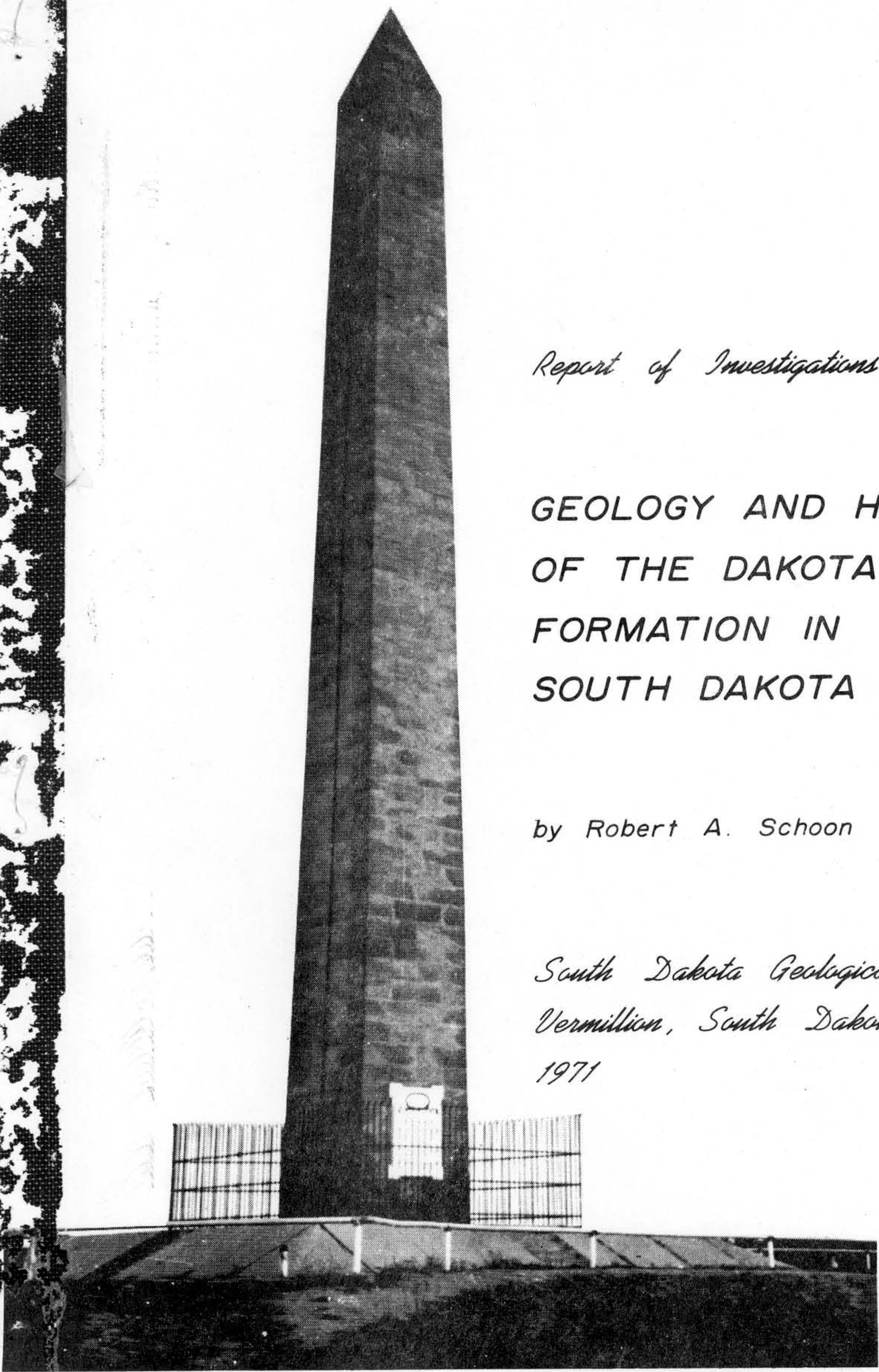

Report of Investigations No. 104

GEOLOGY AND HYDROLOGY OF THE DAKOTA FORMATION IN SOUTH DAKOTA

by Robert A. Schoon

South Dakota Geological Survey
Vermillion, South Dakota
1971

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Cover: *The Sergeant C. Floyd Monument is situated a few hundred yards east of the original gravesite of Sergeant Floyd who was a member of the Lewis and Clark Expedition that left St. Louis in 1804. This expedition explored the Missouri River to its source, westward to the Pacific Ocean. Shortly after the start of the expedition, Captain Lewis, on August 19th and 20th, 1804, entered in his journals the following, "Serjeant Floyd is taken verry bad all at once with a Biliose Chorlick we attempt to relieve him without success as yet, he gets worst and we are much allarmed at his Situation, all [give] attention to him. . . .*

Sergeant Floyd much weaker and no better. Serjeant Floyd as bad as he can be no pulse & nothing will Stay a moment on his Stomach or bowels. Passed two Islands on the S. S. and at the first Bluff on the S. S. Serj. Floyd Died with a great deal of Composure, before his death he Said to me, "I am going away" I want you to write me a letter." We buried him on the top of the bluff ½ Mile below a Small river to which we Gave his name, he was buried with the Honors of War much lamented, a Seeder post with the (1) Name Sergt. C. Floyd died here 20th of august 1804 was fixed at the head of his grave. This Man at all times gave us proofs of his firmness and Determined resolution to doe Service to his Countrey and honor to himself after paying all the honor to our Decesed brother we camped in the Mouth of floyds River about 30 yards wide, a butifull evening." [1]

The Floyd Monument marks an area where the Missouri River flows past bluffs that are composed, in part, of the Dakota Formation which is discussed in this report.

[1]Thwaites, R. G., 1904, Original journals of the Lewis and Clark Expedition 1804-1806, v. 1, p. 114-115.

STATE OF SOUTH DAKOTA
Richard Kneip, Governor

SOUTH DAKOTA GEOLOGICAL SURVEY
Duncan J. McGregor, State Geologist

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ABSTRACT

The enigma of the Dakota problem is probably the result of complex terminology rather than complex stratigraphy. Meek and Hayden's original description of the Dakota Formation was simple and straightforward, but subsequent authors have in various ways corrupted the original meaning of the term beyond recognition. A better understanding of the Cretaceous stratigraphy is obtained if the term Dakota is employed as used by Meek and Hayden in the type area.

In this manner the entire 400 foot section of sediments in the type area in northeastern Nebraska is included in the Dakota Formation. The Dakota thins westward and is represented in the Black Hills by the Newcastle tongues at the base and sporadic outcrops of the Mowry sands at the top; it includes no part of older sandstone bodies.

The Inyan Kara Group which resembles the Dakota Formation and crops out in the Black Hills, is not represented either at the surface or in the subsurface at the type area of the Dakota. It is believed that the Inyan Kara Group and the Dakota Formation are separate stratigraphic and hydrologic units with distinctive water characteristics and hydraulic pressures.

There are three distinct water types in the Dakota Formation. These are: sodium chloride in the western half of the State, sodium sulfate in the eastern part of the State, and a smaller area of calcium-sulfate type water in the southeastern quarter of the State. Information from drill-stem tests and water wells in the southern half of South Dakota indicates that the Roundtop-Inyan Kara interval usually produces sodium-sulfate type water, and the Precambrian-Roundtop interval ordinarily produces calcium-sulfate type water. These two intervals directly and indirectly recharge the Dakota Formation where it overlies the truncated edge of these older rocks. Simply stated, the sodium-chloride water in the Dakota Formation of western South Dakota is connate. In eastern South Dakota where the Dakota yields a sodium-sulfate type water, the formation is recharged by the Roundtop-Inyan Kara interval. In the area of the Sioux Ridge and south of it, the Dakota yields a calcium-sulfate type water. Here the Dakota is recharged by water from the Inyan Kara Group which receives recharge from the Precambrian-Roundtop interval in the area of the Missouri River a short distance north of Chamberlain and south to the southern border of the State.

This theory concerning recharge to the Dakota Formation is supported by hydrologic and stratigraphic data. Earlier theories which employed phenomena such as lenticularity of the Dakota Formation, compaction of the sandstone, weight of overlying sediments and ion exchange capabilities of the sediments to explain recharge, origin of pressure, and water quality variations do not appear valid.

INTRODUCTION

Purpose

Approximately 85 percent of the area of South Dakota is underlain by an artesian system (fig. 1). This artesian system is not made up of any single rock unit but is a combination of several units that transmit water to a main component which is the Dakota Formation.

South Dakota Public Water Supply Data (1961) lists analyses of 249 municipal water supplies. Of the towns listed, 62 obtain their water from either the Dakota Formation or formations that recharge the Dakota. Davis, Dyer, and Powell (1961, p. 1) estimated that 15,000 wells tap the artesian basin. If it is assumed that four persons depend upon each rural artesian well and one-fourth of the cities in South Dakota utilize the Dakota for their water needs then approximately 160,000 persons, or about 25 percent of the population of the State, derive their water supplies from the Dakota Formation.

This indicates that the water stored in the Dakota Formation is one of the State's most valuable resources. Should this source of water be reduced to a point that large-scale pumping is necessary to obtain the water, the result will have a profound detrimental effect upon the economy of the State as a whole. Therefore, it is the purpose of this report to answer as accurately as possible the following questions:

1. What is the origin, areal extent, and thickness of the Dakota Formation?
2. From where does the water in the Dakota originate?
3. What is the storage capacity of the Dakota artesian system?
4. Is recharge sufficient to insure an adequate water supply for future generations?
5. Is it possible to predict the water quality and quantity from a proposed well at any given location?
6. Can the wasteful discharge of water be reduced or halted?
7. Can the life expectancy of a flowing well that taps the Dakota Formation be accurately estimated?
8. What are the possibilities that oil and/or gas accumulations of commercial importance exist in the Dakota Formation?
9. Can the Dakota Formation be safely used for the disposal of waste fluids and/or the storage of natural gas?

History of Exploitation

There is some disagreement in the literature regarding the location of the first well to tap the artesian aquifer in the State. P. F. McClure (1887, p. 186) notes that a well at Andover (approximately 30 miles east of Aberdeen) was drilled to a total depth of 1070 feet from March 20 to June 5, 1881. The 4½ inch well flowed 300 gallons of water per minute, closed in pressure was 90 pounds per square inch, and the temperature of the water was 60°F. According to Shepard (1895, p. 56) the old railroad well at Aberdeen was the first well to tap the Dakota Formation. This well was drilled in 1881-2 by W. E. Swan and had a closed in pressure of 180 pounds per square inch. The depth of the well is unknown, but from records of subsequent wells drilled in the area the well must have bottomed at approximately 1,100 feet.

Perhaps the historic first is not as important as the data that are present in these two reports. For instance, the approximate hydrostatic level of the Dakota Formation at Aberdeen and Andover, South Dakota, was 1716 and 1708 feet, respectively, in the early 1880's and had decreased approximately 50 feet prior to publication of Darton's report in 1909 (pl. XI).

Culver (1890, p. 2) states that "more than 100 successful wells, scattered through thirty or more counties, have been sunk." Darton (1909, p. 64) estimated more than 1,000 wells had been developed in the Dakota east of the Missouri River in South Dakota. Berg (1922, p. 46) stated that the number of artesian wells in South Dakota was 2,626 in 1910. Derr (1916, p. 145-146) believed the total number of artesian wells drilled in the State from

1881 to 1916 was approximately 10,000. However, Berg (1922, p. 56) believed that the total number of artesian wells in the State was probably close to 8,000 in the year 1922, and later (Berg, 1932, p. 71) stated, "Very few record cards prepared by assessors have been received from the counties, hence the office card file is not by any means 'up-to-date.' "

The preceding paragraph illustrates that accurate records of the number of artesian wells in the State do not exist. For lack of these records it can only be assumed that approximately 15,500 artesian wells have been drilled in South Dakota to date.

Nomenclatural Development

The first recorded account of the Dakota Formation is found in the original notes of the Lewis and Clark expedition of 1804-6. An entry by Captain Clark describes a "yellow, soft sandstone" near the Maher (Omaha) Indian Chief Blackbird burial mound in the bluffs on the west side of the Missouri River (Thwaites, 1904, p. 106).

Approximately fifty years later in 1853 the first relatively detailed study of the Dakota was initiated by Meek and Hayden. As a result of this study the Cretaceous rocks that crop out along the upper Missouri River valley were subdivided into five formations in their report published in 1856 (Meek and Hayden, 1876, p. xxiii). These formations were described as they appear in figure 2.

Clays, sandstones, etc., etc., containing remains of Mammalia. The entire thickness of this formation in the Bad Lands is from .... 25 to 250 feet.
5. Arenaceous clays passing into argillo-calcareous sandstones .... 80 feet.
4. Plastic clays with calcareous concretions, containing numerous fossils .... 250 feet. This is the principle fossiliferous bed of the Cretaceous formation on the Upper Missouri.
3. Calcareous marl containing Ostrea congesta, scales of fishes, etc. .... 100 to 150 feet.
2. Clay containing a few fossils .... 80 feet.
1. Sandstone and clay .... 90 feet.
Buff colored magnesian limestone of Carboniferous period.

Figure 2.–Section of the members of the Cretaceous formation on the Missouri and thence westward to the Mauvaises Terres.

From Meek, *in* Hayden, F. V., 1876, Report of the United States Geological Survey of The Territories, Volume IX, p. XXIII.

In 1861 Meek and Hayden revised the nomenclature of Cretaceous rocks of the northwest and employed geographical names to replace the numbered formations used previously (fig. 3). It is interesting to note at this point that Meek and Hayden in 1861 (1876, p. XXIV-XXV) described the Dakota Group (formerly Formation No. 1) as 400 feet thick instead of 90 feet thick as previously described in 1856. The reason for the discrepancy in the thickness of the Dakota published in the two reports of Meek and Hayden can be explained by either one of two possibilities.

It is possible that at some time previous to their report of 1861 Meek and Hayden had correlated the Dakota Group in northeastern Nebraska with what is now known as the Inyan Kara Group in the Black Hills area. However, in his report of 1872 (p. 86), Hayden states, "Formation No. 1, as seen all along the flanks of the mountains from the Bighorn and Wind River ranges to New Mexico, has never yielded a single characteristic fossil, and the lithological characters are quite different in many respects from those which are peculiar to the group, as shown near Sioux City and southward into Kansas."

Also as late as 1876 Meek (fig. 3, this report, and Meek and Hayden, 1876, p. XXV) did not include the Black Hills as a locality in which the Dakota was present. It can be argued that Meek's description was of a general section of the Cretaceous rocks of Nebraska and, hence, would not include the area of the Black Hills. However, the Black Hills were included in the Nebraska Territory at the time of the original study. On March 2, 1861 the Dakota Territory was organized. This act included the Black Hills in the Dakota Territory before Meek and Hayden had delivered their report on the rocks and fossils of the Upper Missouri to the Academy of Natural Science of Philadelphia in December of 1861. In addition, in the same general section of Cretaceous rocks, the Black Hills was given as a locality in which Formation No. 2 was present. Thus it appears that Meek and Hayden were not entirely convinced that the Dakota was present in the Black Hills.

The other possibility for the discrepancy in the reported thickness of the Dakota may have been the receipt of subsurface information from the Sioux City area during the period 1857-1861. In July of 1867 Hayden (1873, p. 7) wrote, "I inclose a section of an artesian boring made at Omaha by the Union Pacific Railroad Company, near 400 feet." In view of this it is quite possible that the reported increase in thickness of the Dakota was a result of subsurface information gained from wells drilled in the Sioux City area. Nowhere in the type area is more than 150 feet of the Dakota exposed. However, a test drilled by the South Dakota Geological Survey (S.D.G.S. No. 1 Huebner, SW¼NW¼ sec. 25, T. 93 N., R. 50 W.) in 1961 indicates the Dakota is at least 400 feet thick near the type area.

Because of the discovery of gold in the Black Hills, Newton and Jenny were selected to make a more thorough study of the geology of the area. Their study did not deal primarily with the Cretaceous rocks, but from their report of 1880 it is apparent they restricted the term Dakota Group to include only the rocks that are now assigned to the Inyan Kara Group.

Ward (1894, p. 265), on the basis of fossil evidence, stated, "It would seem probable that a considerable portion of the deposits underlying the marine Cretaceous of the Rocky Mountain region which have heretofore been referred to the Dakota Group on purely stratigraphic evidence may really be much older." Earlier on the same page he stated, "Leaves of *Pinus* and *Septostrobus* occur quite frequently in the Potomac formation in Virginia, Alabama and New Jersey, but have never been found in the Dakota Group. So far, therefore, as these forms from the Black Hills go they favor the view that the bed in which they occur is Lower Cretaceous." From page 254 of the same report it is obvious that Ward used the term Dakota Group to include only rocks of the upper Cretaceous. However, at that time the upper and lower Cretaceous boundary in the Black Hills area was not definitely known and in effect Ward (1899, facing page 593) applied the term Dakota to rocks that are now included in the Fall River Formation of the Inyan Kara Group.

Darton (1901, p. 526) followed the suggestion of Ward and restricted the term Dakota to include the uppermost sandstone containing the conjectured upper Cretaceous flora (now Fall River). In the same report Darton subdivided the underlying Cretaceous rocks into the Lakota Formation, the Minnewasta Limestone, and the Fuson Formation, all of which are now included in the Inyan Kara Group.

Earlier, Darton (1896, p. 611) believed the Dakota Formation was a relatively flat-lying

Series	Group	Formation	Divisions and Subdivisions	Localities	*	
UPPER SERIES	FOX HILLS GROUP	Formation No. 5	Gray, ferruginous, and yellowish sandstone and arenaceous clays containing *Belemnitella bulbosa, Nautilus Dekayi, Placenticeras placenta, P. lenticularis, Scaphites Conradi, S. Nicolleti, Baculites grandis, Pyropsis Bairdi, Piestochilus Culbertsoni, Pyrifusus Newberryi, Anchura Americana, Pseudobuccinum Nebrascense, Mactra Warrenana, Cardium subquadratum,* and a great number of other molluscan fossils, together with bones of *Mosasaurus Missouriensis*, etc.	Fox Hills, near Moreau River; near Long Lake, above Fort Pierre; along the base of the Big Horn Mountains, and on North and South Platte Rivers.	500 feet	Equivalents of Upper or White Chalk and Maestricht beds (Senomen, d'Orbigny).
	FORT PIERRE GROUP	Formation No. 4	Dark-gray and bluish plastic clays, containing, near the upper part, *Nautilus Dekayi, Placenticeras placenta, Baculites ovatus, B. compressus, Scaphites nodosus, Dentalium gracile, Crassatella Evansi, Cucullaea Nebrascensis, Inoceramus Sagensis, I. Nebrascensis, I. Vanuxemi,* bones of *Mosasaurus Missouriensis*, etc.	Sage Creek, Cheyenne River, and on White River above the Mauvaises Terres.	700 feet	
			Middle zone, nearly barren of fossils.	Fort Pierre and out to Bad Lands; also down the Missouri on the high country to Great Bend.		
			Lower fossiliferous zone, containing *Ammonites complexus, Bacultes ovatus, B. compressus, Heteroceras Mortoni, H. tortum, H. umbilicatum, H. cochleatum, Ptychoceras Mortoni, Odontobasis vinculum, Anisomyon borealis, Amauropsis paludiniformis, Inoceramus sublaevus, I. tenuilineatus,* bones of *Mosasaurus Missouriensis*, etc.	Great Bend of the Missouri below Fort Pierre.		
			Dark bed of very fine unctuous clay, containing much carbonaceous matter, with veins and seams of gypsum, masses of sulphuret of iron, and numerous small scales of fishes. Local; filling depressions in the bed below.	Near Bijou Hill, on the Missouri.		
LOWER SERIES	NIOBRARA DIVISION	Formation No. 3	Lead-gray calcareous marl, weathering to a yellowish or whitish chalky appearance above. Containing large scales and other remains of fishes, and many specimens of *Ostrea Congesta* attached to fragments of *Inoceramus*; also several species of *Textularia*. Passing down into light, yellowish, and whitish limestone, containing great numbers of *Inoceramus problematicus, I. pseudo-mytiloides, I. aviculoides*, and *Ostrea congesta*, fish-scales, etc.	Bluffs along the Missouri below the Great Bend, to the vicinity of Big Sioux River; also below there on the tops of the hills.	200 feet	Equivalents of Lower or Gray Chalk and Upper Green-sand of British Geologists (*Turonien* and *Cenomanien?* of d'Orbigny).
	FORT BENTON GROUP	Formation No. 2	Dark-gray laminated clays, sometimes alternating near the upper part with seams and layers of soft gray and light-colored limestone. *Inoceramus problematicus, I. tenuicostatus, I. latus?, I. fragilis, Ostrea congesta, Veniella Mortoni, Pholadomy papyracea, Ammonites Mullananus, Prionocyclus Woolgari, Mortoniceras Shoshonense, Scaphites Warrenanus, S. larvaeformis, S. ventricosus, S. vermiformis, Nautilus elegans*, etc.	Extensively developed near Fort Benton on the Upper Missouri; also along the latter from ten miles above James River to Big Sioux River; and along the eastern slope of the Rocky Mountains, as well as at the Black Hills.	800 feet	
	DAKOTA GROUP	Formation No. 1	Yellowish, reddish, and occasionally white sandstone, with at places alternations of various colored clays and beds and seams of impure lignite; also silicified wood, and great numbers of leaves of the higher types of dicotyledonous trees, with casts of *Pharella? Dakotensis, Trigonarca Siouxensis, Cyrena arenarea, Margaritana Nebrascensis*, etc.	Hills back of the town of Dakota; also extensively developed in the surrounding country in Dakota County below the mouth of Big Sioux River; and thence extending southward into Northeastern Kansas and beyond.	400 feet	

From Meek, *in* Hayden, F. V., 1876, Report of the United States Geological Survey of the Territories, v. IX, p. XXIV-XXV.

[1]When this was written, all of the Upper Missouri country was known under the general name, Nebraska Territory; and the nomenclature of some of the fossils mentioned has been here changed.

*Estimated Thickness

Figure 3.--GENERAL SECTION OF THE CRETACEOUS ROCKS OF NEBRASKA[1]

aquifer that cropped out on the periphery of the Black Hills and was a continuous artesian aquifer between that locality and the type area at Dakota City, Nebraska. Darton illustrated his concept of the Dakota artesian basin and was subsequently given credit as being the first to grasp the mechanics of recharge of water to the Dakota Formation.

At this point it is noted that in January of 1895 James H. Shepard (1895 p.66-67), a chemist with the South Dakota Agricultural College, stated, "The preponderance of physical and geological evidence points to the outcrops of the Dakota sandstone, lying along the foothills of the Rocky Mountains to the north and west of the Dakota basin, and to outcroppings of the same sandstone around the Black Hills, as the points of entrance of the waters in question." In the same publication Shepard attempted to throw some light upon the origin of the water in the Dakota artesian basin by means of water analyses.

This chemist on the staff of a relatively small institution came closer to recognizing the solution to the enigma of the "Dakota Problem" than many of the prominent geologists of his day. True, Shepard was laboring under the misconception that the Dakota (now Fall River) of the Black Hills was equivalent to the Dakota at the type area in northeastern Nebraska. However, his attempt to determine the origin of the water in the artesian basin is noteworthy in that he approached the problem at a very early date with a new scientific method.

Subsequent investigation did little to correct the misconceptions that prevailed until Russell (1928) discovered that the so-called Dakota of the Black Hills area was older than the Dakota at the type area, and that the Newcastle Sandstone in the Black Hills was older than the upper part of the type Dakota. As a result of his investigations he named the sandstone (previously called Dakota) that crops out in Fall River Canyon in the Black Hills area the Fall River Formation.

It was not until 1954 that Gries demonstrated the relationship that exists between the Dakota Formation of the type area and the Inyan Kara Group of the Black Hills. Subsequent subsurface information derived from water wells and oil tests have confirmed nearly all of his basic arguments.

The authors mentioned in the foregoing paragraphs by no means constitute a complete bibliography of men who concerned themselves with the Dakota Formation. They do constitute a select group that has contributed much to further our understanding of an aquifer that has been a most influential factor in establishing communities and farms in South Dakota.

Recent Miscorrelations

In regard to the work of Russell and Gries mentioned above, it is evident from recent reports that misconceptions still exist. In 1959, E. C. Reed (*in* Condra and Reed, 1959, p. 18) proposed "the name Omadi Sandstone, for the so-called Dakota formation, to include the section lying between the Fuson and Graneros shales." The term Dakota was elevated to the rank of group. On page 19 of the same article a type locality was established. In this type locality the Lakota Formation (lowermost Cretaceous) is overlain by about 75 feet of Fuson Shale which in turn is overlain by 147-1/3 feet of sediments of the Omadi Formation.

Waage (1959, p. 56) states, "The spherulitic siderite in the Fall River and Newcastle Formations is a local feature but the siderite zone beneath the transgressive disconformity has regional extent. I have found it in the Cloverly in the Bighorn and Laramie Basins; in the top of the Lytle formation in northern Colorado, and at Sergeant Bluff, Iowa, across the Missouri River from Meek's and Hayden's type Dakota." In other words, Waage and Reed erroneously correlated the pellet-bearing clay unit in the type area of the Dakota with the pellet-bearing horizon found near the top of the Lakota (formerly Fuson Formation) in the Black Hills area. This hypothesis fails to adequately explain a problem which immediately arises.

According to Bolyard and McGregor (1966, p. 2225) the sediments that comprise the rocks of the Inyan Kara Group were derived in part from the Sioux Ridge. If it is also true that the entire Inyan Kara Group may be traced eastward until it becomes lost in the continuous transgressive blanket of sand overlying the Sioux Quartzite as suggested by Gries (1954, p. 447), and if the Inyan Kara Group is represented by 300 feet of sediments in the

Dakota type area as implied by Waage (1959, p. 56) and Reed (1959, p. 18) then a difficult question arises. For instance, it is well known that the bulk of the Dakota sediments were derived from a southeastern source thus the Dakota would be expected to thicken in a west to east direction through the State. This condition has been previously demonstrated (Schoon, 1965, fig. 1). Evidence indicates that the Sioux Ridge was mildly positive throughout the Cretaceous Period. Therefore, if the Inyan Kara Group ever existed at the type area of the Dakota it is a certainty that the loosely consolidated sands of the Inyan Kara would have undergone extensive erosion. An erosional cycle was initiated in northeastern Nebraska by the westward migration of the Cretaceous shoreline prior to the deposition of 350 feet of Dakota sediments in the central part of South Dakota. Thus, the hypothesis that the Inyan Kara Group is present in northeastern Nebraska cannot logically explain why the Dakota Formation should thicken eastward from 200 feet to 275 feet in Haakon County to 300 feet in Jones County to 400 feet in Lyman County and then reverse this trend and thin eastward in the direction of the source area to less than 100 feet at the type area in the northeastern corner of Nebraska. This hypothesis requires that the resistant rocks of the Sioux Ridge and Canadian Shield furnished sediments to the Dakota and at the same time implies that the younger loosely consolidated rocks of the Inyan Kara Group overlying the Precambrian rocks of the Sioux Ridge somehow escaped truncation.

It appears more plausible that the Dakota Formation maintains a maximum thickness from Lyman County eastward in the direction of the source area to the type section in northeastern Nebraska where it is 400 feet thick and that rocks of the Inyan Kara Group are not represented in the Dakota type area.

More recently Swenson (1968a) advanced a theory of recharge to the Dakota aquifer. His theory is a noteworthy contribution toward furthering our understanding of recharge to the Dakota artesian system. However, as can be seen from page 166 of his report and various pages throughout his report (i.e., p. 171-4), Swenson includes the Inyan Kara Group within the boundaries of the Dakota Sandstone. From the Code of Stratigraphic Nomenclature, Article 9 (A), "A group consists wholly of divisions defined as formations"; therefore, if the term Inyan Kara Group is retained as a subdivision of the Dakota then the term Dakota must be elevated to the rank of supergroup.

The above paragraph may border on being picayunish; however, the Inyan Kara Group and the Dakota Formation are two entities and are readily separable in the western two-thirds of the State. To include the Inyan Kara Group as a subdivision of the Dakota Group or Dakota Formation confuses the reader and in many cases the authors of articles. Perhaps this is one reason Swenson (1968a) failed to recognize the part played by the Inyan Kara sandstones in recharging the Dakota.

Dakota Formation Defined

In 1861 Meek and Hayden described a 400-foot sequence of yellowish, reddish, and occasionally white sandstone with local alternations of varicolored shales and lignite beds, and they called it the Dakota Group. They went on to state that this group "underlies the Fort Benton Group, of which it may only be a member." Translated by using a current issue of the Code of Stratigraphic Nomenclature the preceding quote would probably read thus: The Dakota Group underlies the Fort Benton Group and may be only a formation of the Fort Benton Group.

Meek and Hayden's description of the type area near Dakota City in northeastern Nebraska, the thickness of the Dakota, and the lithological description of the unit are remarkably clear considering the early date of their publication. However, succeeding authors have erroneously expanded or restricted the formation and in various other ways have misinterpreted the original definition of the term. As a result we have a meaningless hodgepodge of geologic terms which serve no purpose other than to obscure the relationships that exist within the Dakota Formation.

Therefore, as used in this report, the term Dakota Formation is used to include the entire sequence of sandstone and clay at the type area in northeastern Nebraska and coincides precisely with the boundaries of the Dakota Group as defined by Meek and Hayden. In other words, the Dakota Formation includes the first relatively continuous sandstone below the Greenhorn Limestone and extends downward to the top of the Skull Creek Shale in western and central South Dakota. Where the Skull Creek is absent the Dakota overlies Precambrian rocks and, to a minor extent, rocks of the Inyan Kara Group. In no case in this report is the term Dakota Formation intended to include any part of the Inyan Kara Group or older sandstones (see fig. 4).

In the type area and in extensive areas in the eastern part of the State the Dakota Formation can be subdivided into three units. The upper unit consists of light-brown to reddish-brown, fine-to medium-grained, friable, quartz and minor feldspar sandstone with interbeds of gray to dark-gray shale. Thin, discontinuous beds of lignite are present in the lower part of the unit. This is the most extensively exposed unit of the Dakota Formation in the type area and it is younger, but stratigraphically equivalent to the Mowry sands that tongue out around the southern periphery of the Black Hills (figs. 1, 5, 6, 7, and 8), and to the Omadi Sandstone of Reed (1959, p. 18). Because of the transitional nature of the Dakota-Belle Fourche contact in the type area an accurate thickness of this upper unit is difficult to determine. In most cases it is approximately 65 feet but does range up to 95 feet thick at some outcrops.

The middle unit is a gray silty clay with small siderite pellets disseminated throughout the interval. These pellets resemble the siderite pellets that are present in the upper part of the Lakota Formation in the Black Hills area. On the basis of these pellets, previous authors (Baker, 1948, p. 2; Waage, 1959, p. 13, 14, and 56; and Reed *in* Condra and Reed, 1959, p. 18, 19) have mistakenly correlated this clay unit with the Fuson Shale. Waage maintains this middle unit marks the transition from continental to marine sedimentation that occurs at the Lakota-Fall River contact. At least 55 feet of this middle clay unit is present in the pits of the Ballou Brick and Tile Company at Sergeant Bluff, Iowa, and a like thickness occurs in many areas in eastern South Dakota. In reality, this middle unit is approximately time equivalent to the lower part of the Belle Fourche Shale in the Black Hills area and is much younger than the Fuson of western South Dakota.

The lower unit is medium-to coarse-grained quartz (minor feldspar) sandstone. This unit is neither exposed in the eastern part of the State nor at the type area; however, drill hole information indicates the thickness is approximately 300 feet. Electric logs show that this sandstone is broken by only four thin (under five feet) shaly intervals. The unit thins in a westward direction and is represented by sandstone tongues that crop out in the Black Hills area. In the western part of the State these sandstone tongues are the Newcastle and younger tongues of the Dakota Formation (figs. 1, 4, 5, 6, and 7).

The three aforementioned subdivisions of the Dakota Formation in the type area are rocks that are characterized by lithologic homogeneity and are mappable in the subsurface of large areas in eastern South Dakota. The tripartite subdivision of the Dakota is not an original concept of this report, but was suggested by C. R. Keyes (1912, p. 148-150) whose descriptions of the Dakota correspond closely with those of this report. The names suggested by Keyes have not been widely accepted and have fallen into disuse. As a result, the term Nishnabotna used by Keyes to describe the lower unit of the Dakota should not replace the well established term of Newcastle in South Dakota (American Commission on Stratigraphic Nomenclature, 1961, p. 652, art. 11b). The relationship of Keyes' two upper units (the upper Ponca Sandstone, 65 feet thick, and the middle Sergeant Shales, 55 feet thick) with the alphabetical nomenclature of the Dakota in western Nebraska and Wyoming are not entirely clear. No well-established geographic names have ever been used in South Dakota to replace the upper two units named by Keyes and therefore his terms have priority. At the present time the South Dakota Geological Survey does not recommend using the names of the two upper units that were suggested by Keyes until the boundaries of equivalent units are more clearly defined. However, if formal names are suggested for the two upper units in the future, due consideration must be given to the past work of Keyes.

In view of the foregoing, rocks that constitute the Dakota at the type locality cannot be relegated to a rank higher than formation because groups of rock should not contain an unnamed formation. Neither should the Dakota Group include the Inyan Kara Group.

DEPOSITIONAL HISTORY

Source Rocks of Cretaceous Sediments

This report is primarily concerned with the Dakota Formation. However, the two lower Cretaceous sandstones (Dakota Formation and Inyan Kara Group) have been erroneously included in the Dakota Group (i.e., Swenson, 1968a and b). To clarify the relationships that exist between these two separate units both intervals are discussed in this section.

There are presently six major structural elements in the State. They are: The Williston Basin, Canadian Shield, Sioux Ridge, Siouxana Arch, Chadron Arch, and the Black Hills Uplift. The Black Hills Uplift was not notably active during Early Cretaceous and sediment contributions by this element were of little consequence. In fact, Bolyard and McGregor (1966, p. 2224, fig. 3) suggest Early Cretaceous downwarping along the axis of the Black Hills.

The pre-Cretaceous paleogeologic map (fig. 9) reveals that prior to Cretaceous sedimentation the eastern part of the State had either undergone extensive erosion or the subcrop pattern was caused by offlap of younger beds. The former appears the more likely in most instances, but in either case rocks ranging in age from Jurassic to Precambrian in eastern South Dakota contributed at least some sediments to the initial Cretaceous formation (Lakota). The Lakota sediments in the Black Hills were deposited in a continental environment and were derived from a western, southwestern, eastern, and southeastern direction. As the Cretaceous sea encroached from the northwest, the depositional environment changed from continental to marine. According to Waage (1959, p. 55-58) this change is marked by a transgressive disconformity that is represented by the pellet-bearing clay (erroneously called Fuson at the Dakota type area) at the top of the Lakota Formation.

While the marine Fall River Formation was being deposited in the area of the Black Hills, Lakota sediments were being deposited farther east and overstepped the Jurassic to Precambrian sediments that offlap the Sioux Ridge and Siouxana Arch. This limited the source area rock types to Sioux Quartzite from the Sioux Ridge, igneous rocks from the Canadian Shield, and pre-existing sediments from the Siouxana Arch.

The normal sedimentary cycle continued and the marine Skull Creek Shale was deposited on the Fall River Formation. Present information is insufficient to establish whether or not rocks of the Inyan Kara Group and the Skull Creek Shale were deposited in easternmost South Dakota. However, Inyan Kara sediments are not present in the type area and the Skull Creek Shale is not present in the subsurface farther east than Douglas County (fig. 10).

After the marine Skull Creek Shale was deposited the initial Cretaceous sedimentary cycle was interrupted. Tester (1931, p. 255) states, "Continued field work on the Dakota rocks in southwestern Iowa has failed to locate a horizon containing a marine or brackish water invertebrate fauna. In fact, the only locality that is known to the writer to have yielded invertebrates is at Sioux City and nearby sections as previously described." Although this is not concrete evidence of the continental origin of the lower Dakota sand, it is sufficient to indicate that an interruption of the normal sedimentary cycle did occur between Skull Creek and early Dakota time.

The sandstone exposure that Tester describes (1931, p. 236-238) as bearing glauconite and marine invertebrate fossils is the upper unit of the Dakota and is stratigraphically higher than the pellet-bearing clay unit exposed at the Ballou Brick and Tile Company at Sergeant Bluff and the Newcastle tongues in the Black Hills area. In view of the continental or transitional environment of the lower unit and the marine affinities of the upper unit, it is believed that the pellet-bearing, silty clay (middle unit) represents sediments deposited during the transition from continental to marine environments similar to that suggested by Waage (1959, p. 56) in regard to the Inyan Kara Group in the Black Hills area. However, at the type area of the Dakota this transgressive disconformity occurs in the second major cycle of sedimentation of the Cretaceous and is neither time nor stratigraphically equivalent to the transgressive disconformity at the top of the Lakota Formation as suggested by Waage and others.

This second Cretaceous cycle of sedimentation was initiated by a migration of the sea of sufficient distance westward to cause the deposition of at least 300 feet of continental sediments in southeastern South Dakota. If sediments of the Inyan Kara Group previously existed in the Dakota type area and at corresponding elevations on the Sioux Ridge and Canadian Shield, they were most probably eroded and redeposited seaward as lower Dakota sediments.

Sediments of the middle clay unit represent a near-marine environment and the marine deposits of the upper unit of the Dakota indicate a continued advance of the sea. Thus, the sediments from the base of the Dakota to the top of the Pierre Shale represent the second Cretaceous sedimentary cycle that exhibits only slight interruptions (e.g., the Codell Sandstone).

Conditions Influencing Deposition

Grace (1952, p. 22) postulated that minor uplift took place in the Black Hills area during or immediately prior to the deposition of the Newcastle tongues of the Dakota Formation. Crowley (1951, p. 89) suggested the existence of a low insular or peninsular landmass on which Precambrian rocks were exposed in the vicinity of Harney Peak.

From either of the above theories one would expect to find coarse-grained sand or gravels in the Newcastle tongues. Such is not the case; therefore, other avenues must be explored.

An isopach of the Greenhorn to Fall River interval (fig. 11) in South Dakota reveals the thickness of this interval increases in a direction at right angles towards the periphery of the Black Hills. For instance, on the crest of the Chilson Anticline (Townships 10, 11, and 12, South, Range 4 East) the Greenhorn to Fall River interval increases in thickness northward from 816 to 825 to 880 feet. A similar trend exists on the north and east side of the Black Hills. In other words, a net increase in the thickness of this interval towards the Black Hills Uplift suggests that the overall movement that occurred in this time interval was in a downward direction in the Black Hills area. This is in agreement with Bolyard and McGregor (1966).

A similar map of the Skull Creek Shale (fig. 10) near the periphery of the Black Hills indicates areas of apparent thinning. Approximately 90 feet above the base of the Skull Creek is a persistant glauconitic siltstone marker (fig. 8). The interval between this marker bed and the base of the Skull Creek is quite uniform. On the other hand, the thickness between the siltstone marker and the top of the Skull Creek is more irregular. This apparent thinning at the top of the Skull Creek Shale could have been caused by small local uplift in the southern Black Hills, regression of the Cretaceous Sea, or by submarine processes.

Previously in this report, it was stated that the lower unit of the Dakota Formation in eastern South Dakota was deposited in a continental environment that resulted from a westward retreat of the Cretaceous sea. This retreat progressed sufficiently far to form a land mass near south-central South Dakota (possibly near the ancient Siouxana Arch). There is no reason to maintain that this retreat extended beyond the present limits of the Black Hills. Siderite pellets are reported from the Newcastle in the Black Hills area. These pellets occur in profusion in the middle clay unit of the type section. If these pellets also indicate a change from marine to continental depositional environments, then the pellet horizon indicates the lateral extent of the sea's withdrawal.

From figure 8 it is apparent that the base of the Newcastle Sandstone migrates in a vertical direction. Previous authors have interpreted this vertical deviation of the base of the Newcastle to represent subaerial erosion and subsequent channel filling at the top of the Skull Creek Shale. It is believed that the apparent channeling of Skull Creek did result from a retreat of the Skull Creek sea. However, this westward retreat of the Skull Creek sea was caused by an excess of materials available for transport over the carrying capacities of the transporting agents. Resulting shoreline accretion progressed westward as far as the western boundary of the main body of the Dakota Sandstone (see fig. 1). Westward beyond this boundary the Dakota sediments occur as sandstone tongues that have been deposited by offshore currents. Thus, the vertical migration of the Newcastle Sandstone in the Black Hills area does not indicate a period of subaerial erosion, but instead represents sediments that were deposited by shifting currents in the Skull Creek sea. Newcastle and younger sands appear to be associated with facies changes within the Skull Creek Shale as speculated by

McGregor and Biggs (1968, p. 1881). The present area of the Black Hills was not a locally emergent area but merely a relatively stable portion of a shelf area that existed in Skull Creek time, and the apparent channeling is probably the result of submarine proccesses. In western South Dakota as in eastern South Dakota post-Skull Creek epeirogenic downwarping resulted in the advent of the second Cretaceous sedimentary cycle that was only slightly interrupted until after the Pierre Shale was deposited in Late Cretaceous time.

In addition to the above arguments the following points must be kept in mind.

1. The Skull Creek Shale (fig. 10) shows irregular thickness patterns. However, if local uplift had occurred in the central Black Hills area there should be some localities in the area that have sands of the Newcastle tongue overlying the Fall River Sandstone with angular unconformity. No such localities are known.
2. The uniform fine-grained nature of Newcastle sediments in western South Dakota suggests low gradient transport.
3. In southern and eastern South Dakota the Newcastle tongues appear to thin toward the Black Hills. This indicates the source of sediments was from the south and east.
4. In Fall River County the thickness of the interval from the top of the Dakota Formation to the top of the Fall River Sandstone averages approximately 400 feet. This is about the same thickness that is present in Harding County in the northwestern part of the State. Thus, even though apparent channeling of the Skull Creek can be demonstrated in Fall River County it is evident that the thinning and/or channeling is in large part due to submarine processes.

A thickened interval of sandstone is present in the northwestern corner of the State (fig. 1). This sandstone is approximately age equivalent to the Newcastle tongues. The rather large area of absent Newcastle immediately to the southeast of the area suggests the possibility of a northwestern source of this sandstone. However, subsurface information is not sufficient to determine whether this sand is equivalent to the Newcastle (more likely) or to the upper Mowry sands (less likely).

Dakota-Newcastle-Muddy Correlations

At this point it is cautioned that one should use caution when correlating the Dakota Formation and its westward extending tongue (the Newcastle) with the "Muddy Sandstone" of Montana. For instance, Reishus (1968, p. 20) indicates that the Recluse and Bell Creek oil fields produce from the Newcastle Formation. Wulf (1968, p. 30-31) contends the Recluse Field produces from the Newcastle (lower Muddy) Sandstone and the Bell Creek Field produces from the Dynneson (upper Muddy) Sandstone. In addition Wulf (p. 32) shows an erosional unconformity between the upper and lower Muddy sandstones.

From Reishus, (1968, pl. 2), Anderson (1967, fig. 2), Haun and Barlow (1962, fig. 7), and this report (fig. 12) it is quite obvious that an area of little or no Newcastle or "Muddy" sediments is present in north-central North Dakota and extends southwestward across that State into northwestern South Dakota to the northern Black Hills area, continues southward to the area of the present Black Hills area, thence southwestward into Wyoming and Colorado. This area of non-deposition exists westward from the main body of the Dakota delta. Tongues of sand extend seaward from the delta front; however, these tongues are discontinuous and in many cases terminate prior to reaching the present outline of the Black Hills area. The Newcastle Sandstone is the most consistent and continuous of these sandstone tongues of Dakota Formation.

On either side of this large area of non-deposition the sand units thicken in opposite directions and it is quite likely that the sources of these sand sediments were from at least two opposite directions. Isopach maps in some cases show that the western and the eastern derived sands coalesce. However, subsurface data is not sufficient to prove or disprove this point. In either event the area of little or no deposition of sand is in large part the result of distance from the source area and does not indicate relative elevation of the area to sea level during Dakota time.

The mapping of lenses of Newcastle Sandstone around the periphery of the Black Hills

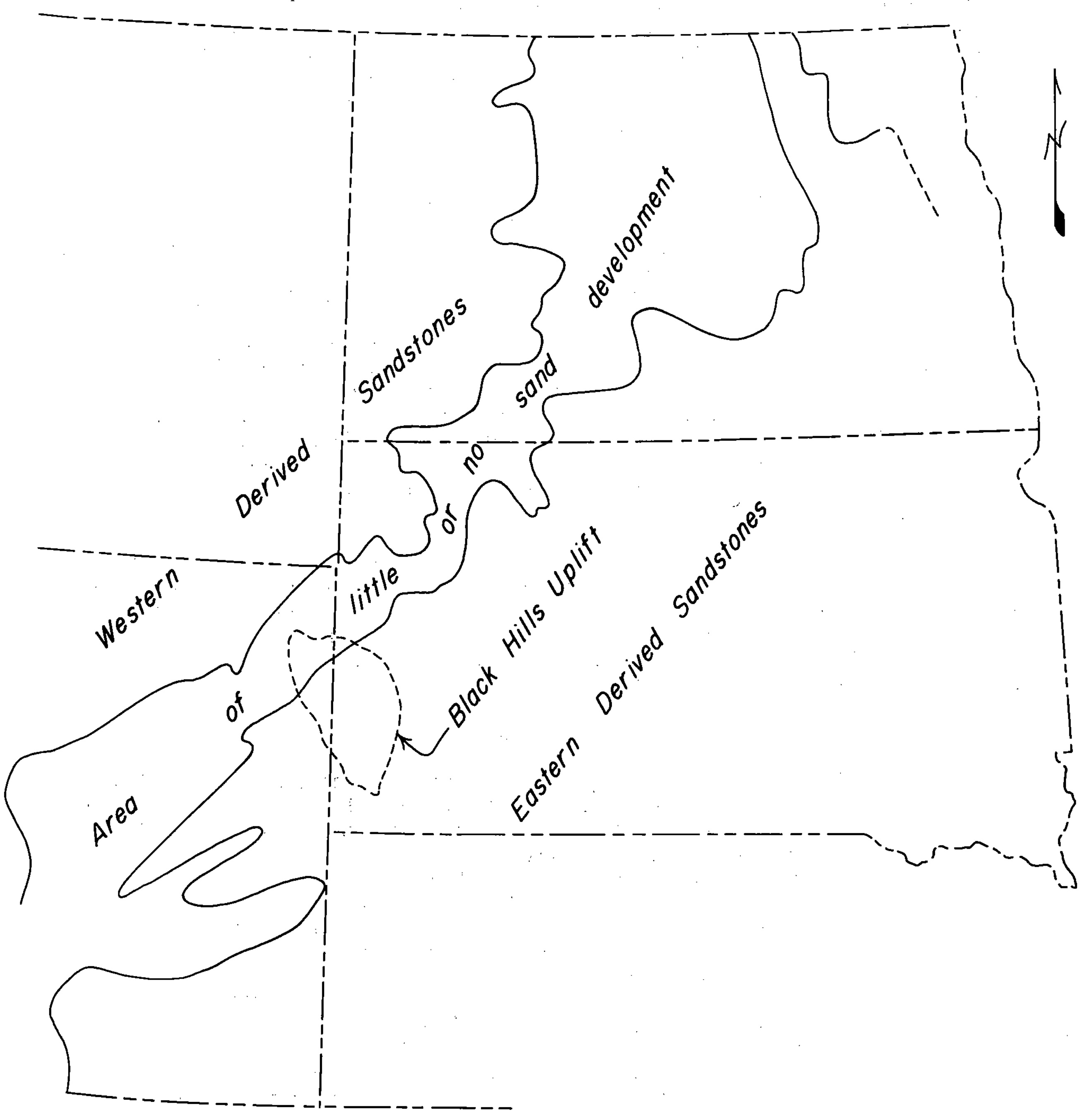


Figure 12. Map of distribution of Dakota Tongues *(Newcastle)* and Muddy Sandstone. *(North Dakota area revised in part from Anderson - 1967, and Reishus - 1962. Wyoming area revised from Haun and Barlow - 1962)*

may be in error. It is a certainty that oil tests have been drilled having the Newcastle as the objective and have been abandoned after encountering a tongue of Mowry sand. The possibility of similar errors in surface mapping also exists.

STRUCTURE

Regional Structure

The dominant regional structure in the State is the Williston Basin which extends from north-central Nebraska, trends northwesterly through South Dakota, thence through western North Dakota. This basin is bordered on the east by the Canadian Shield and the Sioux Ridge, on the south by the Siouxana and Chadron Arches, and on the southwest by the Black Hills Uplift and extensions of the Chadron Arch and Cascade Anticline (fig. 13).

Local Structure

No reliable marker beds have ever been found in the exposed Cretaceous rocks that permit mapping of local structures in the Williston Basin area. The upper Cretaceous rocks tend to slump readily and for this reason most geologists hesitate to delineate structures in this area.

Many small structures exist around the periphery of the Black Hills; however, the closures are rather small and do not appear on the structure map. The more pronounced structures are discussed below.

Structures in Southeastern Fall River and Southwestern Shannon Counties

The area of the Chadron arch and the southeastern Black Hills attracted the attention of early petroleum seekers who recognized the potential traps in the area. Wulf (1964, p. 148) states that the first oil test in the area was drilled in T. 34 N., R. 46 W. in 1902. Sporadic exploratory activity occurred through 1931; however, no commercial production was discovered.

As a result of these oil tests it is known that the geologic history of the Chadron Arch is quite similar to that of the Black Hills. Perhaps it is significant that both of these areas were tectonically active during the Laramide Revolution.

South Dakota Portion of the Chadron Arch

The Chadron Arch is a large uplift located in the northern panhandle of Nebraska. The maximum expression of this uplift is located in T. 33 N., R. 46 W. in Nebraska approximately 10 miles south of the South Dakota boundary (Wulf, 1964, p. 148). According to Wulf (p. 149) the arch has structural relief of 3000 feet. The structure trends northwest to sec. 25, T. 36 N., R. 48 E. in Shannon County, South Dakota, thence west northwest into Fall River County and continues in this direction until it merges into the Cascade Anticline in the southeastern part of the Black Hills Uplift (figs. 13 and 14).

Faults that have been mapped in southern Fall River and Shannon Counties by authors in previous reports are discussed below. These previous reports are for the most part studies of the surface geology in southwestern South Dakota and do not appear to be entirely compatible with subsurface information. For example, the Pine Ridge Structure (Clark and others, 1967, p. 13) may coincide with the Sandoz Ranch Fault (Haywood, H., personal communication). These structures are located on the saddle formed by the Chadron Arch and Cascade Anticline (fig. 14). In this area the vertical disposition of beds can also be explained by steep dips. From figure 14 it is apparent that structural relief is approximately 700 feet on the Greenhorn Limestone. The electric log of Amerada No. 1 Red Eagle oil test (sec. 25, T. 26 N., R. 48 W.) indicates Pennsylvanian rocks directly overlie the Precambrian surface. Also of interest is that this is an area where the Dakota begins to tongue out. At the site of the aforementioned oil test the Dakota Formation is represented by four well defined

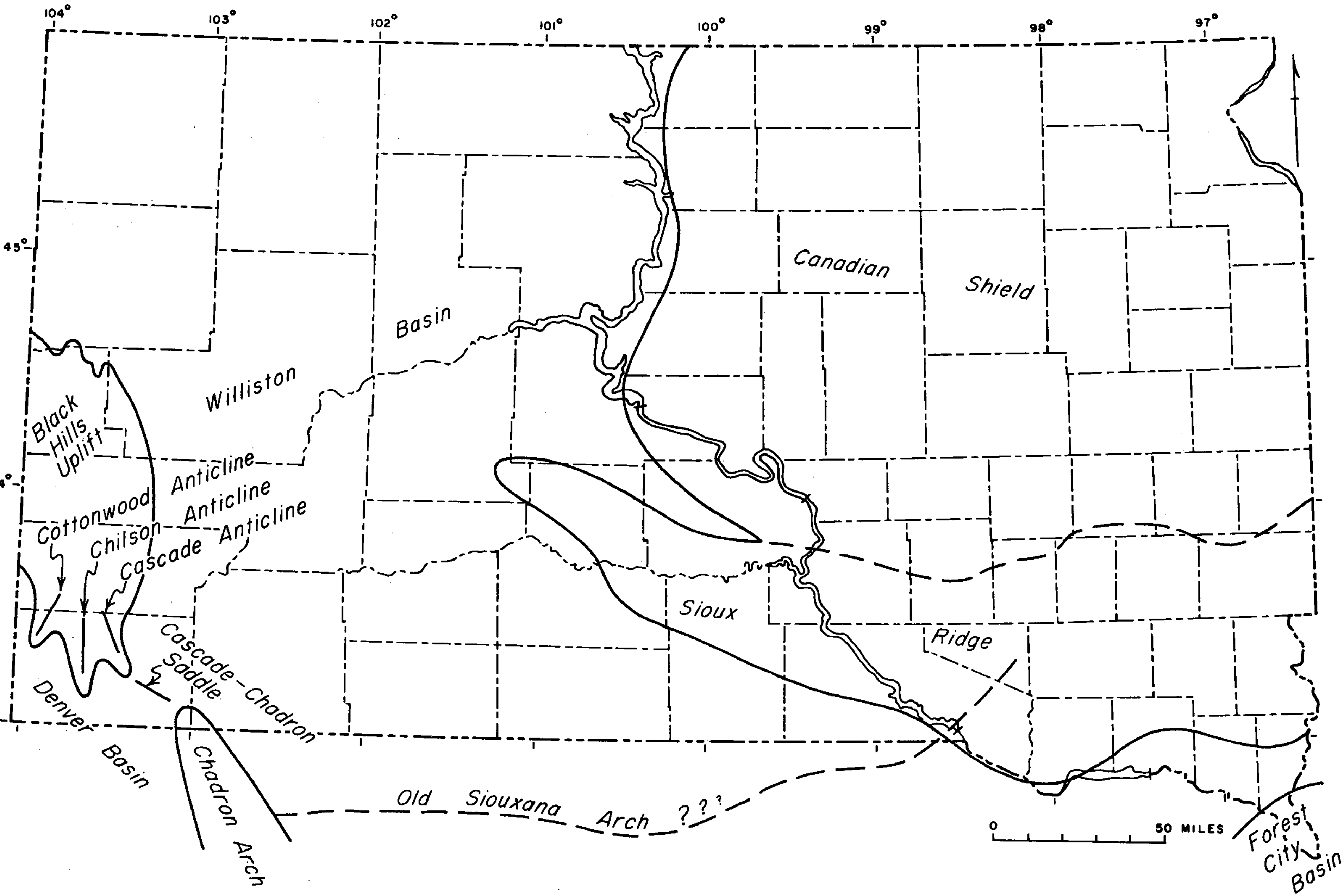


Figure 13. Regional structures in South Dakota.

sand tongues (fig. 8). Thus, the possibility of structural, structural-stratigraphic, and stratigraphic traps should make this area quite enticing to the oil prospector.

The Pine Ridge Structure

The Pine Ridge Structure as mapped by Clark (Clark and others, 1967, p. 13) may coincide with Sandoz Ranch Fault (Haywood, H., personal communication) on the west and the White Clay Fault (Dunham, 1961; and Haywood, H., personal communication) on the east. The concensus of opinions of the above named geologists is that the fault trends N 70 W and is downthrown on the north from 400 (Haywood, H., personal communication) to 1200 feet (Clark and others, 1967, p. 13).

On the other hand, subsurface information in the area of Townships 11 and 12 South, Ranges 7 and 8 East indicates that if a fault does exist the downthrow is on the south side of the fault. The reasons for this statement are as follows:

1. The sea level elevation of the Dakota is approximately 1700 feet on the north side of the fault and is estimated to be 600 feet in a well located south of the fault (SE¼, sec. 2, T. 11 S., R. 7 E.).
2. The thickness of the Pierre Shale is about 400 feet on the north side of the fault and 1600 feet on the south side of the fault. Local relief of the area varies between 0 and 150 feet.
3. Clark (Clark and others, 1967, p. 13) mapped Oligocene sediments on both sides of the fault. If displacement is between 400 and 1200 feet and Oligocene sediments are on both sides of the fault trace, then we know the fault scarp was nearly obliterated prior to Oligocene time. From (2) above it is apparent that movement occurred during post-Pierre and pre-Oligocene time. It is also clear that if a fault does exist different members of the Pierre Shale must be opposite each other across the fault trace.

From the available subsurface data it is not possible to prove the existence of a fault as described by Clark and Haywood because differences in the elevations of formations can also be explained by steep dips (see fig. 14). However, if a fault does exist, and if subsurface interpretations are correct, then it is downthrown on the south.

White Clay Fault

The White Clay Fault (Dunham, 1961; Harksen, 1967) is located in Shannon County. Subsurface data is nil in that area and the reader is referred to the above authors for information.

Horsehead Anticline

Near the headwaters of Horsehead Creek, adjacent to the Nebraska border, subsurface data and stream patterns indicate the possible existence of a gentle anticline. This interpretation is based on widely separated oil tests and may be modified to a large degree by future testing. Differences in elevations indicate a possible closure of 200 feet. The Pierre Shale thins over the structure and the crest is tentatively drawn in secs. 31 and 32, T. 11 S., R. 6 E. (fig. 14).

Cottonwood, Chilson, and Cascade Anticlines

These three structures form a crow's foot off the southern end of the Black Hills Uplift. The structures have previously been described by Rothrock (1949) and the reader is referred to his work for a detailed account. Also see figures 13 and 14 of this report.

Piedmont Anticline

The Piedmont Anticline described by C. L. Baker (unpublished report) is located in southwestern Meade County. According to Baker the anticlinal axis trends north-northwest from sec. 32, T. 3 N., R. 7 E. to the north line of sec. 35, T. 4 N., R. 6 E. The crest of the anticline is located just west of the half section line in secs. 18 and 19, T. 3 N., R. 7 E., and the structure has a minimum closure of 300 feet.

Fairburn Anticline

The Fairburn Anticline is located about 1¼ miles southwest of the town of Fairburn. The axis trends in a north-northeast direction and the crest is in secs. 25 and 36, T. 4 S., R. 7 E. A closure of 20 feet is assured and estimates of fifty feet to 100 feet are not unreasonable (Rothrock, 1930).

Whitewood Anticline

According to Petsch (1949) the crest of the northern part of the Whitewood Anticline is located in secs. 30 and 31, T. 7 N., R. 4 E. The axis trends N 10° W and the anticline plunges about 90 feet per mile to the north.

It is quite probable that numerous other structures are present around the periphery of the Black Hills. Present subsurface data is not sufficient to locate them; however, additional field work and oil test information may well define structures in which hydrocarbons have accumulated.

AREAL EXTENT AND THICKNESS

Because of the relative scarcity of subsurface information, it is difficult to positively delineate the areal extent and thickness of the Dakota Formation. The isopach map (fig. 1) indicates the probable thickness of the formation for any given area within the State boundaries. Examination of figure 1 indicates that of the total 77,047 square miles that constitute the State of South Dakota, the formation underlies approximately 66,500 square miles, and has an average thickness of at least 150 feet.

HYDROLOGY

Storage Capacity of the Dakota Formation

Few cores have been taken from the Dakota and an accurate measure of overall porosity and permeability is not known. However, if the conservative value of 15 percent porosity is used, the computed volume of water stored in the formation is 1.1 billion acre-feet, an amount sufficient to cover the entire State with approximately 20 feet of water.

Withdrawal from the Dakota Artesian System

In 1965 Dyer and Goehring (p. 24) estimated the withdrawal of approximately 62 million gallons per day from the Dakota Formation in 21 counties in southeastern South Dakota. Because this is the area of heaviest production, it is safe to assume that the total amount of withdrawal in South Dakota does not exceed 100 million gallons of water per day or 36.5 billion gallons per year. In other words, 0.01 percent of the water in storage in the Dakota is withdrawn every year.

The magnitude of the above withdrawal figures is impressive; however, it is believed that the loss of water from the Dakota by water wells is less than the loss of water through natural means. For example, the Dakota is responsible for recharge to large buried glacial aquifers in the southeastern part of the State and large amounts of water are fed into the Missouri River between Vermillion, South Dakota, and Sioux City, Iowa (Christensen and Stephens, 1967, p. 33).

An examination of the piezometric maps (figs. 15, 16, and 17) reveals that in the southeastern corner of the State the hydrostatic head in the Dakota has suffered little or no decline since Darton's time. This indicates that the natural outlet in the Missouri River valley between Vermillion, South Dakota, and Sioux City, Iowa, had lowered the pressure at that point to a state of near equilibrium prior to Darton's survey of the area. Thus, the possibility of further depletion of the hydrostatic head in that area does not exist unless future withdrawal in the area of Charles Mix and other eastern counties exceeds the recharge capability of the Precambrian-Roundtop interval at the western boundary of the calcium-sulfate water shown on figure 18.

It is also believed that migration of water occurs along the interface of Precambrian and younger rocks in eastern South Dakota. However, these natural outlets have existed for thousands of years, and it must be admitted that the artesian system was in a state of equilibrium before the advent of man to South Dakota.

Water Quality

Shortly after the Dakota artesian aquifer was discovered various authors recognized that the water was not uniform in quality. Shepard (1895, p. 63-70) was aware of this fact and attempted to define the direction of hydraulic migration by means of water analyses.

Preliminary examination of water analyses indicated that the quality of Dakota water is influenced to a noticeable degree by sodium, chloride, calcium, and sulfate constituents. The Dakota water-quality map (fig. 18) was constructed with regard to only the four aforementioned constituents. The water-quality boundaries mark the point where the ratio of two dominant constituents decrease and are replaced by a different set of characteristics.

Analyses of water obtained from drill-stem tests and water wells drilled throughout the State are found in the appendix. On the basis of these rather meager data, it appears that in the southern half of the State, water from the Pennsylvanian Roundtop Formation to the top of the Cretaceous Fall River Formation is predominantly a sodium-sulfate type water. In the same area the water from the Precambrian-Roundtop interval appears to be predominantly a calcium-sulfate type water.

Origin of Recharge

As previously mentioned, Shepard, in 1895, advanced the proposition that surface water entered the Dakota Formation at outcrops in the Rocky Mountains and the Black Hills area, recharged the Dakota aquifer and eventually was discharged through the outcrops in eastern South Dakota.

Largely through the works of Gries, it is now known the theory of Shepard is not entirely acceptable. For example, the Dakota sediments as now known had their source from the east and south and, therefore, thin in a westward direction and are represented by the Newcastle and Mowry sandstone tongues of the Dakota Sandstone in the Black Hills area (figs. 1, 5, 6, 7, and 8). Around the periphery of the Black Hills, the Newcastle and younger sands crop out sporadically, but are generally too thin and tight to receive a great amount of surface runoff. This belief is strengthened by examination of the water-quality map because it shows a sodium-chloride type water very near any possible intake areas. In other words, the Newcastle tongues and younger Cretaceous sands have not been flushed to any great degree by fresh water near the Black Hills. However, it must be remembered that at the time Shepard advanced his theory of recharge, it was believed that what is now known as the Fall River Sandstone was the Dakota and that it was continuous from the Black Hills to the extreme southeastern part of the State. It is now known that the correlations of Shepard were incorrect; however, an attempt is made later in this text to prove that his mechanics are, at least in part, at work today.

In 1928 Russell challenged the prevailing concept of recharge to the aquifer. He advanced his theory of the compaction of sediments, the incompressibility of water, and the lenticularity of the Dakota and earlier Cretaceous sandstones as the main contributing factors for the origin of artesian pressure in the Dakota Formation. His theory held that water from the Dakota was primarily connate and that the intake of water from western areas was either non-existent or negligible. However, in qualifying this theory, he admitted it was conceivable that water flows through some lower horizon, such as the base of the Cretaceous, or the Minnelusa and then rises to the Dakota. Russell's qualification of his theory is similar in mechanics to that suggested by Swenson (1964, 1968a, and 1968b) which is discussed later under this section.

Russell (1928, p. 137) made much of the fact that the Dakota Formation is lensy and therefore is unable to transmit water from western to eastern South Dakota. The writer disagrees with Russell's statements on this point.

It is recognized that Russell studied only the upper 120 feet of the Dakota as exposed in southeastern South Dakota. This exposed portion of the Dakota is lensy. The contact with the overlying beds is transitional and therefore it may be expected that the closing shaly phase of the Dakota Formation deposition would be lensy. However, in southeastern South Dakota the Dakota is 400 feet thick and an electric log of the South Dakota Geological Survey No. 1 Heubner test indicates that the lower part of the Dakota Sandstone (from 315 to 620 feet) is broken by only four shale beds, none of which are over five feet thick. The same conditions are found in many wells in the eastern half of the State that have been logged electrically. In view of this, it is stated that the lower 300 feet of sediments of the Dakota in the type area are not lenticular and are very capable of transmitting water in all directions. Also, if the Dakota were extremely lensy it would be expected that artesian wells in South Dakota would have an extremely short life as flowing wells because water is only very slightly compressible. On the contrary, many wells have been flowing for over fifty years.

Russell (1928, p. 155) states, "The conditions which the old theory of hydraulic migration is unable to explain are the presence of water of different chemical characteristics in the upper and lower parts of the artesian sandstone, the occurrence of waters of different chemical characters in different regions, the greater head of the waters in the lower strata, the lack of any close relations between the contours of head and the supposed intake and outlet areas of the artesian waters, and the fact that the head is as low in the north-south valleys as on the ridges to the east."

In the light of recent data it is now known that the above arguments can no longer be used to refute the theory of hydraulic migration in explaining the occurrence of pressures in the Dakota artesian system. It has previously been demonstrated in this report that the Dakota yields not two but three water types. The first type is a sodium-chloride type water which is believed to be connate and occurs in the northwestern two-thirds of the State (figs. 18 and 19). A second type of water is present in a belt extending from south-central to the northeastern part of the State, and is a sodium-sulfate type water that originates in the Roundtop-Inyan Kara interval. Due to hydraulic migration from the Roundtop-Inyan Kara intake in the area of the Black Hills, the water from this interval is being flushed out to the Dakota Formation where the Skull Creek is only sporadically present. Wherever a sodium-sulfate type water is found in the Dakota Formation, the Skull Creek Shale is absent a short distance to the west (figs. 18 and 19).

The third type of water in the Dakota is a calcium-sulfate type. On the basis of scattered drill-stem tests and a few water well tests, it is apparent that this type of water is most often found in rocks below the Roundtop Shale (see app. and figs. 18 and 19). Thus, it is believed that wherever the Dakota yields a calcium-sulfate water, recharge is being accomplished by Precambrian-Roundtop rocks. It is very possible that when Russell referred to the upper and lower part of the artesian sandstone he was referring to the Dakota and Inyan Kara Sandstones and failed to recognize that the lower waters were primarily of the sodium-sulfate type. However, it cannot be said with certainty that Russell made this error, because nowhere in his report does he state the thickness of sediments between his "upper and lower parts" of the artesian sandstone.

In view of the foregoing, hydraulic migration easily explains the different water characteristics at different depths and different areas. It also explains the difference in head between the upper and lower parts (Dakota and Inyan Kara Sandstone) of the artesian system. It is also to be expected that piezometric contours of an aquifer that holds connate water and is recharged in different areas by two other separate aquifers would not be equally spaced unless that artesian system were in equilibrium. The Dakota artesian system is not in equilibrium at the present time. Finally, it was suggested by Russell that hydraulic migration cannot explain why the head is as low in the north-south valleys as on the ridges to the east. The reason for this low head can be stated simply: This condition exists because the wells in the valleys are working against approximately 150 feet less hydrostatic head. Therefore, the valley wells produce more, and it is not surprising that areas in valleys have

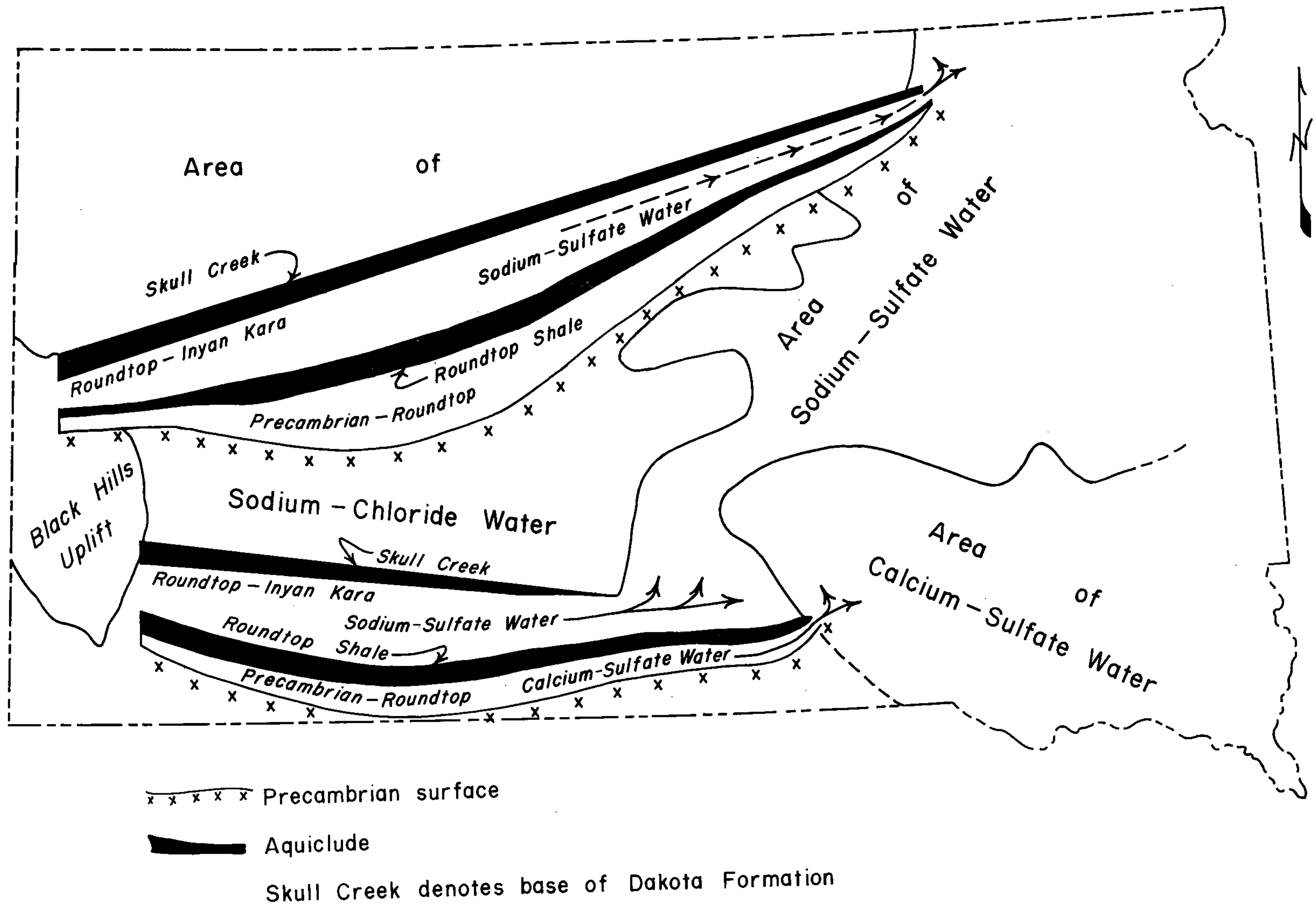


Figure 19. Schematic drawing illustrating recharge to the Dakota Formation.

less pressures than the highlands to the east. However, the writer feels that the variation is caused by rates of production and to a very small degree, if at all, by variations in the weight of overlying sediments or by the lenticularity of the Dakota Sandstone.

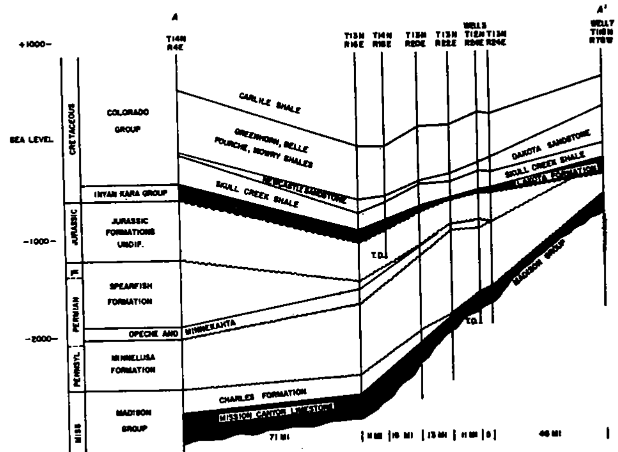
Russell (1928, p. 141) stated, "It is of course conceivable that the water flows through some lower horizons, such as the base of the Cretaceous, or the Minnelusa, and then rises into the Dakota, but there is no evidence of this." Swenson (1964) advanced a new theory accounting for the recharge to the Dakota Formation. Swenson (1964, p. A-177) suggests that, "Water enters the Mississippian Pahasapa Limestone on the flanks of the Black Hills and moves eastward in that formation and its subsurface equivalents, well below the Dakota Sandstone. East of the middle of South Dakota, where the intervening strata were eroded away in pre-Dakota time, the limestone lies directly below the Dakota and recharges it. West of the zone of recharge, water in the Dakota is virtually stagnant and has a high dissolved solids content, principally sodium-chloride. In the zone of recharge the water is of calcium-sulfate type and is less mineralized. To the east, the water 'splits' around the Sioux Quartzite ridge; the water is of sodium-sulfate type to the north where circulation is poor, and of calcium-sulfate type to the south where circulation is better."

If the water quality map (fig. 18) is superimposed on the pre-Cretaceous paleogeologic map (fig. 9) it is seen that the pre-Roundtop sediments subcrop at a point immediately to the southwest of the area that produces a calcium-sulfate type water from the Dakota. Swenson suggests the Dakota is recharged solely by water from the Mississippian Limestone. If this is true it must be explained why water will migrate north of the Sioux Ridge in an eastward direction against a higher hydraulic gradient (fig. 17). In addition the area of sodium-sulfate water is not adequately explained. It is doubted that poor circulation of water is sufficient to change a calcium-sulfate type water, characteristic of the Mississippian, to a sodium-sulfate type water. This is not to say that none of the Mississippian calcium-sulfate water splits around the Sioux Ridge. Some spilling over the ridge does occur in Buffalo, Jerauld, southern Sanborn and southwestern Miner Counties; however, the condition is rather localized (fig. 18) and certainly does not include the entire northeastern quarter of the State.

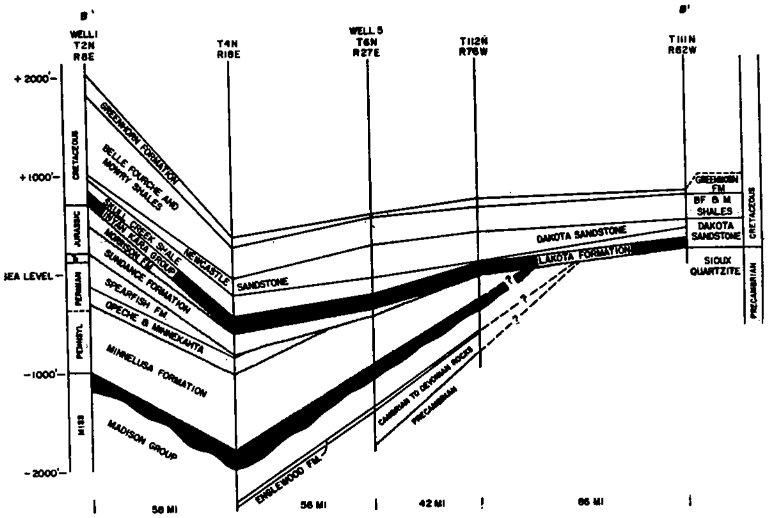
The Dakota Formation does yield three distinct types of water. However, it is apparent that Swenson overlooked the part played by the Inyan Kara sandstones in the recharge to the Dakota and that simple circulation restriction and ion exchange are not responsible for the occurrence of sodium-sulfate type water. The sodium-sulfate water originates in the Roundtop-Inyan Kara interval and is at least in part derived from the outcrops of these rocks in the Black Hills area. If recharge occurs as shown by Swenson (1968b, fig. 2, see also fig. 20, this report) the Inyan Kara should yield a calcium-sulfate type water in the inferred zone of leakage. In reality, in this area the Inyan Kara produces a sodium-sulfate type water, and the Dakota Formation produces a sodium-chloride type water.

Swenson (1968a) prematurely restricts the recharge of the Inyan Kara to water from Mississippian rocks. On page 177, table 2 of his report, Swenson lists analyses of water from the Madison limestones and from these analyses suggests recharge is furnished to the Inyan Kara solely by the Madison limestones. In his report, Well 6 is the Shell No. 2 Herman oil test (sec. 3, T. 1 N., R. 29 E., Jones County). This well was drill-stem tested at the 2868-2969 foot interval which Swenson correctly identifies as the top of the Madison Group at that locality. A portion of the analysis by the Chemical and Geological Laboratories of Casper, Wyoming, is in table 1 of this report. Although probably not available to Swenson the following drill-stem test results are in the South Dakota Geological Survey files. Water surfaced in 105 minutes at an estimated rate of flow of 75 barrels per day with shut in bottom hole pressure of 1380 psi after 15 minutes. A second drill-stem test was completed in the 3050-3210 foot interval (Silurian and Devonian sand section) in the same oil test. An analysis of the recovered water appears in the second column of table 1. Water surfaced in 14 minutes at an estimated flow of 1100 barrels per day with shut in bottom hole pressure of 1590 psi after 45 minutes. A comparison of the water analyses reveals a striking similarity. Noteworthy, also, is the pressure differential between the two intervals.

In the aforementioned table of Swenson an analysis is presented of water obtained from the Madison Group from a drill-stem test of the 3350-3461 foot interval in the Cities Service



GEOLOGIC CROSS-SECTION A-A' SHOWING THINNING OF STRATA BETWEEN MADISON AND INYAN KARA GROUPS.
IN PART FROM GRIES AND HENKES, 1963



GEOLOGIC CROSS-SECTION B-B' SHOWING THINNING OF STRATA BETWEEN MADISON AND INYAN KARA GROUPS.
IN PART FROM SANDBERG, 1962

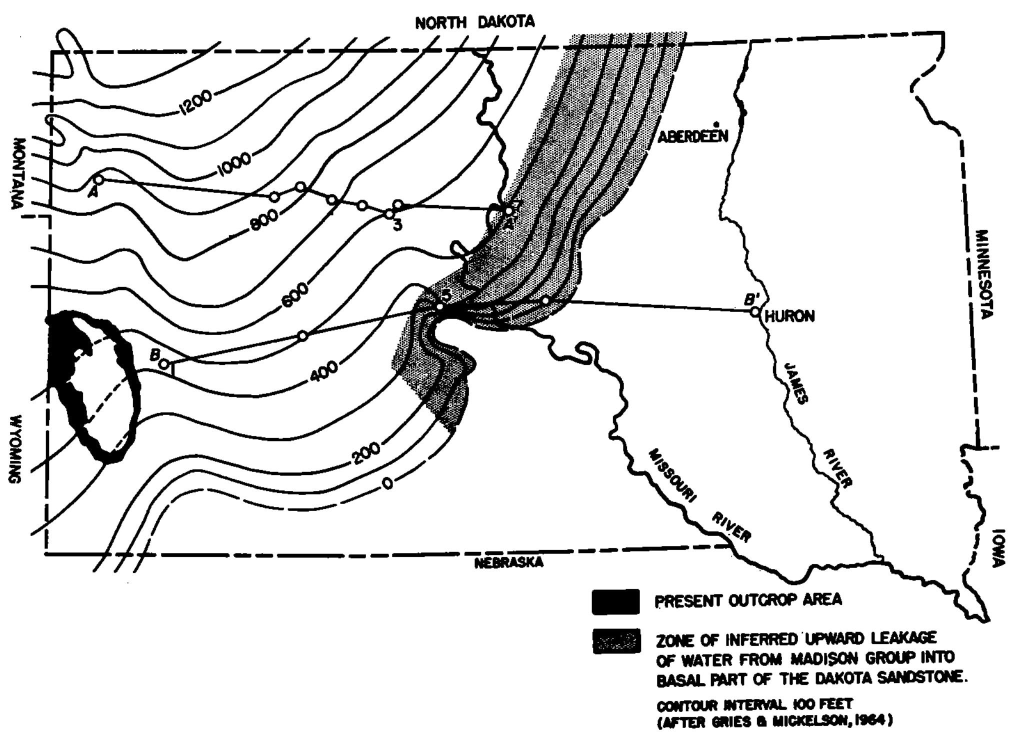


Figure 20. Mechanics of recharge according to Swenson. *(Swenson, 1968 b)*

Table 1.–Analyses of Water from Lower Paleozoic Rocks

(constituents in ppm)

	Shell No. 2 Herman sec. 3, T. 1 N., R. 29 E. Chemical and Geological Laboratory	Shell No. 2 Herman sec. 3, T. 1 N., R. 29 E. Chemical and Geological Laboratory	Pendak No. 1 Cowan sec. 21, T. 13 N., R. 22 E. South Dakota Department of Health	Cities Service No. 1A Barrick sec. 18, T. 7 N., R. 28 E. Chemical and Geological Laboratory	Cities Service No. 1A Barrick sec. 18, T. 7 N., R. 28 E. Chemical and Geological Laboratory	Cities Service No. 1A Barrick sec. 18, T. 7 N., R. 28 E. Chemical and Geological Laboratory
Interval	2868-2969	3050-3210	5047-5059	3350-3461	3574-3660	3848-3906
Sodium	210	216	329	71	70	117
Potassium	----	----	76.64	22	33	46
Calcium	406	364	328.50	367	372	344
Magnesium	25	45	61.97	116	120	94
Silica	----	----	----	----	----	----
Sulfate	1,109	1,001	1,535.0	1,250	1,275	1,275
Chloride	170	250	204.0	80	90	50
Fluoride	----	----	2.80	----	----	----
Nitrate	----	----	0.00	----	----	----
Total Solids	2,108	2,378	2,856	2,009	2,063	2,029
Formation	Madison	Silurian and Devonian Sand	Red River	Madison Limestone and Silurian and Devonian Sand	Silurian and Devonian Sand and Red River	Red River and Winnipeg Sand

South Dakota Department of Health, Pierre, South Dakota
Chemical and Geological Laboratory, Casper, Wyoming

No. 1A Barrick oil test (see column 4, table 1, this report). In reality, the interval tested includes rocks of the lower Madison and the Silurian and Devonian sand section. Apparently Swenson was not aware that two additional intervals were tested. Drill-stem test No. 2 tested the 3574-3660 foot interval (includes part of the Silurian and Devonian sand section and the top of the Red River Formation) and drill-stem test No. 3 tested the 3848-3906 foot interval (lower Red River and Winnipeg Formations). Analyses of the water obtained from these tests are found in columns 5 and 6, respectively in table 1 of this report. Again the water from the older Paleozoic rocks at this locality are very similar.

A fourth analysis of water from the Cities Service No. 1A Barrick oil test was from the depth of 2420 feet (Inyan Kara) and is definitely a sodium-sulfate type water. From this and numerous other cases (see app.), it is apparent that the Roundtop Shale serves as an effective barrier to the commingling of Roundtop-Inyan Kara and Precambrian-Roundtop water. It is also quite apparent from the foregoing that the chemistry of the water in the Precambrian-Roundtop interval is quite similar, and the pressure and production of water from Precambrian-pre-Mississippian rocks is greater than the pressure and production found in Mississippian rocks in this area. In view of this, and coupled with the statement of Brown (p. 24, this report), it is hazardous to suggest that recharge to the Dakota Sandstone is being accomplished solely from Mississippian rocks.

In figure 2, Swenson (1968b) shows two stratigraphic cross sections and the zone of inferred leakage from the Madison Group into the Inyan Kara sandstones (see fig. 20, this report). Swenson's cross section A-A' describes the location of Well 7 as being in T. 118 N., R. 78 W. (Carter No. 1 Whitlock-Smith, sec. 34, T. 118 N., R. 78 W.) and shows an interval of approximately 200 feet of Minnelusa separating the Madison Group from the Inyan Kara Group. The thickness of the intervening strata is essentially correct; however, what is not apparent from the cross section is that in this 200 foot interval is a 90 foot section of Roundtop Shale (2325 to 2415 feet). This 90 foot section of shale is sufficient to prevent Mississippian water from migrating to the Inyan Kara Group as depicted in Swenson's zone of inferred leakage. Approximately 7 miles north of the Carter No. 1 Whitlock Smith test the Dakota-Texas No. 1 Thompson oil test (sec. 27, T. 119 N., R. 78 W.) also encountered a 90 foot section of Roundtop Shale (2405-2495). The Independent No. 1 Hinckly oil test (sec. 7, T. 120 N., R. 74 W.) encountered 55 feet (2390-2445) of Roundtop Shale between the Madison Group and Inyan Kara Group. In all cases it appears the Roundtop Shale is sufficiently well developed to prevent the vertical migration of water from the Madison and older rocks to the Inyan Kara and Dakota Sandstones.

For the well in T. 112 N., R. 76 W. (Swenson, 1968b, fig. 2), the Dakota is depicted as being separated from the Inyan Kara by a very thin interval of Skull Creek Shale. The South Dakota Geological Survey has in its files the record of only one well drilled in this particular township and this is the Ohio No. 1 Reinschmidt oil test located in section 27. The electric log of this well reveals that the Dakota and Inyan Kara are separated by 105 feet of Skull Creek Shale (1635-1740). The interval (1900-2000) between the Inyan Kara and Madison is essentially correct as shown by Swenson, but the interval from 1895 feet to 1953 feet is the Roundtop Shale.

The purpose of the foregoing is to illustrate that water from Mississippian rocks does not recharge the Inyan Kara Sandstone in the zone of inferred leakage as suggested by Swenson because:

1. At the western border of the zone of inferred leakage of water (Swenson, 1968b, fig. 2) the Inyan Kara certainly does not directly overlie the Madison Group. In fact data are not existent that prove this condition even occurs at the eastern border of the zone of inferred leakage.
2. In this area the Inyan Kara yields a sodium-sulfate water just as it does to the west.
3. If water were leaking to the Inyan Kara in the area of inferred leakage, it is probable that the ion exchange capabilities of the clay minerals in the Inyan Kara and Dakota would have been exhausted and both of the Cretaceous formations would produce a calcium-sulfate (Precambrian-Roundtop) type water. From figure 18 and the appendix of this report it is seen that the Dakota produces a sodium-chloride type water and the Inyan Kara produces a sodium-sulfate type water in the area under discussion.

The writer disagrees with Swenson on several other points. For instance, Swenson

(1968a, p. 164) states, "Russell's work also indicated that the sandstone sequence is highly lenticular, and that the Fall River contains considerable shale." Actually Russell (p. 137) stated, "By plotting a large number of sections through these formations in the Black Hills region and in the Dakota exposures in the vicinity of the type locality it was found that the sandstones are highly lenticular. . .As a result of these investigations, it is now clear that the **type** (writer's emphasis) Dakota consists of a series of sandstone lenses embedded in shales, with the latter predominating. In the Black Hills region the formation between the base of the Lakota and the top of the Fall River consists of **more** or **less** (writer's emphasis) lenticular sandstone with a considerable amount of shale. . .The Fall River strata are, however, somewhat more persistent, and some of the sandstones contained in this formation may extend for ten miles or more."

From the foregoing it is apparent that the studies of Russell do not preclude the possibility of the Inyan Kara Group being recharged by surface runoff in the Black Hills region.

Later Swenson (1968a, p. 171) states, "These deposits are extremely lenticular because they are transgressive deposits formed as the site of deposition moved eastward several hundred miles. Thus, there is, in fact, no single bed of permeable sand extending from the recharge area to the discharge area, as would have to be assumed to support the previous concept." Earlier on the same page Swenson maintains, ". . .where the transgressive blanket of sandstone of the Dakota rests directly on the Precambrian. . ."

It is difficult to establish whether or not a single bed of permeable sandstone does or does not exist. If one were to examine a cross section of this interval in two dimensions only perhaps one would be inclined to believe a single transgressive bed does not exist. However, the sediments have three dimensions and a permeable path almost certainly exists from the Inyan Kara outcrops in the Black Hills region to the Dakota in the southeastern quarter of the State.

On page 174, Swenson (1968a) quotes Brown (1944, p. 7), "This limestone (Pahasapa, Madison in subsurface, writer's parenthesis) is one of the principle sources of water loss on streams flowing out of the Black Hills." However if one reads further Brown continues (p. 8), "Examination of the streams through the outcrop area of the Minnelusa shows clear evidence of important water losses in this formation. . .Sealing across the outcrop of the limestone beds of the Minnelusa Formation is fully as important as sealing across the Pahasapa."

Also on page 174, Swenson (1968a) states, "As noted previously, some wells of large yield have been finished in the Minnelusa Formation close to the Black Hills, but oil tests at greater distances from the outcrops have invariably found the formation tight." The Minnelusa is not invariably tight. For instance, the Cities Service No. 1 Wagner "A" oil test (sec. 13, T. 5 N., R. 29 E.) encountered an estimated flow of 5000 barrels of water per day at a depth of 2193 feet (Upper Minnelusa). The Cayman-Murphy No. 1 State "B" oil test (sec. 12, T. 21 N., R. 24 E.) abandonment was delayed for two days because of a water flow from the Minnelusa (William Brown, Drilling Superintendent, personal communication). Glass (1960, p. 2034-35) described a water well (sec. 19, T. 5 N., R. 7 E.) that encountered the Minnelusa at a depth of 3102 feet. Drilling continued to a depth of 3161 feet where the tools entered a 4 foot cavern which yielded a water flow estimated at 4000 gallons per minute. The cavern was cased through and the pipe was perforated. The well was finished in the upper part of the Minnelusa and yielded a flow of 748 gallons of water per minute with a closed in pressure of 160 pounds per square inch. The surface elevation of this well is 2955 feet.

Admittedly, the last example is close to the periphery of the Black Hills, but it is sufficiently far east to preclude the possibility of a great amount of water being lost to resurgent springs above an elevation of 3325 feet. The foregoing does not prove the Minnelusa is invariably porous, but does prove that it is not invariably tight and illustrates that one should not restrict water intake in the Black Hills region to the Pahasapa Limestone. From Swenson (1968a, p. 179) the hydrostatic head of the Madison and the Dakota equivalents (i.e., Newcastle and Inyan Kara) is 2660 and 3100 feet respectively at Rapid City. Thus, there is a pressure inversion between the upper part of the Minnelusa and the Madison, and the Inyan Kara and the Madison. This is quite germane to the problem in that it does indicate that there is no communication between the Upper Minnelusa and the Madison. The pressure differential between the Minnelusa and the Inyan Kara does not, however, preclude the possibility of communication between the Inyan Kara and the Upper Minnelusa.

Again, in reference to the statements of Russell and Swenson that the Fall River (formerly the Dakota of the Black Hills area) is not capable of transporting water for any great distance, the following is noted.

A water well drilled to the Inyan Kara sandstones at the town of New Underwood (see fig. 18 for location of wells) yields a sodium-sulfate type water with total solids of 483 parts per million. At the city of Wall, approximately 24 miles east-southeast of New Underwood, the Inyan Kara yields a sodium-sulfate type water with total solids of 681 parts per million. In the city of Quinn, 6 miles east of Wall, water from the Inyan Kara is a sodium-sulfate type water with total solids amounting to 994 parts per million. Approximately 35 miles east of Quinn, the city of Kadoka produces a sodium-sulfate type water from the Inyan Kara. The total solids of water from this well amount to 1,815 parts per million. At Belvidere, approximately 12 miles east of Kadoka, the Inyan Kara yields water with 1,966 parts per million total solids.

This indicates that fresh water does in fact enter the Inyan Kara outcrop around the periphery of the Black Hills and has nearly entirely flushed the formations of sodium and sulfate ions at least as far east as Quinn, South Dakota. Thus, it is clear that the mechanics of Shepard's theory (p. 6, this report) are in part correct and the mechanics of Russell's and Swenson's theories are in part incorrect.

It has been stated elsewhere in this report that the Dakota Formation in the eastern half of the State transmits water readily in all directions. Also, from the two preceding paragraphs it is quite apparent the Inyan Kara also transmits water readily at least as far east as Belvidere, South Dakota.

Shepard (1895), Darton (1909), Russell (1928), and Swenson (1964) attempted to trace the origin and path of migration of water to the Dakota Formation. Their attempts have been noteworthy; however, in all cases the authors failed to recognize the important part played by the Skull Creek Shale and in effect treated the Dakota Formation and Inyan Kara Group as a single unit. They are not. Where the Skull Creek Shale is present the Dakota and Inyan Kara are individual lithologic and hydrologic units.

The Newcastle and younger tongues of the Dakota are not sufficiently well developed to permit a large amount of water to enter the outcrops in the western part of the State. The water from wells developed in the Newcastle a short distance east of the outcrops in the Black Hills area is predominantly a sodium-chloride type water. If these sandstone outcrops received a large amount of surface runoff the water would not be characterized by a sodium-chloride type water. This indicates that the Newcastle tongues of the Dakota do not recharge the Dakota Formation but instead hold connate water.

From pages 23 to 25, it is quite apparent that the Inyan Kara Group or possibly the Roundtop-Inyan Kara interval receives a large amount of surface runoff at the outcrop area in the Black Hills. The water is confined in the Inyan Kara by the overlying impermeable Skull Creek Shale. Where the Skull Creek Shale is absent the water migrates upward and recharges the Dakota Formation with sodium-sulfate type water (fig. 19). The area of sodium-sulfate type water shown on figure 18 represents water in the Dakota that has been derived mainly from rocks of the Inyan Kara Group and probably in part from rocks included in the Roundtop-Inyan Kara interval.

Quite probably older pre-Pennsylvanian rocks are also recharged by surface runoff in the Black Hills area. As the water moves eastward through limestones to central and southern South Dakota it becomes more heavily charged with calcium but maintains the calcium-sulfate characteristics. The Roundtop Formation (mainly shale a short distance east of the Black Hills) overlies the Mississippian and Ordovician limestone and confines the water. In the southeastern part of the State the Roundtop Formation thins and becomes more sandy and allows underlying rocks to yield water to rocks of the Inyan Kara Group. However, in this same area, or a short distance east, the Skull Creek is also absent and the water migrates from the Inyan Kara to the Dakota Formation (fig. 19).

Examination of analyses of water from wells that tap the pre-Pennsylvanian rocks in the northern half of the State indicates that water characteristics are not as consistent as those from the southern half of the State. A few analyses suggest that the pre-Pennsylvanian rocks also yield a calcium-sulfate type water on the eastern edge of the Williston Basin (see column 3, table 1). If this is representative of true conditions then it is possible that there is a barrier to the migration of water from the Precambrian-Roundtop to the Roundtop-Inyan Kara interval in this area. Meager subsurface information does not concretely establish this. However, logical conjecture coupled with the meager subsurface information available suggests the existence of a barrier; this barrier being the Roundtop Shale. The near absence of calcium-sulfate type water in the Dakota in the northeastern part of the State may be due in part to the fact the Dakota Formation in that part of the State does not have as unrestricted an outlet as exists in southeastern South Dakota. The sodium-sulfate type water that has been derived predominantly from the Inyan Kara sediments is trapped in the Dakota by the Sioux Ridge to the south and the increasing elevation of the Dakota and restricted outlets to the east. Thus, the calcium-sulfate water cannot enter the Dakota and migrate northward because the sodium-sulfate water is trapped in the Dakota Formation in that area. This indicates that as wells continue to be drilled to the Dakota in the James River valley and production overtakes the Inyan Kara recharge to the Dakota the hydrostatic head will decrease and eventually the Precambrian-Roundtop recharge may migrate northward due to pressure depletion and charge the area with calcium-sulfate water.

Decline of Artesian Head

Since the turn of the century many people have been concerned in regard to the decline of the artesian head of the Dakota Formation. That this concern was and still is well founded is illustrated by three piezometric maps (figs. 15, 16, and 17 of this report). Figure 15 is a slightly modified piezometric map of South Dakota as constructed by Darton in 1909. Figure 16 is a piezometric map constructed by the writer from information gathered by the State Engineer during 1914-1915. Figure 17 is modified after Rothrock and Robinson (1936), Erickson (1954 and 1955), and Barkley (1952 and 1953).

Swenson (1968a, p. 173) states, "The ground-water contour map prepared by Darton (1909) presents certain features difficult to explain under previous concepts of recharge and movement of water in the artesian basin. It is, of course, recognized that interpretations made from the map can have no greater accuracy than the map." Darton's map may be in error, especially in the area west of the Missouri River; however, it is believed these errors may be due to lack of information rather than errors in Darton's interpretations. For instance, why should it be assumed that the contours are correct between Midland, South Dakota and the zone of outcrop in the Black Hills where one reference point existed at the time Darton published his report, and then, on the other hand, assume the contours are incorrect in the area east of the Missouri River where Darton had hundreds of reliable reference wells? Although it is quite probable that Darton's map may show inconsistencies (especially in the area of Davison County), the fact remains the map is the most accurate of any map published in regard to artesian conditions prior to the year 1909. It is extremely important in that this map shows more correctly the artesian system in near equilibrium than any map published before or since the year 1909.

On page 173 of his 1968a report, Swenson stated, "When an aquifer transmits a given quantity of water, the gradient should be inversely proportional to the product of the permeability times the thickness of the aquifer." He states further, "Well yields suggest that the permeability of the Dakota Sandstone is greatest in the James River valley at the longitude of Ellendale, Aberdeen, and Huron (fig. 2), and is progressively lower to the west. Permeability of the aquifer is low along the Missouri River; there the gradient of the potentiometric surface is also low, and the thickness of the aquifer is no greater than the James."

In reality, well yields do not suggest that the permeability is greatest in the James River valley. It has long been known that wells yield more in the Missouri Valley than at other locations. Davis, Dyer, and Powell (1961, p. 14) state, "Many of the flowing wells inventoried in the valley of the Missouri River in Bon Homme, Brule, Buffalo, Charles Mix, Gregory, Lyman, and Yankton Counties are classed as uncontrolled wells. The flow from 46 of these wells is more than 16 mgd, most of it unused. For comparison, the total flow from 3,054 wells known or presumed to tap the Dakota Sandstone in 3,500 square miles of the James River valley area is approximately 16 mgd (U. S. Geol. Survey unpublished records)." The elevation of the land surface is approximately the same in both localities. In view of this it cannot be stated that the sediments of the Dakota are less permeable in the Missouri River valley than in the James River valley. Instead, the reverse is implied.

Darton's map of 1909, when used in conjunction with maps constructed from information gathered in 1914-1915 and 1936-1954, is especially useful in tracing the effects on the pressures caused by the exploitation of the Dakota Formation. From Darton's (1909) map of the piezometric surface of the Dakota Formation (fig. 15 this report) it is noted that the hydraulic gradient slopes gradually from west to east. The piezometric contours are essentially oriented in a north-south direction. This condition exists until the 1900 foot contour is encountered. In Hyde County the contours bend eastward around a pressure high that is caused by recharge to the Dakota from the Inyan Kara sandstones.

The 1,600 foot contour has a notable deflection to the east in Charles Mix County. With figure 15 (Darton's map of the piezometric surface) superimposed on figure 9 (pre-Cretaceous paleogeologic map), it is evident that this high pressure area in the Dakota is caused by Mississippian and older rocks furnishing recharge to the Dakota. The amount of recharge taking place is sufficient to bend all the remaining contours in an eastward direction. The same interpretation can be made from superimposing the map of the piezometric surface of 1914-1915 and 1936-1954 (figs. 16 and 17) upon the pre-Cretaceous geologic map.

If the piezometric maps (figs. 15, 16, and 17) are compared, it is evident that during the period between 1909 and 1914 a greater amount of contour shifting has occurred than during the period 1914 to 1953. Thus, the Dakota Formation must transfer water quite readily to have such a pronounced effect in the relatively short period from 1909-1914. If the Dakota were in fact composed of disconnected lenses and pods of sandstone enveloped by shales as implied by Russell (1928) and Swenson (1968a and b), there would be a greater divergence of pressures, especially in areas of greater production; unless one assumes that all disconnected pods were tapped in the area of the James River valley and the lower Missouri River valley during the period 1909-1914. However, this possibility is remote.

In 1954 (p. 71), Erickson stated that the greatest decline in his area of study occurred in T. 116 N., R. 64 W., where a drop of 385 feet was noted. Barkley (1952, p. 32) wrote, "Near Greenwood the water level has dropped approximately 223 feet since 1909. . .The decline at Springfield has been 105 feet and the city well at Yankton has shown a decline of 18 feet." Robinson (*in* Rothrock and Robinson, 1936, p. 46) stated, "From these data it is concluded that the altitude of the piezometric surface at Chamberlain was 1,828 feet in May, 1891. . .and 1,684 feet in August, 1900." Robinson also stated (p. 47) that at Pierre the decline in head amounted to about 300 feet over a period of 35 years. These authors acknowledged that the greatest decline occurred where the greatest amount of withdrawal took place.

From the piezometric maps mentioned above it is very evident that the greatest decline between 1909 and 1952 has occurred along the James River lowlands, and along the Missouri River most notably at Pierre, Chamberlain, and adjacent to the western boundary of Charles Mix County. Prior to 1912 the city of Pierre obtained its gas supply from 13 wells that tapped the Dakota artesian systems. The water associated with the gas in this area was allowed to waste. Robinson (*in* Rothrock and Robinson, 1936, p. 45) quoted Hayes, then City Engineer of Chamberlain, concerning a decrease in pressure of a well located at Chamberlain that, "The decrease in flow is accounted for by the drawing away of the supply of six power wells in the city." From records of wells on file with the South Dakota Geological Survey it is also known that the concentration of artesian wells is greatest in the Missouri lowlands along the western boundaries of Charles Mix and Brule Counties and along the James River lowlands in Brown, Marshall, Day, Spink, Clark, Beadle, Jerauld, Sanborn, and Davison Counties. It is seen from the piezometric maps that a decline of 300 to 350 feet of hydrostatic head has occurred in the aforementioned areas. It is also apparent that this decline is caused by the high concentration of wells that produce in these areas.

According to Darton's map (fig. 15) the piezometric surface sloped gradually from west to east with little or no irregularity. However, from 1915 to the present it is apparent from the water quality maps and figure 19 that the recharge to the Dakota from the Paleozoic formations is no longer entirely transferred to the east, but an unknown amount moves a short distance westward to recharge the area of heavy production along the Missouri River. The remainder of the recharge flows eastward until it is deflected to the south and to a lesser degree to the north by the Sioux Ridge. The water deflected to the north of the Sioux Ridge then recharges the Dakota in the area of the James River lowlands adjacent to the Sioux Ridge. The water that migrates south of the Sioux Ridge flows eastward, in some cases escapes to glacial aquifers, but for the most part is discharged to the Missouri River floodplain near Sioux City, Iowa.

What is not apparent from the piezometric maps is that the area of the James River lowlands lies at an approximate elevation of 1,310 feet above sea level in Brown County and about 1,250 feet in Sanborn County. From the maps it is seen that the hydrostatic head fell from about 1,540 feet in 1909 to 1,400 feet in 1915 and from 1,400 feet in 1915 to 1,340 feet in 1952. In other words, from 1909 to 1915 the decline averaged about 23 feet per year and from 1915 to 1953 it amounted to approximately 1½ feet per year. It appears possible to project these figures and estimate the decline at present to be about 1 foot per year. Thus, it appears that by the year 1980 no Dakota wells will flow in Brown County. This condition will spread southward and by the year 2040 will hold true for the entire James River lowlands from northern Brown County to southern Sanborn County. (This is not quite true because production will taper off very gradually until a point is reached when the wells will only trickle for years. However, a trickle is not sufficient production to warrant a well's existence.)

The foregoing projections assume that present conditions will remain static; however, it is believed that withdrawal from the artesian system will increase. More wells will tap the Dakota artesian system in the James River lowlands. In areas where the Dakota will not flow, well drillers will either install pumps in Dakota wells or penetrate the Inyan Kara as they have been doing recently in Jones, Lyman, Stanley, Sully, Potter, Campbell, and Edmunds Counties. However, the Fall River Formation recharges the Dakota a short distance west of the James River valley and wells drilled to the Fall River will tend to further deplete the amount of recharge to the Dakota Formation that underlies the James River lowlands. It is the inhabitants of the James River lowlands that will be required to drill new, more expensively designed wells in the near future.

Thus it can be said that wells along the Missouri River that waste as much as 3,000 gallons of water per minute per well are forcing a financial and physical hardship on the inhabitants of the James River lowlands.

Local variations in pressure can be used to discredit the foregoing arguments, and it is possible that it is best to deal with a few of these discrepancies before questions arise.

Darton (1909) mentions three water wells in the city of White Lake, South Dakota. These wells had hydrostatic heads of 1691, 1643, and 1638 feet when they were first completed. Barkley (1953, p. 60) records the Glisendorf water well (located in sec. 19, T. 103 N., R. 66 W. and drilled in 1953) as having a hydrostatic head of 1,674 feet. Persons who advocate that pressure in the Dakota is not declining may suggest that this indicates the artesian pressure is not falling and may even be increasing in the vicinity of White Lake. However, it is called to the reader's attention that White Lake is located a short distance east of the area where the older Paleozoic rocks recharge the Dakota Formation. Thus, it is perfectly logical to expect the hydrostatic head to remain relatively constant in localized areas as long as the older Paleozoic rocks maintain a rate of recharge that corresponds with or exceeds the rate of production in that locality.

In central Sully County there is a relatively high pressure area that has lost only 100 feet of head during the period from 1909 to 1952. It is believed that the Skull Creek Shale is absent in this area and that the high pressure is caused by the Inyan Kara Group recharging the Dakota. A comparison of the water-type map tends to reinforce this postulation.

A high pressure ridge also extends from southern Hyde, to southwestern Hand, thence to central Buffalo, Brule, and Charles Mix Counties. This "ridge" of high pressure is a result of the Paleozoic rocks recharging through the Inyan Kara sandstones to the Dakota Formation (figs. 16, 17, and 18).

From these examples it is apparent that local variations exist in the Dakota artesian system. These variations are easily explained, however, when it is understood that different formations recharge the Dakota in different localities.

There are still other factors that indicate the existence of local variations when in fact there may be little or no variation. For example, the well at St. Paul's Mission (sec. 5, T. 94 N., R. 64 W.) is reported to have flowed 500 gallons per minute in 1940. In 1952 Barkley (p. 48) reported the water level at 51 feet above ground level and a flow of 4 gallons per minute from the same well. In 1961 Davis, Dyer, and Powell (p. 55) reported that the head of water in the aforementioned well was 69 feet above ground level when the well was cleaned (no date given on work over). This implies that sand fillup or well cementation caused a pressure differential of 8 pounds per square inch between the top and bottom of the sand plug or cemented zone near the intake of the well.

Another factor illustrating false pressure variation is the length of time pressure is allowed to build up before the reading is taken. For instance, Darton (1909, p. 85) relates that the well at Cheyenne Agency had initial closed in pressure of 187 pounds, but the amount increased to a maximum of 205 pounds in 4 days. The difference in the two pressure recordings amounts to 41.4 feet of hydrostatic head.

The condition of the well casing influences the pressure reading taken on any given well. If the casing has been corroded and permits water to enter permeable formations adjacent to the well bore it is obvious that the reading will be in error. Rothrock (1950, p. 10) estimates there are from 12,000 to 15,000 artesian wells with corroded casing in South Dakota that either run wild or leak into higher porous formations.

Also the vast majority of wells penetrating the Dakota aquifer are completed in a very inferior manner in that casing is simply "hung" in the well. It is assumed by well drillers that the shales above the Dakota will heave and seal the pipe in the well. However, this is certainly not evidenced by the city well at Midland, South Dakota, which was completed in the Madison Limestone. True, the casing was cemented in but it is quite evident from notes on the well that the production string was not cemented above the midpoint of the Fall River Formation. After a period of 8 years the water from the Fall River broke through around the casing at the surface. This ultimately costly, inferior construction resulted in a complete loss of the well to the city and serves to adequately illustrate that heaving shales do not always provide a positive seal. In view of this it is believed that many wells that have been pressure-tested may provide unreliable data.

Another well-known phenomenon is that water under pressure is capable of carrying more minerals in solution than water under less pressure. In the area surrounding the well screen or intake, a cementation of the sediments and the well screen occurs as a result of the pressure reduction. It is very possible that if production continued for a sufficient length of time that cementation could progress to a sufficient degree to completely halt the movement of water through the well screen.

It is apparent that many factors influence the pressure reading of any given well; however, the piezometric maps were drawn for the most part from data obtained from relatively new and reliable wells. Although local variations do occur, the preponderance of data indicate that pressures in the Dakota artesian system are declining and perhaps within a few tens of years there will be few flowing wells in the James River lowlands. In view of this, it appears that it would be wise to regulate the number of wells in any given area. Before a new well can be drilled in an area where an old one exists the old well should be plugged with cement. In view of our past blatant disregard of conservation principles we are fortunate that the artesian system has not already been depleted.

Amount of Recharge to the Dakota Formation

The amount of recharge to the Dakota Formation in South Dakota is in large part proportional to the amount of surface water that enters outcrops in Inyan Kara and older sediments in the Black Hills area.

Carl B. Brown (1944) made a study of water losses of streams flowing east out of the Black Hills. His report deals mainly with only the major streams that lose water in crossing permeable Paleozoic formations. Brown (p. 1) concludes, "Net water losses through the belt of limestone have been reported or estimated at specific dates as follows: Rapid Creek, 2-10 second-feet; Spring Creek before sealing, 6-100 second-feet; Spring Creek after sealing, up to 6 second-feet; Squaw Creek, 7-8 second-feet; Box Elder Creek, 20+ second-feet; Elk Creek, 5+ second-feet; Little Elk Creek, 1+ second-feet; and French Creek, 5+ second-feet." The sink holes in Spring Creek were sealed in 1939-40 by the W.P.A.; therefore, the smaller figure must be used to estimate recharge to the Madison limestones.

Assuming the above figures are minimum and maximum figures, the average water loss to the Madison amounts to approximately 40 cubic feet per second (40 second-feet) or 28,835 acre-feet or 9.4 billion gallons per year. This amounts to slightly over one-fourth of the yearly withdrawal from the Dakota Sandstone.

A more recent report by Gries and Crooks (1968) also deals with the phenomenon of water loss to the Madison (Pahasapa) limestones in the Black Hills. These authors measured water losses to the Madison on Elk, Box Elder, Rapid, Spring, Battle, Grace Coolidge, French and Beaver Creeks over a time span of 21 months. From table 1 of their report it appears the average water loss to the Madison is 26 cfs. Thus, from the study of Gries and Crooks it appears the annual recharge to the Madison is approximately 6.2 billion gallons or slightly more than one-sixth of total withdrawal.

In view of these two independent studies it appears that withdrawal exceeds recharge by a substantial amount. However, smaller streams in the Black Hills also cross Paleozoic limestones and it has previously been shown in this report that the sediments of the Roundtop-Inyan Kara interval also receive recharge from the outcrop area. This illustrates the gloomy predictions under the section "Decline of Artesian Head" found earlier in this report, but does suggest that it is not too late to conserve this water supply for future generations. However, wild wells, wells with faulty casing, and abandoned wells that tap the Dakota Formation must be plugged. Any large-scale attempt to seal the points of entrance of water to formations that crop out in the Black Hills area will certainly diminish the amount of recharge to the Dakota Formation and will almost as certainly promote legal action to recover damages by residents of the eastern two-thirds of the State of South Dakota who use this aquifer as a source for their water needs.

Temperature of Artesian Water

C. E. Van Orstrand has shown that temperatures at the top of folds are greater than those on the flanks (Hager, 1951, p. 415). Hagar presents a table of thermal gradients compiled by Van Orstrand and Spicer, wherein the temperature at a certain depth is given by the formula:

$$y = a + bx$$

where

y = temperature at depth
a = average mean temperature
b = change per foot in degrees
x = depth of hole or stratum

Upon examination of the above formula it is apparent the results of the equation are largely influenced by factors b and x in localities of small area.

It has been recognized recently that the temperature of water produced from the Dakota Formation varies to a rather large degree in small areas. On the basis of meager data contained in the files of the South Dakota Geological Survey, it is apparent that these temperature variations are neither a result of pressure variations nor do they appear to be governed by increase in the depth to the aquifer.

For example, in extreme northwestern Haakon County the temperature of water produced from a well (sec. 7, T. 5 N., R. 18 E.) penetrating the Dakota Formation is 70 degrees Fahrenheit. Approximately 3 miles north (sec. 31, T. 6 N., R. 18 E.) a well produces water from the Dakota with a temperature of 119 degrees Fahrenheit. In this area the beds are essentially horizontal. The elevations of the two wells are approximately equal. Thus, if the formula above were employed to estimate the temperature of the aquifer it is apparent that the two wells should produce water of equal temperatures. Such is not the case; therefore, one must search elsewhere for the phenomenon that would account for a difference of 49°F in waters produced from different sites in the same aquifer at a spacing of a relatively few miles.

It has also long been recognized that the Dakota Formation produces water that contains gas in solution (p. 27, 32-34). The boundaries of this gas-producing area are shown on figure 18 of this report. When gas goes into solution with water, heat is evolved. It is conceivable that gas is being evolved in the Dakota Formation from the shales that confine the Dakota aquifer. If this is the case one would expect abnormally high temperatures in the majority of wells that produce water with gas in solution. However, this premise does not hold true in many cases.

It is possible that structural adjustment has or is presently taking place in the high temperature area because heat is evolved when sediments are deformed. The South Dakota Geological Survey possesses little subsurface information concerning the area under discussion; however, present subsurface information appears sufficient to discount the possibility of any large-scale deformation, but the possibility of small scale-movement cannot be ruled out.

In view of the foregoing a preliminary survey of the temperature of water wells in Haakon County was performed by the writer in the summer of 1967. From this survey it was determined that the temperature variations were a function of the amount of water yielded by individual wells. The higher yielding wells appeared to have higher temperatures and vice-versa. However, additional work must be done to confirm this conclusion.

A more detailed study of this phenomenon was published by Adolphson and LeRoux (1968, p. D60-D62) and they also concluded (p. D62) that, "Temperatures of water flowing from deep artesian wells are related to the depth of the well and the volume of discharge." In view of the similar conclusions of the two independent studies, it may be assumed that the findings are correct for general areas.

A short time prior to the completion of this report the South Dakota Geological Survey was granted funds by the legislature for the purchase of a new logging unit. Since the unit has been obtained the Survey has had the opportunity to run a temperature survey on the Fred Olson water well (NW¼NW¼ sec. 31, T. 2 N., R. 29 E.). This temperature log shows a bore hole temperature of 81°F at 350 feet and at total depth (2204 feet) a temperature of 111½°F which indicates a thermal gradient of .0165°F per foot or 1.65°F per 100 feet. For comparison, the temperature log indicates that from 50 feet above to 50 feet below the top of the Dakota the thermal gradient is 2.5°F per 100 feet, and from 50 feet above to 50 feet below the top of the Inyan Kara the thermal gradient is 5.5°F per 100 feet. From the gamma-ray log of the same well the gamma-ray emission of the shale immediately overlying the Dakota registers 60 counts (t.c.=2 sec.), and the emission rate of the shale immediately overlying the Fall River is 65 counts (t.c.=2 sec.) which is hardly a sufficient disparity to account for the large variance in the thermal gradient. On the basis of one temperature log it appears the abnormal thermal gradient is not caused by the disintegration of radioactive elements in the sediments, at least not in this particular locality. Neither does the disparity of thermal gradients appear to be governed by depth exclusively. As mentioned above, the temperature gradient immediately above the Inyan Kara is more than double the gradient immediately above the Dakota Formation. Furthermore, in this area the Dakota is gas-bearing and the Inyan Kara is not. In view of the foregoing it appears the water in the Inyan Kara is migrating from an area of high temperature in the west (area of deformation?), and the warm water is confined in the Inyan Kara by the Skull Creek Shale as far east as Murdo, South Dakota.

The phenomenon of temperature variations within the Dakota Formation is an enigma and perhaps it is idle to speculate on the cause. However, in view of C. E. Van Orstrand's work mentioned in the first paragraph of this section, the results of future study could be very rewarding.

It is noted that J. A. Jacobs, R. D. Russell, and J. T. Wilson (1959, p. 101) state that at a depth of 20 meters (66 feet) below the surface of the earth, seasonal temperature fluctuations are very small. Along this line it is to be expected that the thermal conductivity of the sediments are nearly constant in relatively local areas. The possibility exists that the temperature differences in the aquifer may be reflected at the surface provided the temperature of the earth were taken at a point approximately 70 feet below the surface. If preliminary tests indicate the foregoing to be true it is possible that areas of deformation could be located by the relatively economical procedure of measuring the temperature of the earth at a depth of 70 feet.

HISTORY OF GAS PRODUCTION IN SOUTH DAKOTA

Ardmore Gas Field

The Ardmore Gas Field, located in Townships 11 and 12 South, Range 4 East on the Chilson Anticline, was developed by the Woodward Oil Company during 1944-1947. Of the ten wells drilled three were dry and abandoned, three were plugged either through necessity or design, and four were shut in with a valve at the surface. The four shut-in wells (the Woodward No. 1, No. 2, No. 3, and No. 5 Schmidt) have been cased to total depth and at this writing appear to be in good condition.

The producing wells had a capacity of about 500,000 cu ft/day per well; however, production tests were never carried out and production over a 24 hour period is not known. Production was from the Newcastle Sandstone (lowest tongue of the Dakota) which varies from 20 to 50 feet in thickness in the area. An analysis of gas from the Woodward No. 1 Schmidt is as follows:

Oxygen	0.37	Average "N" by Pod	1.015
Nitrogen	17.97	Gross B.T.U. by Pod	837
Carbon Dioxide	0.0	Specific Gravity by Pod	0.637
Methane	80.73	Specific Gravity by Weight	0.641
Ethane	0.60		
Propane	0.33		
Isobutane	0		
N-Butane	0		
Isopentane	0		
N-Pentane	0		
Nexanes Plus	0		

Pierre Gas Field

Shortly before the turn of the century it was recorded that gas accompanied the production of water in the central part of the State (see gas outline on water-quality map, fig. 18). For the most part, information concerning gas production in South Dakota can be found only in publications that are out of print and not readily available. It is important that accounts concerning the occurrence of gas in South Dakota be preserved. For this reason the history of gas production in Pierre compiled by Mr. R. B. Hipple, Managing Editor of the Daily Capitol Journal, Pierre, South Dakota is included in this report. The following is nearly a verbatim report of the account as published by Gries (1940).

In November of 1889 the city of Pierre granted a franchise to Tams W. Bixby of St. Paul for the sale of gas in Pierre. A producing plant and system of mains were installed and served the city until 1894.

During the years 1892-1893 the U. S. Indian Service contracted to have an artesian well drilled at the Pierre Indian School on the eastern edge of the city. This well yielded a large flow of natural gas with artesian water. The gas was never used and was allowed to burn as an open torch above the well for many years. The well was plugged in October of 1939 and was producing gas until that time.

In 1893 private adventurers from Pennsylvania drilled a well at the foot of Pierre Street to a depth of 1,100 feet. A flow was not encountered and the test was claimed to have encountered granite.

In 1894 the Locke Hotel Company drilled a well behind the hotel to a depth of 1,300 feet and encountered a strong flow of water and natural gas. The gas was separated and used for cooking, and for heating and lighting the hotel. A surplus was piped across the street to the Publishing Company where it was used to operate an internal combustion engine.

During the year 1894 the city of Pierre drilled a well a few feet from the large expansion tank which had been built by Bixby for his producer plant. This well produced water and natural gas in quantity. The city bought out Bixby's franchise, mains, and took over the business. The natural gas was separated in an expansion tank of about 25,000 cubic feet capacity, and then run into Bixby's tank of about 50,000 cubic feet capacity, and then distributed throughout the city. Practically every home and business in the city used the gas for heat, cooking, and lights. All streets in the city were lighted by gas lights atop iron posts. One of these posts still stands on the J. E. Hipple residence property. The selection of the location for the State Capitol was in progress at this time and the citizens tapped a main on the principal street and set an open torch ablaze that burned day and night for months. During the next year or two additional wells were drilled in the same general location and added to the gas supply in the expansion chamber. The second well came in with the largest pressure ever noted at Pierre and propelled a stream of water approximately 100 feet in the air.

In 1898 C. L. Hyde drilled a well in the adjoining block to operate a flour mill. The gas was used to run a 34 horsepower internal combustion engine.

A few years later two additional wells were drilled about 6 blocks west of the gas plant, but neither produced very large quantities of gas and were cemented shut in 1924 (these two wells are some of the very few wells that have been abandoned in a correct manner, writer's parenthesis).

In 1910 a well was drilled at the State Capitol about 2 blocks north of the gas plant to provide water for an artificial lake. The State Engineer (Derr, 1916, p. 225-227) reports, "This is an 8-inch well. The flow at the time was 5.9 cubic feet of water per second, the equivalent of 2,648 gallons per minute. The pressure is reported to have been about 165 pounds per square inch, although at the present time it has fallen to about 30 pounds. This well yielded about 59 cubic feet of natural gas per minute, equivalent to 84,960 cubic feet per 24 hours. The flow of both water and natural gas has diminished until the latter averages very nearly 15,100 cubic feet per 24 hours."

In 1928 the city of Pierre drilled a fifth well near the original location but it only produced a small amount of gas and water.

The Norbeck Company in 1930 entered into an agreement with the city of Pierre whereby the Norbeck Company was to receive 75 cents per thousand cubic feet of gas delivered to the mains for one year. The well was drilled 6 blocks east of the original plant. Under this arrangement the Norbeck Company received $10,472 indicating a total annual production of about 14,000,000 cubic feet of gas. In nearly every case the gas is reported to have been "dry gas" or gas not associated with oil.

The following gas analyses have been reported by Rothrock (1944, p. 122-124):

State Capitol Well, Pierre, South Dakota Analysts: A. Karsten and Charles Bentley

Methane (CH_4)	94.00%
Carbon Dioxide (CO_2)	.06%
Oxygen (O_2)	.13%
Inert Gas (N_2 etc.)	5.70%
B.T.U. per cu. ft.	907.0 B.T.U.

Municipal Wells, Pierre, South Dakota Analyzed by the Carter Oil Company

Methane (CH_4)	74.80%
Ethane	13.20%
Propane	10.70%

Iso-Butane	.40%
N-Butane	.90%

Well in sec. 5. T. 118 N., R. 78 W., Potter County Analyzed by U. S. Geological Survey

Methane (CH_4)	92.10%
Ethane and higher	3.77%
Carbon Dioxide (CO_2)	0.25%
Oxygen (O_2)	0.49%
Nitrogen	3.48%

Calculated B.T.U. cu. ft. .... 1015 B.T.U.

Lacy Post Office Well, sec. 35, T. 7 N., R. 28 E., Stanley County Analyzed by U. S. Bureau of Mines

Carbon Dioxide (CO_2)	3.10%
Oxygen (O_2)	0.60%
Methane (CH_4)	88.70%
Ethane	0.00%
Nitrogen and Helium by diff.	7.60%
	100.00%

Helium content 0.04%

This well (Lacy Post Office) produced 354 cubic feet of water and 59 cubic feet of gas (see above analysis) per minute. The aquifer is at a depth of 1,225, and the water was under a pressure of 695 pounds per square inch at that depth. The temperature of the water at the well head was very near 90 degrees Fahrenheit.

POSSIBILITY OF OIL ACCUMULATIONS IN THE DAKOTA FORMATION

In 1909 Darton published his Water-Supply Paper 227. As a result of Darton's paper it has generally been believed that the Dakota Formation was a continuous artesian horizon from the Black Hills intake to the outlet at Sioux City, Iowa. This established the belief that this formation was entirely flushed of any accumulations of oil that may have existed. This opinion is now known to be erroneous. In view of this it is necessary to re-evaluate the oil potential of the Dakota Formation in the western half of the State where the formation has not been flushed (area of sodium-chloride type water, see fig. 18).

To date no commercial oil wells have been completed in the Dakota Formation in South Dakota. However, adjacent to the Black Hills in Wyoming and Montana numerous commercially important fields have been discovered in Cretaceous sandstones that are age and stratigraphically equivalent to the Dakota Formation.

It is noted that the tripartite subdivision of the Dakota in the eastern part of the State (see p. 8) was not used on a statewide basis in the construction of isopach maps in this report. The reason for this is that the lower three tongues that are present in the western part of the State have coalesced prior to reaching the type area near southeastern South Dakota. Tongue 1 is probably equivalent to the uppermost marine sandstone that is present at the type area. The middle clay unit at the type area closely corresponds with that part of the Mowry Shale that lies between the upper two tongues that are designated tongues 1 and 2 (figs. 7 and 6). Figure 1 is an isopach of the lower-most consistent sandstone tongue, the Newcastle Sandstone, as it fans out from the main body of the Dakota Sandstone. The isopachs of tongues 3, 2, and 1 in ascending order (figs. 5, 6, and 7) are quite self-explanatory. An illustration of the juxtaposition of these sand tongues is provided in figure 8.

Needless to say, the writer is aware that four tongues of the Dakota do not accurately define all of the tongues of the Dakota, for there are many. However, the isopach intervals have been keyed to the Greenhorn Limestone and are believed to correlate in a manner which most accurately portrays tongues which may be connected even though they occur at slightly different intervals. As far as oil exploration is concerned the plates in this report should be used only as a rough guide and any oil prospect should be researched from information available in the files of the South Dakota Geological Survey.

Previously in this report the statement was made that the source of the bulk of Dakota sediments was from the east and southeast and that the Black Hills area was not uplifted during Dakota time. If this is true then it is to be expected that the Dakota Formation tongues out in a general west and northwest direction (see figs. 1, 5, 6, and 7). After the Black Hills area was uplifted (Laramide Revolution) these west and northwest trending tongues of the Dakota were truncated by erosion. Thus, accumulations of oil that may have existed in areas immediately to the east and southeast of the present Black Hills were in part allowed to escape. This may explain why no commercial production has been established in the Dakota Formation in Fall River, Custer, Pennington, and southwestern Meade Counties even though a relatively large number of oil tests have been drilled in this area. However, it is entirely possible that accumulations of oil exist in updip tongues of the Dakota Formation that terminate prior to reaching the Cretaceous rim of the Black Hills and in areas where tongues of the Dakota cross over noses or anticlinal structures.

In the area immediately to the northeast and north of the Black Hills, the northwest and west trending tongues of the Dakota Formation were not opened up by the truncation which followed the Black Hills uplift. Thus, the conditions that affect the accumulation of oil in this area are similar to conditions that exist south and southwest of the Black Hills in Wyoming and potential petroleum traps exist where:

1. Tongues of the Dakota Formation cross noses or anticlinal structures.
2. Tongues of the Dakota terminate updip towards the Black Hills. This may occur anywhere west of the axis of the Williston Basin.
3. Tongues of the Dakota in plan view exhibit convexity updip.
4. Closed anticlines and stratigraphic traps exist in the area of sodium-chloride type water.
5. Beach bar and channel deposits are present.

Because the Dakota Formation in the western half of the State is not being flushed by water entering the outcrops of the Newcastle Member, hydraulic traps probably do not exist between the Black Hills and the axis of the Williston Basin. However, in the south-central part of the State where the Inyan Kara recharges the Dakota it is possible that hydraulic traps do exist.

From the isopach of the Newcastle Sandstone (fig. 1) in the area to the north of the Black Hills (northern Butte and Harding Counties) there is a western-derivedDakota equivalent (probably Muddy Sandstone) sand development. If the Dakota isopach is projected northward into North Dakota (fig. 12) an area of little or no Dakota (or Dakota equivalent) sediments is present in north-central North Dakota. This area extends southwestward across that State into northwestern South Dakota and continues southward to the northern Black Hills area and the extreme northeastern corner of Wyoming. From the Muddy Sandstone distribution map of Haun and Barlow this trend may continue from northeastern Wyoming southeastward to the east-central part of that State, thence in a south direction to Colorado. If this trend is in fact continuous it possibly marks the limits of the western-derived Muddy Sandstone and the eastern-derived Dakota Formation and these limits are approximately as shown in figure 12.

Subsurface information is lacking in the northeastern quarter of the State. The barrier (very likely the Roundtop Shale) that prevents pre-Pennsylvanian rocks from recharging the Dakota with calcium-sulfate water in this area may also trap accumulations of hydrocarbons in the eastern and north-central parts of the State.

Because the Precambrian-Roundtop rocks in southern South Dakota furnish a large amount of recharge to the Dakota in the southeastern part of the State; it is believed that the migration path of the water has been extensively flushed. However, this path of migration is not State-wide but is restricted to a band approximately 100 miles wide between the Black Hills and the southeastern one-fifth of the State. The younger

Pennsylvanian rocks on the other hand have not been flushed to a great degree in that area. The large number of oil shows reported from Pennsylvanian formations make this the most promising prospecting horizon in the Paleozoic section in South Dakota.

It is, perhaps, idle to speculate whether or not the gas that accompanies the flow of water from the Dakota in the central part of the State is dissolved in the formation water or if this is gas that has somehow accumulated in an imperfect trap and is migrating toward the outcrop. Unfortunately, the Dakota artesian basin was discovered in the James River valley in northern South Dakota. If the discovery well had been drilled at Pierre in 1881 and had the water not been associated with gas then it would be a simple matter to determine the origin of the gas. Then one could say that possibly there are structures or stratigraphic traps west of Pierre that were filled with gas and that pressure decline in the Dakota Formation triggered the expansion of this gas and the excess is now being released. The possibility exists, but this too is speculation.

CONCLUSION

The purpose stated in the introduction of this report was summarized by nine questions. In conclusion, these nine questions are answered in the order posed and are as follows:

1. What is the origin, areal extent and thickness of the Dakota Formation?

The sediments of the main body of the Dakota were derived exclusively from an eastern and southern source. In the northwestern corner of the State is a sand deposit that is certainly age equivalent to the Dakota but was derived from a northwestern source. The areal extent of the Dakota Formation is as drawn in figures 1, 5, 6, and 7, and from these maps it appears the average thickness is approximately 150 feet.

2. From where does the water in the Dakota artesian system originate?

There are three main types of water obtained from the Dakota (fig. 18). The sodium-chloride type water found in the northwestern two-thirds of the State is connate.

The sodium-sulfate type water originates as rainfall in the Black Hills area, and enters the outcrops of rocks of the Roundtop-Inyan Kara interval. Moving eastward, it is confined by the Skull Creek Shale until it recharges the Dakota in the area of sodium-sulfate type water as outlined in figure 19.

The calcium-sulfate type water present in the Dakota in the southeastern quarter of the State also originates as rainfall in the area of the Black Hills. As streams emanate from the Black Hills and cross outcrops of rocks in the Precambrian to Roundtop interval, water enters these rocks and moves eastward under the confining Roundtop Shale. Near the Missouri River in the southern part of the State the Roundtop is absent and the calcium-sulfate type water rises to the Inyan Kara. However, here the Skull Creek Shale is also absent and the calcium-sulfate water continues to migrate to the Dakota and is confined in this formation until it reaches its natural outlets in the extreme southeastern part of the State (figs. 18 and 19).

3. What is the storage capacity of the Dakota artesian system?

The storage capacity of the Dakota Formation is approximately 1.1 billion acre-feet; however, the Dakota is only a fractional part of the artesian system. The Roundtop-Inyan Kara interval yields water to this artesian system and the sandstones of the Inyan Kara Group store at least as much water as does the Dakota Formation. In addition to this, the Precambrian-Roundtop interval also stores an unknown amount of water. Thus, in answer to the question, it appears quite probable that the artesian system has at least 3 billion acre-feet of water in storage that will eventually be transferred to the Dakota Formation. In other words, there is probably sufficient water in the Dakota artesian system to cover the State of South Dakota with water to a depth of about 60 feet.

4. Is recharge sufficient to insure an adequate water supply for future generations?

From the studies of Brown (1944) and Gries and Crooks (1968) it is known that measured water losses of streams crossing the Madison (Pahasapa) outcrop is from 6 to 9.4 billion gallons per year. This amount of water loss serves as available recharge to the Dakota artesian system. However, this figure represents only the water loss of some of the major streams along the eastern rim of the Black Hills. It is quite probable that many smaller streams also lose water to the Madison outcrops. From Brown (1944, p. 8) important water losses also occur in streams crossing the Minnelusa outcrops. These losses to the Minnelusa have not been extensively studied. In addition to these losses it has been demonstrated in this report that the Inyan Kara sandstones also receive recharge from the Black Hills area. Thus, the total recharge to the Dakota artesian system is probably much larger than heretofore believed.

The fact that withdrawal from the artesian system exceeds recharge is clearly demonstrated by declining pressures. Most of the wells that penetrate to the Dakota have been allowed to flow with no restriction since the day they were completed, and in many cases the water is put to no beneficial use. If this practice is allowed to continue it is a certainty that future generations will receive no benefit from this extraordinary artesian system. On the other hand, if basic conservation practices are enforced it is quite likely that beneficial withdrawal will be less than total recharge. So the question becomes not whether recharge is sufficient for future use, but rather, whether or not we wish to expend the effort required to insure a water supply for our sons and daughters who shall follow after us.

5. Is it possible to predict the water quality and quantity from a proposed well at any given location?

The quality of the water from the main body of the Dakota Formation can be predicted with some degree of accuracy by using maps such as figure 18, and by referring to water analyses from nearby wells listed in the appendix. However, in areas west of the Missouri River, especially in the northern part of the State, care must be taken by the water well driller to be certain that sufficient penetration of the Dakota is accomplished in order to assure reaching the main body of the sandstone. If sufficient penetration is not established, it is quite possible that only the upper tongue of the sandstone is opened up for production and the water quality may vary to a large degree. The water characteristics will be relatively constant (e.g., the Dakota will yield a sodium-chloride type water); however, the total concentration of ions may vary greatly. In most cases a penetration of 150 feet after the top of the Dakota has been reached will insure opening up the main body of the sandstone.

The quantity of water a proposed well will yield cannot be accurately forecast. Ordinarily one would expect the yield of any projected well to equal that of nearby existing wells.

6. Can the wasteful discharge of water be reduced or halted?

It is a certainty that many, if not all, of the wells that run wild or leak into higher formations can be brought under control. This was recognized as early as 1955 and the South Dakota Compiled Laws (1967) state, "The Commission shall, as soon as feasible, inaugurate a program for plugging abandoned and wild wells throughout the State to prevent further decline in the heads of the several artesian reservoirs, this program to be completed as rapidly as means can be found for carrying it out."

Many of the more recently constructed wells have been designed with no visible means of restricting the flow of water. This practice must be discontinued if we are to reduce the wasteful discharge of water from the Dakota artesian system.

7. Can the life expectancy of a flowing well that taps the Dakota Formation be accurately estimated?

If the Dakota artesian system were a simple artesian aquifer such as envisioned by

Shepard and Darton, it would be possible to quite accurately predict the life of a flowing well. This artesian system is not a simple system in that it is recharged by two other separate aquifers. Recharge to the Dakota is nearly entirely dependent upon water from these two aquifers. Thus to accurately forecast the life of a flowing well one would need an accurate estimate of the amount of recharge furnished by the two lower aquifers. Also one would have to be able to predict the number and the amount of withdrawal of wells that will be drilled to the lower aquifers in the future. Gross estimates of well life can be made by employing the three piezometric maps found in this report.

8. What are the possibilities that oil and/or gas accumulations of commercial importance exist in the Dakota Formation?

Gas and/or oil accumulations of commercial importance are almost certain to exist in the Dakota Formation. The possibilities are best west of the axis of the Williston Basin where westward extending tongues terminate updip towards the Black Hills. In this same general area the formation is not flushed of connate water and, therefore, it is not expected to be flushed of oil accumulations. In central Corson County there appears to be a southwestward extending tongue of the Dakota that has its origin in North Dakota (fig. 7). Prospecting should be carried out on the updip side of the deposit. The western derived sand section in northwestern South Dakota should be further tested on the updip extensions of the southeast trending tongues.

9. Can the Dakota Formation be safely used for the disposal of waste fluids and/or the storage of natural gas?

Sufficient data is not available in the files of the South Dakota Geological Survey to answer this question explicitly. If interpretations in this report are correct it appears that the Dakota Formation would be an ideal storage horizon where updip tongues terminate around the periphery of the Black Hills. The maps in this report should be used only as a general guide in selecting possible storage sites because at the present time in most areas the density of drilling is not sufficient to definitely establish the terminus of the sand tongues.

The Dakota is not extensively used as a source of water in this area and damage claims are not likely to be sufficient to discourage a storage or disposal project. However, near the periphery of the Black Hills, wells ordinarily penetrate to the Inyan Kara which lies below the Dakota. If radioactive or corrosive fluids are disposed of in the Dakota, due consideration must be given to pre-existing wells developed in the Inyan Kara and older formations.

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APPENDIX

PART A

WATER ANALYSES FROM WELLS DRILLED EAST OF THE MISSOURI RIVER

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
AURORA COUNTY												
5-102-66	2343	---	112	414	1299	93	0.0	1.7	3.0	Gillon Farm	810	Dakota
11-103-66	2286	131	103	405	1291	90	0.2	3.0	3.0	White Lake City	860	Dakota
28-104-63	2385	---	122	396	1319	88	0.4	4.6	3.0	Hoefort Oil Test	1082	Dakota
25-105-64	2181	---	72	341	1249	82	0.3	0.0	3.0	Larson Farm	750	Dakota
BEADLE COUNTY												
14-109-62	2050	593	128	50	1150	15	---	.65	2.4	Schumaker Farm	760	Dakota
19-109-63	1960	362	94	177	1180	53	---	.6	2.8	Barbe Farm	860	Dakota
22-109-59	2030	676	119	8.7	1100	1.8	.10	2.1	1.8		784	Dakota
21-109-65	2040	318	105	230	1210	64.0	.03	1.1	2.0		956	Dakota -- Temp 61 °F
1-110-62	2090	285	136	269	1210	65.0	---	1.2	36.0	State Fairgrounds	1000	Dakota
1-110-62	2010	400	132	170	1130	44.0	---	5.1	22.0	Courthouse Well	1000	Dakota
7-110-62	1990	410	136	166	1130	49.0	.06	1.2	1.7		822	Dakota -- Temp 67 °F
32-110-63	2355	324	151	258	1225	71	0.0	0.9	2.2	Virgil City	800	Dakota
6-110-58	2520	630	100	143	1430	34	0.6	2.9	2.6	Iroquois City	1008	Dakota
6-110-58	2200	736	150	10	1130	2	0.0	.2	4.2	Iroquois City	980	Dakota
1-111-66	2196	319	154	251	1162	61	0.0	0.6	2.8	Wessington City	1100	Dakota
12-111-60	2159	731	135	14	1143	4	0.0	0.6	2.5	Yale City	850	Dakota
4-111-62	1990	368	117	184	1150	51	---	1.3	3.2	Smith Farm	800	Dakota
24-111-64	2083	478	158	140	1119	35	0.1	3.3	2.7	Wolsey City	930	Dakota
24-111-64	2120	178	108	364	1301	74	.10	1.4	2.7	Wolsey City	1220	
14-112-61	2090	326	122	231	1230	58	.09	1.2	1.7		1000	Temp 66 °F
14-112-61	2000	650	182	16	985	2.4	.03	.23	1.9		770	Dakota -- Temp 61 °F
24-112-63	2110	217	121	308	1250	78	---	.08	2.8	Abramson Well	750	Dakota
24-112-64	2140	417	139	228	1210	21	---	.05	2.8	Kalure Well	800	Dakota
3-113-63	-----	261	96.8	266.9	1256	88.5	---	11.0	---	Hitchcock City	953	Dakota
4-113-63	2080	201	89	316	1280	82	---	2.8	1.2	Hitchcock City	1150	
4-113-65	2110	154	98	369	1280	85	.14	2.3	2.7		1000	Temp 71 °F
12-113-59	2430	862	294	6.9	965	2.9	.07	6.3	8.0		1002	Temp 54 °F
BON HOMME COUNTY												
4-93-59	1960	113	145	389	1130	73	0.14	3.2	2.7	Nauratil Farm	460	Dakota
23-93-60	2497.5	329	143	335	1450	71.8	---	---	---	State Normal	680	Dakota
23-93-60	2032	120	138	364	1095	70	0.2	2.2	2.9	Springfield City	620	Dakota
31-95-59	-----	128.3	148	365.5	1180.4	81.5	---	---	---	Tyndall City	736	Dakota
31-95-59	2226	125	148	125	1209	75	0.1	3.6	2.0	Tyndall City	800	Dakota
BROWN COUNTY												
4-121-62	2219	667	290	56.9	1059	17.5	0.0	0.3	1.6	Stratford City	1140	Dakota
6-121-60	2228	758	173	11.0	1111	3.0	0.0	0.6	4.0	Ferney City	1100	Dakota
28-121-61	-----	835	350	4.0	950	2.0	---	.37	3.7	Knickrehm Farm	1120	Dakota
33-121-64	1962	724	485	14.0	609	3.0	0.0	0.0	2.2	Mansfield City	1180	Dakota
19-123-60	2192	598	110	78.0	1252	21.0	0.0	1.0	2.3	Groton City	1000	Dakota
	-----	585	174	63	995	12.0	---	---	2.5	Aberdeen City	1250	Dakota

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
BROWN COUNTY – continued												
15-123-63	-----	634.09	144.83	35.16	1117.97	23.36		6.57	---	Aberdeen City	1300	Dakota
13-123-64	1971	643	271	40.02	848.24	.69				Aberdeen City	1101	Dakota
21-124-65	-----	600	100	20.0	1150	12.0	---	.29	3.0	County Well	1120	Dakota
25-124-65	2136	----	67	79.0	1236	23.0	0.0	1.2	2.8	Arlt Farm	1285	Dakota
1-125-60	2543	----	321	17	1186	2	---	.5	5.	Claremont City	975	Dakota
2-125-60	2560	849	322	18	1188	0.0	0.0	0.8	4.8	Claremont City	975	Dakota
29-125-62	2334	----	----	----	479	---	---	---	4.5	Columbia City	965	Dakota
7-125-64	-----	963.6	912.4	8.0	282.4	11.1	---	8.2	---	Westport City	1030	Dakota
6-126-61	1820	607.46	574.03	32.49	310.14	1.43	---	---	---	Houghton City	1081	Dakota
20-128-61	2454	810	282	23.0	1088	2.0	0.0	1.2	4.8	Hecla City	1000	Dakota
	2374	880	87	28	1224	6.0	0.0	0.7	2.4	Walter (Walker) Daily		
BRULE COUNTY												
3-103-68	2299	102	109	412	1293	86	0.1	3.4	3.2	Kimball City	1200	Dakota
15-104-71	2082.6	187.7	109.3	324.2	1255.2	95.7	---	8.1	---	Chamberlain Mill	600	Dakota
15-104-71	-----	187.9	199.3	325.3	1252.3	95.6	---	---	---	Chamberlain City	815	Dakota
26-104-70	2518	112	118	407	1268	89	0.2	14.0	3.0	Pukwana City	1018	Dakota
BUFFALO COUNTY												
22-107-72	2191	112	97	372	1248	88	0.0	0.6	3.0	Peck Farm	1350	Fall River
30-107-71	2006	----	92	243	1115	59	0.0	3.8	3.0	Christenson Farm	775	Dakota
30-107-71	3962	----	2057	48	101	25	0.0	14.0	1.0	Christenson Farm	575	Greenhorn
36-108-72	2173	----	105	416	1298	97	0.0	1.0	3.0	Knippling Ranch	1150	Dakota
CAMPBELL COUNTY												
5-127-78	-----	----	58.4	242.1	1298	---	---	---	---	Ronald Dienert Farm	2362	Inyan Kara
21-127-77	-----	----	66.8	273.2	1400	---	---	---	---	C. Diebert Farm	2226	Inyan Kara
35-128-78	-----	----	1055.8	12.9	2.5	---	---	---	---	A. Dienert Farm	2250?	Dakota
CHARLES MIX COUNTY												
-94-64	1633	38	99	308	867	58	---	2.0	3.2	Bobcock Farm	712	Dakota
4-95-65	1358	516	354	17	171	6	---	.06	3.1	Ft. Randall	854	Dakota and Codell
7-96-61	1849	106	141	317	930	57	---	.6	---	Rest Haven	-----	Dakota
1-99-68	1323.7	----	----	----	----	----	---	7.7	---	Smit Farm	900	Dakota
13-99-68	1893	----	606	21	255	6.0	---	1.0	3.2	Platte City	464	Codell
13-99-68	2142	----	308	37.7	1093	157	---	3.2	3.4	Platte City	815	Dakota
13-99-68	2034	140	206	33	1034	71.0	0.1	10.0	2.8	Platte City	930	Dakota
CLARK COUNTY												
17-114-59	2430	830	262	5.7	1080	2.9	---	1.2	4.5	Iverson Farm	943	Dakota
18-115-59	-----	840	230	12.0	1100	1.0	---	.23	4.0	Helkenn Farm	980	Dakota
20-115-59	-----	860	265	8.0	1100	7.0	---	.07	4.0	Arne Farm	954	Dakota
-116-57	2245	774	22.0	11.2	1046	1.6	---	---	---	Mann Farm	1100	Dakota

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
CLARK COUNTY – continued												
15-117-59	-----	825	225	0.0	950	----	---	0.0	3.0	Hurlburt Farm	1073	Dakota
29-117-59	2274	791	220	8.0	984	2.0	0.0	0.2	5.6	Raymond City	1000	Dakota
9-119-59	2320	791	231	15.0	1012	4.0	0.0	2.6	4.0	Dubs Farm	1260	Dakota
9-119-59	2210	750	228	11.0	995	2.6	---	4.0	4.0	Lederman Farm	1200	Dakota
CLAY COUNTY												
7-92-52	1200	50	52	257	689	41.0	0.17	4.6	1.7	Mathis Farm	500	Dakota
DAY COUNTY												
3-122-59	-----	774.3	201	9.9	1120.4	12.9	---	4.2	---	Andover City	1075	Dakota
5-123-59	2230	742	163	9.0	1110	2.8	---	2.7	4.8	Hansmier Farm	1000	Dakota
6-123-58	1816	589	188	27.0	779	10.0	0.1	1.0	2.9	Pierpont City	1165	Dakota
25-124-59	2300	772	172	8.6	1150	3.3	---	2.4	4.1	Salens Farm	1200	Dakota
DOUGLAS COUNTY												
12-98-64	-----	152	175	372	865	10.1	---	---	---	Armour City	757	Dakota
EDMUNDS COUNTY												
3-121-66	-----	820	750	12.0	375	7.0	---	0.5	3.1	Anderson Farm	1020	Dakota
27-123-68	2167	304	60	237	1257	69.0	0.2	1.0	3.0	Ipswich City	1196	Dakota
27-123-68	2261	137	53	359	1264	80.0	---	1.0	3.4	Ipswich City	1400	Dakota
28-123-68	-----	789	491	9.6	343	16.0	---	4.34	---	Ipswich City	1265	Dakota
30-123-70	2343	814	440	9.0	480	5.0	0.0	0.7	3.0	Roscoe City	1500	Dakota
FAULK COUNTY												
21-117-72	-----	62	105	429	1200	72	---	0.06	---	Baloun Farm	2038	Paleozoic
31-117-66	2004	702	329	6	627	2	0.0	0.0	3.4	Rockham City	1100	Dakota
33-117-67	2378	747.7	324	17.6	750	8.7	---	---	---	C. F. Bues Farm	975	Dakota?
1-117-68	1759	609	287	8.4	593	8.8	---	---	---	Miranda City	1162	Dakota
36-117-69	1801	639	340	24	538	9.0	0.0	0.7	2.9	Orient City	1365	Dakota
9-118-70	-----	540	170	36	750	17.0	---	0.6	2.5	Faulkner Farm	1526	Dakota
14-118-69	2007	699	378	22	541	7.0	0.0	0.2	2.8	Faulkton City	1281	Dakota
14-118-69	1966	----	387	25	529	19.0	---	0.8	2.8	Faulkton City	1400	Dakota
16-118-67	2030	717	408	19.0	557	5.7	---	6.1	3.0	Bierman Farm	1020	Dakota
19-118-68	-----	155	55	345	1350	87	---	0.2	---	Lenhoff Farm	1500	Dakota
20-118-72	2130	----	68	255	1225	91	---	0.5	---	Hunt No. 1 Guten Kauf	2500-2575	Ordovician
20-118-72	2200	----	67	339	1272	103.0	---	0.5	---	Hunt No. 1 Guten Kauf	2334-2418	Devonian
11-119-66	1780	500	272	68	770	19.0	---	0.4	1.9	Steward Farm	1080	Dakota
31-120-67	2147	586	----	25	348	11.0	---	3.3	2.4	Cresbard City	1100	Dakota
23-120-72	-----	697	600	25	52	8.7	---	---	1.1	C. Duckell	1300-1800?	Dakota
HAMLIN COUNTY												
17-113-55	3004	1004	421	14	1226	4.0	0.1	0.6	4.8	Bryant City	1360	Dakota

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
HAND COUNTY												
7-112-67	2127	491	157	117	1138	36.5	---	1.0	3.2	St. Lawrence	-----	Dakota
10-112-68	2155	363	95	215	1222	57	0.0	1.5	2.4	Miller City	1100	Dakota
18-112-67	1958	568.6	102	53	1135	15.9	---	3.9	---	Humphrey	1296	Dakota
6-113-67	2038	235	113	324.8	1080	19.7	---	---	---		1200	Dakota
32-113-66	2351	453	315	215	1125	52.0	0.0	1.4	2.8	Snodgrass Farm	1263	Dakota or Fall River
21-116-69	2108	460	158	76	824	9	0.0	0.0	2.8	Dvorak Farm	1050	Greenhorn? Dakota?
HUGHES COUNTY												
3-109-76	3131	1182	1445	21	7	11.0	0.0	Trace	0.6	Schmidt Farm	816	Greenhorn
6-109-75	3172	1092	1203	26	8	20	0.0	0.0	1.2	Etzkorn Farm	836	Greenhorn
13-111-76	-----	82	90	384	1200	83	---	0.17	3.3	Dromey Farm	1850	Madison?
33-111-79	3464	1303	1902	41	----	19	---	---	---	State Capitol No. 2	1260-1385	Dakota
33-111-79	3479	1350	1702	30.8	Trace	1.4	---	3.8	---	Indian School	1192	Dakota
35-111-79	2238	112	88	368	1232	95	---	3.0	2.8	Airport Well	-----	Fall River -- Temp 109 °F
35-111-79	2466	56	95	329	1014	91	---	1.0	4.0	Airport Well	-----	Minnelusa
35-111-79	2386	59	91	340	1040	91	---	---	4.0	Airport Well	-----	Madison
8-112-76	2129	630	837	102	324	33	0.0	0.0	1.2	Blunt City	1400	Dakota
9-112-74	1746	629	487	11.4	306	16.6	---	---	---	Harrold City	1453	Dakota
16-112-76	2102	688	774	68.4	301	19.9	---	---	---	C&NW Railroad	1335	Dakota
-112-78	2082	1087	1056	42	699	14	---	2.4	---	Brown Well	1600	Dakota
HUTCHINSON COUNTY												
1-97-58	2080	122	138	411	1220	76	0.25	3.0	3.1	Schoenfish Farm	308	Dakota
3-97-57	2411	133	127	395	1230	82	0.0	8.2	2.8	Menno City	530	Dakota
HYDE COUNTY												
11-109-72	2011	286	76	225	1120	57	0.0	6.8	2.7	Stephan Mission	1456	Dakota
12-112-72	4487		2136	22	116	14	---	---	2.0	Highmore City	1500	Dakota
12-112-72	1707	601	290	18.2	498	9	---	---	---	Highmore City	1566	Fall River
23-113-73	4487	----	2136	21.5	116	14	---	---	2.0	Larson Farm	1500	Dakota
28-114-71	1967	513	297	40.3	700	15.5	---	---	---	King Farm	1417	Dakota
31-116-73	2218	----	79	325	1178	101	0.0	0.0	1.6	Hunt No. 3 School Land	2300-2400	Madison
31-116-73	2324	299	101	266	1289	48	---	---	---	Hunt No. 1 State		Ordovician
JERAULD COUNTY												
21-106-64	-----	140	70	332	1250	75	---	1.96	2.7	Hinrichs Farm	890	Dakota
4-107-65	2076	----	65	257	1217	68	0.0	0.7	4.5	Shyrock Farm	841	Dakota
17-107-63	2077	----	----	----	1232	----	---	---	2.6	Lane City	870	Dakota
17-107-63	2136	332	71	208	1223	67	0.0	2.2	2.2	Lane City	830	Dakota
20-107-64	-----	180	60	288	1200	63	---	1.7	2.6	Easton Farm	900	Dakota
1-108-64	2131	----	91	143	1245	48	0.0	2.0	2.5	Neumeyer Farm	921	Dakota
11-108-63	2047	----	84	176	1233	57	---	1.0	2.2	Alpena City	790	Dakota
11-108-63	2149	357	90	214	1233	59	0.0	3.0	2.3	Alpena City	900	Dakota
11-108-63	2147	352	90	204	1245	56	0.1	1.2	2.3	Alpena City	975	Dakota

Location	Total Solids	Na	Cl	Ca	SO_4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
KINGSBURY COUNTY												
3-109-54	2195	762	167	10	1130	2	0.0	0.7	4.0	Esmond City	850	Dakota
21-109-54	2448	853	242	7	997	4	0.0	1.8	8.5	Oldham City	1050	Dakota
1-110-55	2254	796	180	13	1122	2	0.0	0.3	6.8	Lake Preston City	830	Dakota
1-110-55	2210	----	----	----	----	----	---	---	6.0	Lake Preston City	1175	Dakota
31-111-58	2215	736	150	10	1125	2	0.0	0.2	4.2	Iroquois City	980	Dakota
22-111-56	2208	810	214	12.8	930	21.4	---	---	---	DeSmet City	1100	Dakota
24-112-59	2185	736	215	10	959	3	0.0	0.0	4.5	Bancroft City	1065	Dakota
LAKE COUNTY												
29-108-53	1875	589	93	46	877	13	0.0	1.3	1.9	Ramona City	850	Dakota
LINCOLN COUNTY												
32-96-50	954	165	80	115	391	30	0.0	0.7	3.2	Beresford City	735	Dakota
13-97-49	776	211	22	42	263	17	---	---	.4	Newton Hills Park	502	Dakota
4-98-50	400	77	9	60	75	9	0.0	0.2	1.2	Worthing City	470	Dakota
18-98-48	800	----	36	----	329	----	---	---	---	Indian Asylum	322	Dakota
23-98-49	706	181	25	61	222	21	0.0	0.2	1.3	Canton City	430	Dakota
23-98-49	705	----	33	86	241	30	---	0.8	---	Canton City	448	Dakota
32-99-51	2272	----	10	399	1136	99	---	0.2	---	Lennox City	487	Dakota
36-100-50	2783	152	11	433	1382	151	0.2	1.8	0.4	Harrisburg City	550	Dakota-Pleistocene contamination
McPHERSON COUNTY												
22-125-66	2536	934	880	10	307	7	0.0	0.1	2.5	Wetonka City	1300	Dakota
20-126-67	2196	764	530	20	384	9	0.0	1.6	2.2	Leola City	1375	Dakota
35-127-73	2305	152	64	342	1321	103	0.0	1.5	3.6	Eureka City	2085	Fall River
MARSHALL COUNTY												
3-125-59	2683	----	310	38	1329	10	0.0	2.2	5.0	Hartberg Farm	1300	Dakota
17-125-58	2540	835	222	13	1240	5.5	---	.17	7.2	Jones Farm	-----	Dakota
32-125-58	2601	865	223	13	1225	4.0	0.0	1.6	8.0	Langford City	1000	Dakota
23-127-58	2547	842	318	20	1207	5.0	0.0	0.3	6.7	Britton City	1000	Dakota
23-127-59	2629	902	397	21	1093	1.0	0.0	---	9.0	Mockly Farm	920	Dakota
3-128-58	-----	777	278	31	1115	7.5	---	---	---	Newark City	940	Dakota
MINER COUNTY												
19-105	2246	----	140	288	1224	74	0.0	0.5	2.0	Schave Farm		
8-106-57	2169	524	153	135	1158	36	0.0	1.0	2.8	Roswell City	611	Dakota
30-106-56	2134	470	214	163.9	1139	50.6	---	---	---	Vilas City	515	Dakota?
8-108-57	2173	745	245	36	1212	10	0.0	0.5	3.0	Carthage City	1140	Dakota

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
						POTTER COUNTY						
25-118-76	2010	742	482	8.5	384	4.6	0.01	0.1	2.7	Gettysburg City	1928	Dakota-Inyan Kara Recharge
27-118-76	2215	371	61	215	1281	57	---	---	---	Williams Farm		Fall River
25-118-76	2108	750	665	8	185	4	0.1	1.2	2.4	Gettysburg City	1950	Dakota-Inyan Kara Recharge
12-119-76	2009	----	2592	21	0	11	0.0	0.6	0.0	Unknown		Dakota-Well produced much gas
						ROBERTS COUNTY						
24-126-52	-----	1160	700	32	1250	15.0	---	0.14	4.0	Rath Farm	900	Dakota
10-127-51	7001	2469	1257	86	1033	52.0	0.0	1.2	1.0	Peterson Farm	660	Dakota-Pleistocene contamination
						SANBORN COUNTY						
23-105-61	2086	418	62	259	1219	2.0			3.0	Letcher City		Dakota??
1-106-61	2082	----	72	167	1222	49.0	0.0	0.4	1.0	Forestburg City	705	Dakota
2-106-61	2173	335	77	164	1028	46.0	0.0	2.0	2.4	Forestburg City	700	Dakota
4-106-59	2011	----	----	----	1132	----	0.0	---	2.8	Artesian City	800	Dakota
28-107-61	2040	422	86	158	1230	45.0	---	3.3	2.4	Peterson Farm	750	Dakota
21-107-62	1970	316	74	212	1200	58.0	---	0.95	2.8	Woonsocket City	775	Dakota
22-107-62	2010	302	68.5	223	1211	74.8	---	5.0	---	Woonsocket City	725	Dakota
6-108-62	2201	----	104	241	1249	69	0.0	1.4	2.0	Jensen Farm	1200	Dakota
20-108-60	1870	694	162	1.4	556	.5	---	.92	3.6	Unknown	500	Greenhorn
18-108-61	2100	653	98	28	1170	8.2	---	2.9	2.8	Unknown	800	Dakota
27-108-61	2273	216	136	275	1255	72	0.0	1.3	3.0	Loring Farm	950	Dakota
						SPINK COUNTY						
29-114-62	2110	663	203	30	1050	10	---	.49	2.8	Unknown	850	Dakota
22-114-64	2230	638	189	66	1190	18	---	.91	2.8	Unknown	975	Dakota
27-115-64	2090	506	139	114	1180	32	---	.06	2.4	Tulare City	850	Dakota
35-115-64	2135	525	132	117	1179	30	0.0	1.2	2.0	Tulare City	1200	Fall River
4-116-62	2102	676	200	26	1029	8	0.0	0.3	2.2	Frankfurt City	1000	Dakota?
10-116-61	2188	751	190	10	999	4	0.0	7.9	4.0	Remily Farm	1070	Dakota
10-116-63	2110	716	225	12	939	4	---	2.8	3.6	Unknown	900	Dakota
10-116-64	2232	736	226	31	1097	9	0.0	0.2	3.0	Redfield City	1080	Dakota?
30-117-60	2149	745	226	10	1033	1	0.0	0.2	3.4	Doland City	1000	Dakota
35-118-64	2358	584	198	99	1137	29.0	0.0	1.1	2.6	Ashton City	1006	Dakota
2-119-64	1985	685	320	6	773	2.0	0.0	1.2	3.0	Mellette City	1010	Dakota
6-119-64	2041	745	408	5	585	1.0	0.0	0.1	3.4	Northville City	1095	Dakota
11-119-63	2122	722	315	16	824	9.0	0.0	0.0	3.5	Hammer Farm	968	Dakota
20-120-63	2070	710	358	20	728	4.9	---	3.0	3.3	Geiser Farm	1042	Dakota
31-120-60	2384	800	273	10.0	1078	3.0	0.0	0.5	4.3	Conde City	1000	Dakota
32-120-62	2220	736	195	18	1155	4.0	0.0	0.9	3.0	Brentford City	1000	Dakota
						SULLY COUNTY						
23-113-77	2027	729	404	58	806	19	0.0	Trace	1.4	Johnson Farm	1495	Dakota
?-113-81	5537	1915	2900	48	26	43	0.0	---	1.2	Marks Ranch	?	Dakota
2-114-77	2268	60	67	417	1323	109	0.1	1.7	3.6	Onida City	2139	Fall River-Paleozoic recharged?

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
SULLY COUNTY -- continued												
2-114-77	2009	501	205	107	1002	35	0.1	0.3	2.2	Onida City	1700	Dakota
23-116-77	1981	713	526	10	355	2.0	0.0	0.2	2.8	Agar City	1800	Dakota
TURNER COUNTY												
5-98-53	1418	184	106	179	702	42	0.0	2.1	2.4	Viborg City	720	Dakota
27-99-52	3127	186	22	449	1641	156	1.7	1.9	1.5	Chancellor City	560	Dakota
UNION COUNTY												
13-90-49	1414	----	60	244	780	52	---	1.6	2.5	LaFleur Oil Test	835	Paleozoic
19-91-49	1355	113	53	236	720	39	0.0	1.4	2.3	Elk Point City	560	Dakota
YANKTON COUNTY												
4-93-55	1320	64	69	267	745	52	.22	2.4	2.8	Frick Farm	407	Dakota
13-94-54	2258	110	116	270	1112	72	0.2	3.1	2.8	Volin City	500	Dakota
7-94-56	2040	94	111	370	1107	71	0.0	3.2	3.0	Utica City	760	Dakota
36-94-36	2036	106	120	377	1137	67	0.2	3.2	3.0	Mission Hill City	600	Dakota
9-95-55	1690	110	117	325	956	61	.18	4.0	2.5	Gunderson Farm	468	Dakota
WALWORTH COUNTY												
19-121-78	4963	----	2592	21	0.0	11	0.0	0.6	0.6	Eiteneier Farm	?	
25-122-78	5219	----	2696	17	0.0	10	0.0	0.7	0.6	Wilson Farm	?	

APPENDIX

PART B

WATER ANALYSES FROM WELLS DRILLED WEST OF THE MISSOURI RIVER

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
BUTTE COUNTY												
2-8N-3E	2530	58	61	582	1610	92.0	---	.74	2.7	Dusing Farm	2000+	Minnelusa
7-8N-5E	567	192	5.0	6.8	237	2.2	0.0	0.9	0.45	Nisland City	1000	Greenhorn?
7-8N-5E	708	251	8.0	2.0	321	0.0	0.0	0.2	1.0	Nisland City	2050	Inyan Kara
32-8N-6E	532	185	6.0	5.6	199.5	1.46	0.02	1.4	0.58	Vale City	2300	Inyan Kara?
14-9N-8E	5685	680	541	428	1877	75.0	---	---	---	Sipila Ranch	4100	Minnelusa (Broom Creek)
19-9N-4E	1167	86	3.5	183	640	57.0	---	2.7	---	Orman	1417	Dakota?
24-9N-5E	816	261	39	.8	87	2.4	---	---	2.2	U.S.D.A.	2200	Inyan Kara
24-9N-5E	1061	393	14	----	337	2.0	---	0.4	4.0	U.S.D.A.	2580	Inyan Kara
27-9N-3E	2018	41	40	600	700	50.0	---	4.0	---	Olson Test	3240	Madison
27-10N-5E	688	234	48	2.5	180	0.5	5.02	2.4	0.0	U.S. Govt.		Inyan Kara
11-11N-7E	1140	408	130	2.5	120	0.5	0.38	1.5	0.68	U.S. Govt.		Inyan Kara
13-11N-1E	680	203	21.5	1.6	298	0.25	1.0	0.9	0.54	U.S. Govt.		Inyan Kara
CORSON COUNTY												
26-18N-21E	----	16592	25440	1540	4740	312	---	---	---	Kilroy No. 1 Schull	4470-4558	Madison (Charles)
26-18N-21E	-----	1744	1917	700	2996	192	---	---	---	Kilroy No. 1 Schull	4583-4743	Madison (Charles-Mission Canyon)
26-18N-21E	-----	1936	3815	860	1478	204	---	---	---	Kilroy No. 1 Schull	5873-5897	Red River (Upper Unit)
8-21N-19E	17300	4380	----	1050	9000	129	---	---	--	Youngblood No. 1 Macheel	5820	Madison (Mission Canyon)
11-22N-19E	4599	1702	1600	11.9	25	1.7	---	---	---	Shell No. 1 Winter	3793-3825	Inyan Kara
11-22N-19E	140637	51000	83600	2920	2400	540	---	---	---	Shell No. 1 Winter	5175-5196	Minnelusa (Fairbank)
11-22N-19E	7238	1280	----	696	2250	322	---	---	---	Shell No. 1 Winter	5606-5659	Madison (Mission Canyon)
11-22N-19E	13438	3570	6290	1060	2000	198	---	---	---	Shell No. 1 Winter	5758-5820	Madison (Mission Canyon-Lodgepole)
11-22N-19E	76680	24000	43600	4210	3800	730	---	---	---	Shell No. 1 Winter	7182-7305	Red River (Upper part of DST)
11-22N-19E	130740	42400	79500	5510	950	1160	---	---	---	Shell No. 1 Winter	7182-7305	Red River (Lower part of DST)
11-22N-19E	39670	13630	22300	1370	1950	156	---	---	---	Shell No. 1 Winter	7980-8010	Deadwood
23-22N-19E	12740	3060	3160	1010	4600	165	---	---	---	Youngblood No. 1 Winter	5455-5479	Madison (Mission Canyon)
CUSTER COUNTY												
9-3S-8E	447	115.4	4.98	26.4	149.4	11.4	---	1.4	---	Unknown	905	Inyan Kara
25-4S-8E	2174	45.7	10.0	492.1	1336.9	71.7	---	---	---	Palensky Oil	-----	Minnelusa
15-6S-6E	198	----	24.7	41	9.0	15.5	---	---	---	Palensky No. 1 Streeter	939	Madison
32-6S-7E	579	34	3.0	92.9	91.6	25.3	0.1	0.0	0.6	Buffalo Gap City		
34-6S-2E	18814	5572.0	1940	592	9800	120.0	---	0.0	---	Ozark No. 2 Coffing	1338-1375	Minnelusa (Hayden)
34-6S-2E	10430	2740	1054	538	5430	59.0	---	0.4	2.0	Seppala No. 1 Hey Govt.		Minnelusa (Wendover-Meek)
34-6S-2E	-----	731.4	126	548.8	3438	194.2	---	0.67	---	Evans Hotel	1300	Minnelusa
DEWEY COUNTY												
2-12N-31E	5404	2090	2374	7.1	20.2	9.4	---	---	---	Cheyenne Agency	1337	Dakota-Gas-Temp 79.5°F
17-12N-24E	2263	97	71	373	1281	102	0.0	1.4	4.4	Eagle Butte City	4322	Madison
21-13N-22E	2856	329	204	382.5	1535	62	---	4.8	2.8	Pendak No. 1 Cowan	5133	Red River (Upper unit)
36-14N-29E	4460	699	650	435.0	23	120		.35	3.5	V. E. Ranch	2505	Inyan Kara-Temp 90°F
8-15N-31E	2110	400	73	159.0	1170	45	---	1.8	3.3	Bartells Ranch	2266	Inyan Kara-Temp 84°F
12-15N-26E	6400	2400	3550	28.0	2.5	15.0		0.4	.8	Whitehorse	2021	Dakota-Temp 85°F
13-15N-23E	2804	----	150	----	1555	----	---	---	1.0	Herndon No. 1 O'Leary	5050	Red River (Upper Unit)
26-15N-30E	2800	753	274	94.0	1310	26.0		.63	4.8	V. E. Ranch	2215	Inyan Kara-Gas-Temp 90°F
29-15N-30E	5730	1460	1100	299.0	2290	74.0	---	1.1	3.2	V. E. Ranch	2200	Inyan Kara-Dakota-Temp 91.5°F
25-16N-22E	5000	947	894	433	2000	107	---	---	---	Youngblood No. 1 Galvin	4589	Madison (Mission Canyon)

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
FALL RIVER COUNTY												
1-9S-2E	1109	186	250	127	316	35	---	0.9	1.4	Edgemont City No. 1	2250	
1-9S-2E	1111	---	265	123	351	35	---	---	1.6	Edgemont City No. 2	3357	
1-9S-2E	1123	---	250	125	314	35	- -	- -	1.8	Edgemont City No. 3	3200	
25-9S-7E	4706	468	151	695	1932	94	4.0	56.0	---	Ohio No. 1 Hedrick	4047-4042	Minnelusa (Hayden)
3-10S-2E	1070	213	270	114	315	31	---	0.25	1.2	B. H. Ord. Depot No. 2	3955	Madison
12-10S-2E	1280	247	340	126	345	34	0.0	0.3	1.3	B. H. Ord. Depot No. 1	3990	Madison
HAAKON COUNTY												
6-1N-25E	2686	---	850	6.5	2.0	1.5	---	1.0	2.5	Stroppel Well	1880	Dakota-Temp 116°F
6-1N-25E	---	1578	311	428	3887	168.0	---	7.0	---	Midland City	---	Inyan Kara
6-1N-25E	1724	26	31	292	861	67	0.0	Trace	2.8	Midland City	3311	Madison
13-1N-20E	1733	720	259	8.8	8.1	2.0	---	---	---	Philip City	2293	Dakota
13-1N-23E	981	385	410	6.4	23	1.5	---	---	---	Nowlin City	1842	Dakota-Temp 120°F
1-1N-20E	1210	21	22	232	650	58.0	---	---	2.2	Philip City	3784	Madison
24-1N-20E	2055	---	456	6.0	54	3.0	0.0	1.4	3.0	Philip City	2300	Dakota
27-3N-20E	3578	1115	153	17.3	1860	3.2	.12	2.8	0.0			Inyan Kara
8-5N-23E	6769	2680	3200	14.3	---	8.44	---	2.09	---	Chicago Cattle Co.		Dakota
11-6N-21E	7870	2512	632	70	4554	23	---	---	---	Bierwagen Est.	2090	Dakota-Greenhorn?
31-6N-18E	2022	836	234	9.0	3.0	---	---	---	---	McIlravy		Dakota-Temp 102°F
15-7N-22E	4998	1830	1835	28	4.0	---	---	---	---	Allen Towne		Dakota-Temp 109°F
20-7N-20E	5916	2115	2273	16	5.0	---	---	---	---	Bart Parson		Dakota-Temp 122°F
20-7N-22E	5717	2300	2470	6.8	4.3	2.9	0.0	---	1.6	Parson Well		Dakota-Yields gas
21-7N-22E	6147	2452	2857	22.0	14.0	4.0	0.0	1.7	2.4	Pohle No. 1 Govt.	1790-1910	Dakota-Yields Gas
24-7N-21E	3702	1250	323	21	1529	---	---	---	---	Jetter Brothers		Inyan Kara-Temp 113°F
28-7N-22E	2910	1000	270	9.0	1152	---	---	---	4.4	Buckholtze Well	2665	Inyan Kara
6-9N-19E	5477	2197	2417	9.6	1.4	4.5	---	---	2.8	Norbeck Well	2385	Dakota
HARDING COUNTY												
1-17N-1E	3332	874	595	242	1461	23.0	---	---	---	N. Ord. State	7960-7971	Winnipeg Sand
35-18N-1E	4097	596	63	542	2394	83.8	---	---	---	St. Roy. Pet. No. 1		Madison
7-20N-3E	21300	6160	7890	1254	5400	146	---	---	---	Hunt No. 1 Peterson	7160-7300	Madison (Mission Canyon)
36-23N-2E	7326	1871	2426	624	2185	75	---	---	---	Signal No. 1 State	6807-6873	Madison (Charles)
36-23N-2E	3765	748	827	480	1477	46	---	---	---	Signal No. 1 State	6987-7054	Madison (Mission Canyon)
36-23N-2E	28321	8733	12597	1516	5169	151	---	---	---	Signal No. 1 State	8528-8550	Red River (Upper Unit)
36-23N-2E	25837	8264	12054	1210	4013	111	---	---	---	Signal No. 1 State	8464-8479	Red River (Upper Unit)
23-21N-3E	14212	4254	7600	646	1050	122	---	Trace	---	Clarkson-Schlaikjer No. 1 Groves	8481-8495	Red River (Upper Unit)
11-20N-4E	5527	1611	1600	185	1750	27	---	Trace	---	Shell No. 12-11 Tilus	8365-8367	Red River (Upper Unit)
4-21N-4E	19590	6380	10850	618	1050	122	---	Trace	---	Shell No. 14-4 State	8575-8576.5	Red River (Upper Unit)
28-21N-4E	7233 °	2124	2450	259	1930	48	---	Trace	---	Shell No. 14-28 Haivala	8601-8603	Red River (Upper Unit)
8-21N-4E	13315	4338	6300	388	1825	61	---	Trace	---	Shell No. 32-8 State	8530-8537	Red River (Upper Unit)
11-20N-4E	4987	1426	1440	191	1540	34	---	Trace	---	Shell No. 32-11A Seppala	8331-8338	Red River (Upper Unit)
17-21N-4E	14348	4417	7700	584	1000	112	---	Trace	---	Shell No. 32-17R Graves	8630-8636	Red River (Upper Unit)
6-21N-4E	11828	3655	5600	416	1650	85	---	Trace	---	Cardinal-Sun No. 1 State	8657-8667	Red River (Upper Unit)
			2214	18	10-	5	---	- -	---	Harrison No. 1 Johnson	3463-3470	Newcastle

Location	Total Solids	Na	Cl	Ca	SO_4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
JACKSON COUNTY												
34-1S-22E	2616	1100	132	5.4	930	1.0	0.1	---	0.95	-------	-----	Inyan Kara
4-2S-23E	32002	10885	13000	620	6800	137.0	---	Trace	---	Cities Svc. No. 1 Phipps	3370-3378	Minnelusa (Hayden)
4 2S-23E	10605	2877	420	575	6200	27.0	---	0.0	---	Cities Svc. No. 1 Phipps	3801-3838	Minnelusa (Fairbank)
4-2S-23E	9756	2791	300	400	5700	19.0	---	---	---	Cities Svc. No. 1 Phipps	4367-4420	Winnepeg Sand
16-2S-18E	1280	408	22.5	2.4	202	0.5	0.38	4.7	0.88	-------	-----	Inyan Kara
32-2S-22E	1798	561	76.0	32.8	968	5.4	.1	1.2	1.35	Kadoka City	2730	Inyan Kara
32-2S-22E	1775	----	67.0	47.0	1005	4.0	---	2.0	1.6	Kadoka City	2640	Inyan Kara
32-3S-22E	1873	675	74.5	11.6	647	----	---	1.7	---	Weaver No. 1 Granger	3640	Inyan Kara-Yielding flow?
28-2S-22E	-----	-----	29.0	13.4	1200	---	---	---	---	Jeff's Frontier Svc.		Inyan Kara
JONES COUNTY												
3-1S-27E	-----	630	95	24	1250	10	---	0.07	3.0	Wilson Well	2395	Inyan Kara
27-1S-30E	1992	801	436	7.1	3.0	2.4	0.0	7.0	2.7	Draper City	-----	Dakota
13-3S-31E	2250	108	181	402	1230	73	---	.16	2.0	Booth Well	-----	Inyan Kara
1-1N-29E	1938	574	84	42	881	10	---	---	---	Shell No. 1 Herman	2339-2385	Minnelusa (Upper)
3-1N-29E	2108	210	170	406	1109	25	---	---	---	Shell No. 2 Herman	2868-2969	Madison (Lodgepole?)
3-1N-29E	2376	216	250	364	1001	45	---	---	---	Shell No. 2 Herman	3050-3210	Ordovician Sandstone
6-2N-28E	3230	1300	1110	9.5	0.0	.4	.01	.16	2.2	VanMeter City	1500	Dakota
8-2N-26E	10484	2917	1930	666	4304	----	---	---	---	Shell No. 1 Olson	2514-2619	Minnelusa (Upper)
8-2N-26E	2624	116	243	406	1026	87	---	---	---	Shell No. 1 Olson	3480-3522	Ordovician
22-2N-26E	2848	----	762	6.2	3.0	3.0	---	---	---	C&NW Railroad	1690	Dakota-Temp 118° F
22-2N-26E	2897	1180	778	8.3	21.2	1.8	---	---	---	C&NW Railroad	1690	Dakota
LAWRENCE COUNTY												
15-7N-2E	1300	2.5	1.4	325	781	51	---	.17	.4	Perkins Well	965-1218	Minnelusa (Lower)
32-7N-1E	410	2.5	.6	80	119	31	---	.05	.4	Tullock Well	488-495	Minnelusa (Lower)
LYMAN COUNTY												
6-104N-74W	2084	----	120	374	1124	65	0.3	0.3	2.5	Burkhardt Oil Test		Inyan Kara
9-104N-72W	2192	----	----	346	988	80	---	2.0	---	M. Q. Sharpe	893	Dakota
24-104N-72W	1950	103	128	370	1150	80.0	.17	1.9	2.7	Oacoma City	630	Dakota
3-105N-79W	1857	747	630	9.2	2.8	2.3	---	0.6	0.7	Vivian City	1706	Dakota
15-105N-77W	1573	265	174	159	722	38	0.0	1.2	2.7	Presho City	1500	Dakota
17-105N-75W	1807	----	94	290	992	65	0.0	1.2	2.8	Kennebec City	1300	Dakota
19-105N-79W	2288	111	235	390	1046	70	---	0.05	4.0	Oller Ranch		Inyan Kara
19-105N-78W	2370	144	247	392	1136	94	.48	.15	3.0	Williams Ranch		Inyan Kara
20-105N-73W	2149	131	104	359	1196	77	0.2	2.1	3.0	Reliance City	1188	Dakota
-107N-73W	1910	378	83	154	1130	41	---	---	2.0	Ind. School	894	Dakota-Temp 70° F
MEADE COUNTY												
19-3N-7E	644	47.3	4.1	108.5	223	35.9	---	---	---		----	Unkpapa
19-3N-7E	1044	41.1	39.0	170	628	75.4	---	---	---	Kucera No. 2 Gingras	985	Minnelusa
19-3N-7E	624	108	225	63.8	92.4	34.8	---	---	---	Kucera No. 2 Gingras	1642	Madison
19-3N-7E	485	38.9	122	72.9	48	51.3	---	---	---	Kucera No. 2 Gingras	1626-1897	Madison
24-3N-17E	4791	1715	2680	111	109	31	---	---	---	Phillips No. 2 Harrington	1584-1689	Dakota
11-5N-5E	1060	45	4	210	605	56	---	1.7	.7	Vet Administration	1800	Minnelusa
18-6N-6E	1213	2.3	5.3	288	752	61	---	---	.6	Bear Butte No. 1	690	Minnelusa
18-6N-6E	1604	----	2.5	256	814	62.2	---	---	---	Bear Butte No. 1	830	Minnelusa

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
MEADE COUNTY -- continued												
20-6N-11E	728	260	46	1.2	145	0.7	.32	1.2	0.0			Inyan Kara
25-7N-6E	664	234	16	1.7	180	1.0	.06	0.39	0.6			Inyan Kara
16-9N-17E	4315	----	1706	40.5	1.9	35	---	0.3	---	Cosden No. 1 Zeal	2065	Dakota?
16-9N-17E	2118	250	159	8.8	626	2.6	---	0.3	---	Cosden No. 1 Zeal	2970	Inyan Kara
MELLETTE COUNTY												
8-40N-29E	1846	630	259	11	351	.2	---	2.1	---	Krogman Ranch	-----	Dakota
12-40N-25W	1727	516	120	71	768	9.8	---	---	---	Mosher City	1680	Dakota
25-41N-27W	1744	687	372	10	172	4.9	---	---	---	Wood City	1836	Dakota
PENNINGTON COUNTY												
6-1S-17E	994	363	13	2.4	308	0.0	0.0	---	3.0	Quinn City		Inyan Kara
6-1S-16E	671	250	8.0	3.2	225	0.97	0.0	0.6	2.0	Wall City		Inyan Kara
8-2S-14E	10587	4261	1090	90.4	42	45.2	---	43.0	---	Kuirna Farm	1312	Niobrara
10-1N-8E	1031	281	84	21	250	10.0	---	0.3	1.0	Keliher	1197	Inyan Kara
7-2N-9E	904	----	10.6	24	450	9.4	---	---	---	RCAFB		Inyan Kara
7-2N-9E	434	21	2	84	153	22.0	0.0	0.2	0.4	RCAFB	4336	Minnelusa (Lower)
7-2N-9E	393	6	4	73.0	134	29	0.0	0.2	0.5	RCAFB	4645	Madison
13-2N-8E	898	172	55	5.5	386	27.3	---	---	---	RCAFB	2400	Inyan Kara
31-2N-11E	481	151	4.0	10.0	158	2.0	0.1	0.7	0.7	New Underwood City	2680	Inyan Kara
35-4N-17E	1138	400	26.7	1.6	236	0.5	0.32	0.5	0.68			Inyan Kara
25-5N-16E	1836	730	274	8.0	55	----	---	---	4.6	Gabriel Ranch	2740	Inyan Kara-Dakota contamination
PERKINS COUNTY												
7-17N-15E	3857	1230	804	6.0	5	2.1	---	---	---	Shell No. 1 Veal	3854-3855	Inyan Kara
7-17N-15E	30336	10000	12660	917	6000	139	---	---	---	Shell No. 1 Veal	5368-5418	Minnelusa (Fairbank)
7-17N-15E	69340	22040	40320	3400	2350	790	---	---	---	Shell No. 1 Veal	5479-5655	Madison (Charles)
7-17N-15E	4386	487	697	833	2100	129	---	---	---	Shell No. 1 Veal	5752-5795	Madison (Mission Canyon)
7-17N-15E	3624	430	648	585	1550	94	---	---	---	Shell No. 1 Veal	5949-5973	Madison (Lodgepole)
7-17N-15E	150000	46400	91400	9180	1550	1650	---	---	---	Shell No. 1 Veal	6569-6633	Devonian
7-17N-15E	7411	1760	3180	648	1250	163	---	---	---	Shell No. 1 Veal	6851-6895	Silurian
7-17N-15E	30874	9660	17630	1580	1180	244	---	---	---	Shell No. 1 Veal	7131-7166	Red River (Upper Unit)
7-17N-15E	8738	2320	2430	578	3850	63	---	---	---	Shell No. 1 Veal	7901-7977	Deadwood
13-20N-12E	3660	1270	1190	8	110	1	---	---	---	Shell No. 1 Homme	4276-4305	Inyan Kara
13-20N-12E	6542	1120	970	890	3200	72	---	---	---	Shell No. 1 Homme	6440-6483	Madison (Charles-Mission Canyon)
13-20N-12E	4157	936	955	398	1560	38	---	---	---	Shell No. 1 Homme	6140-6230	Madison (Charles)
13-20N-12E	19140	6410	9780	730	1850	50	---	---	---	Shell No. 1 Homme	7596-7660	Silurian
13-20N-12E	6148	830	780	935	3030	113	---	---	---	Shell No. 1 Homme	7666-7894	Silurian
13-20N-12E	32975	9600	18090	2390	2350	320	---	---	---	Shell No. 1 Homme	8069-8134	Red River (Upper)
13-20N-12E	199500	61000	122300	15900	700	1370	---	---	---	Shell No. 1 Homme	8141-8191	Red River (Upper)
STANLEY COUNTY												
5-3N-29E	-----	1272	1383	11.5	----	5.5	---	---	---	C&NW Railroad	1395	Dakota-Temp 108 °F
32-3N-25E	3264	1145	219	25	1306	----	---	---	---	Ernest Nemee		Inyan Kara-Temp 90 °F
9-4N-27E	2372	108	111	395	1185	83.0	---	---	---	Shell No. 1 Abbott	2637-2740	Minnelusa (Reclamation)
13-5N-29E	1666	263	120	175	970	56.0	---	0.0	---	Cities Svc. No. 1 Wagner		Minnelusa and Inyan Kara

Location	Total Solids	Na	Cl	Ca	SO4	Mg	Mn	Fe	Fl	Well Name	Depth	Producing Formation
STANLEY COUNTY – continued												
30-5N-26E	4727	1865	2014	11.2	4.5	2.0	---	---	2.0	Hayes City	2000	Dakota
-5N-31E	-----	1438	1831	26.9	5.0	14.9	---	0.9	---	Ft. Pierre City		Dakota
6-6N-28E	5094	2530	----	32.0	3.0	20	---	0.2	0.4	Lacy Well		Dakota
16-6N-27E	-----	192	95	238	827	48	---	---	---	Phillips No. 1 State	2565-2787	Minnelusa (Fairbank)
18-7N-28E	2485	739	150	73	1300	19	---	0.0	---	Cities Svc. No. 1 Barrick	2420	Minnelusa (Upper)
18-7N-28E	2009	71	80	367	1250	116	---	0.0	---	Cities Svc. No. 1 Barrick	3350-3461	Madison (Lodgepole)
18-7N-28E	2063	70	90	372	1275	120	---	0.0	---	Cities Svc. No. 1 Barrick	3574-3660	Red River
18-7N-28E	2029	117	50	344	1275	94	---	0.0	---	Cities Svc. No. 1 Barrick	3848-3906	Red River
ZIEBACH COUNTY												
32-8N-22E	4600	1810	1840	9.0	.8	2.6	---	0.5	2.9	Cherry Creek School	1878	Dakota-Gas-Temp 106°F
6-9N-19E	4990	2000	2900	7.3	1.3	2.7	---	0.4	3.3	Red Scaffold School	2385	Dakota-Gas-Temp 119°F
13-10N-23E	7820	2990	4150	26.0	2.5	11.0	---	3.1	.8	Clavel Well	1800	Dakota-Gas-Temp 100°F
21-12N-22E	3363	495	270	454	1925	79.0	---	0.0	---	Cities Svc. No. 1 Jensen	5042-5079	Red River (Upper)
27-12N-24E	7590	1520	2140	744	2400	86.0	---	21.0	3.2	Boarding School	3020	Inyan Kara-Temp 107°F