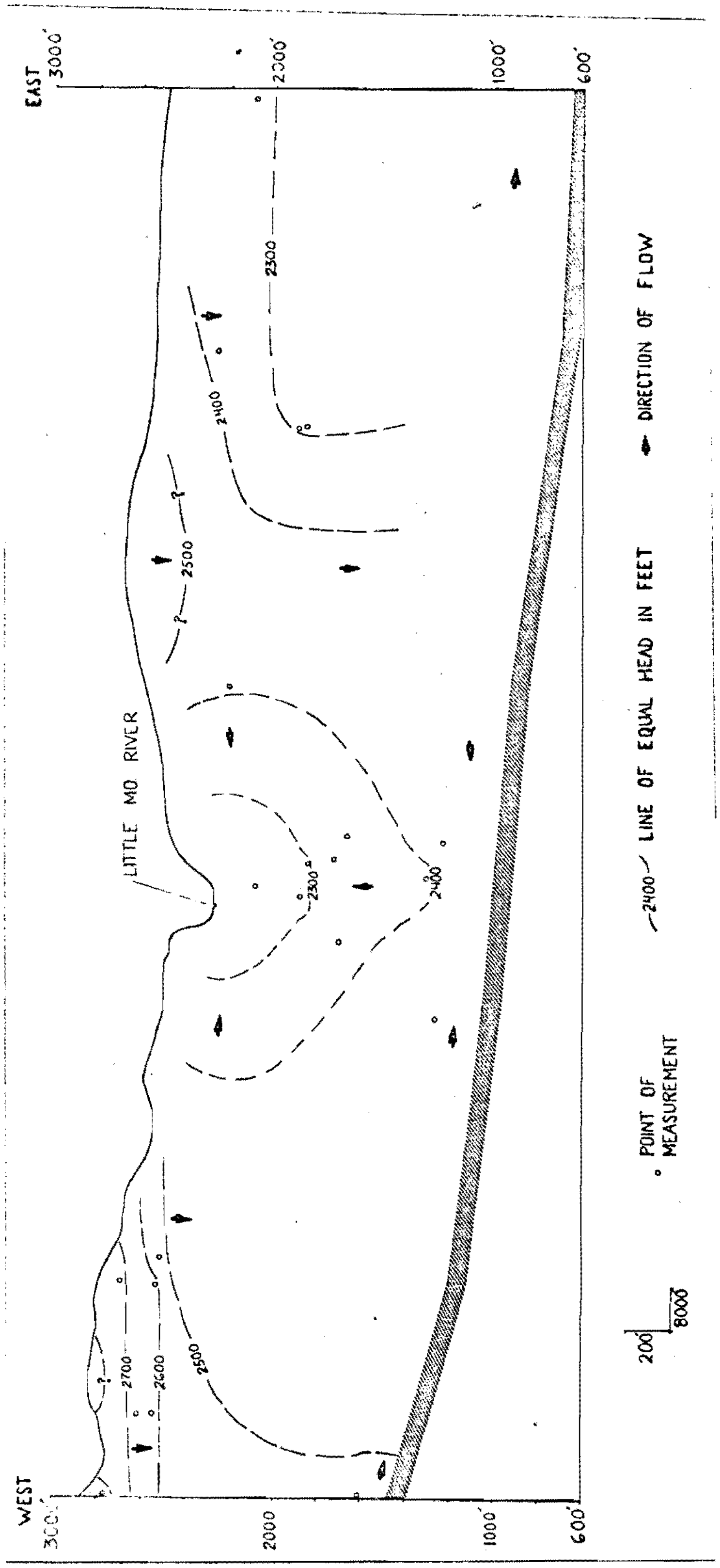
The regional flow pattern

The regional flow pattern is represented (fig. 18) by a section through the center of the study area. The groundwater divides are not symmetrical with respect to the river. The divide of the western half of the flow system is at least 22 miles from the valley, and the eastern divide about 12 miles from the valley. The groundwater divides correspond approximately to the surface-water divides. In the eastern half of the flow system the groundwater moves up the regional dip from the recharge to the discharge area.

The vertical components in the discharge area and the eastern recharge area are of similar magnitude, whereas the near-surface part of the western recharge area has a vertical recharge component, about twice the vertical discharge component. This difference can be explained by examining hydrogeologic differences in the flow field.

The western recharge area is 200 feet higher than the eastern recharge area, resulting in a larger potential in the western recharge area; that is, the values of total head are greater than in the eastern system. However, the potential distribution around the discharge area is nearly

Figure 18.--Pattern of regional groundwater flow. The cross section extends from T. 140 N., R. 106 W. to T. 139 N., R. 98 W. The diagonal pattern indicates the approximate top of the Pierre Shale.


EAST
3000'
2000'
1000'
600'
WEST
3000'
2000
1000'
600'
LITTLE MO RIVER
2300
2400
2500
2600
2700
?
200
8000
POINT OF MEASUREMENT
2400 LINE OF EQUAL HEAD IN FEET
DIRECTION OF FLOW

symmetrical, indicating that the greater potential of the western system has been dissipated in the recharge area. The closely spaced lines of equal head indicate (fig. 18) that the dissipation occurs in the vertical recharge component. Why is the energy dissipation restricted to the vertical component of the western recharge area? The flow path of this system is longer; why is the excess energy not used up over this greater distance?

An examination of oil and water well logs suggests that the overall permeability in the western recharge area is less than in both the discharge area and eastern recharge area. Sand units of significant thickness are absent down to depths of 1,000 feet below the surface in the western recharge area. If the amount of recharge per unit area can be assumed equivalent for both systems, then a direct application of Darcy's law requires that the system of lower permeability have a steeper gradient. Therefore, the larger values of total head and the steeper gradient in the western recharge area can be explained by its higher topographic position and it relative lower permeability.

<u>The total flow vector</u>.-Tóth (1963) suggested that the longitudinal component (along the trench) of groundwater flow would be of little significance compared with the lateral and vertical components in a vertical cross section constructed parallel to the dominant topographic slope (essentially normal to the trench). If this reasoning is

valid, a projection of the total flow vector on the plane of the cross section is a good approximation of the total flow vector. This assumes that the sediment can be considered homogeneous and isotropic; that is, the ratio of horizontal to vertical permeability is one ($K_h:K_v = 1.0$). In the Little Missouri River discharge area, the vertical gradient is at least 100-times larger than the longitudinal gradient. If the anisotropy were $K_h:K_v = 100$, the total flow vector would be oriented at about 45 degrees to the horizontal and the flow resultants in a vertical cross section would not be close approximations of the total flow vector. A value of anisotropy of 100 is not unlikely. Meyboom, van Everdingen, and Freeze (1966, p. 40) concluded that the discrepancy between the flow resultant and total flow vector can be measured by installation of triangularly nested piezometers; this was not possible in this study. It can only be assumed, at this point, that the total flow vector is significantly inclined downstream (relative to the slope of the river valley) in the discharge area. Further consideration of the total flow vector will be made in a discussion of the groundwater chemistry.

Groundwater Chemistry

Chemical analyses from more than 300 samples were evaluated during the study; over 50 percent of the samples are from deep groundwater sources.

Deep groundwater chemistry

The type and abundance of chemical constituents in the deep groundwater varies both laterally and vertically. The cations are dominated by sodium in the regional discharge area and below a depth of 200 to 300 feet in the recharge areas. The abundance of sodium in relation to total cations in the discharge area is shown in figure 19. The cations of all but four of the samples plotted are composed of 95 percent or more sodium. The figure contains data from samples ranging in depth from 100 to 1,500 feet below the valley floor. The anion portion of the water samples from the discharge area is of variable character. The chemical facies in the Little Missouri flow system are sulfate, sulfate-bicarbonate, bicarbonate-sulfate, bicarbonate, and bicarbonate-chloride.

Water from the Fox Hills Formation.-All samples from the Fox Hills Formation are represented by figure 20. The water is classified as sodium bicarbonate-sulfate in the southern part of the discharge area grading to sodium bicarbonate-chloride in the northern part. Only three samples from the recharge areas were evaluated; these are classified as sodium sulfate-bicarbonate water. The data points in figure 20 are connected by dashed lines because they probably represent a gradational change. However, the change occurs rather abruptly over a distance of about 8 miles (T. 144 N. to T. 145 N.). Unfortunately, no wells penetrate to the Fox Hills Formation in this

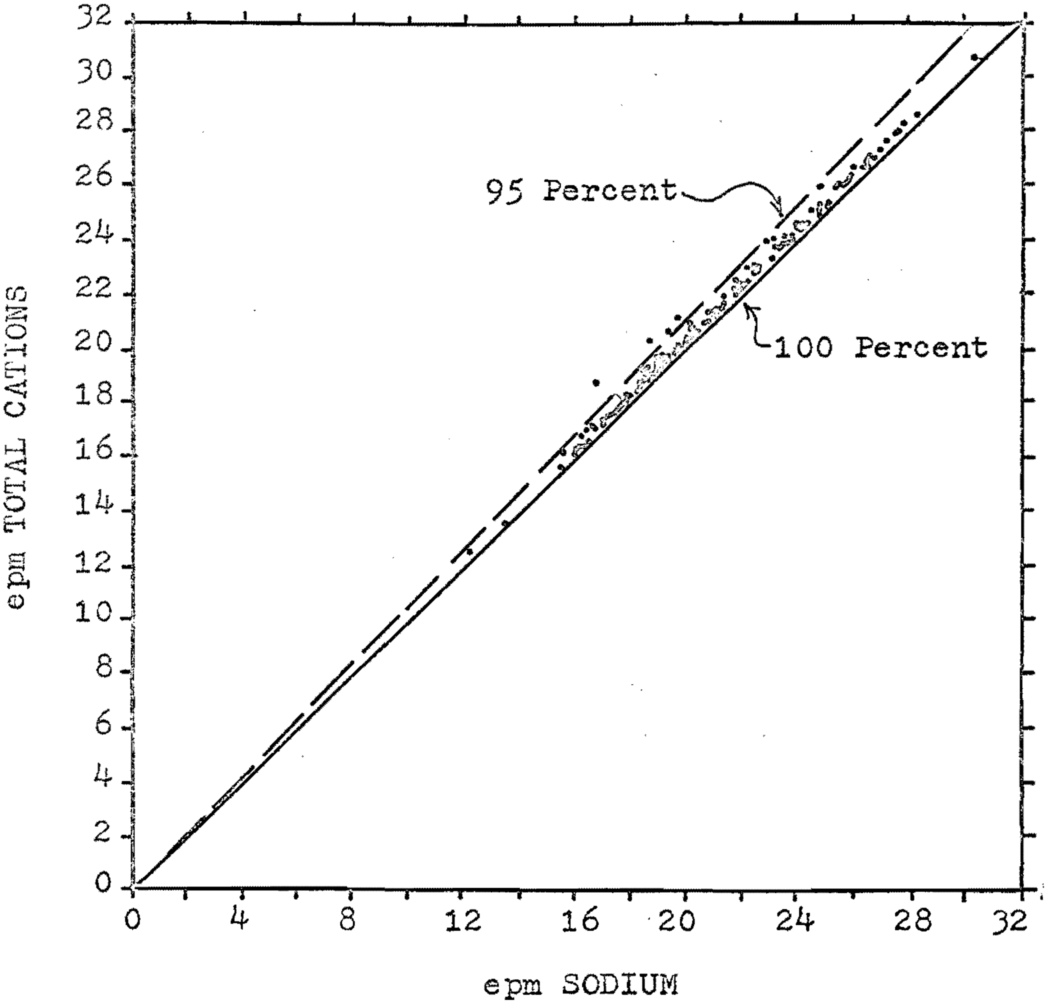


Figure 19.--Sodium in relation to total cations in water samples from the discharge area.

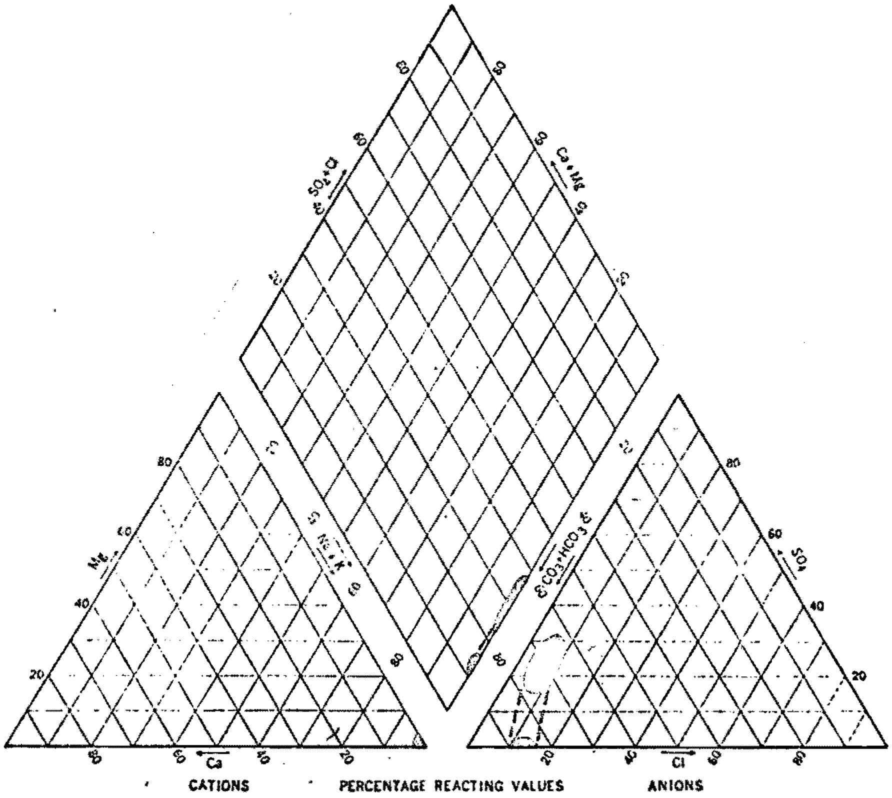


Figure 20.--Chemical analysis diagram of groundwater from the Fox Hills Formation. The darkened regions indicate the areas of sample plots.

interval.

The variation of sulfate with respect to bicarbonate is shown by figure 21. A trend toward a decrease in sulfate relative to bicarbonate from south to north is obvious. The spatial distribution of fluoride (fig. 22) and chloride (fig. 23) shows a rather constant increase from south to north. The concentration of total dissolved solids (in reactive equivalents per million, fig. 24) is relatively constant throughout the discharge area, with the exception of the northern-most and southern-most areas.

From the western recharge area (T. 140 N., R. 106 W.) to the discharge area there is a decrease in sulfate relative to bicarbonate, an increase in chloride, an increase in fluoride, and a decrease in total dissolved solids.

Several reasonable explanations of these chemical trends are possible. Chloride is very soluble relative to the other constituents and once in solution should remain in solution; therefore a trend toward an increase in chloride indicates long residency. Considering that the flow path is at least a few tens of miles long in the Fox Hills Formation and that flow rates generally decrease with depth (Tóth, 1968, p. 27), it is conceivable that some water in the Fox Hills Formation has been there for at least several thousand and possibly several tens of thousands of years. Apparently there is a very limited source of chloride in this system, because the values are much

Figure 21.--Map showing the variation of the sulfate-bicarbonate ratio in groundwater from the Fox Hills Formation.

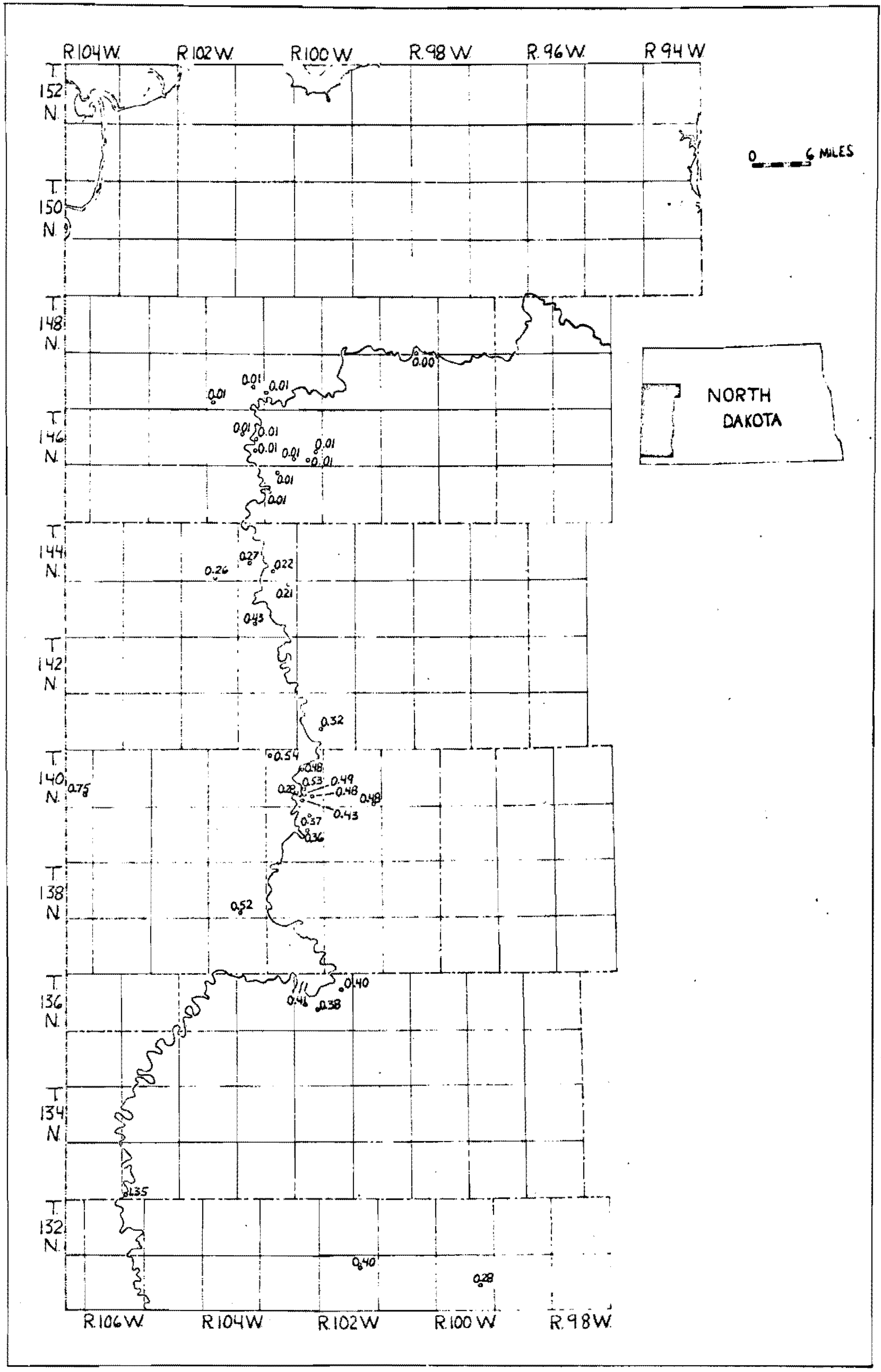

R104W.
R102W.
R100W
R.98W.
R.96W.
R94W
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
0 6 MILES
NORTH DAKOTA
0.00
0.01
0.01
0.01
0.01
0.01
0.01
0.01
0.01
0.01
0.01
0.01
0.26
0.27
0.22
0.21
0.43
0.32
0.54
0.48
0.53
0.49
0.28
0.48
0.48
0.43
0.37
0.36
0.75
0.52
0.40
0.41
0.38
0.35
0.40
0.28
R106W.
R104W
R102W
R100W
R.98W.

Figure 22.--Map showing the variation of fluoride in ppm in groundwater from the Fox Hills Formation.

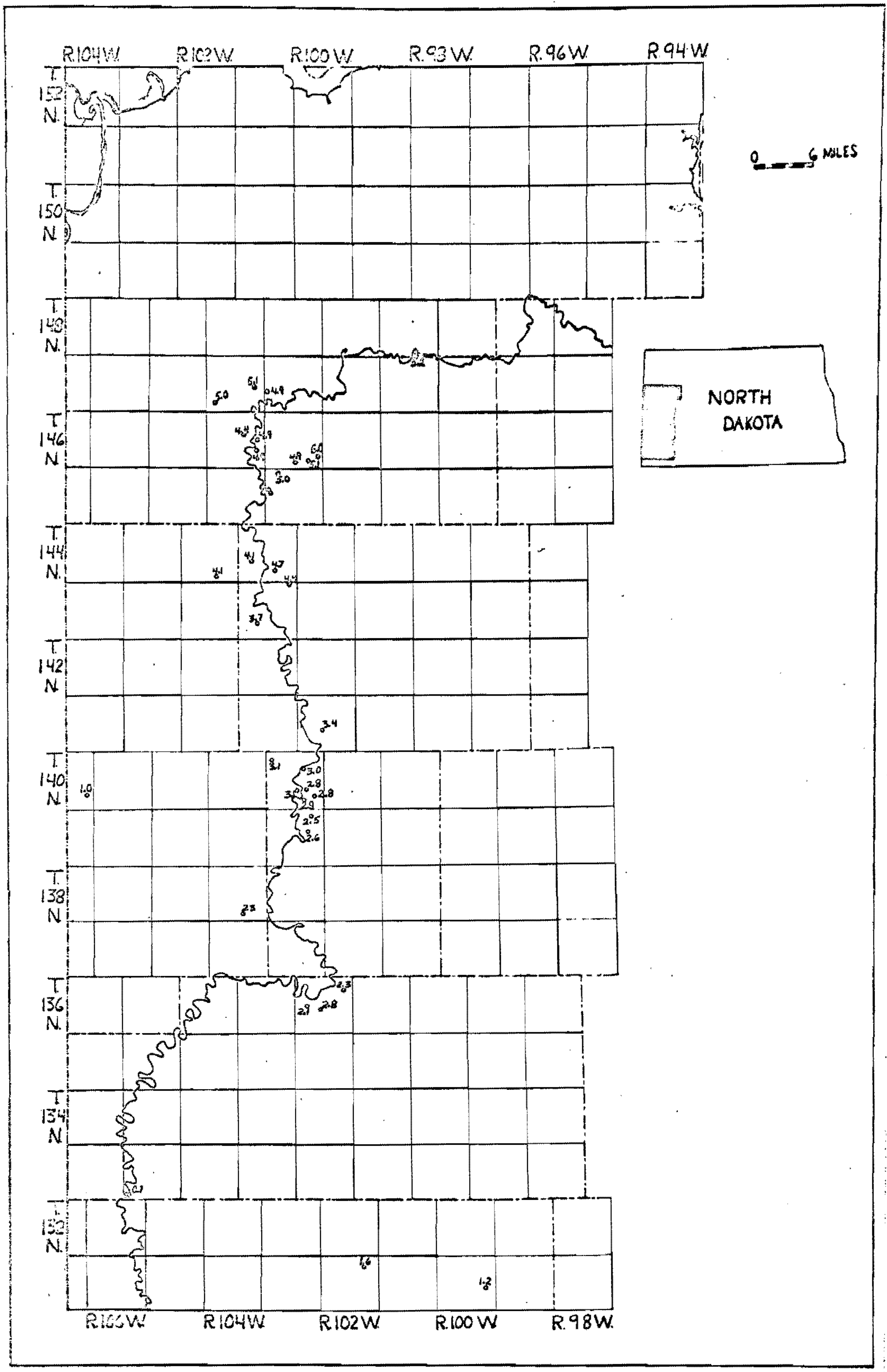

R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.
0 6 MILES
NORTH DAKOTA
5.0
5.1
4.9
4.4
4.9
4.9
6.0
5.0
4.1
4.1
4.7
4.4
3.7
3.4
3.1
3.0
2.8
2.8
2.9
2.5
2.6
2.3
2.3
2.9
2.8
1.0
1.6
1.2

Figure 23.--Map showing the variation of chloride in ppm in groundwater from the Fox Hills Formation.

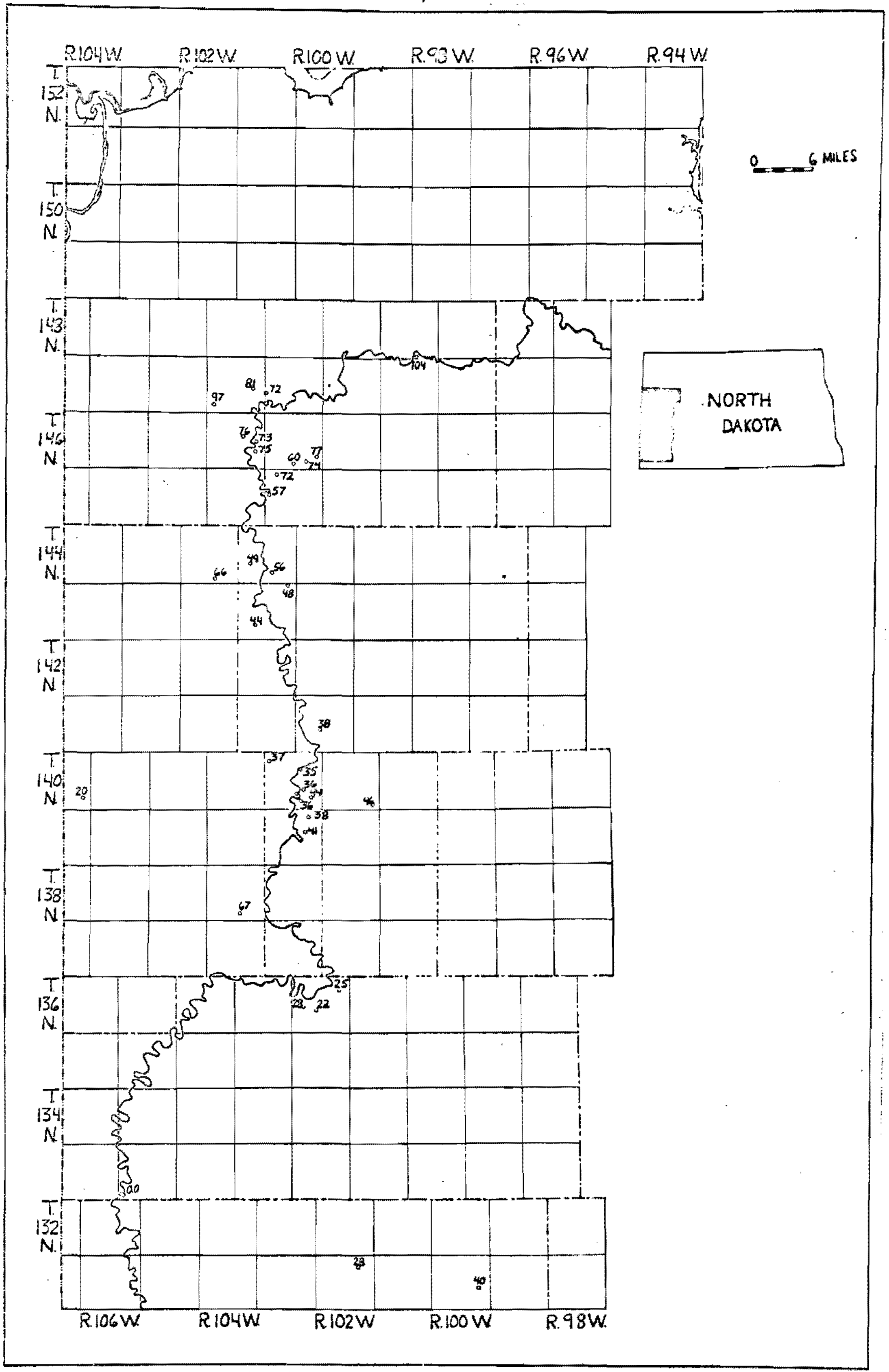
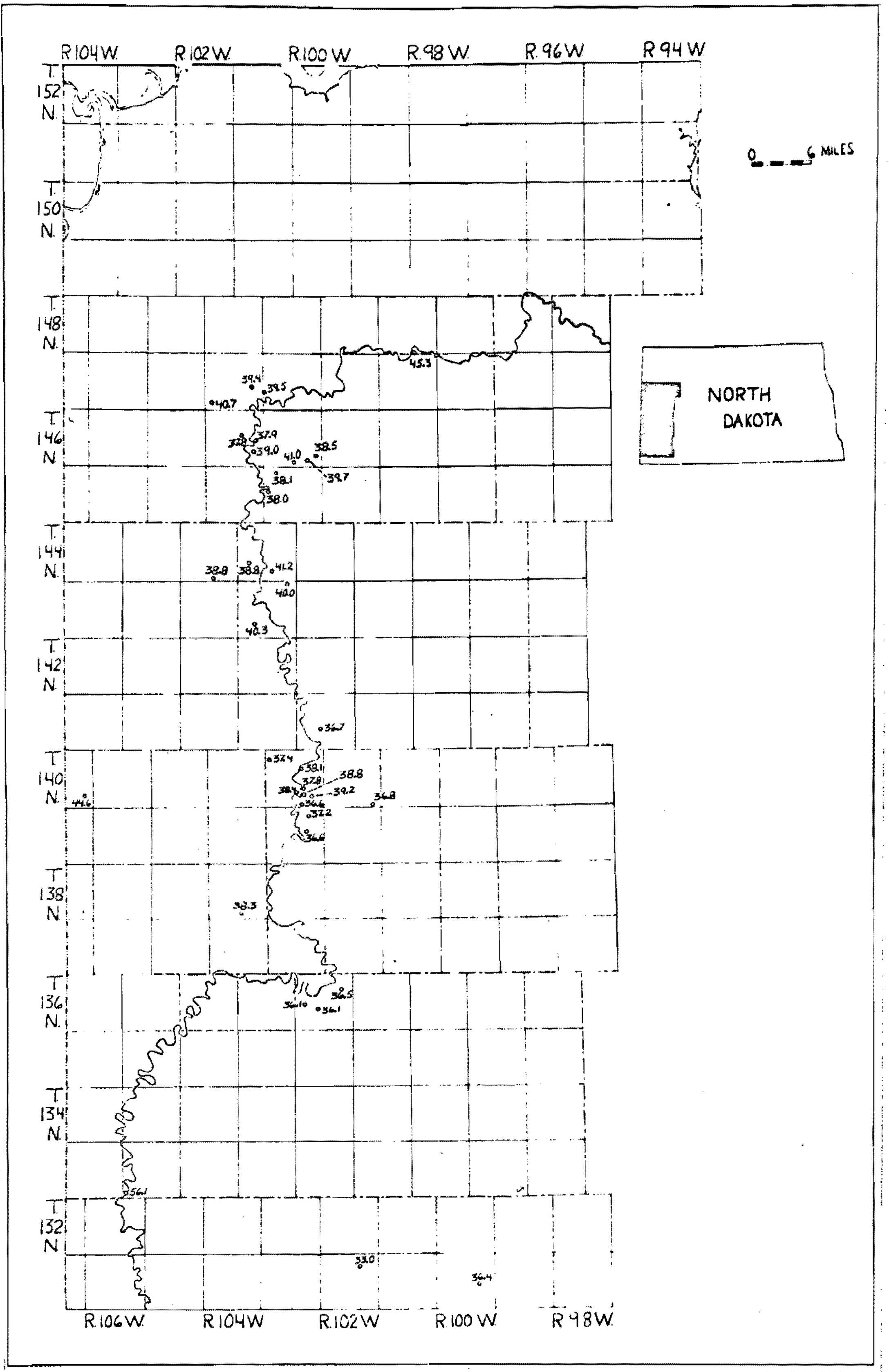

R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
0 6 MILES
NORTH DAKOTA
104
97
81
72
76
73
75
60
77
74
72
57
66
59
56
48
44
38
37
35
20
36
44
46
36
38
41
67
25
28
22
100
28
40
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.

Figure 24.--Map showing the variation of total dissolved solids in epm in groundwater from the Fox Hills Formation.


R104W.
R102W.
R100W
R.98W.
R.96W
R94W
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
0 6 MILES
NORTH DAKOTA
45.3
39.4
39.5
40.7
37.9
37.8
39.0
41.0
38.5
39.7
38.1
38.0
38.8
38.8
41.2
40.0
40.3
36.7
37.4
38.1
38.8
37.8
38.4
39.2
36.8
36.6
37.2
36.6
44.6
38.3
36.5
36.10
36.1
36.1
33.0
36.4
R.106W.
R104W
R.102W
R100W.
R98W.

lower than might be expected. Nevertheless, there is an increase northward in the discharge area. This may indicate the presence of a significant longitudinal component (northward) of the total flow vector, or it may indicate that the west to east flow length (normal to the valley axis) is greater to the north. Possibly more chloride is available in the northern end of the study area (fossil water?) and the increase is not reflecting flow-path length. Fluoride is similar to chloride in its chemical behavior (though much less abundant) and explanations of fluoride variation analogous to those for chloride variation appear plausible.

Total dissolved solids remain relatively constant or show only a slight increase northward. Assuming that similar lithologies occur throughout the study area, the nearly constant concentration of dissolved solids indicates that flow-path lengths are nearly equal; this tends to negate the existence of a significant longitudinal flow vector. The removal of sulfate from the system does not appear related to length of flow-path. A discussion of its disappearance is included in a following section.

Water from the Hell Creek Formation.-All samples from the Hell Creek Formation are represented by figure 25. The water can be classified as sodium bicarbonate-sulfate grading to sodium bicarbonate. The variation of sulfate with respect to bicarbonate (fig. 26) shows a decrease in sulfate northward. Chloride (fig. 27) increases south to

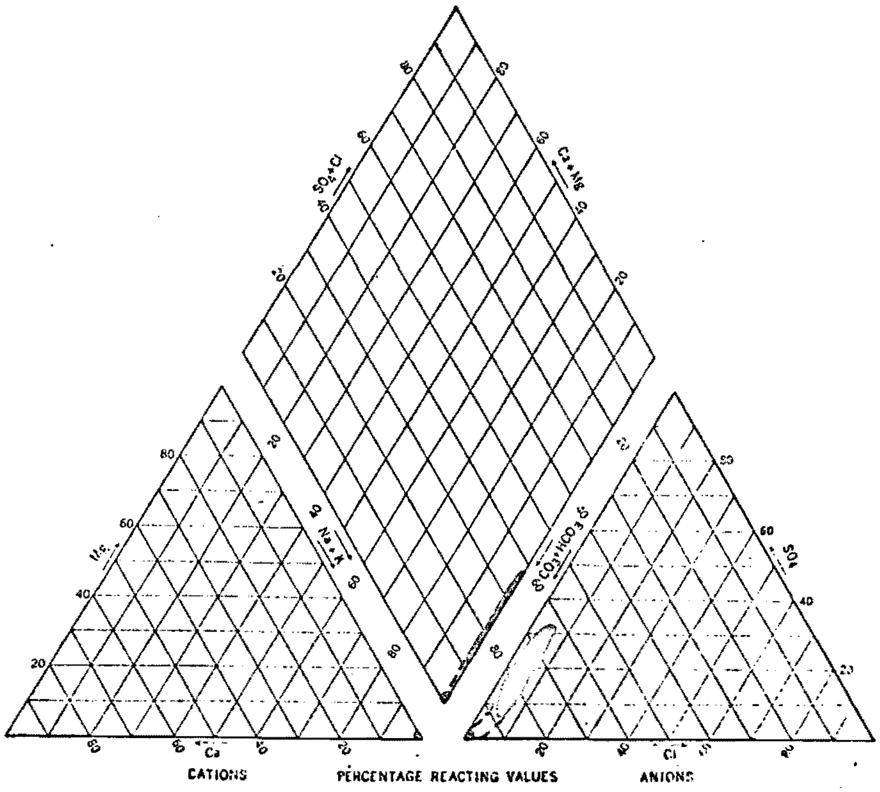


Figure 25.--Chemical analysis diagram of groundwater from the Hell Creek Formation. The darkened regions indicate the areas of sample plots.

Figure 26.--Map showing the variation of the sulfate-bicarbonate ratio in groundwater from the Hell Creek Formation.

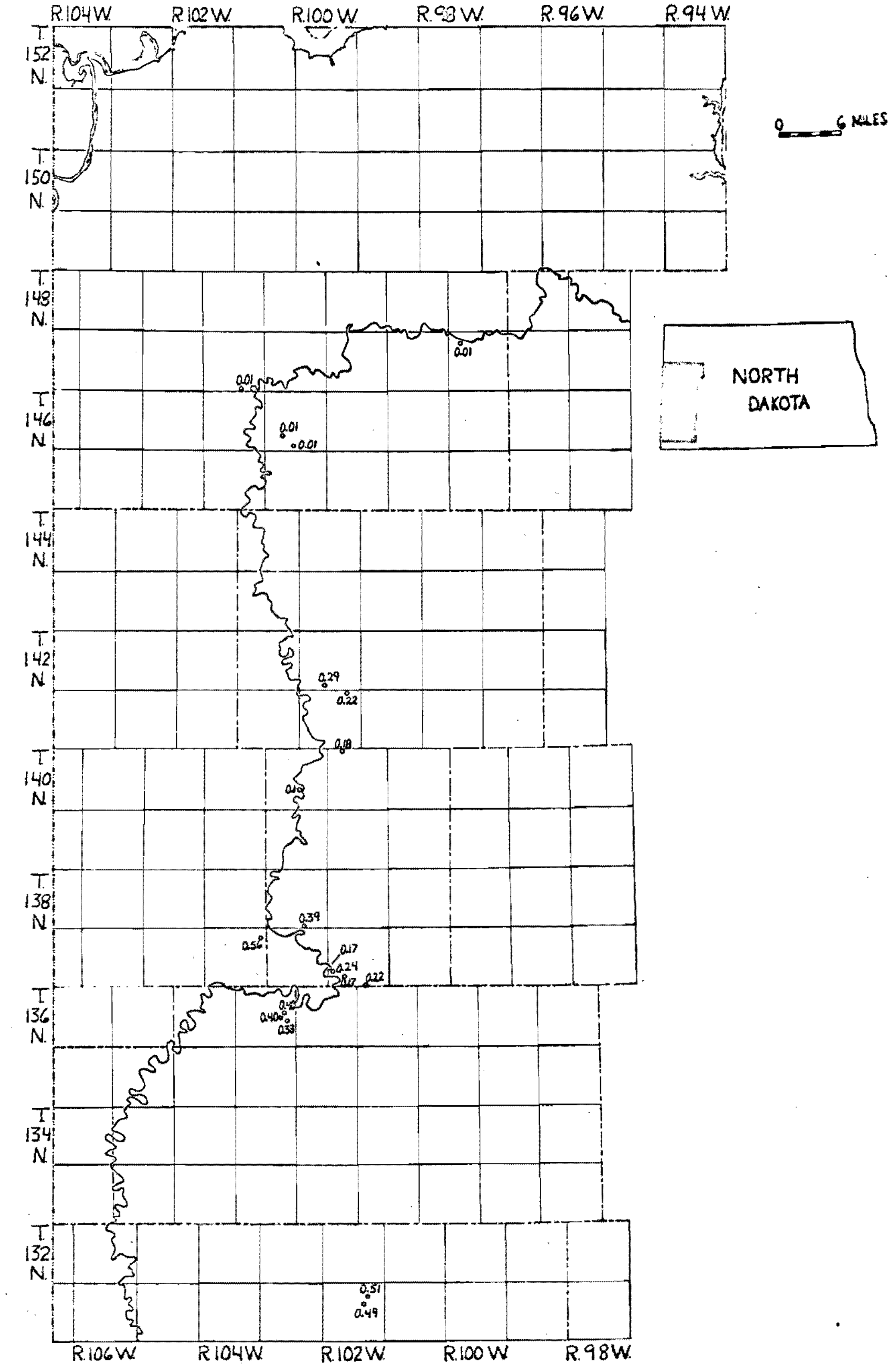
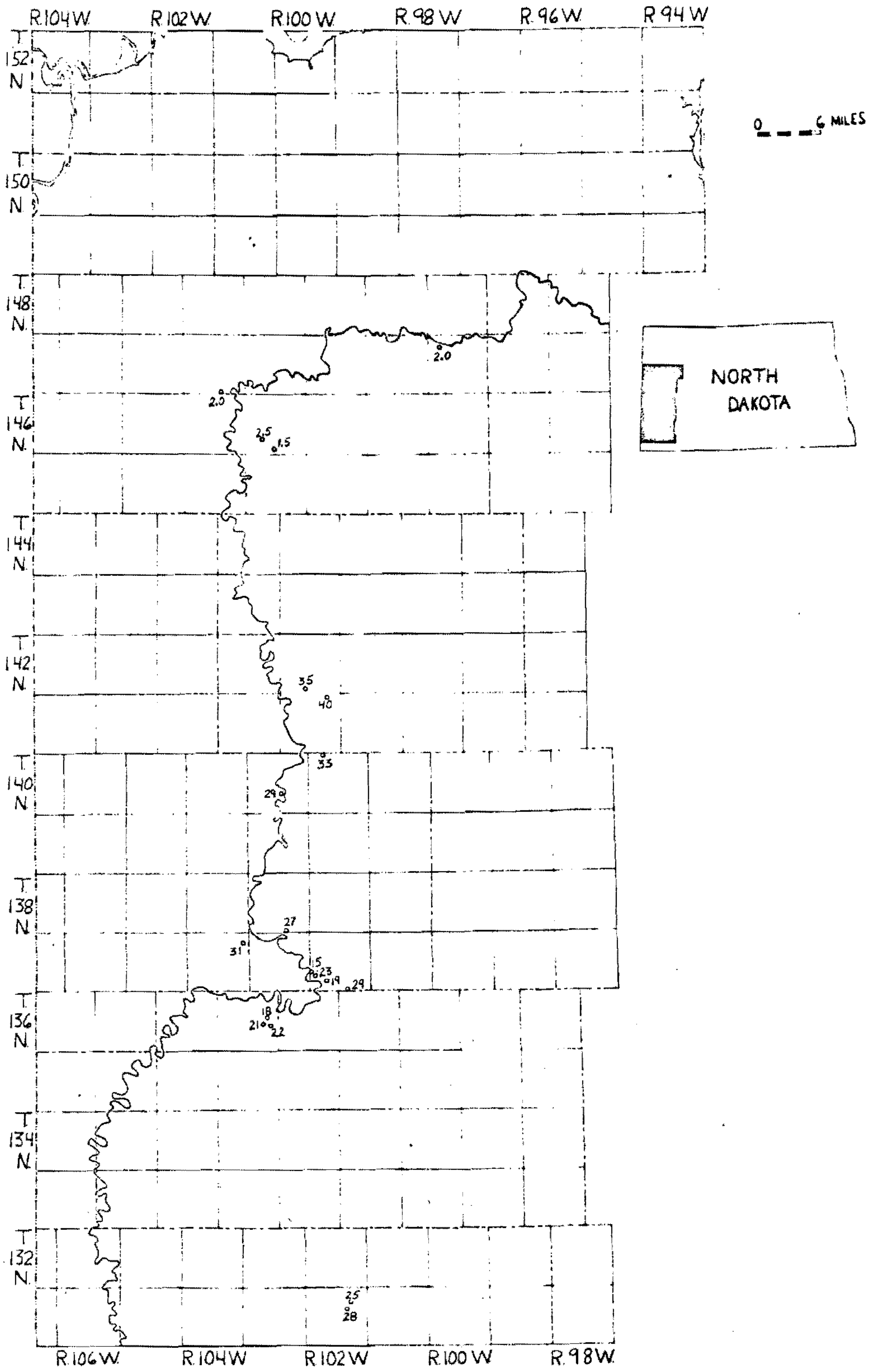

R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
0 6 MILES
NORTH DAKOTA
0.01
0.01
0.01
0.01
0.29
0.22
0.18
0.39
0.56
0.17
0.24
0.17
0.22
0.42
0.40
0.33
0.51
0.49
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.

Figure 27.--Map showing the variation of chloride in ppm in groundwater from the Hell Creek Formation.


R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T 152 N.
T 150 N.
T 148 N.
T 146 N.
T 144 N.
T 142 N.
T 140 N.
T 138 N.
T 136 N.
T 134 N.
T 132 N.
0 6 MILES
NORTH DAKOTA
2.0
2.5
2.5
1.5
3.5
4.0
3.3
2.9
2.7
3.1
1.5
2.3
1.9
2.9
1.8
2.1
2.2
2.5
2.8
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.

north, then falls off to a low constant value in the north. The distribution of total dissolved solids (fig. 28) shows a northward increase.

The near disappearance of chloride can be accounted for in two ways: (1) a lithologic change northward with little or no chloride available for solution, or, (2) flushing of the system by either very rapid turnover of water or "fossil" flushing resulting from Pleistocene glaciation in the area of the northern Little Missouri River and to the east of the study area (Clayton, 1969). However, the minimum amount of time since glaciation is about 10,000 years and assuming flow path lengths on the order of 20 miles, the rate of groundwater movement would have to be less than 10 feet per year to retain any Pleistocene water. A groundwater flow rate of 10 feet or less per year is not inconceivable; however, it is improbable that an adjustment toward chemical equilibrium could not be attained in a period of 10,000 years, unless glacial flushing was so intense that it removed all soluble chlorides from the system. Flushing from below would not explain the disappearance of chloride, but (3) a decrease in upward seepage from the Fox Hills Formation, which contains abundant chloride in this area, could account for the chloride reduction in the Hell Creek.

The general northward increase in total dissolved solids appears contrary to the chloride distribution; the generally accepted view is that both chloride and total

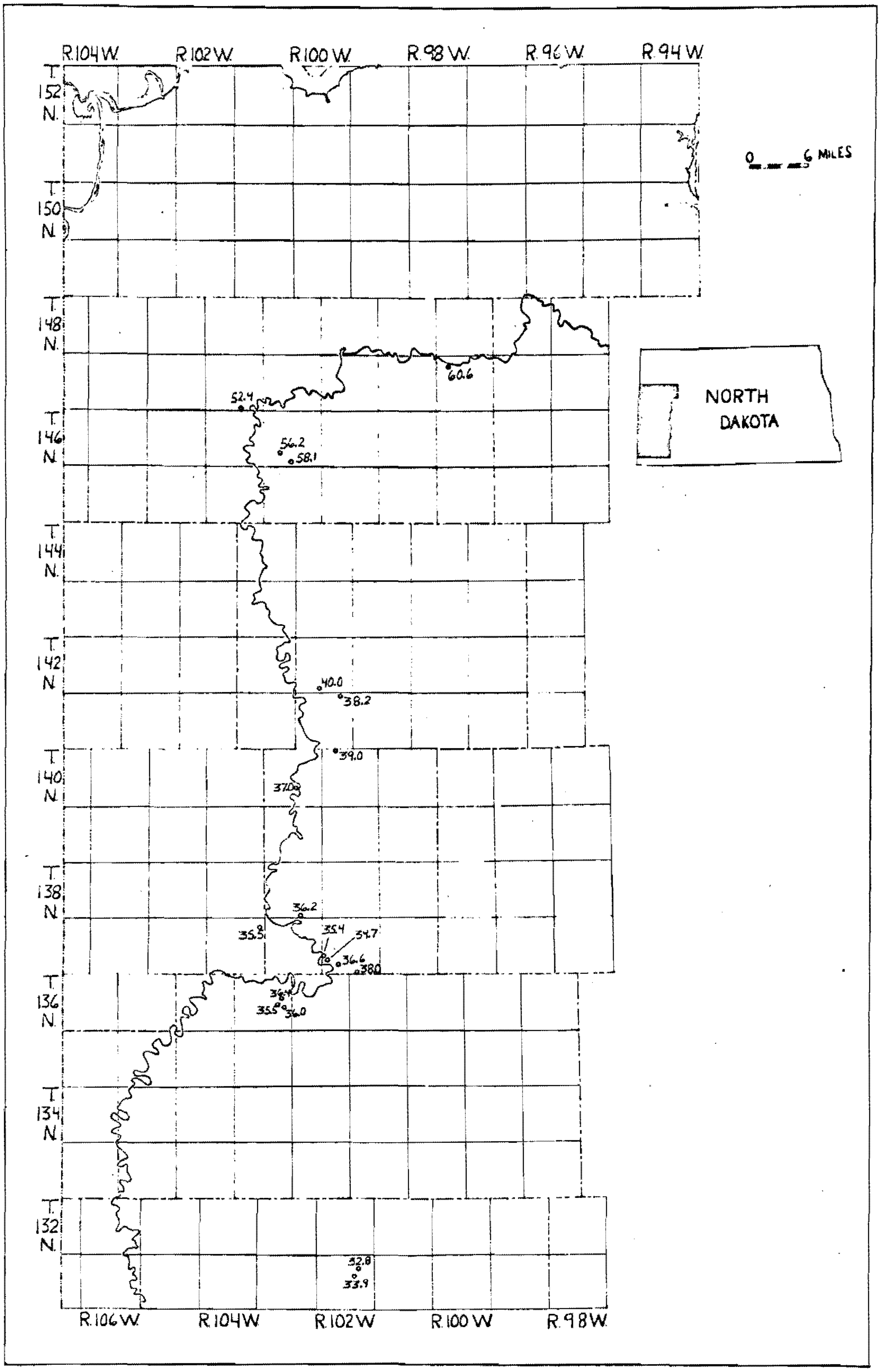
Figure 28.--Map showing the variation of the total dissolved solids in epm in groundwater from the Hell Creek Formation.

dissolved solids increase with a long flow path. A possible chemical mechanism accounting for an increase in total dissolved solids but not related to flow-path length is included in the following section.

Water from the Cannonball Formation.-A plot of chemical constituents (fig. 29) in water from the Cannonball Formation indicates that the only chemical facies occurring at this stratigraphic position is a sodium bicarbonate type. Sulfate and chloride are essentially absent throughout the area. Total dissolved solids (fig. 30) in general increase south to north; both sodium and bicarbonate increase northward.

Why should water at this position in the flow system be so consistently devoid of sulfate? Either sulfate is not available in the unit or it is being removed as rapidly as it is introduced. It is not likely that sulfate is not available because the Cannonball is overlain and underlain by sediments containing sulfate water (at least in the southern part of the study area), and as a result of the groundwater flow (as potential distributions indicate) there must be interchange at various places in the system. Therefore, it seems probable that sulfate is being introduced into the formation and is being removed by some process.

An explanation for the removal of sulfate involves the reduction of sulfate to sulfide. This process was concluded by Cederstrom (1946) to be the mechanism generating


R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
0 6 MILES
NORTH DAKOTA
60.6
52.4
56.2
58.1
40.0
38.2
39.0
37.0
36.2
35.5
35.4
34.7
36.6
38.0
36.4
35.5
36.0
32.8
33.9
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.

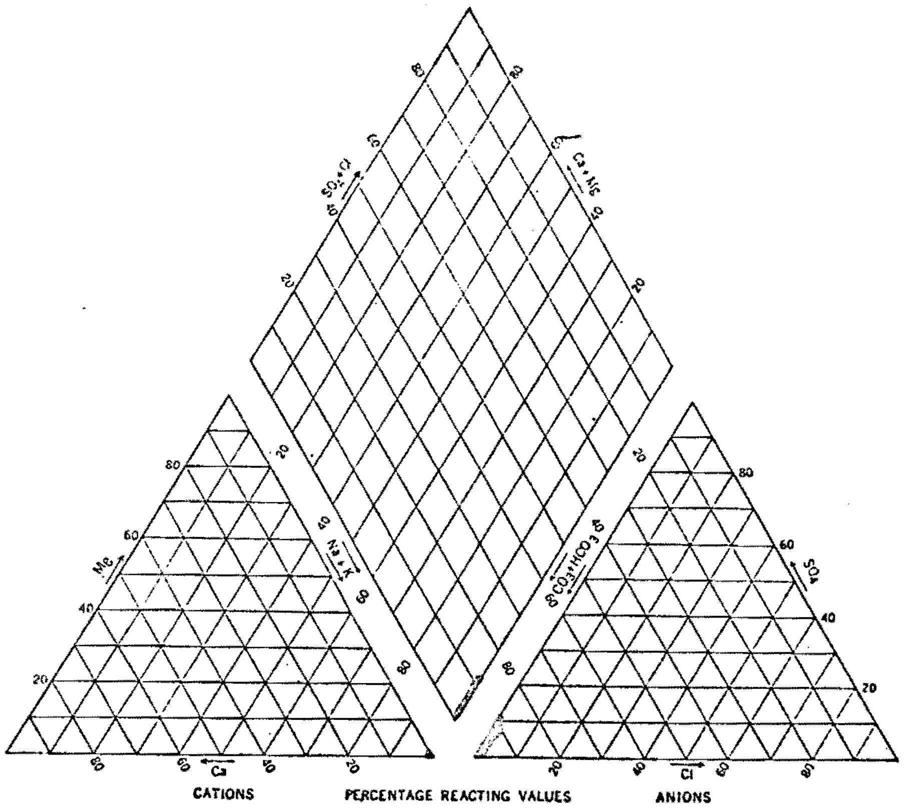
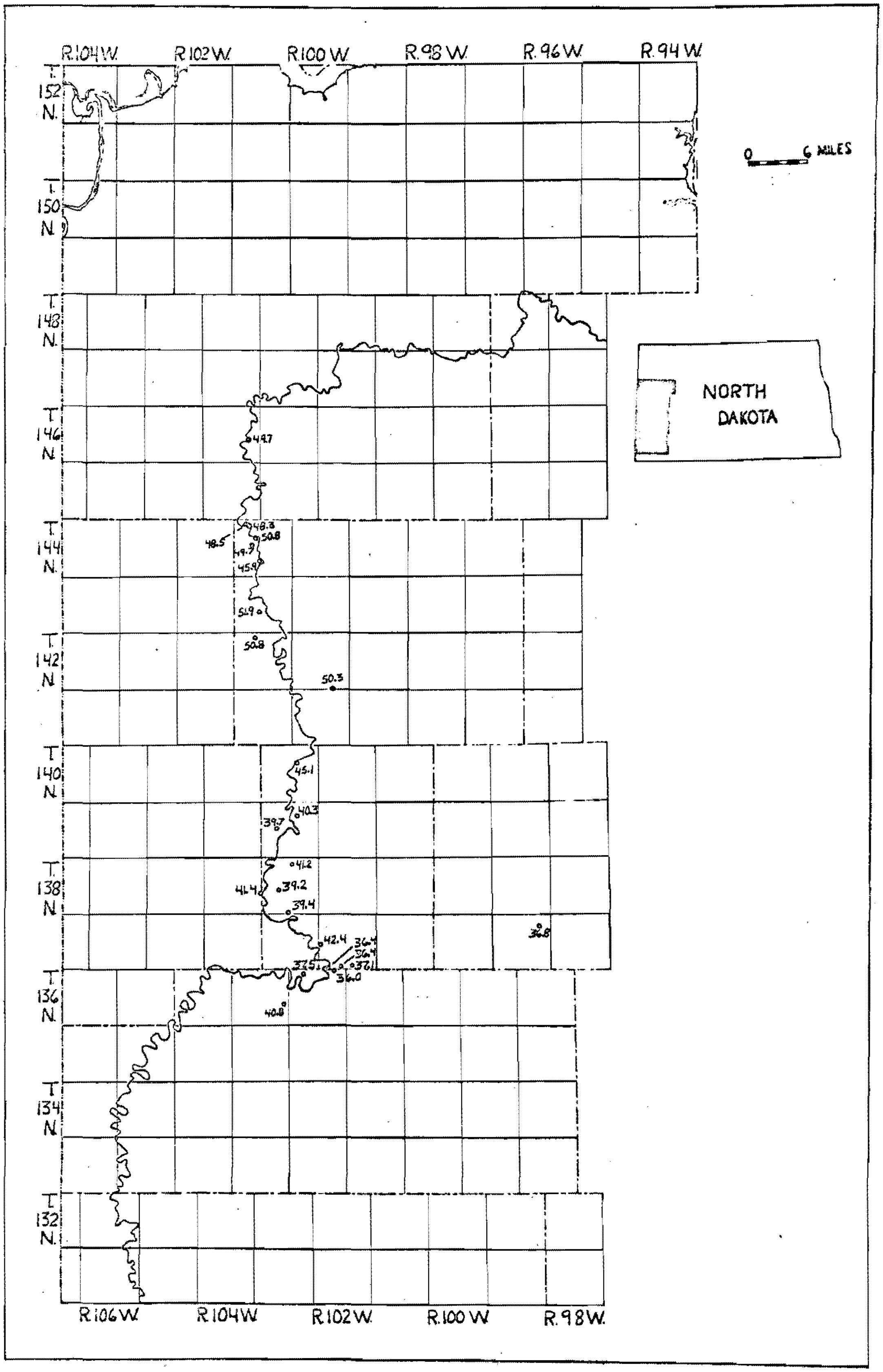


Figure 29.--Chemical analysis diagram of groundwater from the Cannonball Formation. The darkened regions indicate the areas of sample plots.

Figure 30.--Map showing the variation of total dissolved solids in epm in groundwater from the Cannonball Formation.


R.104W.
R.102W.
R.100W.
R.98W.
R.96W.
R.94W.
T. 152 N.
T. 150 N.
T. 148 N.
T. 146 N.
T. 144 N.
T. 142 N.
T. 140 N.
T. 138 N.
T. 136 N.
T. 134 N.
T. 132 N.
0 6 MILES
NORTH DAKOTA
49.7
48.3
50.8
48.5
49.9
45.9
51.9
50.8
50.3
45.1
40.3
39.7
41.2
41.4
39.2
39.4
42.4
36.4
36.4
37.5
37.1
36.0
40.8
36.8
R.106W.
R.104W.
R.102W.
R.100W.
R.98W.

carbon dioxide and resulting in increased bicarbonate in groundwater in Virginia. Feely and Kulp (1957) employed reactions resulting from sulfate reduction to explain salt-dome sulfur deposits.

The reduction of sulfate occurs when it comes in contact with organic matter. Using the simplest organic compound, methane (CH_4), Krauskopf (1967, p. 276) presents the reduction reaction

$$2H^+ + SO_4^{--} + CH_4 \longrightarrow H_2S + CO_2 + 2H_2O \qquad \Delta F^o = -24.8 \text{ kcal} \quad (7)$$

in which sulfur is reduced from a +6 to a -2 valance state. This kind of a reaction has been demonstrated in the laboratory only with more complex organic compounds, never with methane; therefore, the reaction is only symbolic. Reduction in the presence of organic matter proceeds too slowly to be significant unless a catalyst in the form of anaerobic bacteria is present (Krauskopf, 1967); this group of sulfate-reducing bacteria are classified under a single genus, Desulfovibrio (Feely and Kulp, 1957, p. 1809). There is evidence for the existence of free organic matter in water from the Cannonball Formation. A flowing well (sec. 2, T. 141 N., R. 101 W.) was observed to be periodically emitting minute globules of material which rose to the surface of a stock tank and produced an iridescent sheen. The frequency of emission was about 10 seconds over a period of observation of several minutes. Iridescent surfaces on other stock tanks had earlier been noticed but were at the time considered to be a result of contamination. Apparently some immiscible liquid is present in the formation; an organic compound seems probable. One necessary ingredient for sulfate reduction is apparently readily available in the Cannonball Formation.

Feely and Kulp (1957, p. 1810) cite evidence indicating that anaerobic bacteria are known to occur at depths exceeding 1,500 feet. They also indicate that the optimum bacterial growth is between the pH values of 6.3 and 8.6 (p. 1809); the pH values of Cannonball water are contained within this range.

The products of sulfate reduction indicated by equation 7 are hydrogen sulfide (H_2S), carbon dioxide (CO_2) and water. Carbon dioxide and water can be considered to be respiration products of the bacteria, and the energy loss (24.8 kcal) is the amount utilized by the bacteria in the conversion process. The reduction of sulfate is but a first step in altering the groundwater chemistry as a consequence of the products of the reaction (H_2S and CO_2). Hydrogen sulfide is a weak acid and can dissociate:

$$H_2S \rightleftharpoons H^+ + HS^-. \qquad (8)$$

If ionization is incomplete some H_2S can remain in solution as a dissolved gas. An odor H_2S was noticed at some wells bottomed in the Cannonball. The second product of equation 7, CO_2, combines with water to form carbonic acid (H_2CO_3), which can ionize to form hydrogen ions (H^+) and bicarbonate (HCO_3^-):

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-. \qquad (9)$$

The increase in hydrogen ions as indicated by equations 8 and 9 can result in the solution of $CaCO_3$ to form Ca^{++} and HCO_3^-:

$$CaCO_3 + H^+ \rightleftharpoons Ca^{++} + HCO_3^-. \qquad (10)$$

The direct effect of sulfate reduction is an increase in HCO_3^- (high values are characteristic of the Cannonball Formation) and Ca^{++}. However, it was noted earlier that Ca^{++} is essentially nonexistent in the groundwater (with the exception of the upper 200 to 300 feet of sediment in the recharge areas). The removal of Ca^{++} could be the result of cation exchange in clay minerals and zeolites. A general example of the process involved for zeolites is:

$$\text{Na-Zeolite} + Ca^{++} \rightleftharpoons \text{Ca-Zeolite} + Na^+. \qquad (11)$$

This reaction would increase the Na^+ concentration.

The net result of reactions 7 through 11 is a decrease in SO_4^{--}, an increase in HCO_3^- and Na^+, and as a consequence an increase in the total dissolved solids. These results are characteristic of water samples from the Cannonball Formation, and the qualitative reaction scheme presented is believed to be a reasonable explanation of observed chemical changes. These types of reactions might also account for chemical changes occurring in water from other units in the northern end of the study area.

Water samples from the Ludlow and Tongue River Formations.-The Ludlow and Tongue River Formations are the highest stratigraphic units sampled. Water from the Ludlow is represented graphically by figure 31, and can be classified as sodium bicarbonate-sulfate grading to sodium bicarbonate (south to north). The Tongue River Formation contains the shortest and shallowest flow paths of the wells sampled. Groundwater motion in the Tongue River Formation is more affected by local topography than any of the deeper units. These conditions are reflected by the variability of its water chemistry, which is represented by figure 32. Chemical facies range from sodium sulfate-bicarbonate to sodium bicarbonate. As with previously discussed units, low values of sulfate occur in the northern part of the discharge area. Some of the highest values of total dissolved solids were obtained from sulfate-rich samples of Tongue River water, indicating that abundant soluble sulfides and sulfates are present in the sediment of the recharge areas.

Samples from springs.-A few samples from springs located along the toe of the valley wall of the Little Missouri River were analyzed. The springs were associated with lignites and the groundwater flow path was relatively short, on the order of a few hundred feet. The samples

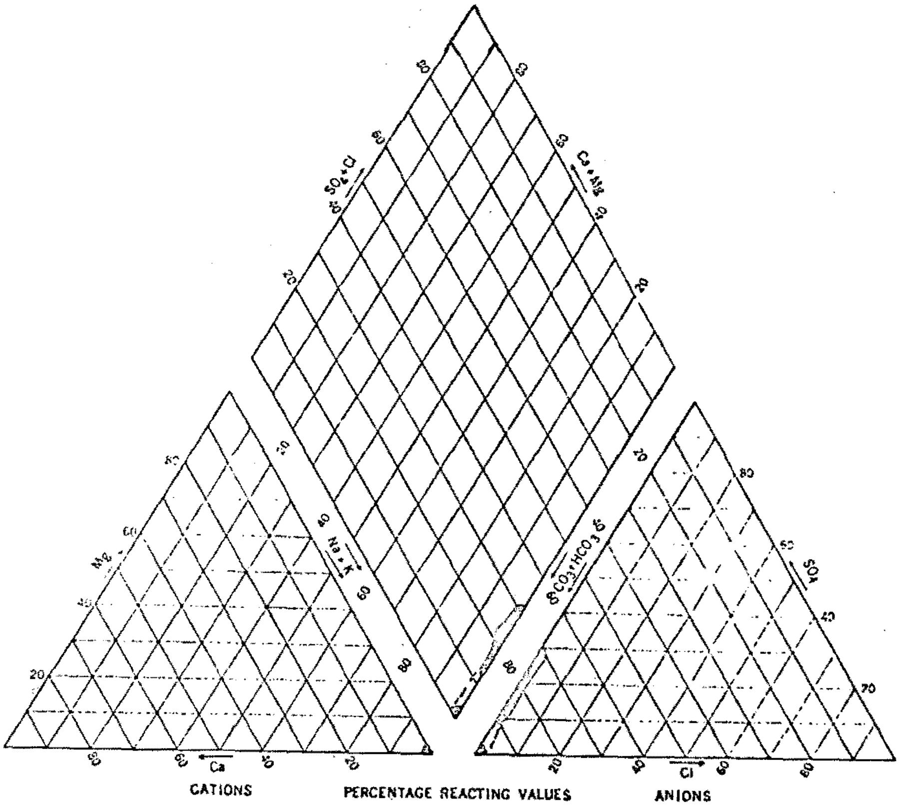


Figure 31.--Chemical analysis diagram of groundwater from the Ludlow Formation. The darkened regions indicate the areas of sample plots.

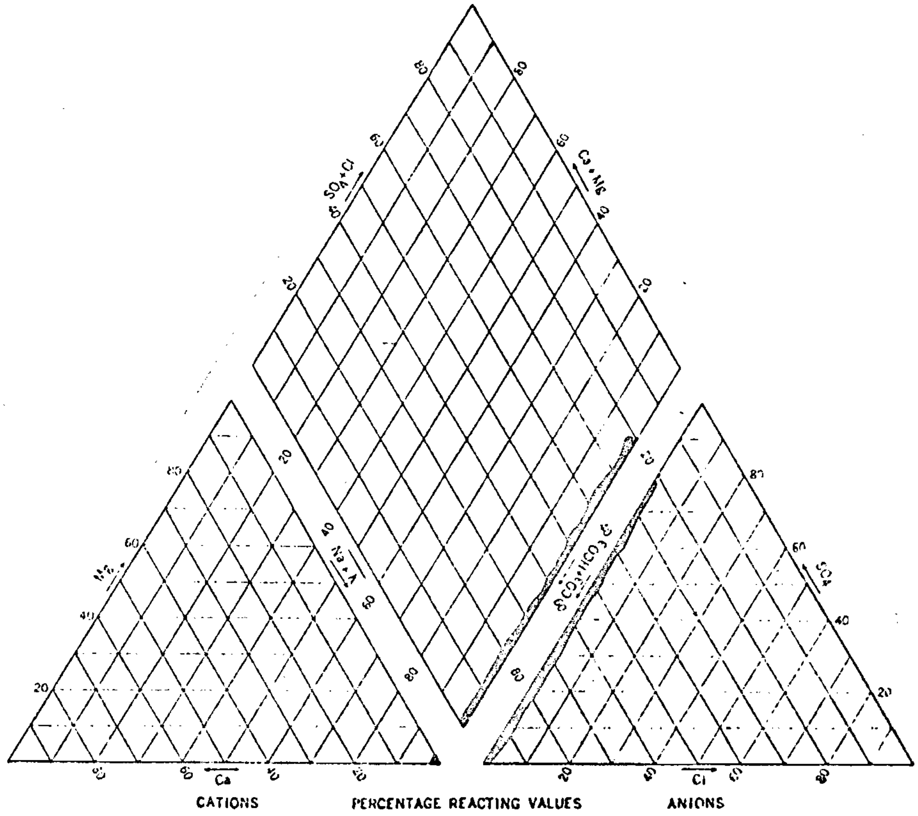


Figure 32.--Chemical analysis diagram of groundwater from the Tongue River Formation. The darkened regions indicate the areas of sample plots.

were composed of predominately sodium sulfate water (fig. 33); however one sample contained 30 percent (of total cations) calcium and magnesium. Spring locations along the valley wall were marked by accumulations of white sodium-sulfate salts. Spring water has a chemical character similar to samples from shallow wells in the discharge area with the exception that the spring water contains more calcium and magnesium. The largest values for total dissolved solids (upwards of 300 total equivalents per million) were from spring samples.

Calcium-magnesium facies.-Calcium and magnesium concentrations in groundwater are apparently inversely related to flow-path length. Therefore calcium and magnesium decrease with depth in the recharge areas.

Copies of water-analysis worksheets were obtained from the North Dakota State Department of Health and values of total hardness (calcium and magnesium as $CaCO_3$ in ppm) of 169 samples from all parts of the study area were used to evaluate the decrease of calcium and magnesium with depth. The majority of these samples were from private wells. The samples were collected by the owners in most cases. The only analyses evaluated were those with reported depths and locations. Samples from the Little Missouri valley were excluded from the evaluation. The results (table 2) indicate that the amount of calcium and magnesium does decrease with depth and that a rather abrupt change occurs between 200 to 300 feet. Below 300 feet the

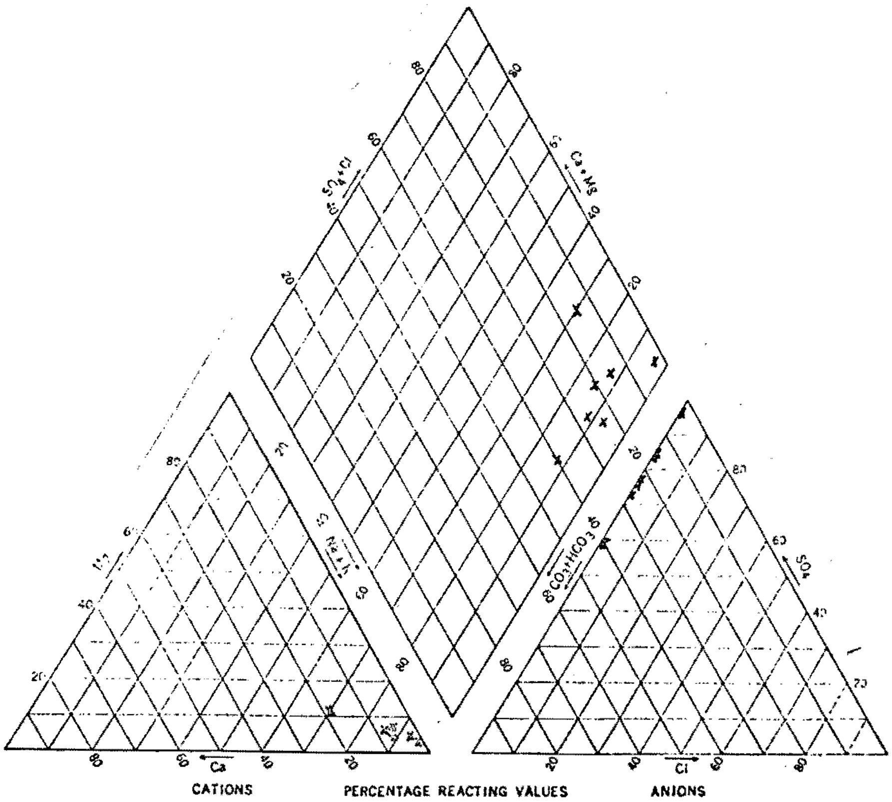


Figure 33.--Chemical analysis diagram of water from springs.

Table 2.--Variation in ppm total hardness (Ca^{++} and Mg^{++} as $CaCO_3$) with depth of 169 water samples from the recharge areas.

Depth (ft)	0-50	51-100	101-150	151-200	201-250	251-300	301-400	350-1250
Percent of total sample	22.5	24.3	15.4	10.0	4.5	3.0	5.3	15.0
High Value	3230	2310	988	1012	840	200	40	50
Low Value	9	6	5	10	14	25	10	1
Mean	793	578	301	235	210	64	19	15
Standard Deviation	718	468	285	228	308	68	9.9	10

values are equivalent to those in the discharge area. An analogous situation was observed by Renick (1924) in Montana. He attributed the decrease in calcium and magnesium and increase in sodium to cation exchange by silicate minerals.

Minerals occurring in the sediment of the flow system that are capable of cation exchange are clay minerals (in intergranular spaces and in bentonite beds) and probably zeolites. A general equation for cation exchange for zeolites (equation 11) indicates equilibrium between Na^+ and Ca^{++} members. Sodium is readily given up in exchange for Ca^{++}, even for very dilute Ca^{++} solutions. However, the reverse reaction (Ca-Zeolite exchanging Ca^{++} for Na^+) occurs only when the concentration ratio $(Na^+)/(Ca^{++})$ is much greater than 1 (Krauskopf, 1967, p. 162).

Why must the groundwater move through at least 200 feet of sediment, on the average, before exchange equilibrium is established? Some of the most important variations to be considered are (1) the distribution of cation-exchange minerals in the sediment, (2) the rate of cation exchange, (3) the length of time that the water has been in contact with the sediment (the rate of downward movement), and (4) possible additions with depth of Ca^{++} and Mg^{++} to the water in this zone.

(1) The distribution in the sediment of minerals with high cation exchange capacity is unknown. Renick (1924, p. 70) indicates that zeolites and clays with high exchange

capacity do occur vertically throughout an equivalent section in east-central Montana, but can be locally more abundant. This is probably the case in western North Dakota. (2) The time required for cation exchange in clay minerals ranges from almost instantaneous to several hours, depending on the conditions and minerals involved (Grim, 1968, p. 200). Reaction time for some zeolites may be many hours. (3) Groundwater moves very slowly through most sediment in the section. Thus, a given particle of water should be in contact with most cation-exchange minerals long enough for nearly complete exchange to occur. (4) The thickening of this zone by additions of Ca^{++} and Mg^{++} with depth cannot be accurately evaluated with the available data.

A reasonable explanation of the thickness of this zone of groundwater rich in Ca^{++} and Mg^{++} is that it is a result of the near-exhaustion of the exchange capacity of the sediment. The water chemistry reflects the present position of a downward migrating front of altered sediment (the originally Na-rich clays and zeolites have been altered to Ca types), with the most complete alteration occurring near the surface.

Many factors relating to diagenesis of the sediment are involved in this process. If the surface of the sediment remains at the same position with time (lowering by erosion is minimal), the thickness of the altered zone of cation exchange minerals would increase with time; likewise, the depth of Ca^{++} and Mg^{++}-rich groundwater would also increase. However, erosion in western North Dakota is rapid (Clayton, 1969). If the rate of surface lowering is equal to the rate of migration of the downward moving front then the thickness of the altered zone would be maintained with time. The relative rates of these two process are unknown.

Summary of the groundwater chemical flow system.-The variation of chemical facies of the Little Missouri River groundwater flow system at first appears to be best evaluated on the basis of individual stratigraphic units. Many of the observations appear almost contradictory to the conclusion that the Little Missouri valley is the locus of converging groundwater flow lines of a single regional flow system. There is typically much vertical variation of bicarbonate and sulfate in the study area. The relationship between bicarbonate and sulfate in samples from all stratigraphic horizons in the discharge area is shown in the scatter diagram, figure 34. The samples with the highest values of sulfate are from the areas of the shortest groundwater flow path. Several conclusions can be drawn from this nonlinear plot. (1) Sulfate readily goes into solution in the groundwater of western North Dakota and is an indicator of young groundwater. (2) The trend appears to be asymptotic to a reacting value of approximately 8 to 9 equivalents per million of bicarbonate. This value is interpreted as the bicarbonate base line and

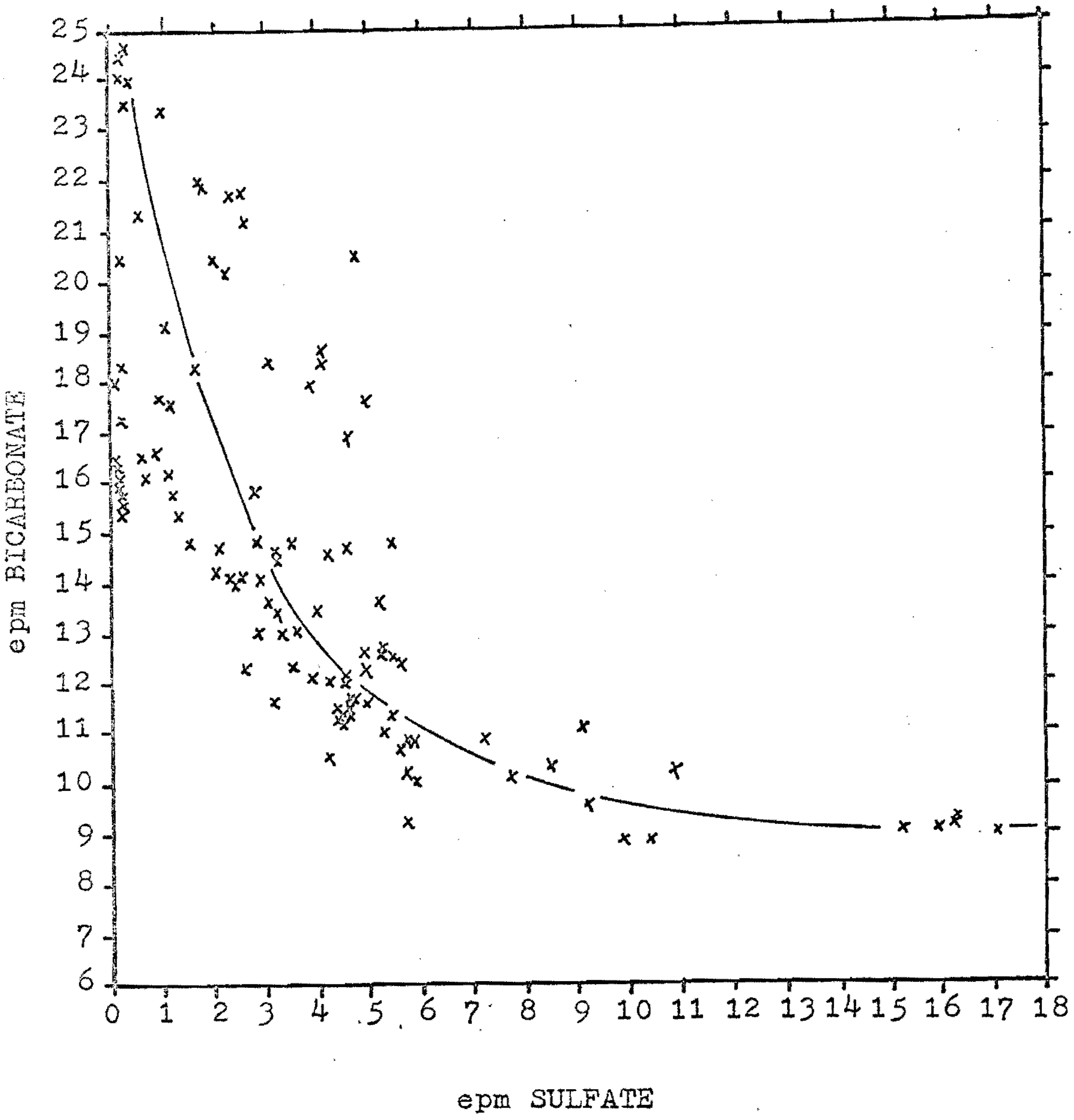


Figure 34.--Bicarbonate as a function of sulfate in ground-water samples from the discharge area.

probably represents the initial amount of HCO_3^- formed in the presence of free CO_2 in the recharge areas. (3) A disproportionate increase in HCO_3^- relative to the decrease in SO_4^{--} is a result of sulfate reduction; HCO_3^- and SO_4^{--} comprise at least 90 percent or more of the total anions in all but a few samples.

The very low values of chloride in samples from all but the deepest parts of the flow system probably reflect an absence of soluble chlorides in most of the sediment. The marked decrease in chloride from south to north in water from the Hell Creek Formation may be the result of flushing by a very active flow system induced in the northern part of the study area by Pleistocene glaciers. Or the decrease in chloride may indicate a decrease in upward seepage from the underlying Fox Hills Formation. This could indicate a separation in the flow system in which the Fox Hills Formation no longer participates in the Little Missouri River flow system but assumes a more longitudinal flow component. A lack of sufficient data prevents a more thorough analysis in the northern end of the study area, and the complexity of the water chemistry makes further elaboration on the total flow vector difficult.

A generalization of the Chebotarev sequence for the Little Missouri flow system, beginning in a recharge area, might be as follows.

$$HCO_3^- \text{ or } HCO_3^- + SO_4^{--} \longrightarrow SO_4^{--} + HCO_3^- \longrightarrow$$

$$SO_4^{--} \longrightarrow SO_4^{--} + HCO_3^- \longrightarrow HCO_3^- + SO_4^{--} \longrightarrow$$

$$HCO_3^- \text{ or } HCO_3^- + Cl^-$$

The general vertical variation in cations in the regional flow system (west to east) is shown by figure 35. The distribution of anion facies (west to east) is shown by figure 36. The variation of anion facies along the longitudinal flow component (south to north) in the discharge area is approximated by figure 37. It is obvious that the presence of these alternating facies prevents placing a single analysis of bicarbonate-sulfate water at a unique position within the flow system.

Analyses of water samples from oil-well drillstem tests of formations just below the Pierre Shale indicate that on the average this water contains about 100 times more chloride and at least 10 times more total dissolved solids than water from the Fox Hills Formation. Apparently the Pierre Shale forms a significant groundwater-chemical boundary in western North Dakota.

Chemistry of shallow groundwater

The chemistry of shallow groundwater samples may show considerable local variation in amount of the major constituents. Figure 38 represents two samples collected at the same time from approximately the same depth below the water table. The sample wells were aligned normal to the

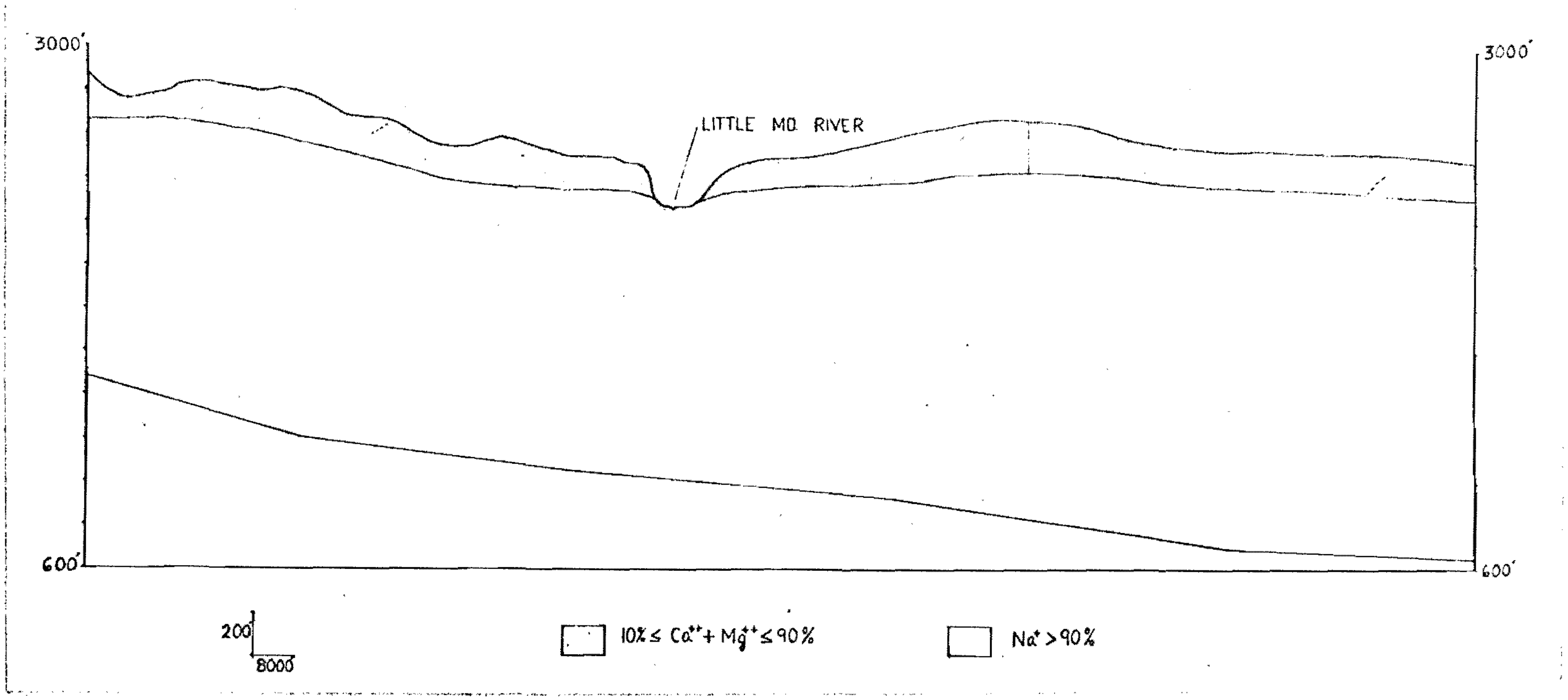


Figure 35.--Cross section showing the general regional vertical variation in cation facies. The line of the section corresponds to figure 18.

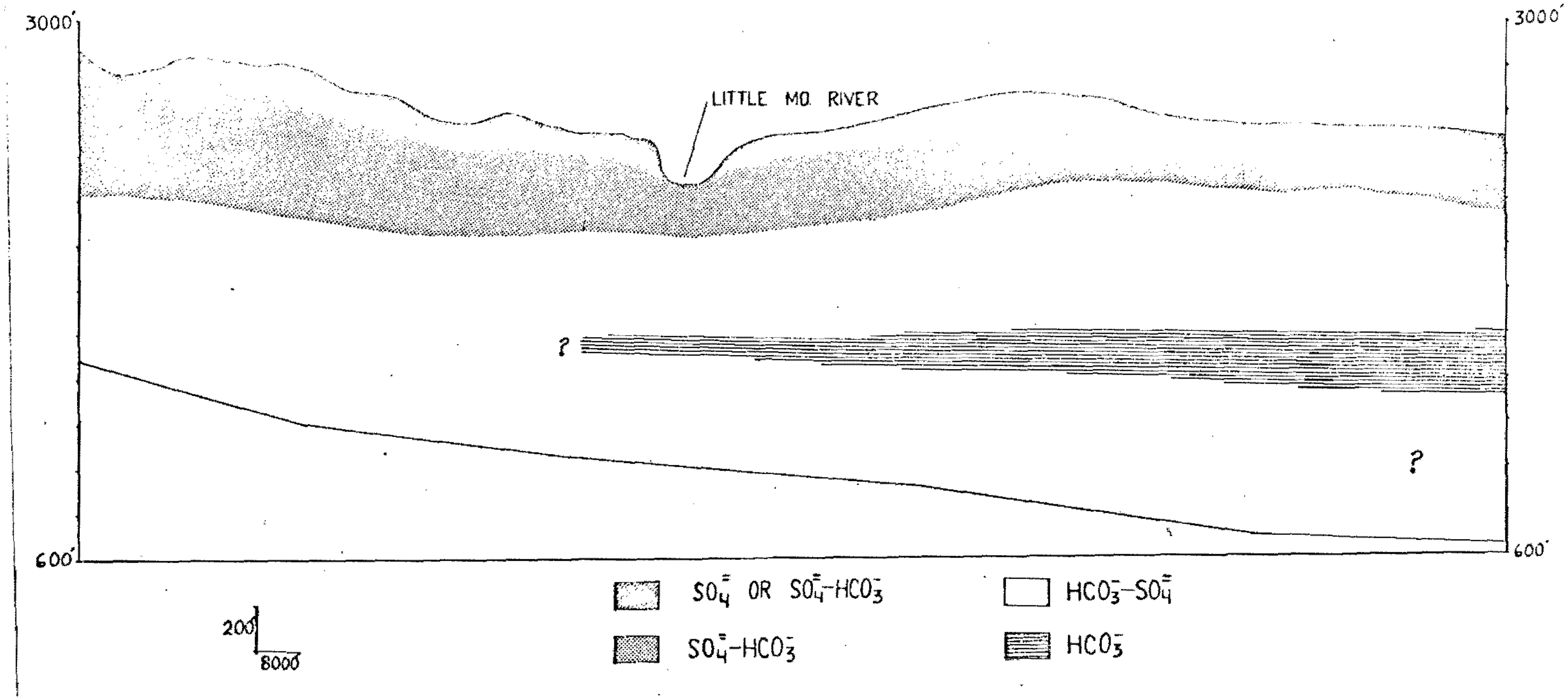


Figure 36.--Cross section showing the regional vertical variation in anion facies. The line of the section corresponds to figure 18.

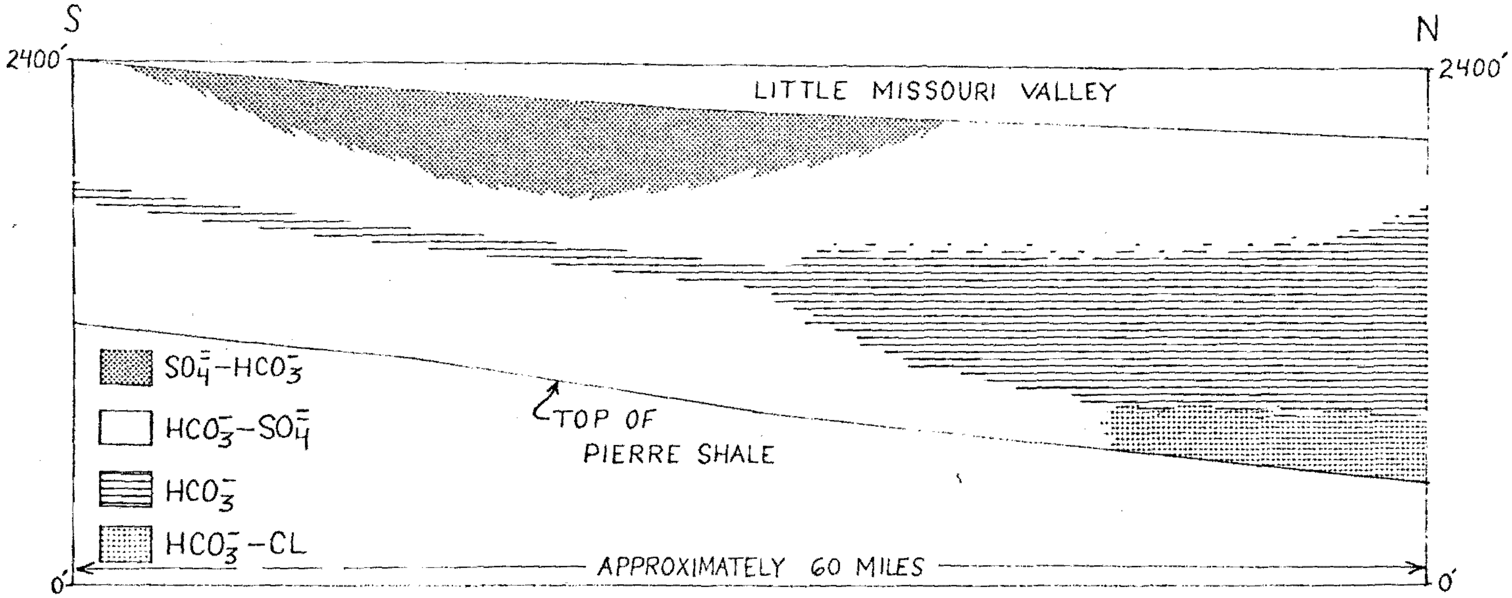


Figure 37.--Generalized cross section showing the south to north variation of anion facies in the discharge area.

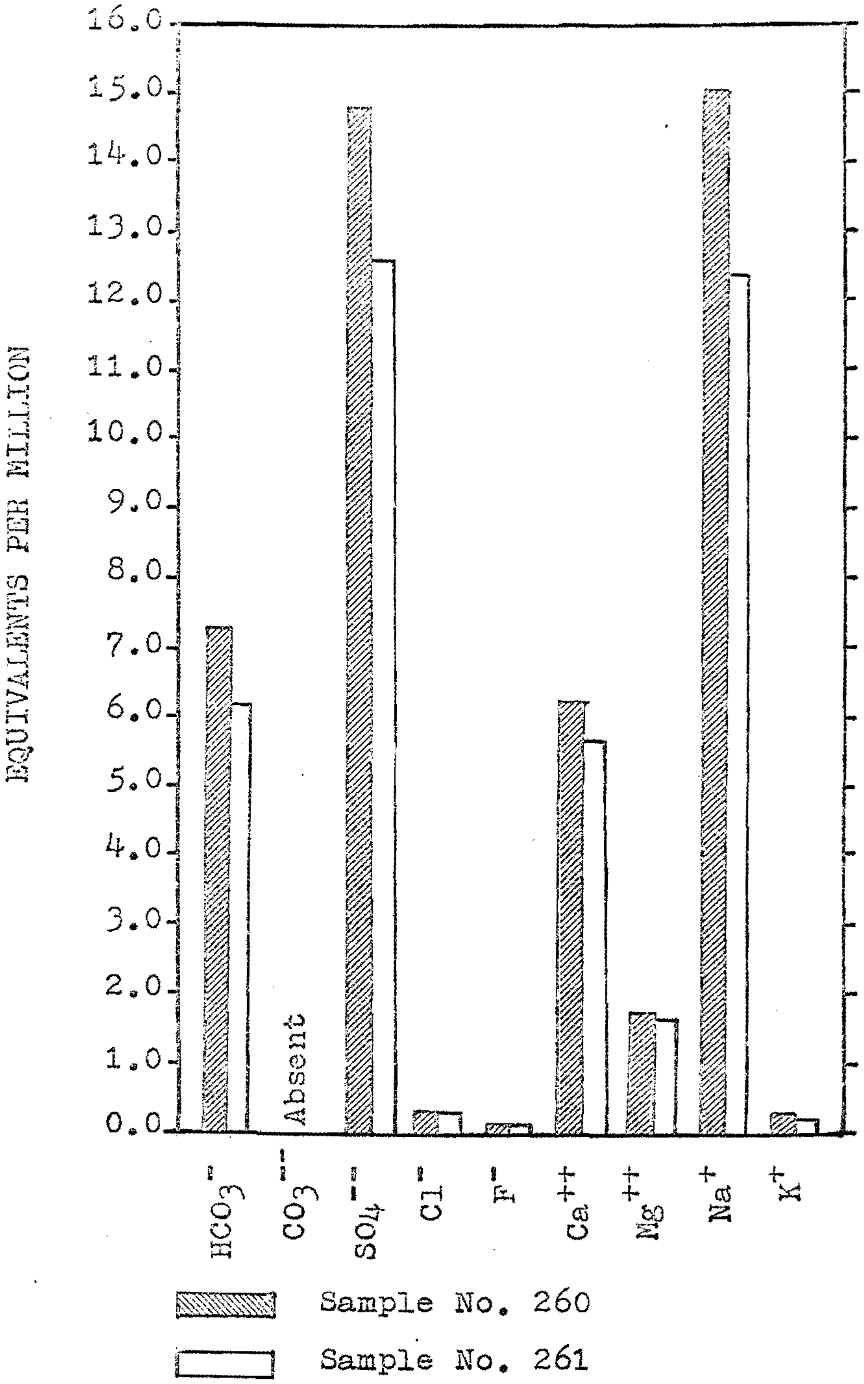


Figure 38.--Water chemistry of two shallow groundwater samples indicating dilution resulting from seepage from the Little Missouri River.

river channel; sample number 261 was 20 feet from the river and sample number 260 was 70 feet from the river. The decrease of the major constituents in the sample nearest the stream resulted from dilution of the shallow groundwater by seepage from the stream; large amounts of rainfall had resulted in prolonged high stage. It is difficult to describe the average shallow groundwater chemistry because of this type of transient condition.

A few widely spaced (covering about 120 river miles) samples of shallow groundwater, collected during extended periods of low stream stage, are assumed to be representative of the normal chemical conditions (fig. 39). The waters are predominately sulfate-bicarbonate; calcium plus magnesium comprise from 30 to 50 percent of the total cations. Most of the samples showing the lowest percentages of sulfate are from the northern end of the study area. However, the limited amount of data does not warrant proposing this as a real trend.

Stream flow at low stage is maintained by groundwater seepage; therefore, samples at low stage should be indicative of the chemical character of the groundwater. It was observed that the Little Missouri River consisted of reaches of alternating increasing and decreasing flow at low stage. Late in August, 1967, several discharge measurements were made during the course of one afternoon. Starting at the southern boundary of the South Unit of Roosevelt Park, where the discharge was 17.5 cfs, measure-

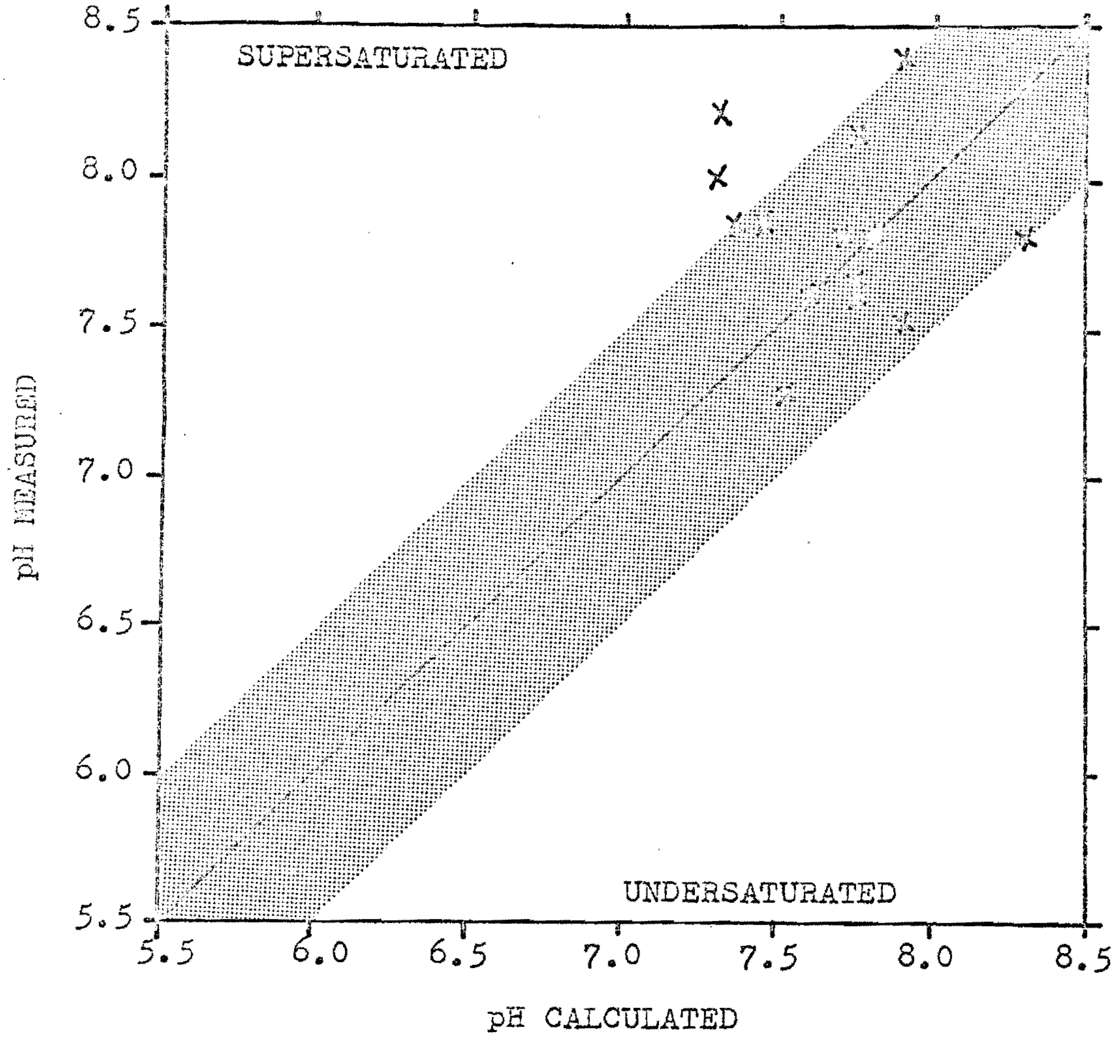


Figure 42.--Relationship of measured to calculated pH for some surface-water samples. The calculated pH is for solutions in contact with calcite. The stippled area indicates assumed equilibrium.

is assumed that a large quantity of the shallow groundwater is a result of seepage from the deep flow system, only one aspect of the shallow groundwater chemistry remains unresolved. The concentration of Ca^{++} and Mg^{++} in the deep groundwater has been shown to be consistently very low beneath a depth of about 200 feet from the ground surface in the recharge areas, whereas Ca^{++} and Mg^{++} comprise 30 to 50 percent of the total cations in the shallow groundwater.

It was concluded in the previous section that the upper 200 feet of sediment in the recharge areas has probably had the original Na-rich zeolites and clays altered to a certain extent to Ca-rich types. The bulk of the fine-grained sediment filling the valley has been derived from erosion of sediment in the recharge areas. That sediment contains Ca-rich zeolites and clays. It was also noted earlier that the equation for cation exchange (equation 11) is reversible only with a concentration ratio of $(Na^+)/(Ca^{++})$ much greater than 1. However, this is the case in deep groundwater, which in the discharge area has a concentration ratio of at least 90:1. The Ca^{++} and Mg^{++} in the shallow groundwater are increased relative to Na^+ by cation exchange, with equilibrium being maintained as the concentration ratio approaches 1.

The most consistent characteristic of the shallow groundwater chemistry is its apparent haphazardness. The details of the chemical system are poorly understood. However, its general character appears to be explainable in relation to the chemistry of the deep groundwater.

Seepage Contributions to the Valley Fill Sediment

The purpose of this section is to provide a rudimentary analysis of the relative relationships of various seepage contributions to the shallow groundwater system.

Seepage from the stream channel at high stage

When the level of water in a channel is above the groundwater table the potential gradient is reversed and water moves from the channel into the sediment, resulting in mounding of water adjacent to the stream. This contribution to groundwater is called bank storage. During the flood wave recession the gradient is again reversed and water in bank storage is released to the stream. A result of bank storage, in a stream having highly permeable bank sediment, can be a smoothing of the flood peak.

Evidence of bank storage along the Little Missouri River is the dilution of the shallow groundwater chemistry by seepage from the river (fig. 38) and the slight increases in groundwater head during the passage of a flood wave. The channel bottom of the Little Missouri River consists primarily of gravelly sand. The banks are primarily sandy silt. Gravelly sand or sandy gravel are the predominate sediment types below channel level. The sediment has a relatively high hydraulic conductivity.

The Little Missouri River has a very high suspended sediment load during flood stage. Samples collected at flood stage and allowed to settle for an extended period can have a mud slurry which is about one-third or more of the volume of the sample. Values of suspended sediment exceeding 25,000 ppm were reported by the U. S. Geological Survey (1956, p. 222). As a result of this abundant suspended sediment a mud seal (Harrison and Clayton, 1970, p. 223) is formed on the channel bottom and banks when the stream is losing water to groundwater storage. The seal is effective in reducing the amount of water that can move into bank storage.

The amount of bank storage for a given flood depends on many factors, such as the stage height and length of a flood, the position of the water table prior to the flood, and the effect of the mud seal.

Infiltration through ephemeral stream channels

The vast majority of tributaries of the Little Missouri River are ephemeral arroyos with channel bottom widths ranging from a few feet to a few tens of feet. The channel bottom sediment is predominantly sandy gravel with accumulations of silt and clay in the pore spaces. Streams of this type typically have large losses of water as a result of infiltration (Babcock and Cushing, 1942; Qashu and Buol, 1967). Runoff in these streams, resulting from the typical high intensity and short duration summer rains of western North Dakota, shows a rapid peak and recession.

The amount of infiltration may be highly variable between channels for a given period of runoff, depending on such factors as channel shape, sediment type, the nature and rate of surface flow, antecedent moisture conditions, and the amount of suspended sediment.

Infiltrometer measurements were made in two channels using a single piece of thick-walled, 8-inch casing which had a cutting edge. The most difficult part of obtaining the measurements was carrying the instrument. However, less sturdy tubes would not withstand being driven 1½ to 2 feet into the channel bottom. A constant head of 1 foot was maintained during the period of measurement.

The infiltration rate was determined from the slope of the cumulative infiltration (fig. 43). Johnson (1963) described the apparatus and methods used in determining infiltration rates and discussed the large number of factors that effect infiltration. He notes (p. 15) that, as a result of the many factors involved, a particular rate for a given sediment type is "virtually nonexistent".

In general two rates of infiltration for the channel sediment were found, very fast and very slow. Very slow rates were controlled by low permeability layers. These layers were encountered at various depths in about one-fourth of the measurements. They are related to areas of ponding on the channel bottom toward the end of a runoff period, and are usually thin but very effective in reducing local infiltration rates.

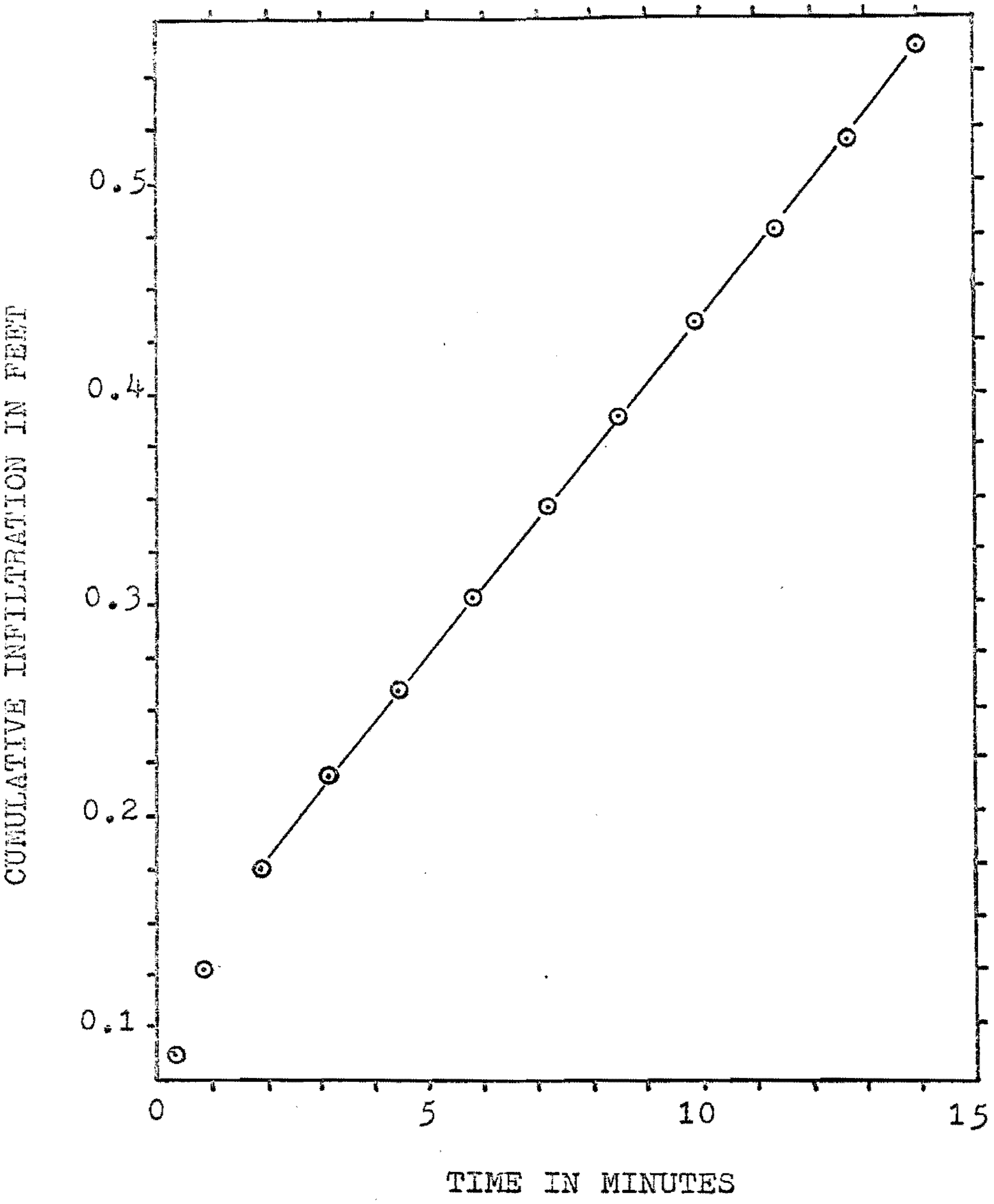


Figure 43.--Cumulative infiltration as a function of time.

Infiltration rates for tests not encountering a low permeability layer ranged from 8 X 10^{-2} ft/min to 7 X 10^{-3} ft/min with an average rate of about 4 X 10^{-2} ft/min. Assuming that local low permeability layers occupy an area equivalent to one-fourth of the channel bottom, the average rate of effective infiltration would be reduced to 3 X 10^{-2} ft/min. A thin layer of mud-cracked sediment covers the bottom of all ephemeral channels during dry periods and probably represents a mud seal that was formed during runoff. This condition was not introduced in the infiltrometer tests. Even though this thin seal is probably only slightly permeable, very large gradients are induced across it during periods of runoff so that significant quantities of water may move through it. An effective infiltration rate of 1 X 10^{-2} ft/min may therefore be a reasonable estimate for the ephemeral streams of western North Dakota.

Hagmaier (1970) arrived at a value of approximately 25 miles of stream channel length/mi^2 of area bordering the Little Missouri River. This value was determined from the aerial photos of a tributary basin near the center of this study area. A channel width of 5 feet is a reasonable average value (Hagmaier, 1970, "oral communication") for this basin. There is therefore, about 7 X 10^5 ft^2 of channel bottom/mi^2 bordering the river.

Applying these calculations to a stream flow 1 foot deep and of 1 hour duration (a reasonable estimate for a 1-inch rainfall) indicates that the total recharge may be about 4 X 10^5 ft^3/mi^2 or about 2 percent of the total rainfall on that area. A quantity of this recharge moves vertically into the deep groundwater flow system and the remainder moves longitudinally down the tributary valley fill and is added to the shallow groundwater storage of the Little Missouri valley.

Values of recharge associated with infiltration through the ephemeral stream channels may vary by several orders of magnitude for a given runoff period depending on a large number of conditions. However, the approximation presented here indicates that a large quantity of recharge to both shallow and deep groundwater may be through the bed of ephemeral streams.

Seepage contributions from deep groundwater

The seepage contribution from the regional flow system to the valley fill sediment could be accurately calculated if values of hydraulic conductivity were known for the predominately poorly permeable sediment underlying the valley fill. Values of hydraulic conductivity for the deeper, more permeable sediments (such as basal Tongue River sand) are of no use in estimating seepage contributions to the valley fill, because the rate is controlled by the less permeable overlying sediments. If the average sediment underlying the valley is composed primarily of silt and clay then an estimate of the hydraulic conductivity might be 1 X 10^{-2} ft/day. Cedergren (1968, p. 35) gives general values of hydraulic conductivity ranging from about

3×10^{-1} to 3×10^{-3} ft/day for mixtures of silt and clay. Meyboom (1966b, p. 25) indicates that the hydraulic conductivity of a section of the Riding Mountain Shale in Canada is about 5×10^{-2} ft/day, based on tritium counts. Applying the value 1×10^{-2} ft/day in Darcy's law for 1 ft^2 of area using a seepage gradient of 1.5×10^{-1} ft/ft yields a value of seepage/ft^2 which is 1.5×10^{-3} ft^3/day.

The width of the regional discharge area has been shown to coincide approximately to the width of the valley floor, which averages three-fourths of a mile. Summing the amount of seepage/ft^2 over a 1 foot wide strip of valley floor yields 6 ft^3/day/ft of valley length or about 3×10^4 ft^3/day/mi of valley length.

Possible relative orders of magnitude

The calculations presented above are understood to be only gross estimates involving many assumptions and unknowns. They were made to point to areas of possible future evaluation.

The dry weather, low water discharge of the Little Missouri River during summer and early fall, averages about 10 to 15 cfs at the Medora gaging station (sec. 27, T. 140 N., R. 102 W.). There is very little change in discharge for many tens of miles up or down the river. This amount of base flow could probably be supplied entirely from recharge by infiltration through ephemeral stream channels and release from bank storage. Usually by December the river has little or no flow, indicating that groundwater in storage above the channel bottom has been depleted. There is, however, a large amount of seepage from the deep regional flow system, but it moves through the highly permeable valley fill sediment under the river (as underflow) and out of the basin. A base flow analysis of the Little Missouri River would therefore give only a minimal indication of the total groundwater storage in the basin.

The exact order of importance of the three sources of seepage to the valley fill sediment is unknown. However, bank storage is probably not as significant a contributor as either of the other two sources, and because seepage from the regional flow system is continuous the probable order is (1) seepage from the regional flow system, (2) seepage through the bed of ephemeral tributaries, and (3) seepage through the stream banks at high stream stage.

Recharge to the regional flow groundwater system may be primarily controlled by infiltration through the beds of low order ephemeral streams.

CONCLUSIONS

Summary of Conclusions

The results of the study support the following interpretations.

(1) The Little Missouri valley is the discharge area of a regional groundwater flow system.

(2) The discharge area is approximately the same width as the valley floor.

(3) The valley affects the groundwater potential at least down to the top of the Pierre Shale, at a depth of greater than 1,000 feet below the valley floor.

(4) The ratio of the vertical to longitudinal flow components (in terms of the gradient) is at least 100 in the discharge area.

(5) The groundwater divides, in the center of the study area, are asymmetrically spaced and correspond approximately to the surface-water divides.

(6) The western recharge area of the regional flow system has a higher potential and steeper gradient than the eastern recharge area as a result of its higher elevation and overall lower permeability.

(7) The groundwater chemistry is characterized by a sodium facies in the discharge area and below a depth of about 200 feet in the recharge areas.

(8) The dominant anions (either bicarbonate or sulfate) and the total dissolved solids show vertical and lateral variation. Much of the variation is attributable to a sequence of chemical reactions initiated by the reduction of sulfate.

(9) The water chemistry reflects several lithologic characteristics. (a) There is an abundance of soluble sulfate in the sediment of the recharge areas. (b) The sediment contains minerals with high cation-exchange capacity which are being altered from predominantly sodium-rich types to calcium-rich types in the recharge areas. (c) Much of the sediment is apparently devoid of soluble chlorides. (d) A reduction in total dissolved solids along some flow paths reflects diagenesis of the sediment by precipitation of dissolved constituents from groundwater.

(10) The probable order of importance of seepage contributions to the valley-fill sediment is, (a) seepage from the regional flow system, (b) seepage through the bottom of ephemeral tributary channels, and (c) seepage through the river banks at high stage.

(11) Most of the groundwater in the valley-fill sediment leaves the basin as underflow.

(12) Other more tentative conclusions are suggested. (a) Much of the recharge to the regional flow system may be through the beds of low order ephemeral streams. (b) Reduced chloride concentrations in some units in the northern end of the study area may be the result of flushing by an active flow system associated with Pleistocene glaciers. (c) The Pierre Shale is a significant groundwater-chemistry boundary.

Usefulness of Present Groundwater Flow-System Models

Application of the physical concepts of existing flow-system models appears to be most useful in groundwater studies in western North Dakota. The models can form a basis for maximizing quantitative interpretations from a minimum of planned sampling.

The chemical variables are more complex and a large deviation from a general model may be expected. However, the variation of groundwater facies can be reasonably explained when considered in terms of a continuous flow system.

APPENDICES

Appendix A

METHODS OF DATA COLLECTION AND ANALYSIS

Water Level Measurements

An accurate measurement of the static water surface in a well requires that two conditions be met. (1) The level measured must be assumed to indicate the potential at the bottom of the casing; that is, the casing is not perforated and is sealed in the borehole so that no upward leakage can occur. (2) The level measured should be constant for the time of measurement (recovery from pumping or flowing of the well should be nearly complete).

Assurance that these conditions are satisfied is sometimes slight, particularly for very old wells or wells that were poorly completed. Many of the wells completed in recent years in western North Dakota are being cemented, which, when done with care, should seal the casing to the borehole and eliminate upward leakage. Therefore, if the casing is well cemented and is not rusted through, the first condition will be satisfied. The second condition can be satisfied if sufficient time is allowed for approximate equilibrium conditions to be established and if there is no interference from nearby pumping or flowing wells. It is felt that these two conditions were satisfied, at least within the bounds of an acceptable error (a few feet at most), for the values of total head used in this report.

Nonflowing wells

The determination of the water level in wells was made with an electric water-level indicator (Soiltest, Model DR-760A). The total head was determined by subtracting the measured depth below the land surface from the land-surface elevation.

Flowing wells

The static pressure of water in flowing wells was determined using a bourdon gauge. The pressure reading was converted to feet of water, and this amount was added to the land surface elevation to yield the total head. Attaching the gauge to a casing that was constantly flowing presented some problems, particularly for high pressure wells (35 to 100 psi). The problem was solved by using a right angle pipe with one end attached to a gauge and a packer on the other end. The device was designed in such a way that the packers were interchangable, so that pipes ranging from 5/8-inch to 1½-inch could be sealed. The packers were ordinary rubber laboratory stoppers drilled to fit the connecting pipe (fig. 44). The packer was expanded to fill the pipe by tightening a nut on the threaded connecting pipe. If the casing was nearly round a very tight seal

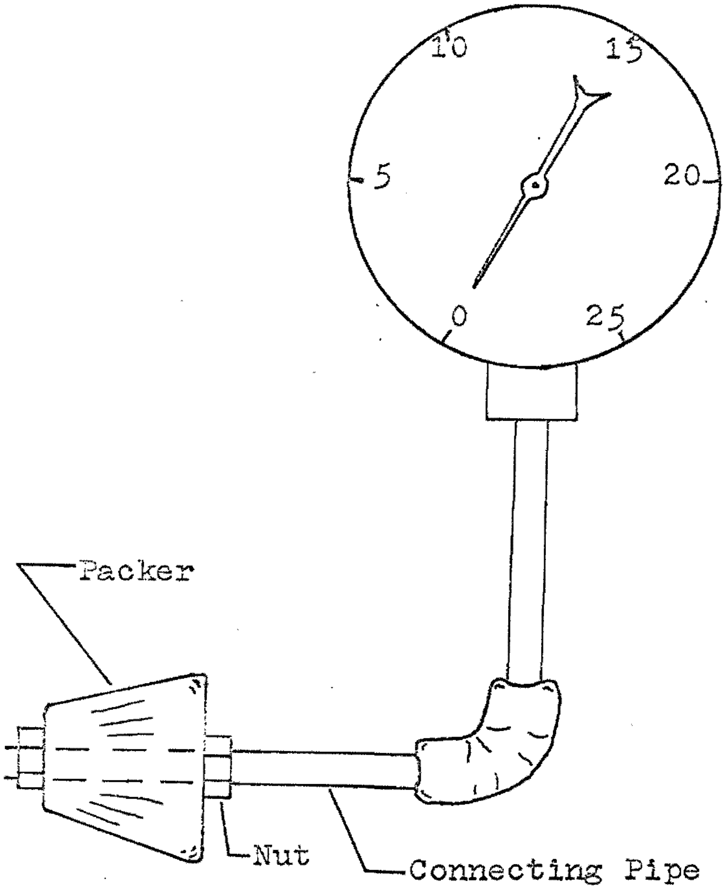


Figure 44.--Schematic diagram of the packer-gauge assembly used to measure the water pressure of flowing wells.

could be obtained.

Most wells flowed unchecked. It was therefore necessary to shut them in for a period of time to insure a close estimate of the potential. The amount of shut-in time ranged from one half to several hours. When the gauge showed no detectable change in pressure with time it was assumed that static conditions had been reached.

Collection of Water Samples

Collection of water samples that are representative of the source at the time of collection is essential if an interpretation of the chemical processes is to be undertaken. Exact procedures for collecting different types of water samples vary among investigators. The procedure followed by the U. S. Geological Survey is outlined by Rainwater and Thatcher (1960). The source of water sampled in this study included springs and seeps, surface water, and groundwater (from both flowing and nonflowing wells). In this study the samples were collected in high density polyethylene bottles with polyethylene-lined bakelite screw-caps. The sample bottles were rinsed several times with the water to be sampled before collection. The samples were collected and the cap tightly secured and sealed with plastic tape to insure a lasting seal during transport.

Surface-water samples

The greatest number of surface-water samples were collected at the gaging station at Medora, North Dakota under varying states of discharge and suspended-sediment concentration. An attempt was made to sample near the center of flow; however, this was impossible at high stage. Samples containing abundant suspended sediment were allowed to settle, and the clear water was pipetted into fresh bottles.

Groundwater samples

Groundwater samples came from three kinds of wells: shallow sample wells (cased, hand-augered wells a few feet deep), pumped wells, and flowing wells. In each case the collection methods varied slightly.

The shallow wells were installed in valley-fill sediment for the purpose of collecting water samples. Samples were collected by lowering a device to the bottom of the casing, tripping a stopper, and allowing it to fill.

Many of the pumped wells are in excess of 150 feet deep; some were several hundred feet deep. This situation presents the possibility of a considerable amount of stagnant water being present in the casing if the well had not been pumped for a period of time. In this case the well was pumped until the casing was cleared of stagnant water before the sample was collected.

Most of the flowing wells were unrestricted at the surface and flowed continuously. This eliminated the problem of insuring a fresh sample; however, many high-pressure wells caused extreme turbulence in the bottle which introduced air into the sample. This undesirable situation was avoided where possible by choking down the flow.

Analysis of Water Samples

All major chemical constituents, pH, and specific conductance of 309 samples were determined as a part of this study. Other chemical analyses obtained from the North Dakota State Department of Health and the U. S. Geological Survey (analysis by the North Dakota State Water Commission) were evaluated. The following discussion of methods pertains only to those samples that I analyzed.

The method of analysis during the first field season (1967) followed procedures recommended by Hach Chemical Company. Sodium and potassium values were calculated for these samples; therefore less emphasis is placed on their accuracy.

During the field season of 1968 some constituents were analyzed in the field at the time of collection in an attempt to determine if the water chemistry had altered significantly during the period of transport to the laboratory. Field analysis was abandoned because it was time consuming and the working conditions were poor. All of the analytical procedures maintain their accuracy only within a limited temperature range and corrections for field analysis of some samples was questionable. An evaluation of the field and laboratory analyses indicated that no significant changes occurred during transport.

The following procedures are described in the order in which the samples were analyzed. Estimates of reproducibility were determined by duplicate analyses of about 15 percent of the samples.

pH

The pH was measured in the laboratory with a Beckman Zeromatic pH meter. The instrument was standardized with a buffer solution of pH 7.0 and checked frequently with buffered solutions of pH 5.0 and 10.0. All solutions were temperature corrected. The readings were reproducible to ±0.03 pH unit.

Measurements at the time of collection were made with a Beckman model 180 portable pH meter. The instrument was standardized against a buffer solution prior to each measurement. A check against the zeromatic indicated that this instrument gave relatively stable results if standardized before each measurement. No significant change in the pH of the solution was assumed if the variation between field and laboratory measurements was within ±0.3 pH unit. A variation larger than this value occurred only for a few samples. This discrepancy might, in some cases, be the result of the pH of those field samples not being measured under static conditions. Barnes (1964, p. H4) observed a reproducible streaming potential corresponding to -0.10 pH units at a water velocity of 1 ft per sec.

Alkalinity

Alkalinity, as used in water chemistry, refers to the capacity of a water to neutralize strong acids to pH 4.5 (Rainwater and Thatcher, 1960, p. 93). The determination was made by titrating a 50.0 ml sample with a strong acid (0.02 N H_2SO_4). The relative amounts of carbonate and bicarbonate were determined from the titration. The end points of the titration were taken as pH 8.2 (carbonate) and pH 4.5 (bicarbonate) following the procedure of Rainwater and Thatcher (1964, p. 94), who indicate that these pH values are the inflection points on a graph of a titration of Na_2CO_3 with H_2SO_4. This should have given good results for the predominatly sodium-bicarbonate groundwater from deep sources, but may have introduced an error in samples containing considerable amounts of other constituents. The values for total alkalinity as $CaCO_3$ were reproducible to within 2 percent.

Calcium and magnesium

Calcium and magnesium in solution impart the property called hardness. The determinations were made by titration using a standard solution called Hexa Ver (Hach Chemical Company) which is the name give to a 0.02 N solution of disodium dihydrogen -1, 2-cyclohexanediaminetetraacetate (CDTA). The calcium determination was carried out by making a 50 ml sample strongly basic (adding 8 N KOH) and titrating with CDTA in the presence of Murexide to an endpoint (color change from reddish-pink to pure blue). The total hardness (calcium plus magnesium) of a buffered sample was determined by titration. The amount of magnesium was calculated from the difference of the two titrations. The stability of the reagents was checked periodically by titration of a standard solution of calcium chloride.

The calcium determination was found to be accurate and reproducible to within ±0.3 ppm and the magnesium on the order of ±2 ppm. The error introduced in the analysis of water containing abundant calcium and magnesium was small.

Chloride

Chloride was determined by titration with a 0.0141 N solution of mercuric nitrate ($HgNO_3$) in a buffered sample using diphenylcarbazone as an indicator (reagents from Hach Chemical Company). The reagents were checked by titrating against a standard solution of NaCl. The results were accurate and reproducible to within ±1 ppm for the range of concentrations involved.

Sulfate

Sulfate was determined using a turbidimetric method (APHA, 1960) and Fisher photometer (Electrophotometer II, model 81). A blue filter (transmittance range 400 to 475 mu) and a light path of 23 mm was used. A suspension of barium sulfate was formed in the sample using a dried, preweighed powder called Sulfaver (Hach Chemical Company). The suspension was stable for several hours. A calibration curve was constructed using values of absorbance from five standard solutions over the range of 0 to 100 ppm. Samples that contained SO_4^{--} exceeding the range of the working curve were diluted.

The instrumental accuracy is ±0.5 percent or better in the range of optimum light conditions. The error involved with this determination may be on the order of several percent. Use of this procedure may have introduced a relatively large error in samples containing abundant SO_4^{--}.

Sodium and Potassium

Amounts of sodium and potassium were determined using a Beckman flame photometer with an acetylene flame. A calibration curve was derived for both sodium and potassium using values of transmittance and concentration for five standard solutions of each. A new calibration curve was derived each time the flame photometer was used. Sodium was measured at 589 mu. A sample was placed in the atomizer and the wavelength indicator was moved from above and below this figure until the setting for a maximum peak was obtained. A similar procedure was followed for potassium using a setting of 768 mu. The range of concentration of sodium for optimum instrument response was well below the average concentration of most samples, thereby necessitating dilution. The sodium samples were diluted by a factor of 20 to 50. The values for potassium very nearly coincided with the optimum working range of the instrument; occasionally samples had to be diluted by a factor of 5.

Results were accurate and reproducible under good instrument conditions. The largest deviation to be expected for reproducibility is ±1 percent.

Silica

Silica concentrations were determined with the Fisher photometer (Electrophotometer II, model 81) by measuring the absorbance of molybdenum blue developed from the reduction of a silicomolybdate complex with sodium sulfite using a red filter (range of 625 to 675 mu) and a light path of 23 mm. The silica content of unknowns was determined from a calibration curve derived from standard solutions. The silica standard solution was made by dissolving meta sodium silicate nonahydrate in distilled water. The concentration of the unknowns fell well within the working range of the calibration curve and no dilution was necessary. The exact procedure is given in the manual accompanying the photometer.

The results for silica were accurate and reproducible to ±0.5 ppm.

Fluoride

Fluoride was determined for 222 water samples using a

Hach Kit (Hach Chemical Company) procedure. This method has been given approved status in the 12th Edition of the APHA Standard Methods Manual. Results were reproducible to within ±2 percent. No corrections were made for interferences in the procedure from other ions.

Total dissolved solids

Total dissolved solids were determined by calculation following the procedure of Rainwater and Thatcher (1960, p. 271). The solid constituents were converted to forms that would be expected to exist in the anhydrous state and summed. This assumes that all constituents have been analyzed. In the analyses no values were reported for iron and nitrate. Some samples were analyzed for iron but the quantity present was very small (usually less than 1 ppm), and it was therefore assumed that no large error would be introduced by ignoring it. No determinations of nitrate were made, but again it was assumed that its contribution to the total would be small.

Specific conductance

The conductivity was determined at the time of sample collection with a Solu Bridge (model A-105) conductivity meter (Soiltest Inc.). The meter was self contained, had a dip electrode, measured conductance in the range of 50 to 8,000 micromhos/cm, and had a manual temperature compensator.

Error Analysis

As a gross estimate of the analytical error a computational check was made for each sample having an analysis of all major and most minor constituents. The total equivalent weight of all cations and anions in solution must balance. It was assumed that the unanalyzed minor constituents represented an insignificant percentage of the total ions. Therefore, the difference between cations and anions was assumed to approximate the analytical error. Values for percent-error were determined by

$$E_r = \frac{|\text{Total Cations} - \text{Total Anions}|}{\text{Cations} + \text{Anions}},$$

with all values in equivalent weights.

The mean percent error of 222 samples was 1.6 with a standard deviation of 1.5.

Elevation Determinations

Much of the study area lacks detailed topographic control. The only maps that encompass the entire area are at a scale of 1:250,000 with a contour interval of 100 feet, which was wholly inadequate for determinating the surface elevations of wells. The Little Missouri River has been mapped from the southern border of the South Unit of Roosevelt National Park to the southern border of the study area, but only for one mile or less, on the average, on either side of the river. A few quadrangles to the west of the South Unit of the Park and in the area of the

North unit of the Park have been mapped on an interval of 20 feet. No other detailed topographic coverage exists. This necessitated the determination of elevations for most sample sites.

Elevations were determined with an American Paulin Micro Altimeter (model M-1). Vertical control stations were established using existing bench marks. Because the determination of vertical variations from one site to another is dependent upon an accurate measurement of the barometric pressure a recording Micro Barograph was used for base control. This instrument was unfortunately found to be about as dependable as the town drunk. It would on the average record barometric fluctuations for about one half the time required to close a surveying loop. The time of an individual loop was usually less than 3 hours. Despite these minor frustrations, by a process of reoccupation of surveyed sites and resurveying it was felt that usable surface elevations were obtained for most sample sites. The surveying procedure and methods of elevation correction are given in the instrument instruction manual or in most text books on field geology.

Location Format

The location format used in reporting some basic data follows the alpha-numeric system of the U. S. Bureau of

Land Management (fig. 45). In this system, the first number represents the township north of the base line, the second number indicates the range west of the principal meridian, and the third number represents the section. The letters denote quarter-subdivisions of the section. For example, a well located in the NE¼NW¼SW¼ sec. 26, T. 140 N., R. 102 W. is located in this system by the notation 140-102-26cba.

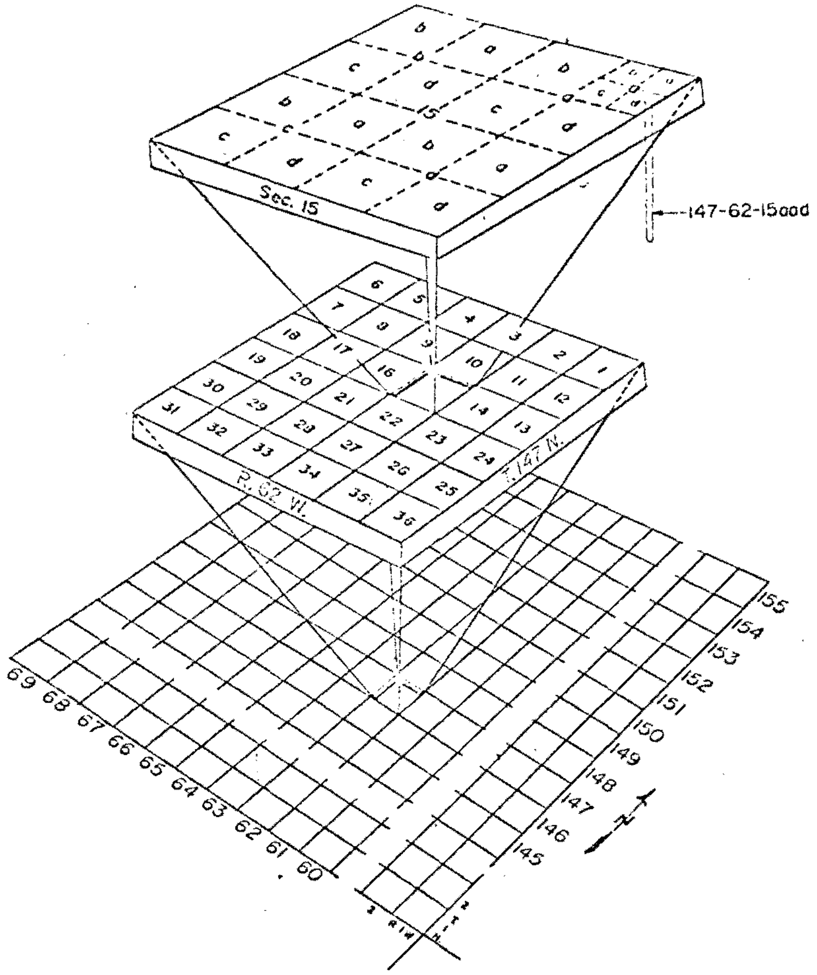


Figure 45.--Diagram illustrating the location format, from Trapp (1968, p.5).

Appendix B

SAMPLE LOGS

The following are the sample logs of water wells and test holes used in constructing the cross section (fig. 10). They are presented in the order that they occur on the section from "1" to "2". The first five sample logs were compiled by private well drillers. A copy of the sixth log (139-99-21ccc) was sent to me by Mr. Henry Trapp, Jr. of the U. S. Geological Survey at Bismarck, North Dakota.

140-102-11add

Owner: National Park Service Elev.: 2265

Source	Lithology	Thickness (feet)	Depth (feet)
Alluvium:			
	Sandy clay	15	15
	Gravel	10	25
Tongue River Formation:			
	Sandy clay	30	55
	Coal	5	60
	Sandy clay	10	70
	Limestone	3	73
	Gray clay	82	155
	Streaks of sand	50	205
	Shale	35	240
	Coal	18	258
	Shale	4	262
	Coal	1	263
	Shale, gray	2	265
	Coal	1	266
	Shale, sandy	9	275
	Coal	6	281
	Shale, sand streaks	19	300
	Hard shell	1	301
	Shale	6	307
	Shale, light gray	17	324
	Coal	4	328
	Shale, greenish	12	340
	Sand	4	344
	Shale	3	347
	Sand	3	350
	Shale	15	365
	Coal	3	368
	Shale	7	375
	Sand	45	420
	Sandy shale	4.5	424.5

140-102-10bdd

Owner: National Park Service Elev.: 2315

Comment: The well was originally drilled to 825 feet and later deepened to 1233 feet.

Source	Lithology	Thickness (feet)	Depth (feet)
	No record	825	825
Cannonball Formation:			
	Sandstone	5	830
Ludlow Formation:			
	Dark shale with thin coal streaks	59	889
Hell Creek Formation:			
	Sandrock	14	903
	Dark shale	142	1045
	Sandrock	10	1055
	Dark shale	90	1145
	Light sandy shale	32	1177
Fox Hills Formation:			
	Sand	11	1188
	Dark shale	8	1196
	Sand	37	1233

140-102-26bbb

Owner: National Park Service Elev.: 2265

Source	Lithology	Thickness (feet)	Depth (feet)
Alluvium:			
	Surface soil	3	3
	Gray clay	11	14
	Yellow clay	4	18
	Sand and gravel	15	33
Tongue River Formation:			
	Yellow clay	1	34
	White sand	4	38
	Sandstone, hard	2	40
	White clay	11	51
	Coal	1	52
	Carbonaceous shale	2	54
	Gray sand	86	140
	Sandy clay	8	148
	Dark clay	4	152
	Coal, hard	30	182
	White soapstone	26	208
	Dark clay	11	219
	Light gray clay	19	238
	Blue clay	56	294
	Blue loose fine sand	26	320
	Fine sandy clay	10	330
Ludlow Formation:			
	Clay	5	335
	Sandy clay	15	350
	Blue clay	11	361
	Sandy clay	26	387
	Blue clay	15	402
	Sandstone, hard	2	404
	Blue clay	41	445
	Sandy blue clay	11	456
	Blue clay, hard	18	474
	Sandy clay	4	478
Cannonball Formation:			
	Sandstone	2	480
	White sandy clay, fine	10	490
	Fine sand, very silty	31	521
	Blue clay	2	523
	Dark clay, hard	7	530
	Soapstone	8	538
	Coal	2	540
	Fine sand, hard	31	571
	Fine sandy clay	35	606

140-102-26bbb, Continued

Source Lithology	Thickness (feet)	Depth (feet)
Ludlow Formation:		
Coal	7	613
Sandstone	2	615
Gray clay	2	617
Soapstone, hard	53	670
Cannonball Formation:		
Quicksand	16	686
Stone, hard	3	689
Fine sand	26	715
Ludlow Formation (?):		
Coal	2	717
Soapstone	9	726
Coal	4	730
Blue clay	10	740
Coal	4	744
Hell Creek Formation (?):		
Dark clay	26	770
Coal	4	774
Blue clay	30	804
Coal	5	809
Blue clay	5	814
Coal	8	822
Soapstone, hard	38	860
Coal	4	864
Dark shale, hard	16	880
Coal	10	890
Dark clay, hard	50	940
Fine sand and sandstone	22	962
Blue clay	5	967
Brown shale, carbonaceous	8	975
Coal	2	977
Soft shale	41	1018
Hard shale	22	1040
Fox Hills Formation:		
Soft, fine silty sand	69	1109

140-102-26cbb

Owner: Abandoned Elev.: 2276

Comment: The log of this well is from Simpson (1929, p. 78).

Source	Lithology	Thickness (feet)	Depth (feet)
Alluvium:			
	Sand	30	30
Tongue River Formation:			
	Coal	1	31
	Soapstone	44	75
	Coal	0.5	75.5
	Soapstone and sand	47.5	123
	Coal	23.5	146.5
	Soapstone and sand	39.5	186
	Quicksand	85	271
Ludlow Formation:			
	Soapstone	5	276
	Coal	2.5	278.5
	Soapstone and sandstone	85.5	364
	Coal	7.5	371.5
	Sandstone and shale	22.5	394
	Coal	2	396
	Soapstone and sandstone	18	414
	Hard sandrock	5	419
	Soapstone	24	443
	Coal	3	446
	Soapstone	38	484
	Coal	2	486
	Soapstone	12	498
	Coal	2	500
Cannonball Formation:			
	Soapstone	14	514
	Hard sandrock	5	519
	Fossil shells, soapstone, and sandstone	50	569
	Quicksand	35	604
Ludlow Formation:			
	Coal	2	606
	Soapstone	3	609
	Coal	5	614
	Soapstone	55	669

140-102-26cbb, Continued

Source Lithology	Thickness (feet)	Depth (feet)
Cannonball Formation:		
Soapstone with fossil	2	671
Quicksand	18	689
Ludlow Formation (?):		
Soapstone	72	761
Coal	5	766
Hell Creek Formation (?):		
Soapstone	78	844
Coal	3	847
Soapstone	35	882
Coal	1	883
Soapstone and sandstone	32	915
Coal	1	916
Coarse soft sand	15	931
Sand and gravel	10	941

139-101-10cca

Owner: Abandoned Elev.: 2595

Comment: The log of this well is from Simpson (1929, p. 78).

Source Lithology	Thickness (feet)	Depth (feet)
Sentinel Butte Formation:		
Shale	56	56
Coal	1	57
Shale	29	86
Tongue River Formation:		
Coal	12	98
Shale	148	246
Rock	3	249
Shale	64	313
Coal	9	322
Shale	99	421
Sand and shale	135	556
Ludlow Formation (?):		
Shale	24	580
Rock	6	586
Sand and shale	45	631

139-99-21ccc

Owner: NDSWC (#3539) Elev.: 2620

Comment: This log contained tentative picks for the Sentinel Butte-Tongue River and Tongue River-Ludlow contacts. These picks were agreed with and incorporated into the cross section. The top of the Cannonball Formation was not indicated on the log. That pick is solely the responsibility of the writer.

Source	Lithology	Thickness (feet)	Depth (feet)
Sentinel Butte Formation:			
	Topsoil, dark yellowish gray, very fine sandy loam	1	1
	Shale, yellowish gray to dusky yellow with iron stains to brownish gray, silty, soft, oxidited	19	20
	Lignite	6	26
	Shale, light to medium gray and brownish-black, silty, carbonaceous, smooth, tight	14	40
	Shale, light gray to light greenish gray with brown stains, silty	10	50
	Shale, moderate dark greenish gray, sandy	9	59
	Sandstone, dark greenish gray and brownish black, fine, clayey, carbonaceous in part, soft	9	68
	Sandstone, dark greenish gray, fine and medium, contains lignite flakes, fairly clean, weakly consolidated	11	79
	Sandstone, greenish gray, indurated	2	81
	Sandstone, dark greenish gray, fine and medium, weakly consolidated	7	88
	Shale, white, sandy, clayey, soft	2	90
	Sandstone, as above, takes drilling fluid	8	98
	Shale	2	100
	Lignite, black and brown, soft to hard, takes drilling fluid	15	115
	Shale, light greenish gray, silty, smooth, moderately hard	5	120

139-99-21ccc, Continued

Source	Lithology	Thickness (feet)	Depth (feet)
Sentinel Butte Formation, Continued:			
	Shale, greenish gray to dark gray, silty, with thin layers of white bentonitic clay--------	20	140
	Shale, greenish gray, silty, smooth, tight-------------------	10	150
	Shale, as above but medium gray--------------------------	10	160
	Shale, variegated gray and green with carbonaceous streaks-----------------------	18	178
	Siltstone (?), yellowish-gray, highly calcareous, indurated----	1	179
	Shale, medium gray, bentonitic--	9	188
	Lignite-------------------------	1	189
	Shale, as above-----------------	11	200
	Shale, interbedded medium gray, silty, and dark greenish gray, sandy, and white soft clay------	14	214
	Sandstone, greenish gray, partly indurated---------------	3	217
	Shale, greenish gray and medium gray, silty--------------	9	226
	Shale, greenish gray and medium gray, bentonitic---------	10	236
Tongue River Formation:			
	Lignite-------------------------	9	245
	Shale, medium gray, tight, with thin interbeds of yellowish buff slightly calcareous siltstone or indurated bentonite----	12	257
	Shale, carbonaceous-------------	4	261
	Shale, medium gray, silty-------	10	271
	Shale, brownish black, carbonaceous-------------------	5	276
	Lignite-------------------------	3	279
	Shale, light gray, very silty---	4	283
	Sandstone, light gray, very fine, semiconsolidated---------------	33	337
	Shale, sandy--------------------	4	341
	Sandstone, as above, but somewhat clayey--------------------	24	365
	Sandstone, light olive gray, very fine to fine, cleaner than above, semiconsolidated----	24	389
	Shale, sandy--------------------	13	402

139-99-21ccc, Continued

Source	Lithology	Thickness (feet)	Depth (feet)
Tongue River Formation, Continued:			
	Sandstone, light olive gray, very fine to fine, clayey, semiconsolidated	6	408
	Shale, sandy	3	411
	Sandstone, light greenish-gray silt to very fine, clayey, tight	8	419
	Shale, sandy	3	422
	Sandstone, as above	3	425
	Shale, sandy	3	428
	Siltstone, light gray, sandy, semiconsolidated	6	434
	Shale, light gray, silty	3	437
	Lignite	3	440
	Shale, light gray, silty, bentonitic	5	445
	Siltstone, light gray, clayey	4	449
	Shale, silty	2	451
	Siltstone, as above	6	457
	Lignite	2	459
	Shale, light olive gray, sandy, with clayey, soft sandstone interbeds	10	469
	Sandstone, light olive gray, silt to fine, semiconsolidated	9	478
	Shale, light gray, silty, tight	7	485
	Siltstone, light gray, sandy, clayey, soft	8	493
	Sandstone, light olive gray, silt to fine, weakly consolidated	22	515
	Siltstone, light gray, very sandy, clayey, soft	7	522
	Sandstone, as above, lignitic	8	530
	Shale, sandy	3	533
	Siltstone, light olive gray, very sandy, soft	15	548
Ludlow Formation:			
	Shale, silty to sandy	6	554
	Lignite	2	556
	Shale, silty to sandy	3	559
	Siltstone, light greenish gray and light gray, sandy, soft, with interbeds of silty and locally carbonaceous shale	19	578

139-99-21ccc, Continued

Source	Lithology	Thickness (feet)	Depth (feet)
Ludlow Formation, Continued:			
	Siltstone and shale as above, with thin lignite interbeds	42	620
	Cored: Recovered 10 feet of dark gray, silty, lignitic shale	10	630
	Siltstone and shale, interbedded as above	12	642
	Shale, light to medium gray, silty, smooth, tight, with occasional hard drilling	12	654
	Sandstone, light gray, brownish gray, and greenish gray, silt to very fine, clayey, soft	10	664
	Shale	3	667
	Lignite	3	670
	Shale, carbonaceous	4	674
	Shale, silty and sandy	4	678
	Siltstone, greehish gray, sandy, mostly soft, with thin indurated layers	7	685
	Shale, silty and sandy	13	698
	Siltstone, as above, interbedded with very fine soft sandstone and sandy shale	20	718
	Lignite	3	721
	Siltstone, light gray, clayey, soft, interbedded with very fine clayey soft sandstone and occasional shale beds	19	740
	Shale, carbonaceous	5	745
	Lignite	9	754
	Shale, carbonaceous	8	762
	Siltstone, clayey, soft (poor samples)	5	767
	Sandstone, silt to very fine, weakly consolidated	28	795
	Lignite	2	797
	Sandstone, as above	12	809
	Sandstone, indurated	1	810
	Sandstone, silt to very fine, increasingly clayey downward, weakly consolidated	20	830
	Sandstone, indurated	1	831
	Shale, silty to sandy	15	846
	Siltstone, brownish-black, sandy, lignitic, soft	5	851
	Lignite	3	854

139-99-21ccc, Continued

Source	Lithology	Thickness (feet)	Depth (feet)
Cannonball Formation:			
	Siltstone, as above------------	2	856
	Shale, dark gray, silty to sandy, carbonaceous------------	11	867
	Siltstone, iron-cemented--------	9	876
	Shale, dark gray, sandy (poor sample return)-----------	15	891
	Sandstone, clayey, indurated in part-----------------------	8	899
	Shale, medium to dark gray and greenish gray, silty and sandy-------------------------	14	913
	Lignite------------------------	1	914
	Shale, sandy-------------------	7	921
	Shale, gray and greenish gray, very tight, with a few thin lignite interbeds-------------	16	937
	Shale, gray and greenish gray, tight-------------------	13	950

Appendix C

ELEVATION OF THE PIERRE SHALE

Well names, locations, and elevations of the Pierre Shale used in this study are listed below. The listings are organized alphabetically by county and sequentially by North Dakota Geological Survey well number (fig. 11). The elevations given are above mean sea level and were determined by subtracting the depth of the formation top from the depth reference; either the Kelley bushing (K.B.) or ground level (G.L.). The format for locations follows that given earlier in the paper.

Billings County

291. Amerada Petroleum Corp. - Herman May #1
139-100-9ba
K.B. 2774

Pierre Shale 852

555. Stanolind Oil and Gas Co. - N. W. I. (N.P.) #1
143-100-17dd
K.B. 2815

Pierre Shale 673

849. Stanolind Oil and Gas Co. - Alfred Schwartz #1
138-100-34dd
K.B. 2828

Pierre Shale 852

1508. Amerada Petroleum Corp. - Scoria Unit #1
139-101-10aa
K.B. 2626

Pierre Shale 891

2294. Shell Oil Co. - N. P. R. R.
141-100-21ad
K.B. 2668

Pierre Shale 761

2357. The California Co. - Govt. #1 Bullion Butte
137-102-20ab
K.B. 2718

Pierre Shale 1198

2426. Amerada Petroleum Corp. - M. Serensen #1
139-100-17bb
K.B. 2802

Pierre Shale 852

2689. Hunt Oil Co. - Nick Haag #1
144-99-21aa
K.B. 2721

Pierre Shale 502

2745. Hunt Oil Co. - William Palanuk #1
144-99-15ca
K.B. 2727

Pierre Shale 497

2768. H. L. Hunt - U. S. A. #1
140-100-4dd
K.B. 2736

Pierre Shale 666

2798. Lamar Hunt - N. P. R. R. #1
144-100-9bc
K.B. 2592

Pierre Shale 592

2853. Shell Oil Co. - N. P. R. R.-Govt. 41X-5-1
143-101-5aa
K.B. 2572

Pierre Shale 764

3333. Pan American Petrol. Corp. - Lucy Fritz #6
137-100-15bc
K.B. 2919

Pierre Shale 914

3679. Cardinal Petrol. Co. - S. Cymboluk #1
141-99-6cb
K.B. 2735

Pierre Shale 615

3746. Davis Oil Co. - Kevin Fed. #1
138-100-10cc
K.B. 2814

Pierre Shale 812

3761. Amerada Petroleum Corp. - U. S. A. Hellickson Unit #1
139-102-2dd
K.B. 2359

Pierre Shale 921

3797. Amerada Petroleum Corp. - U. S. A. Bruce #1
139-102-14ad
K.B. 2370

Pierre Shale 945

3885. Amerada Petroleum Corp. - Scoria Unit #10
139-101-9ad
K.B. 2488

Pierre Shale 848

4012. Amerada Petroleum Corp. - Roberts Unit #1
139-102-22ab
K.B. 2305

Pierre Shale 1015

4031. Tom Jordan - Thompson #1
144-99-29da
K.B. 2641

Pierre Shale 511

4035. Tom Jordan - State #1
144-100-36dd
K.B. 2597

Pierre Shale 560

4091. Sunray DX - N. D. Fed. "A" #1
138-102-10da
K.B. 2528

Pierre Shale 1098

4176. Fundamental Oil Corp. - Fed. #2-24
138-101-24db
K.B. 2732

Pierre Shale 860

4268. Amerada Petroleum Corp. - Burkhardt #1
139-102-8bb
K.B. 2496

Pierre Shale 1028

4419. Shell Oil Co. - Shell-N. P.-Govt. #44-14
144-102-14dd
K.B. 2341

Pierre Shale 741

4455. Shell Oil Co. - Govt. #41X-8
143-101-18aa
K.B. 2468

Pierre Shale 772

4642. Amerada Petrol. Corp. and Kewanee Oil Co. -
U. S. A. Melvin Tract 1 #1
140-102-30cb
K.B. 2585

Pierre Shale 950

Bowman County

4440. International Nuclear Corp. - Lutz #1-6-21
131-103-8ba
K.B. 3106

Pierre Shale 1920

4444. International Nuclear Corp. - State N. Dak. #1-4-5
131-101-36dc
K.B. 2940

Pierre Shale 1589

4448. International Nuclear Corp. - Brewer #1-9-9
132-101-35aa
K.B. 2966

Pierre Shale 1566

4449. International Nuclear Corp. - Lewton #1-5-8
131-101-19cc
K.B. 2932

Pierre Shale 1747

4451. International Nuclear Corp. - Freitag #1-8-7
132-99-32dd
K.B. 2904

Pierre Shale 1366

4452. International Nuclear Corp. - Peterson #1-12-20
132-106-27ac
K.B. 2921

Pierre Shale 2606

4457. International Nuclear Corp. - R. C. Werre #1-27-18
131-103-25ba
K.B. 3046

Pierre Shale 1913

4475. International Nuclear Corp. - Gunvaldsen #1-11-22
132-104-21ac
K.B. 3110

Pierre Shale 2007

4489. International Nuclear Corp. - Oien #1-1-2-X
132-102-7cb
K.B. 2981

Pierre Shale 1671

4502. International Nuclear Corp. - Wegner #1-32
132-101-12bb
K.B. 2940

Pierre Shale 1482

4506. International Nuclear Corp. - Beier #1-31-22
131-104-27dd
K.B. 3215

Pierre Shale 2105

4516. International Nuclear Corp. - Bennett #1-41
132-103-15da
K.B. 3096

Pierre Shale 1778

4517. International Nuclear Corp. - Norem #1-49
131-104-13aa
K.B. 3182

Pierre Shale 1944

4518. International Nuclear Corp. - Moss brucker #1-47
132-102-9aa
K.B. 2943

Pierre Shale 1643

4529. International Nuclear Corp. - Hanna #1-25
132-105-15aa
K.B. 2989

Pierre Shale 2200

4540. International Nuclear Corp. - L. Roen #1-48
132-101-32bb
K.B. 2958

Pierre Shale 1598

4544. International Nuclear Corp. - Evans #1-46
132-104-12cc
K.B. 3131

Pierre Shale 1889

Dunn County

897. W. H. Hunt - T. W. Darwin #1
145-96-35cc
K.B. 2519

Pierre Shale 339

1408. The California Co. - C. Danielson & Bank of N. D.
148-97-20bc
K.B. 2162

Pierre Shale 429

2230. Continental Oil Co. - State #1
147-96-36cc
K.B. 2609

Pierre Shale 281

2615. Stewart Petrol. Corp. - Jack Dvirnak #1
146-96-20aa
K.B. 3039

Pierre Shale 305

4611. Helmerich and Payne Inc. - N. Dak. State #1
146-96-36cc
K.B. 2435

Pierre Shale 355

Golden Valley County

410. Gulf Oil Corp. - N. P. Dorough Federal #1
143-103-24ac
K.B. 2515

Pierre Shale 815

470. Blackwood and Nichols - Gillman #1
140-105-15ad
K.B. 2867

Pierre Shale 1255

586. Gulf Oil Corp. - #1 Federal
143-103-3ba
K.B. 2365

Pierre Shale 813

1705. North American Royalties - #1 Badlands
143-103-22dd
K.B. 2479

Pierre Shale 811

1907. Shell Oil Co. and N. P. R. - N. P. #41-35
139-103-35aa
K.B. 2503

Pierre Shale 1131

3695. Amerada Petroleum Corp. - N. P. "C" Tr. 1 #1
138-103-11cd
K.B. 2616

Pierre Shale 1163

4130. Amerada Petroleum Corp. - Ramona Waldron #1
138-105-9cb
K.B. 2867

Pierre Shale 1537

4308. Skelly Oil Co. - Arthur Reinholz #1
139-104-23db
K.B. 2766

Pierre Shale 1164

4357. Kewanee Oil Co. - Federal #1
140-103-13da
K.B. 2556

Pierre Shale 981

4359. Shell Oil Co. - Govt. #11-5
139-103-5bb
K.B. 2819

Pierre Shale 1094

4466. Lamar Hunt - Emmett Dailey #1
142-104-22dd
K.B. 2595

Pierre Shale 945

4467. Lamar Hunt - Knute Farstreet #1
140-105-21cb
K.B. 2765

Pierre Shale 1333

4490. Lamar Hunt - U. S. A. #1
138-103-29dc
K.B. 2765

Pierre Shale 1357

4525. Lamar Hunt - State of N. D.-Kannenberg #1
138-104-16dc
K.B. 2828

Pierre Shale 1350

4647. Union Oil Co. of Calif. - Jones Ranch #1
143-104-21bb
K.B. 2457

Pierre Shale 867

4729. Target Oil Co. - N. P. R. R. #2
144-105-29dd
K.B. 2399

Pierre Shale 969

4730. Target Oil Co. - N. P. R. R. #3
144-103-17dd
K.B. 2391

Pierre Shale 783

4732. Target Oil Co. - N. P. R. R. #5
145-103-9cc
K.B. 2630

Pierre Shale 683

4733. Target Oil Co. - N. P. R. R. #6
142-103-17dd
K.B. 2599

Pierre Shale 879

4735. Target Oil Co. - N. P. R. R. #8
143-105-17aa
K.B. 2669

Pierre Shale 975

4741. Mule Creek Oil Co. - Shell State #1
140-103-16dd
K.B. 2618

Pierre Shale 1043

4791. Woods Petroleum Corp. - Slocomb #1
141-104-29b
K.B. 2895

Pierre Shale 1165

4801. Target Oil Co. - N. P. R. R. #9
144-104-29aa
K.B. 2610

Pierre Shale 850

McKenzie County

33. Amerada Petroleum Corp. - Ben Homer Risser #1
149-96-12cd
K.B. 2438

Pierre Shale 576

277. Amerada Petroleum Corp. - N. Dak. "B" Tract 2 #1
149-95-16aa
K.B. 2364

Pierre Shale 529

303. Amerada Petroleum Corp. - N. D. "B" Tract 3
150-95-16cc
K.B. 2264

Pierre Shale 714

341. Stanolind Oil and Gas - Woodward Starr #1
152-94-21cd
K.B. 2140

Pierre Shale 579

527. The California Co. - Rough Creek Unit #1
148-98-13ba
K.B. 2472

Pierre Shale 377

545. Phillips, Skelly, and Gulf - Hoehn A-1
152-102-13ad
K.B. 2278

Pierre Shale 292

920. Amerada Petroleum Corp. - Halvor Rolfrud Tract 1 #1
151-97-11da
K.B. 2370

Pierre Shale 757

956. Gulf Oil Corp. - Bennie-Pierre Federal #1
148-104-28bc
K.B. 2339

Pierre Shale 549

1066. Amerada Petroleum Corp. - Sam Grimestad "A" #1
152-95-30ab
K.B. 2451

Pierre Shale 893

1624. Investors Oil Inc. - Ida and Edna Mae Shaide #1
151-103-8cd
K.B. 2200

Pierre Shale 410

1798. Amerada Petroleum Corp. - 1 A. W. S. Belquist
150-95-2dc
K.B. 2273

Pierre Shale 711

1995. Skelly Oil Co. - Otto Tank #1
152-96-34ab
K.B. 2328

Pierre Shale 883

2469. Shell and N. Pacific R. - N. P. 32-15
145-101-15ca
K.B. 2294

Pierre Shale 644

2667. Texaco Inc. - Govt.-Mary Pace #1
146-101-14cb
K.B. 2382

Pierre Shale 573

2678. Shell and N. Pacific R. - N. P. #32X-23-1
145-101-23ca
K.B. 2401

Pierre Shale 650

2707. Shell and N. Pacific R. - N. P. 14-35-1
145-101-35cc
K.B. 2218

Pierre Shale 684

2723. Hunt Oil - 1 U. S. A.-A-1-10
145-101-10ac
K.B. 2320

Pierre Shale 612

2786. H. L. Hunt - U. S. A. "A" #1
148-102-15bc
K.B. 2383

Pierre Shale 465

2821. W. H. Hunt - Eva Glovatsky #1
145-99-3ba
K.B. 2177

Pierre Shale 476

2849. Lyda H.-H. Hunt Trust Estate - Henry C. Hystad #1
152-99-31ac
K.B. 2316

Pierre Shale 214

2906. Texaco Inc. - Govt. Dorough "E" (N.C.T.-2) #8
151-95-21ba
K.B. 2573

Pierre Shale 754

3020. Sinclair Oil and Gas - Fed.-7009-McK. #1
146-104-33ab
K.B. 2501

Pierre Shale 718

3084. Sinclair Oil and Gas - Fed.-7020-McK. Unit #1
147-103-11cd
K.B. 2330

Pierre Shale 628

3157. Caroline Hunt Trust Estate - Martin Nelson #1-A
149-98-11bd
K.B. 2232

Pierre Shale 226

3614. Calvert Drilling and Producing Co. - Alfred Brown #1
151-96-34aa
K.B. 2415

Pierre Shale 801

3645. Quintana Petroleum Corp. - U. S. A. #1
145-105-24dd
K.B. 2379

Pierre Shale 774

4050. Amerada Petroleum Corp. - Skjelvik Unit #1
150-97-26dc
K.B. 2237

Pierre Shale 552

4088. F.U.C.E.-National Refinery Assoc. - N.P.R.R. #14-21
145-101-21cc
K.B. 2305

Pierre Shale 686

4240. Amerada Petroleum Corp. - Antelope-Devonian Unit #4
152-94-7bb
K.B. 2200

Pierre Shale 676

4385. Shell Oil Co. - Turnquist #13X-15
148-101-15bc
K.B. 2246

Pierre Shale 416

4617. King Resources - Anton Zurn Estate #1
145-99-1ba
K.B. 2652

Pierre Shale 432

4728. Target Oil Co. - N. P. R. R. #1
145-103-9cc
K.B. 2630

Pierre Shale 683

4734. Target Oil Co. - N. P. R. R. #7
146-103-9ba
K.B. 2288

Pierre Shale 651

4807. Consolidated Oil and Gas Incorp. and Miami Oil - Federal Land Bank #24-1
151-101-24db
K.B. 2130

Pierre Shale 332

Slope County

378. D. D. Feldman Oil and Gas - Benz #1
135-98-20ca
K.B. 2954

Pierre Shale 1052

1464. Skelly Oil Co. - Bismarck "A" #1
135-100-16cc
K.B. 2807

Pierre Shale 1192

2805. North American Royalties - Hanna Estate #1
135-101-9dd
K.B. 2795

Pierre Shale 1257

4075. H. L. Hunt - N. P. R. R. "A" #1
136-101-9ac
K.B. 2777

Pierre Shale 1224

4124. H. L. Hunt - Eva Hayden #1
136-101-4d
K.B. 2740

Pierre Shale 1155

4450. International Nuclear Corp. - Braun #1-16-15
133-100-19da
K.B. 2931

Pierre Shale 1389

4460. International Nuclear Corp. - Govt. #1-21-27
135-105-21cc
K.B. 2666

Pierre Shale 1946

4461. International Nuclear Corp. - Long #1-28-26
134-105-20aa
K.B. 2913

Pierre Shale 2042

4464. International Nuclear Corp. - Teskie #1-14-11
133-99-11dd
K.B. 2819

Pierre Shale 1296

4471. International Nuclear Corp. - Johnson #1-24-16
136-104-8aa
K.B. 2614

Pierre Shale 1493

4472. International Nuclear Corp. - Rustan #1-19-13
134-98-22da
K.B. 2764

Pierre Shale 1174

4476. International Nuclear Corp. - Silbernagel #1-17-23
133-103-26cb
K.B. 2941

Pierre Shale 1711

4477. International Nuclear Corp. - State #1-22-30
136-102-16ba
K.B. 2433

Pierre Shale 1283

4478. International Nuclear Corp. - B. Foust #1-23-29
136-103-15cc
K.B. 2708

Pierre Shale 1418

4480. International Nuclear Corp. - Govt. M. Wyckoff
#1-29-24
135-103-12dd
K.B. 2650

Pierre Shale 1414

4481. International Nuclear Corp. - Govt. J. Cole #1-18-25
133-104-18aa
K.B. 3074

Pierre Shale 2100

4482. International Nuclear Corp. - Davis #1-30-28
136-104-26cd
K.B. 2862

Pierre Shale 1512

4495. International Nuclear Corp. - Stockart #1-20-14
134-99-22cc
K.B. 2844

Pierre Shale 1239

4496. International Nuclear Corp. - Govt. #40
134-106-4bb
K.B. 2837

Pierre Shale 2327

4499. International Nuclear Corp. - Govt. Foe #1-37
134-103-34bc
K.B. 2943

Pierre Shale 1722

4503. International Nuclear Corp. - Gatzke #1-36
135-99-7cc
K.B. 2756

Pierre Shale 1078

4504. International Nuclear Corp. - Davis #1-39
135-104-20cc
K.B. 2857

Pierre Shale 1710

4505. International Nuclear Corp. - Hagenstad #1-35
135-99-32aa
K.B. 2794

Pierre Shale 1179

4515. International Nuclear Corp. - Stockert #1-34
134-99-2aa
K.B. 2941

Pierre Shale 1273

4521. International Nuclear Corp. - Meagers #1-43
134-104-36ba
K.B. 3068

Pierre Shale 1744

4522. International Nuclear Corp. - Pierce #1-44
134-99-35cc
K.B. 2806

Pierre Shale 1238

4528. International Nuclear Corp. - Wolfgram #1-33
136-103-33bc
K.B. 2898

Pierre Shale 1473

4530. International Nuclear Corp. - Roen #1-13-12
134-101-35dd
K.B. 3051

Pierre Shale 1349

4531. International Nuclear Corp. - Dilse #1-45C
133-99-19dd
K.B. 2842

Pierre Shale 1392

4532. International Nuclear Corp. - Berquist #1-38
135-103-26dd
K.B. 2775

Pierre Shale 1562

4541. International Nuclear Corp. - Wellstandt #1-52
134-98-31ac
K.B. 2796

Pierre Shale 1238

4543. International Nuclear Corp. - Flor #1-56
133-106-29dd
K.B. 2850

Pierre Shale 2428

4547. International Nuclear Corp. - Swanson #1-54
133-99-6cc
K.B. 2882

Pierre Shale 1347

4565. International Nuclear Corp. - Overbo #1-51
134-98-31ad
K.B. 2799

Pierre Shale 1264

4570. International Nuclear Corp. - Arneson #1-57
133-98-5db
K.B. 2785

Pierre Shale 1245

4578. International Nuclear Corp. - Arneson #1-58
133-98-6ac
K.B. 2779

Pierre Shale 1271

Stark County

344. Plymouth Oil Co. - Frank A. Fischer #1
137-98-11ca
K.B. 2797

Pierre Shale 733

539. W. H. Hunt - Victor H. Kudrna #1
139-97-20cb
K.B. 2590

Pierre Shale 672

613. Amerada Petroleum Corp. - R. E. Newton #1
140-99-31bc
K.B. 2697

Pierre Shale 685

657. Sun Oil Co. - W. Beaudoin #1
138-99-9cb
K.B. 2640

Pierre Shale 720

810. So. Prod. and Texota - F. J. Wanner #1
137-97-9bb
K.B. 2690

Pierre Shale 740

850. W. H. Hunt - A. A. Privratsky #1
138-98-15bb
K.B. 2652

Pierre Shale 712

1536. Skelly Oil Co. - A. Weigum #1
138-99-25db
K.B. 2644

Pierre Shale 740

1574. Northern Pump Co. - C. Braun #1
137-99-15bb
K.B. 2733

Pierre Shale 850

2075. Shelly Oil Co. - S. Merrill #1
140-98-33db
K.B. 2526

Pierre Shale 589

2117. Tenneco Gas and Trans. Co. - Casmer Steele
Duletski #1
139-99-16bb
K.B. 2644

Pierre Shale 684

3767. Tom Jordan - N. P. R. R. #1
139-98-3da
K.B. 2550

Pierre Shale 622

4237. Continental Oil Co. - Zander Anderson #1
140-97-34db
K.B. 2484

Pierre Shale 577

REFERENCES CITED

Abbott, G. A. and Voedisch, F. W., 1938, The municipal ground water supplies of North Dakota: North Dakota Geol. Survey Bull. 11.

APHA, 1960, Standard methods for the analysis of water and wastewater: New York, Am. Public Health Assoc., 626 p.

Babcock, H. M. and Cushing, E. M., 1942, Recharge to groundwater from floods in a typical desert wash, Pinal County, Arizona: Trans. Am. Geophy. Union, pt. 1, 49-55.

Back, W., 1960, Origin of hydrochemical facies of groundwater in the Atlantic Coastal Plain: Proc. 22nd Int. Geol. Cong., Copenhagen, 1960, v. 1, pt. 1, p. 87-95.

Barnes, I., 1964, Field measurement of alkalinity and pH: U. S. Geol. Surv. Water-Supply Paper 1535-H, 17 p.

Brown, I. C., 1963, Chemical methods as an aid to hydrogeology: Proc. Hydrol. Symp. No. 3, Natl. Res. Council Canada, p. 181-203.

Brown, R. W., 1962, Paleocene flora of the Rocky Mountains and Great Plains: U. S. Geol. Surv. Prof. Paper 375, 119 p.

Carlson, C. G., 1969, Bedrock geologic map of North Dakota: North Dakota Geol. Survey Misc. Map No. 10.

Cedergren, H. R., 1968, Seepage, drainage, and flow nets: John Wiley & Sons, 498 p.

Cederstrom, D. J., 1946, Genesis of ground waters in the Coastal Plain of Virginia: Econ. Geol., v. 41, p. 218-245.

Charron, J. E., 1965, Groundwater resources of the Emerson area, Manitoba: Geol. Surv., Can., Paper 64-7, 39 p.

Chebotarev, I. I., 1955, Metamorphism of natural waters in the crust of weathering: Geochim. et Cosmochim. Acta, v. 8, p. 22-48, 137-170, 198-212.

Clayton, L., 1969, Preliminary geologic map of Dunn County: North Dakota Geol. Surv. Misc. Map 11.

Everitt, B. L., 1968, Use of the cottonwood in an investigation of the recent history of a flood plain: Am. J. Sci, v. 266, p. 417-439.

Feely, H. W. and Kulp, J. L., 1957, Origin of Gulf Coast salt-dome sulphur deposits: Am. Assoc. Petrol. Geol., v. 41, p. 1802-1853.

Feldman, R. M., 1967, Bivalvia and paleoecology of the Fox Hills Formation (upper Cretaceous) of North Dakota: Univ. North Dakota, Grand Forks, N. Dak., (unpublished Ph.D. thesis), 343 p.

Freeze, R. A. and Witherspoon, P. A., 1966, Theoretical analysis of regional groundwater flow. 1. Analytical and numerical solutions to the mathematical model, Water Resources Res., v. 2, p. 641-656.

______________________________, 1967, Theoretical analysis of regional groundwater flow. 2. The effect of water-table configuration and subsurface permeability variation: Water Resources Res., v. 3, p. 623-634.

______________________________, 1968, Theoretical analysis of regional groundwater flow. 3. Quantitative interpretations: Water Resources Res., v. 4, p. 581-590.

Frye, C. I., 1969, Stratigraphy of the Hell Creek Formation in North Dakota: North Dakota Geol. Survey Bull. 54, 65 p.

Grim, R. E., 1968, Clay mineralogy: McGraw-Hill Book Co., 596 p.

Hagmaier, J. L., (in press), Surface morphology of the Little Missouri Badlands, North Dakota: Compass.

Hamilton, T. M., 1967, Late-recent alluvium of western North Dakota: North Dakota Geol. Survey Misc. Series 30, p. 151-159.

Harrison, S. S., and Clayton, L., Effects of ground-water seepage on fluvial processes: Geol. Soc. of America Bull., v. 81, p. 1217-1226.

Hem, J. D., 1961, Calculation and use of ion activity: U. S. Geol. Survey Water-Supply Paper 1535-C, 17 p.

Hennen, R. V., 1943, Tertiary geology and oil and gas prospects in Dakota Basin, North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 27, p. 1567-1594.

Hitchon, B., 1969a, Fluid flow in the western Canada sedimentary basin. 1. Effect of topography: Water Resources Res., v. 5, p. 186-195.

____________, 1969b, Fluid flow in the western Canada sedimentary basin. 2. Effect of geology: Water Resources Res., v. 5, p. 460-469.

Hubbert, M. K., 1940, The theory of groundwater motion: J. Geol. v. 48, p. 785-944.

Johnson, A. I., 1963, A field method for measurement of infiltration: U. S. Geol. Survey Water-Supply Paper 1544-F, 27 p.

Krauskopf, K. F., 1967, Introduction to geochemistry: McGraw-Hill Book Company, 721 p.

Linsley, R. K., Kohler, M. A., and Paulhus, J. L., 1958, Hydrology for engineers: McGraw-Hill Book Company, 340 p.

Maxey, G. B., 1968, Hydrogeology of desert basins: Ground Water, v. 6, p. 10-22.

Meinzer, O. E., 1927, Plants as indicators of groundwater: U. S. Geol. Surv., Water-Supply Paper 577, 95 p.

Meyboom, P., 1963, Patterns of groundwater flow in the prairie profile: Proc. Hydrol. Symp. No. 3, Natl. Res. Council Canada, p. 5-33.

____________, 1966a, Current trends in hydrogeology: Earth Science Reviews, v. 2, p. 345-364.

____________, 1966b, Groundwater studies in the Assiniboine River drainage basin, Pt. I, The evaluation of a flow system in south-central Saskatchewan: Geol. Surv. Can., Bull. 139, 65 p.

Meyboom, P., 1967a, Mass transfer studies to determine the groundwater regime of permanent lakes in hummocky moraine of western Canada: J. Hydrol, v. 5, p. 117-142.

____________, 1967b, Groundwater studies in the Assiniboine River drainage basin, Pt. II, Hydrologic characteristics of phreatophytic vegetation in south-central Saskatchewan: Geol. Surv. Can., Bull. 139, 64 p.

Meyboom, P., van Everdingen, R. O., and Freeze, R. A., 1966, Patterns of groundwater flow in seven discharge areas in Saskatchewan and Manitoba: Geol. Surv. Can., Bull. 147, 57 p.

North Dakota State Dept. of Health, 1964, Chemical analyses of municipal waters in North Dakota: N. Dak. State Dept. of Health, 25 p.

Piper, A. M., Garrett, A. A., and others, 1953, Native and contaminated waters in the Long Beach-Santa Ana area, California: U. S. Geol. Survey Water-Supply Paper 1136, 320 p.

Qashu, H. K. and Buol, S. W., 1967, Hydraulic and Micromorphological properties of stream channel sediments: Water Resources Res., v. 3, p. 465-469.

Rainwater, F. H. and Thatcher, L. L., 1960, Methods for collection and analysis of water samples: U. S. Geol. Survey Water-Supply Paper 1454, 301 p.

Renick, B. C., 1924, Base exchange in groundwater by silicates as illustrated in Montana: U. S. Geol. Survey Water-Supply Paper 520, p. 53-72.

Riffenburg, H. B., 1925, Chemical character of ground waters of the Northern Great Plains: U. S. Geol. Survey Water-Supply Paper 560, p. 31-52.

Royse, C. F., 1967, Tongue River-Sentinell Butte contact in western North Dakota: North Dakota Geol. Surv. Rept. Inv. 45, 53 p.

Simpson, H. E., 1929, Geology and ground-water resources of North Dakota: U. S. Geol. Survey Water-Supply Paper 598, 312 p.

Taylor, O. J., 1965, Ground-water resources along Cedar Creek anticline in eastern Montana: Mont. Bur. Mines and Geol., Mem. 40, 99 p.

Tóth, J., 1962, A theory of groundwater motion in small drainage basins in Central Alberta, Canada: J. Geophys. Res., v. 67, p. 4375-4387.

__________, 1963, A theoretical analysis of groundwater flow in small drainage basins: J. Geophys. Res., v. 68, p. 4795-4812.

__________, 1966, A hydrogeological study of the Three Hills area, Alberta: Res. Coun. Alberta Bull. 24, 117 p.

Trapp, H., 1968, Geology and ground water resources of Eddy and Foster Counties, North Dakota, Pt. III, Ground water resources: North Dakota Geol. Survey Bull. 44, 110 p.

U. S. Geological Survey, 1956, Quality of surface waters of the United States 1951, Pts. 5-6: Geol. Survey Water-Supply Paper 1198, 586 p.

van Everdingen, R. O., 1963, Groundwater flow-diagrams in sections with exaggerated vertical scale: Geol. Surv. Can., Paper 63-27, 21 p.

Williams, R. E., 1968, Flow of ground water adjacent to small, closed basins in glacial till: Water Resources Res., v. 4, p. 777-783.