Technical Report

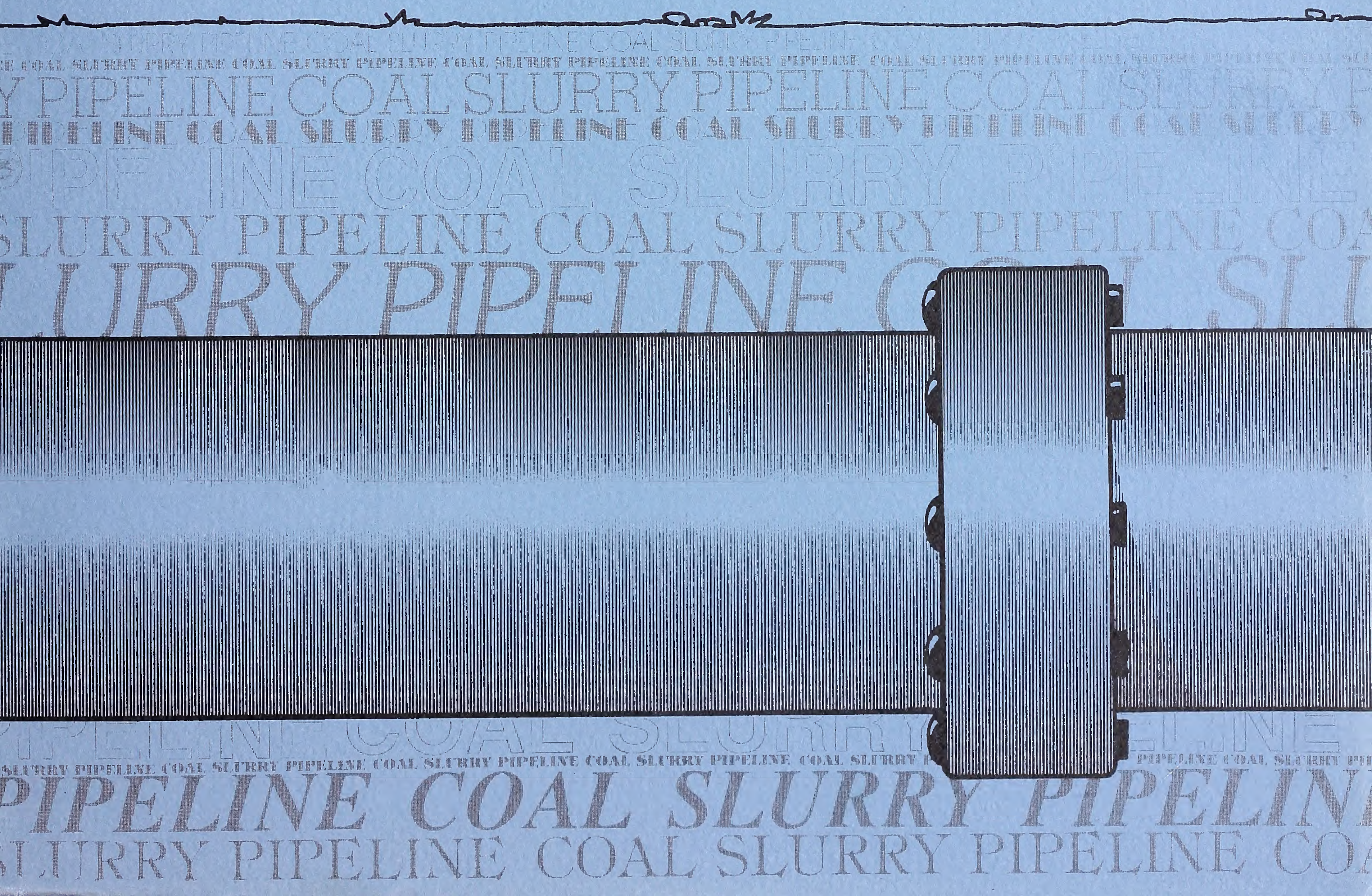
Well-Field Hydrology

Prepared for

Bureau of Land Management

November 1980

Woodward-Clyde Consultants



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1. INTRODUCTION

1.A BACKGROUND

ETSI filed permit applications with the state of Wyoming to appropriate ground water from a proposed well field in Niobrara County before requesting a right-of-way permit from the Bureau of Land Management in 1974. The water requested would be used in the preparation and transport of coal slurry. The permits (Appendix A) entitle ETSI to pump from the Madison aquifer, at depths greater than 2500 feet, 15,000 acre-feet of water on an average annual basis, and no more than 20,000 acre-feet in any year for export from Wyoming. In addition, the Wyoming State Engineer has the authority, as stated in the permit, to increase the amount of water that may be withdrawn by ETSI during the life of the permit (within 50 years of initiation of water production by ETSI), as well as to increase the average annual withdrawal. Approval to increase production longevity and average annual increases would be granted only if a hydrologist recognized by the Wyoming State Engineer states that such increases would not adversely affect other users of the Madison aquifer. In order to minimize the possibility for adverse effects, as well as to provide a data base for future analysis which would be a major determinant in permitting additional withdrawals by ETSI, the State Engineer required that ETSI: (1) design and operate five monitoring wells around the proposed well field, and (2) agree to certain corrective criteria if any beneficial use of the Madison aquifer was endangered by ETSI's pumping. On the basis of the 50-year life of the permit and the ability of the State Engineer to increase volumes so that production can be maintained throughout the permit life, ETSI designed its coal slurry system to also have a 50-year life. The capacity of the system as designed is 37.4 million (short) tons per year of coal, requiring 20,000 acre-feet of water per year for slurry makeup and an additional 200 to 500 acre-feet for coal preparation. Thus, this analysis considers the withdrawal of 20,500 acre-feet of ground water from the Madison aquifer for a period of 50 years, or a total of 1,025,000 acre-feet of water over the permit and design life of the project.

The analysis considers withdrawal of ground water from proposed well fields in Niobrara or Crook County and from the new well field owned by the city of Gillette, Wyoming. Locations of these well fields are shown in Figure 1-1. The following development plans for individual well fields or a combination of well fields (hereafter called plans 1, 2, 3, and 4) are considered:

Plan	Name of Well Field(s)	Annual Production per Well Field (acre-feet)	Total Annual Production (acre-feet)
1	Niobrara County	20,500	20,500
2	Niobrara County and Gillette	13,700 6,800	20,500
3	Crook County	20,500	20,500
4	Crook County and Gillette	13,700 6,800	20,500

For plans 2 and 4, the annual production rates given above for the Gillette and Niobrara or Crook County well fields represent average annual production over the proposed 50-year life of the project. Pumping rates at each well field would vary with time, depending on the excess capacity available from the Gillette well field. These variations have been taken into consideration and are discussed in Section 5.

1.B PURPOSE AND SCOPE

The purpose of this report is to assess the potential impacts of the proposed ETSI development on the ground- and surface-water resources, to describe the methods used in making the assessment, and to recommend a program for monitoring these potential impacts.

The potential impacts that were considered consisted of declines in water levels, changes in water quality, and reductions in spring flow and stream flow. These impacts were evaluated for each of ETSI's four alternative development plans, along with cumulative impacts that would be caused by ground-water withdrawals by ETSI and by present and planned Madison water users.

The recommended monitoring network was designed to provide for the early warning of impending impacts and to provide a data base upon which

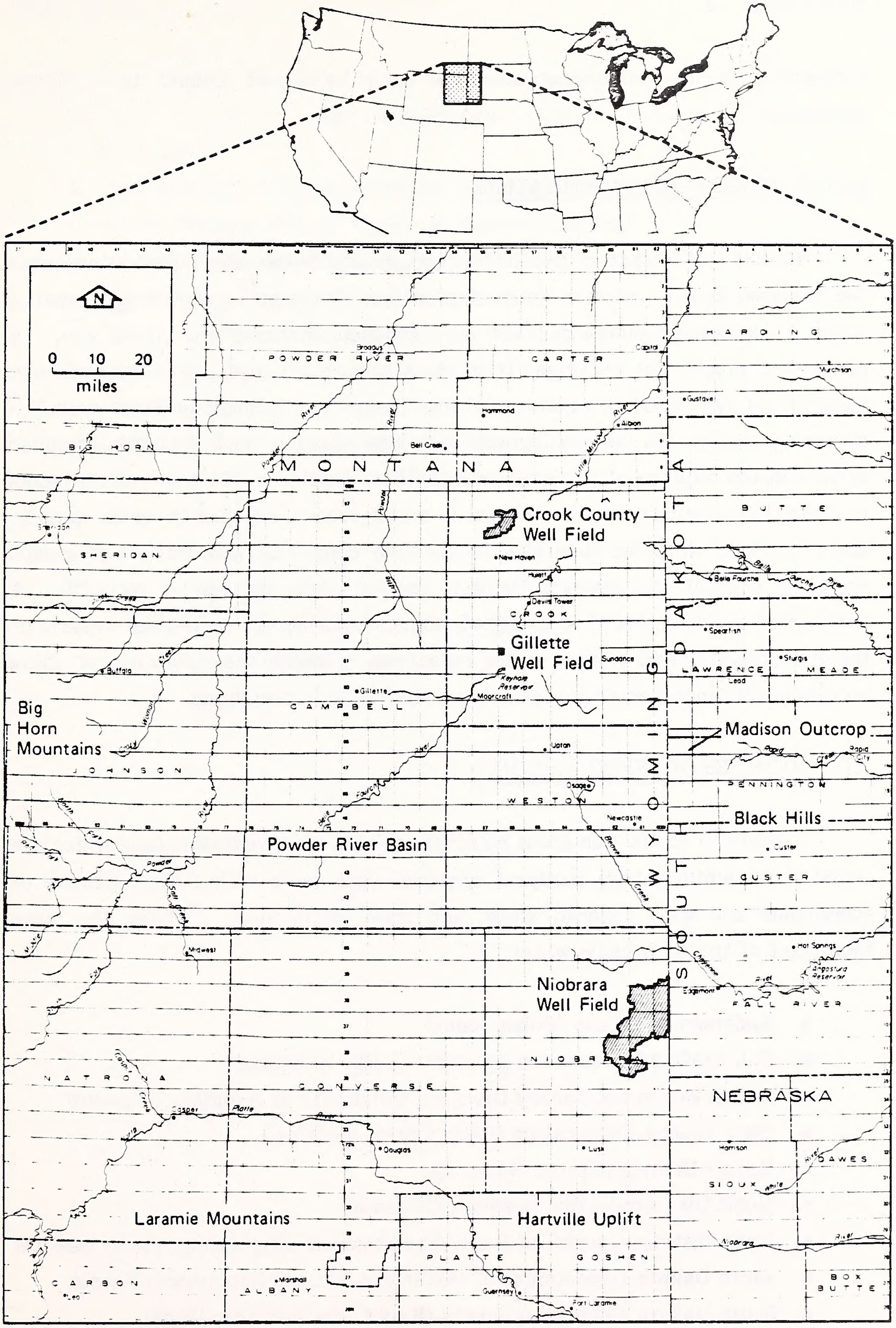


Figure 1-1. PHYSIOGRAPHIC FEATURES NEAR THE NIOBRARA, GILLETTE, AND CROOK COUNTY WELL FIELDS

reassessments and mitigation measures can be based, should this become necessary.

1.C METHODS OF INVESTIGATION

Studies were made of available geologic and hydrologic information about the Madison aquifer system, including earlier attempts at assessing potential impacts caused by pumping from the proposed Niobrara well-field site. A conceptual model was developed from these studies which explains the hydraulic behavior of the Madison aquifer system. Based upon the conceptual model, a numerical model was designed to simulate the behavior of the Madison aquifer system in the vicinity of the proposed ETSI developments. This numerical model was used to calculate future declines in water levels, changes in water quality, and reductions in spring flow and stream flow caused by withdrawals of ground water by present and planned Madison aquifer users, as well as by ETSI. A monitoring program was then designed which would monitor potential impacts on the ground-water and surface-water resources. Finally, the reliability of these impact predictions was evaluated using a Monte Carlo technique.

1.D SOURCES OF INFORMATION

In addition to the numerous publications that were reviewed (and which are listed in the bibliography), personal contacts were made with a large number of individuals and with federal, state, and local institutions. Among the more important of these contacts were:

- Anderson and Kelly (Boise, Idaho)
- C.J. Stafford, petroleum geologist (Lusk, Wyoming)
- Conservation and Survey Division, University of Nebraska (Lincoln)
- Gary Energy Corporation (Belle Creek, Montana)
- Materi Drilling (Upton, Wyoming)
- Mobil Oil Corporation (Denver, Colorado)
- Sixth District Council of Local Governments (Rapid City, South Dakota)
- South Dakota Department of Water and Natural Resources (Pierre)
- South Dakota Geological Survey (Rapid City and Vermillion)

- South Dakota School of Mines and Technology (Rapid City)
- U.S. Bureau of Land Management (Denver, Colorado; Cheyenne, Wyoming)
- U.S. Geological Survey (Denver, Colorado; Cheyenne, Wyoming; Huron, South Dakota; Billings, Montana; Reston, Virginia)
- University of Wyoming (Laramie)
- Wulf Oil Corporation (Chadron, Nebraska)
- Wyoming Department of Environmental Quality (Cheyenne)
- Wyoming Geological Survey (Laramie)
- Wyoming Oil and Gas Commission (Casper)
- Wyoming State Engineer's Office (Cheyenne)
- Wyoming Water Resources Research Institute (Laramie)

2. OTHER ASSESSMENTS OF THE PROPOSED ETSI DEVELOPMENT

The potential hydrologic impacts that would be caused by ETSI's proposed ground-water withdrawals from the Madison aquifer have been the subject of several studies (Rahn 1975, 1979; Halepaska 1975; Huntoon and Womack 1975; Konikow 1976). These studies assessed the effects of ground-water withdrawals from the Madison aquifer at the Niobrara County well field at a rate of approximately 20 cfs (15,000 acre-feet per year), over periods ranging from 11.5 to 100 years. Analytical or numerical models were used to simulate the hydraulic behavior of the Madison aquifer and to predict the long-term hydrologic effects that would be caused by ETSI's development. The results of these analyses are summarized in Table 2-1.

These previous studies were based on data available in the mid-1970s. Additional data collected since that time (discussed later in this report) have considerably increased the understanding of the hydraulic behavior of the Madison aquifer along the western flanks of the Black Hills. The additional data and resulting interpretations of the data have led to the recognition of some important factors that need to be considered in assessing the long-term effects of development from the Madison aquifer, and which are pertinent to the discussion of previous studies:

- The Madison aquifer has well-defined outcrops at the Black Hills and at the Hartville uplift area. In these outcrop areas, the aquifer is unconfined. These geometric and hydraulic characteristics, as well as proximity to areas of major withdrawals, will be important factors in assessing system response.

- Randomly distributed karst and other secondary porosity and permeability features form zones of high transmissivity in the upper part of the Madison Group. These zones also play an important role in determining the hydraulic behavior of the Madison aquifer system and the response of the system to stress.

- The aquifer is hydraulically connected to adjacent formations. While this hydraulic connection may not have significant effects on short-term developments, this connection cannot be ignored when considering long-term developments.

TABLE 2-1

PREVIOUS SIMULATIONS OF PROPOSED WITHDRAWALS FROM THE MADISON AQUIFER AT THE NIOBRARA WELL FIELD

			Parameter Estimates			Calculated Impacts			
Author(s) and Date(s)	Method of Analysis	Pumping Rate and Duration: cfs (ac-ft/yr)	Transmissivity Distribution: ft^2/sec (ac-ft/yr)	Storage Coefficient	Leakage: sec^{-1}	Drawdowns At Well Fields (ft)	Drawdowns At Edgemont (ft)	Spring Flow Reduction: cfs	Comments
Rahn (1975; 1979)	Analytical (Theis equation)	20.06 (14,480) for 45 yr	9.9×10^{-3} (6400)	6.5×10^{-5}	Not considered	1100 at 45 yr	500 at 45 yr	Not calculated	
Halepaska (1975)	Finite-difference numerical model	20.72 (15,000) for 11.5 yr	spatially distributed 6.2×10^{-3} (4000) at well field	10^{-1} at outcrop; 10^{-5} in vicinity of well field	Not considered	2500 at 11.5 yr	1200 at 11.5 yr	Not calculated	Study team could not duplicate results
Huntoon & Womack (1975)	Analytical (Theis equation)	20.72 (15,000) for 20 yr	3.09×10^{-3} (2000)	5×10^{-5}	Not considered	2000 at 20 yr	500-1400 at 20 yr	Not calculated	Included sensitivity analysis looking at effect of Fanny Peak Lineament
Konikow (1976)	Finite - difference numerical model	20.06 (14,480) for 100 yr	Spatially distributed 2×10^{-2} (12,925) at well field	5×10^{-5}	0	700 at 20 yr	330 at 20 yr	4.0 at Cascade Springs, 1.2 at Hot Springs and Stockdale-Beaver Creek at 20 years	Modeling procedure included steady-state calibration and sensitivity analysis of various parameters
					10^{-12}	390 at 20 yr	160 at 20 yr	1.2 at Cascade Springs	

The earliest of these studies was by Rahn. Rahn (1975, 1979) used an analytical model, the Theis (1935) equation, to predict water-level declines in the potentiometric surface of the Madison aquifer as a result of ETSI's development. This equation, which assumes that the aquifer is homogeneous, isotropic, nonleaky, and of infinite areal extent, is not an appropriate model for forecasting long-term Madison aquifer behavior. The equation used by Rahn predicts drawdowns beyond the natural boundaries of the aquifer system and cannot incorporate the unconfined characteristics of the outcrop areas, or consider the hydraulic connection to adjacent formations. Furthermore, the transmissivities do not reflect the influence of high-transmissivity zones within the Madison aquifer.

Huntoon and Womack (1976) also used an analytical model based on the Theis equation. Their study considered the potential effects of the Old Woman fault west of the Niobrara well field, but otherwise their study is subject to the same limitations as Rahn's (1975, 1979) studies.

Halepaska (1975) was the first to recognize that high-transmissivity zones might be responsible for the observed stabilization of water levels during pumping tests conducted at the Niobrara well field. He constructed a local numerical model of the Madison aquifer to simulate the pumping test behavior, and a regional numerical model to assess the impacts of ETSI's development. However, inconsistencies between the local and regional models and the boundary conditions used in the models raise questions about the validity of his predictions.

Konikow's (1976) numerical model of the Madison represents the best conceptualization of the aquifer system in terms of the data available in the mid-1970s, as has also been recognized by the Office of Technology Assessment (1978).

Presently, a numerical model of aquifer systems for the northern Great Plains region, including the Madison aquifer, is being developed by the U.S. Geological Survey (USGS) as part of a study entitled "Hydrology of the Madison Limestone and Associated Rocks in Parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming." The study, scheduled for completion in late fall of 1980, will include an assessment of the impacts that would be caused by the proposed ETSI withdrawals (Dutcher 1979, 1980). A preliminary set of data from this model, suitable for steady-state simulations of the aquifer system, was released in July 1980 (Downey and Weiss 1980). An attempt to use this data set for assessing the ETSI impacts was made by the study team, as will be discussed in Section 4.

3. HYDROGEOLOGY OF THE MADISON AQUIFER SYSTEM

The Madison aquifer system is a regional system composed of geologic units from the Precambrian basement rocks to the Cretaceous shales. The most important aquifer within this system is the Mississippian-age Madison Group (also called the Madison Limestone, Madison Formation, Pahasapa Formation, or Guernsey Formation) and adjacent hydraulically connected strata.

The Madison Group is found in parts of Wyoming, Montana, North and South Dakota, and Canada, covering an area of more than 180,000 square miles. Rock units equivalent to the Madison Group have been recognized throughout many other parts of the western United States and Canada. Composed largely of limestone and dolomite, the Madison Group is a source of water for domestic, stock, industrial, and agricultural users. In some places, oil is also produced from the Madison Group. In the area of interest, the Black Hills region and the eastern part of the Powder River Basin, the Madison Group has not been fully developed, but it is the potential source of water supply for large-scale energy development, as well as other developments that demand less water (USGS 1975).

3.A GEOLOGIC SETTING

3.A.1 STRATIGRAPHY

The major water-bearing units in the Madison aquifer system in the Black Hills region and eastern Powder River Basin are the Paleozoic carbonates of the Madison Group and of the Red River Formation. These units outcrop in a narrow elliptical band around the core of the Black Hills, and adjacent to the Rawhide fault in the Hartville uplift (Figure 3-1). The outcrop area of these Paleozoic carbonates is approximately 480 square miles in the Black Hills and approximately 13 square miles in the Hartville uplift area.

The Paleozoic carbonates of the Madison Group and the Red River Formation (Figure 3-2) thin rather uniformly from southeastern Montana south through the Black Hills region. The Madison Group thins from over 1200 feet in southeastern Montana southward to the erosional boundary of the Madison Group in southeastern Wyoming and northwestern Nebraska. The Red River Formation thins from over 400 feet in southeastern Montana to zero thickness in the northern part of the Black Hills uplift.

The Madison Group in the Black Hills region is composed almost entirely of carbonates, with dolomite comprising over 50 percent of these carbonates. For the most part, the carbonates are dense with low porosity and permeability, though high intergranular porosity exists in localized beds of coarsely crystalline dolomite. The importance of the Madison Group as an aquifer is due largely to the presence of well-developed zones of secondary porosity and permeability formed by solution activity in the upper part of the Madison Group when it was exposed to weathering and ground-water solution in Late Mississippian time. Karst and other secondary solution features, which include enlarged joints, solution cavities, caves, sinkholes, and collapse breccias, are randomly distributed in the Madison Group throughout the area.

The Red River Formation is a crystalline dolomite and fossiliferous fragmental limestone unit (Peterson 1978). Generally south of the Wyoming-Montana border, the Red River Formation changes from a predominantly fossiliferous limestone facies to a characteristic crystalline sucrosic dolomite facies. The water-yielding properties of the Red River Formation, like those of the Madison Group, are related to secondary porosity and permeability development.

In the southern part of the area, the Paleozoic carbonates overlie the Deadwood Formation. In the northern part of the area, the carbonates overlie the Winnipeg Formation, which overlies the Deadwood Formation. The Winnipeg Formation consists of about 200 feet of sandstones, interbedded with shales. The Winnipeg-Aladdin Sandstone, which is over 100 feet thick in extreme northeastern Wyoming, has excellent porosity but the unit is not tapped as a water supply. The Deadwood Formation, which averages about 400 feet in thickness in the Black Hills region, is composed of sandstones and sandy dolomites. The Deadwood Formation is usually very dense, includes partings of shale, and is not considered to be an important aquifer.

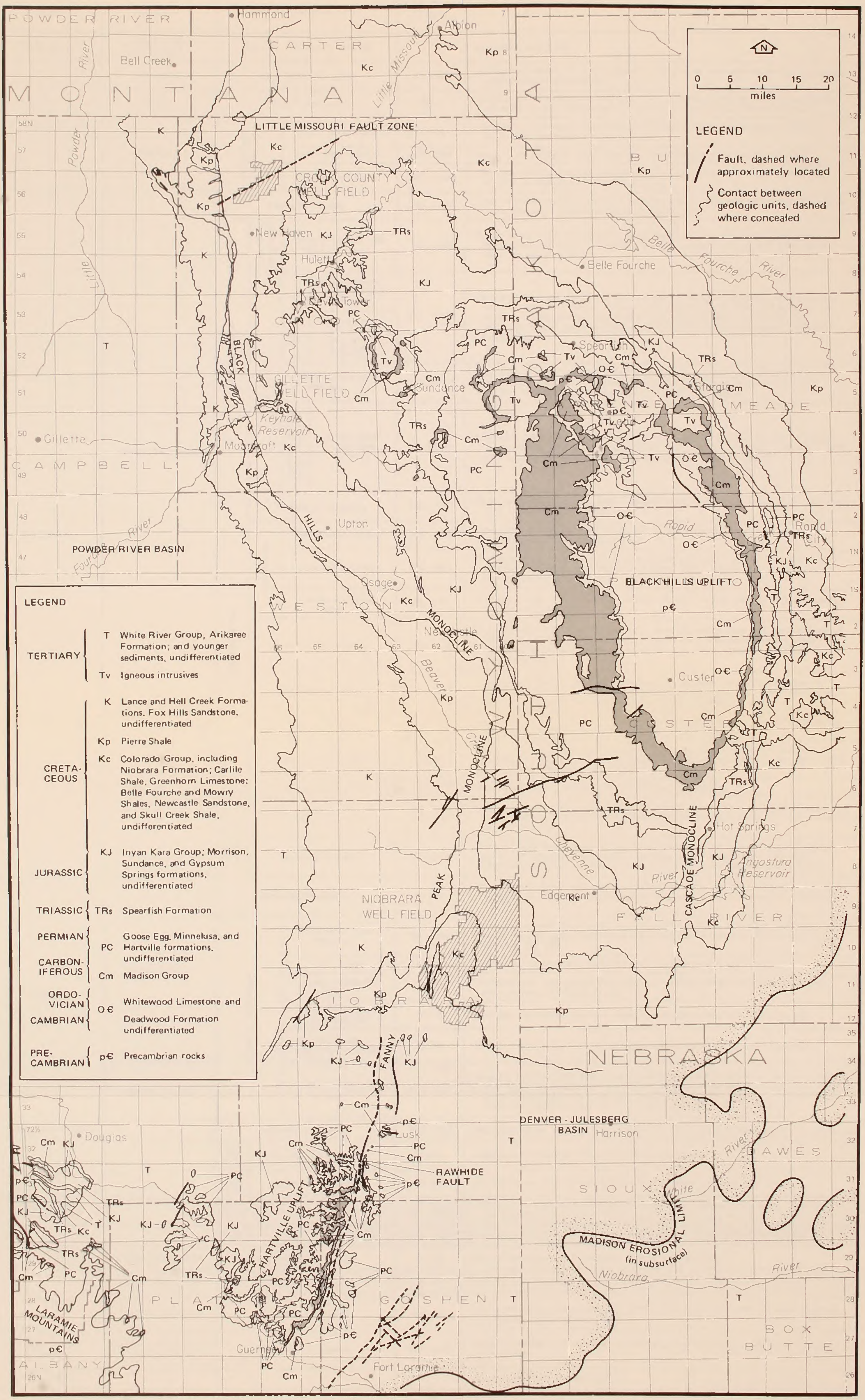


Figure 3-1. GENERALIZED SURFICIAL GEOLOGY OF THE BLACK HILLS AND EASTERN POWDER RIVER BASIN

SYSTEM	SERIES	STRATIGRAPHIC UNIT (Group)	STRATIGRAPHIC UNIT (Formation)	STRATIGRAPHIC UNIT (Member)	THICKNESS (FEET)	DESCRIPTION
Quaternary	Recent and Pleistocene		Alluvium and stream terraces			Silt, sand, and gravel.
			Unconformity			
Tertiary	Oligocene		White River Formation		0 - 150	Light-gray medium- to coarse-grained sandstone at base overlain by light brownish-gray claystone and siltstone.
			Unconformity			
Tertiary	Eocene		Wasatch Formation		300 +	Grayish-yellow sandstones and gray shale, numerous coal beds; thick extensively burned coal bed (Roland bed of U.S. Geol. Survey Bull. 796-A) at base.
Tertiary	Paleocene		Fort Union Formation	Tongue River member	500 - 800 ±	Yellowish-gray massive sandstone and light-gray shale; numerous coal beds; thickest in Montana; thins southward.
Tertiary	Paleocene		Fort Union Formation	Lebo shale member	200 - 250	Medium- to dark-gray shale, light-gray sandstone, and a few thin coal beds.
Tertiary	Paleocene		Fort Union Formation	Tullock member	500 - 1,100	Light-gray and light-brown sandstone, gray shale, and numerous thin coal beds; thinnest in Montana; thickens southward.
Cretaceous	Upper Cretaceous		Lance Formation		500 - 1,600	Gray to yellowish-gray sandstone and gray shale; a few thin beds of carbonaceous shale; thinnest in Montana; thickens southward.
Cretaceous	Upper Cretaceous	Montana Group	Fox Hills Sandstone	Colgate member, 50-100 ft.	125 - 200	Brown sandy shale and siltstone, light-gray sandstone, and brown ferruginous sandstone concretions; the Colgate member, a prominent massive white sandstone, at top in Montana.
Cretaceous	Upper Cretaceous	Montana Group	Pierre Shale	Upper part: Kara bentonitic member, 100 ± ft.; Monument Hill bentonitic member, 150-220 ft.	800 - 1,500	Dark-gray shale and claystone; locally beds of siltstone; abundant limestone concretions some fossiliferous in upper and lower parts; thickens southward from Montana. Kara and Monument Hill bentonitic members, gray bentonitic shale and impure bentonite with a few limestone concretions and small barite concretions.
Cretaceous	Upper Cretaceous	Montana Group	Pierre Shale	Mitten black shale member	145 - 1,000	Dark-gray to black shale with beds of yellowish-gray bentonite at base and numerous large yellowish-brown-weathering fossiliferous septarian limestone concretions in upper part; thickens southward from Montana.
Cretaceous	Upper Cretaceous	Montana Group	Pierre Shale	Gammon ferruginous member: Groat sandstone bed, 0-125 ft.	0 - 1,000	Light-gray claystone and shale with abundant reddish-brown iron-stained concretions and thin lenses of siderite. Groat sandstone bed, mapped north of T. 55N., consists of gray fine-grained glauconitic and ferruginous sandstone.
Cretaceous	Upper Cretaceous	Colorado Group	Niobrara Formation		150 - 225	Chalk marl and calcareous shale; numerous thin beds of bentonite, dark gray when fresh, weathers light yellow.
Cretaceous	Upper Cretaceous	Colorado Group	Carlile Shale	Sage Breaks member	200 - 300	Grayish-black noncalcareous shale with numerous beds of septarian limestone concretions that weather light gray.
Cretaceous	Upper Cretaceous	Colorado Group	Carlile Shale	Turner sandy member	150 - 260	Dark-gray shale, locally sandy and silty, with numerous beds of light-yellow and red silty limestone concretions; commonly a thin bed of light-gray medium-grained sandstone at the base.
Cretaceous	Upper Cretaceous	Colorado Group	Carlile Shale	Lower unnamed number	40 - 130	Dark-gray shale with a few limestone concretions; locally slightly silty and sandy; thickest in Montana.
Cretaceous	Upper Cretaceous	Colorado Group	Greenhorn Formation		70 - 370	In northeastern and southeastern parts; gray calcareous shale and marl with some light-gray, thin-bedded limestone; in central part; gray noncalcareous shale containing prominent light-gray weathering septarian limestone concretions; thins westward.
Cretaceous	Upper Cretaceous	Colorado Group	Belle Fourche Shale		350 - 850	Dark-gray to black shale with numerous dark purplish-red weathering siderite concretions in lower part, and several beds of light-gray and yellow-weathering limestone concretions in middle and upper parts; thickens westward.
Cretaceous	Lower Cretaceous	Colorado Group	Mowry Shale		180 - 230	Dark-gray siliceous shale, weathers light gray; numerous fish scales along partings; many thin bentonite beds; Clay Spur bentonite bed at top.
Cretaceous	Lower Cretaceous	Colorado Group	Newcastle Sandstone		0 - 95	Lenticular beds of light-gray sandstone and siltstone and dark-gray shale and claystone; a few beds of impure coal and bentonite; thickness varies within short distances, but averages about 40 feet.
Cretaceous	Lower Cretaceous	Colorado Group	Skull Creek Shale		180 - 270	Black shale with a few dark-red ferruginous concretions.
Cretaceous	Lower Cretaceous	Inyan Kara Group	Fall River Formation		95 - 200	Fine- to medium-grained light yellowish-brown to brown sandstone with interbedded gray and black shale and gray siltstone; averages about 135 feet in thickness near its outcrop.
		Inyan Kara Group	Unconformity			
Cretaceous	Lower Cretaceous	Inyan Kara Group	Lakota Formation		45 - 300	Light yellowish-gray to white fine- to coarse-grained sandstone and conglomeratic sandstone irregularly interbedded with red, green, yellow, gray, and black claystone; coal beds near base locally; thickness varies within short distances.
Jurassic	Upper Jurassic		Morrison Formation		0 - 150	Greenish-gray, green, and grayish-red claystone with a few thin discontinuous beds of light-gray sandstone and limestone; thickness at most places between 80 and 120 feet.
Jurassic	Upper Jurassic		Sundance Formation	Redwater shale member	30 - 195	Greenish-gray soft fissile sandy and silty shale; includes some thin beds of glauconitic sandstone and oolitic and coquinoid limestone; thickness at most places between 160 and 190 feet.
Jurassic	Upper Jurassic		Sundance Formation	Lak member	40 - 80	Yellow and pink crudely bedded fine-grained sandstone and siltstone.
Jurassic	Upper Jurassic		Sundance Formation	Hulett sandstone member	55 - 90	Yellowish-gray fine-grained thin-bedded to massive calcareous sandstone; locally pink northeast of Devils Tower.
Jurassic	Upper Jurassic		Sundance Formation	Stockade Beaver shale member	50 - 90	Soft gray calcareous shale with some thin beds of yellowish-gray sandstone.
Jurassic	Upper Jurassic		Sundance Formation	Canyon Springs sandstone member	0 - 40	Friable yellowish-gray or pink sandstone, some light greenish-gray siltstone.
			Sundance Formation	Unconformity		
Jurassic	Middle Jurassic		Sundance Formation	Gypsum Spring member	0 - 125	At base, massive white gypsum with interbedded red gypsiferous claystone; overlain near Hulett by interbedded gray cherty limestone and red claystone; thins southward from a maximum observed thickness of 125 feet near the junction of Deer Creek and the Belle Fourche River (SW ¼ sec. 13, T. 55 N., R. 64 W.).
			Unconformity			
Triassic and Permian			Spearfish Formation		450 - 825	Red sandy shale, siltstone, and sandstone; beds of massive white gypsum in lower half.
Permian		Goose Egg Formation	Minnekahta Limestone		40 ±	Light-gray thin-bedded limestone, pink on outcrop.
Permian		Goose Egg Formation	Opeche Formation		60 - 90	Reddish-brown and maroon fine-grained sandstone, siltstone, and shale.
			Unconformity			
Permian and Pennsylvanian			Minnelusa Formation		650 - 800	Light-gray and red sandstone, gray limestone and dolomite, red shale, local gypsum and anhydrite.
			Unconformity			
Mississippian			Madison Group		500 - 600	Light-gray limestone, locally dolomitic.
Mississippian	Lower Mississippian		Englewood Limestone		50 - 60	Pink or purplish-gray thin-bedded limestone; locally shaly.
			Unconformity			
Ordovician	Upper Ordovician		Red River Formation		50 - 60	Mottled grayish-yellow massively bedded dolomite, locally cherty near top.
Ordovician	Middle Ordovician		Winnipeg Formation		60 - 70	Upper part greenish-gray siltstone, lower part greenish-gray shale (Furnish, Barragy, and Miller, 1936; Carlson, 1958).
			Unconformity			
Cambrian and Ordovician	Upper Cambrian and Lower Ordovician		Deadwood Formation		300 - 500	Brown sandstone, gray glauconitic limestone and edgewise limestone conglomerate, and green shale.
			Unconformity			
Precambrian						Metamorphic and igneous rocks.

Source: Robinson, Mapel and Bergendahl, 1964.

Figure 3-2. GENERALIZED STRATIGRAPHIC COLUMN FOR THE EXPOSED SEDIMENTARY ROCKS ON THE NORTHERN AND WESTERN FLANKS OF THE BLACK HILLS UPLIFT

Overlying the Madison Group is the Minnelusa Formation of Pennsylvanian and Permian age. The Minnelusa Formation varies in thickness from about 400 feet in southeastern Montana to over 1400 feet in northwestern Nebraska. The Minnelusa Formation has been divided into three informal members by Foster (1958). The middle and lower members, which are composed predominantly of dolomites and limestones interbedded with shales, evaporites, and sandstones, are Pennsylvanian in age; and the upper member, composed of sandstone, carbonates, and evaporites is Permian in age. The basal part of the lower member, called the Bell Sand, is a discontinuous clastic unit which can be as thick as 200 feet. The Bell Sand fills the irregular karstic surface on the top of the Madison Group. The upper member of the Minnelusa Formation changes from predominantly sandstones of up to 400 feet in thickness in the northern part of the Black Hills region to a unit of over 600 feet in thickness composed of predominantly carbonates and evaporites south of the Black Hills. In most of the Black Hills region, the upper member of the Minnelusa Formation consists of sandstones interbedded with carbonates and evaporites. The upper member of the Minnelusa yields large quantities of water in Crook County, Wyoming, and in Butte and Lawrence counties, South Dakota.

Above the Minnelusa Formation in the Black Hills region is a 1000- to 1500-foot-thick sequence consisting predominantly of clastic sediments (mainly siltstones) comprising the Goose Egg, Spearfish, Sundance, and Morrison formations. The Minnekahta Limestone member of the Goose Egg Formation and the Hulett Sandstone member of the Sundance Formation are, locally, water-yielding units within this sequence. Overlying the Morrison Formation is the Inyan Kara Group, which varies in thickness from 150 to 400 feet in the Black Hills region. The Fall River Formation (Dakota Sandstone equivalent) of the Inyan Kara Group is an important aquifer in Niobrara and Crook counties; wells open to this unit yield small to moderate quantities of potable water.

A 4000- to 5500-foot sequence of Cretaceous shales, which includes the Skull Creek Shale, the Mowry Shale, the Greenhorn Formation, the Carlile Shale, the Niobrara Formation, and the Pierre Shale, overlies the Inyan Kara Group. This thick sequence of shales has a very low vertical hydraulic conductivity that, in effect, hydraulically isolates the aquifer systems below the shales from the

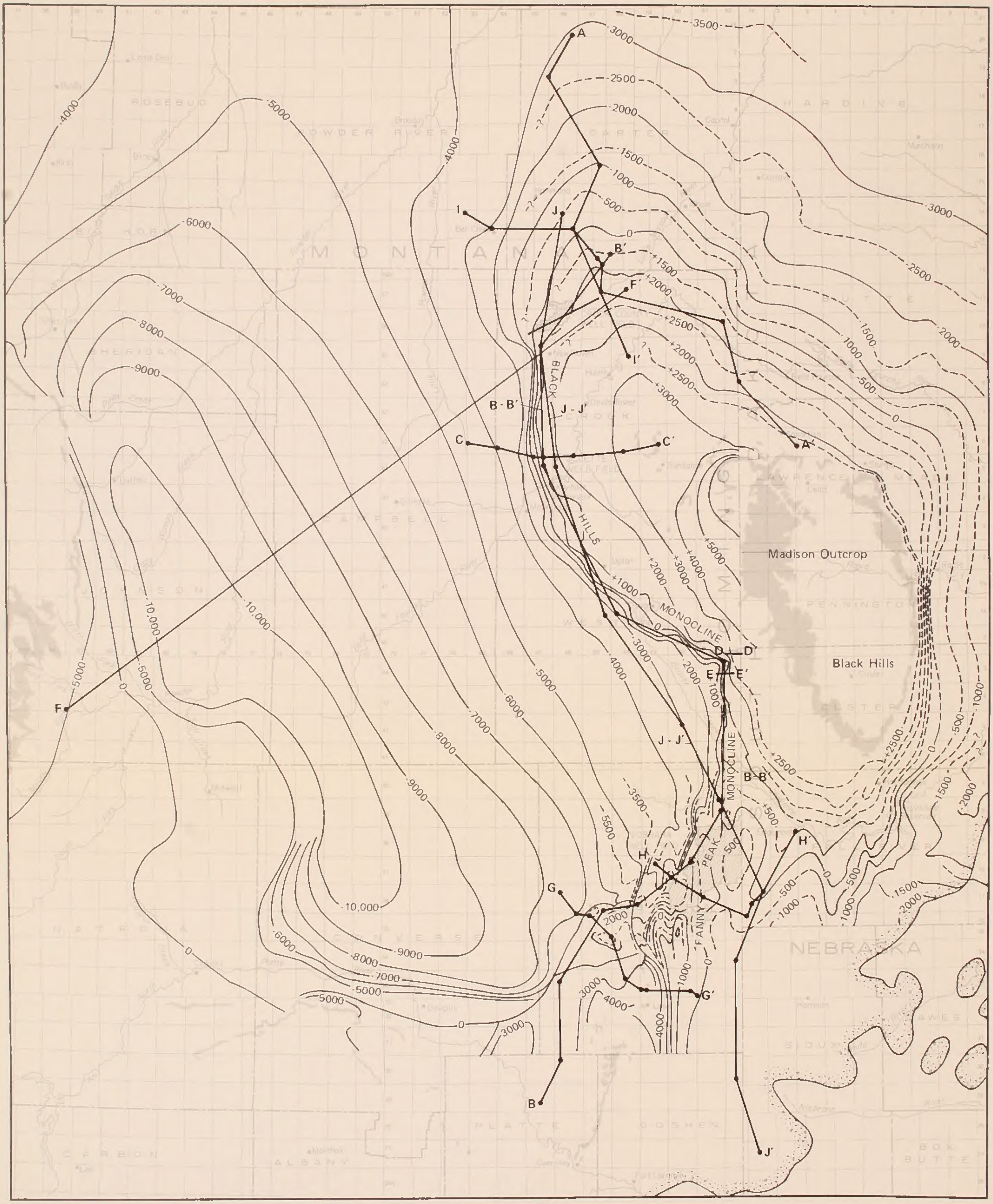
Cretaceous aquifers above the shales. Important aquifers above the Cretaceous shales are the Cretaceous Fox Hills and Lance Creek formations and the Tertiary Fort Union, Wasatch, and Arikaree formations.

3.A.2 STRUCTURE

Water movement in the Madison aquifer system is influenced by the geologic structure in the Black Hills and eastern Powder River Basin region (Figure 3-3). The Madison Group is exposed on the flanks of the Black Hills and in the Hartville uplift, but it lies more than 10,000 feet below the land surface in the deepest part of the Powder River Basin, about 100 miles west of the Black Hills. A sharp line of folding and faulting defines the western extent of the Black Hills uplift and the eastern extent of the Powder River Basin. This sharp zone of folding and faulting has from 2,000 to 10,000 feet of structural relief with dips as great as 90 degrees, and is usually interpreted as a series of basement faults that are generally expressed at the surface as drape folding in monoclines. The Madison Group may be faulted and displaced along this zone, as occurs in the Hartville uplift. This structure, which extends southwest of the Crook County well field through the Hartville uplift, is called the Black Hills monocline north and west of Newcastle, and the Fanny Peak monocline between Newcastle and the Niobrara County well field. South of the Niobrara well field, the sharp zone of folding and faulting bifurcates into the Shawnee flexure, which separates the Powder River Basin from the Hartville uplift, and the Rawhide Fault, which separates the Hartville uplift from the Denver-Julesberg Basin.

Large, sharp monoclinal flexures do not occur east or north of the Black Hills, but a sharp monoclinal flexure called the Cascade anticline, which dips westward at up to 70 degrees and has a maximum structural relief of over 1600 feet, occurs south of the Black Hills. Several large Madison aquifer or Minnelusa aquifer springs occur at the apex of the Cascade anticline.

Prominent zones of faulting in which little displacement of strata occurs also may influence water movement in the Madison aquifer. The Little Missouri fault zone, a zone several miles wide in which many faults with displacement of less than 30 feet occur, parallels the Little Missouri River near the Crook



LEGEND

Structure contour on top of Madison Group, elevation in feet (Mean Sea Level). Dashed where approximately located; queried where uncertain.

A —— A′ Location of geologic cross section and well logs used for section control

0 5 10 15 20
miles

Source: Adapted from DeGolyer and MacNaughton, 1974; Gott and others, 1974; Head and Merkel, 1977; Horton, 1953; Keefer, 1974; Keene, 1973; Lisenbee, 1978; Northrup, 1939; Old West Regional Commission, 1976; Petroleum Information Service, 1980; Stafford, 1979; Swenson and others, 1976; Whitcomb, 1965; Wulf, 1963; Wulf, 1974; Pierce and Girard, 1952.

NOTE: The structure contours on this map were constructed by adapting the shape of structure contours prepared by various source authors on higher stratigraphic units such as the Fall River Sandstone, the top of the Minnelusa, and the Minnelusa Red Shale Marker. The depth interval between the higher stratigraphic unit and the Madison at oil well control points was determined and used to adjust the contours.

Figure 3-3. STRUCTURAL GEOLOGY ON THE MADISON GROUP IN THE BLACK HILLS AND POWDER RIVER BASIN AND LOCATIONS OF CROSS SECTIONS

County well field in northeastern Wyoming and in southeastern Montana. The Dewey fault zone, located northeast of the Niobrara well field, is a zone of small faults running from the Madison outcrop area in the Black Hills to the Fanny Peak monocline. North of the Black Hills region, a structure trending along the strike of the Lake Basin fault zone (a major structure mapped to the northwest in central Montana) apparently influences ground-water movement in the Madison aquifer system, since hydraulic properties appear to change north and south of this trend.

3.B HYDROLOGIC SETTING

3.B.1 GROUND-WATER MOVEMENT IN THE MADISON AQUIFER SYSTEM

The potentiometric surface of the Madison aquifer has been recently mapped by Miller and Strausz (1980) (Figure 3-4). The potentiometric surface of the Madison aquifer in the vicinity of the Black Hills has also been mapped by Swenson and others (1976) and by Eisen and others (1980). The contour maps prepared by the three groups are similar, except that Eisen and others (1980) mapped the Madison aquifer potentiometric surface within the Madison Group outcrop area of the Black Hills. Potentiometric data are abundant near the Black Hills, where there are many wells and springs, but data points are few outside the Black Hills uplift area.

The Madison aquifer potentiometric surface dips steeply in a semiradial pattern away from the extensive Madison Group outcrop area on the western flanks of the Black Hills and toward the Powder River Basin. The steepest potentiometric gradients occur near the Black Hills monocline in the Osage-Newcastle area, where the hydraulic gradient is over 100 feet per mile. The Madison aquifer potentiometric surface is poorly defined west of the Black Hills monocline in the Powder River Basin where the surface is nearly flat. East and north of the Black Hills, the Madison aquifer potentiometric surface dips gently to the northeast at an average rate of approximately 20 feet per mile from the outcrop areas. South of the Black Hills and east of the Hartville uplift, the potentiometric surface dips east and northeast away from the Powder River Basin and the Hartville uplift and is parallel to the southeastern erosional boundary of the Madison Group.

Little is known about the potentiometric surface of the Red River, Minnelusa, and Inyan Kara Group aquifers in the vicinity of the Black Hills. The U.S. Geological Survey, as part of its Madison Limestone Aquifer Study, has mapped the fresh-water potentiometric heads of the Red River Formation and the Lower Cretaceous (Inyan Kara) aquifers of the northern Great Plains (Miller and Strausz 1980, Lobmeyer 1980). These maps are not adequate for defining the vertical potentiometric gradients in the Madison aquifer system.

The vertical component of the potentiometric gradient in the Madison aquifer system can be described by the relationship between potentiometric heads in the Madison aquifer and land surface elevations (Figure 3-5). The potentiometric surface of the Madison aquifer is above land surface in most of the area north, east, and south of the Black Hills, and in the larger stream valleys west and northwest of the Black Hills. The potentiometric surface of the Madison aquifer is generally below land surface outside major stream valleys west of the Black Hills and in the Powder River Basin south of the Wyoming-Montana state line.

The potentiometric gradients in the Madison aquifer indicate that water recharges the Madison aquifer system at outcrop areas in the Black Hills and in the Hartville and Laramide uplifts, and then flows away from these outcrop areas. Ground water that recharges the Madison aquifer on the northern and eastern flanks of the Black Hills moves toward the northeast. The major discharge area for this water is probably the Missouri River valley, as hypothesized by Swenson (1968a). Water that recharges the Madison aquifer in the Hartville uplift also moves toward the east and northeast. The water that recharges the Madison aquifer on the western flanks of the Black Hills and in the Laramide uplift flows toward the Powder River Basin. The low potentiometric gradients of the Madison aquifer in the Powder River Basin, relative to those along the western flanks of the Black Hills, imply either that little of the water that recharges the Madison aquifer at the outcrop area flows into the basin or that the transmissivity of the Madison aquifer is relatively high in the Powder River Basin.

The steep monoclinal flexures which define the western, southern, and eastern sides of the Powder River Basin are likely zones of relatively low

Source: Miller and Strausz, 1980.

LEGEND

?—?—4700 Line of equal potentiometric head distribution (in feet). Dashed where approximately located, queried where uncertain

Figure 3-4. POTENTIOMETRIC HEAD DISTRIBUTION IN THE MADISON AQUIFER (feet)

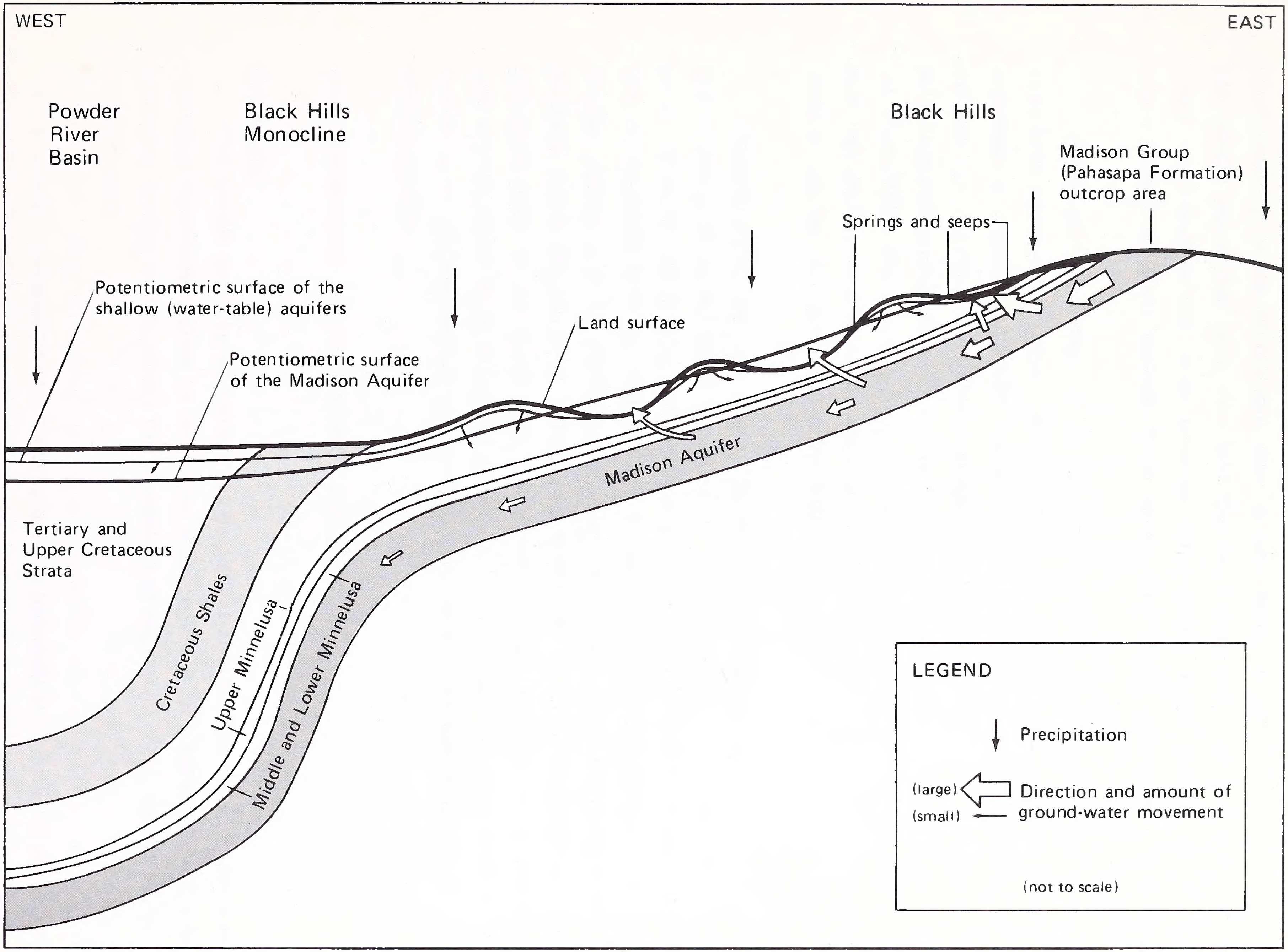


Figure 3-5. SCHEMATIC OF THE OCCURRENCE AND MOVEMENT OF GROUND WATER IN THE MADISON AQUIFER SYSTEM ON THE WESTERN FLANKS OF THE BLACK HILLS

transmissivity, which effectively limit ground-water movement into the basin. The ground water that does flow into the basin from the outcrop areas across these low-transmissivity zones probably moves very slowly toward the north, where steep monoclinal flexures do not define the basin, or toward the southeast.

North, east, and south of the Black Hills, the Madison Group dips steeply away from the outcrop areas. Within several miles of the outcrop areas, a thick sequence of Cretaceous shales separates the Madison aquifer from the land surface. As a result of the thick capping of Cretaceous shales, large upward potentiometric gradients exist in the Madison aquifer north, south, and east of the Black Hills. The low effective vertical hydraulic conductivity of these shales does not permit significant amounts of ground water to leak upward from the Madison aquifer, even where large potentiometric gradients exist.

Ground water that recharges the Madison aquifer at the western Black Hills outcrop areas moves in a semiradial pattern away from these recharge areas. Most of this ground water probably discharges from the Madison aquifer east of the Black Hills and Fanny Peak monoclines as springs and seeps in the stream valleys and to shallower aquifers where an upward potentiometric gradient exists (Figure 3-5). The Pennsylvanian- to Lower Cretaceous-age sediments west of the Black Hills Uplift between the Madison Group outcrop area and the Black Hills monocline provide a hydrogeologic environment that is conducive to upward leakage of significant amounts of ground water from the Madison aquifer.

3.B.2 RECHARGE TO THE MADISON AQUIFER

<u>Black Hills</u>

The actual quantity of water that recharges the Madison aquifer and the overlying Minnelusa aquifer in the Black Hills region is not known. Data are available, though, which permit the placement of upper and lower bounds on the recharge rate.

Potential recharge to the Madison aquifer includes: (1) the direct recharge that occurs by precipitation falling on the outcrop area, (2) indirect recharge which occurs by the downward movement of water from the Minnelusa Formation, and (3) recharge by influent streams that cross the outcrop area (Figure 3-6). In some areas, the Madison aquifer may also receive recharge from strata that are stratigraphically below the Madison Group.

The upper bound on recharge is determined by the available precipitation minus estimated evapotranspiration and runoff. The amounts of precipitation that fall directly on Madison Group and Minnelusa Formation outcrop areas are estimated at approximately 509,000 and 999,000 acre-feet per year, respectively (Table 3-1). The amount of recharge to the Madison aquifer that occurs from stream flow losses was estimated by Rahn and Gries (1973) as 32,000 acre-feet per year. The amount of total precipitation which runs off the Madison Group and Minnelusa Formation outcrop areas as surface flow in the Black Hills is small. In the Spearfish Creek drainage, which includes a large part of the Madison Group outcrop areas west of the Precambrian core of the Black Hills, all water contributed to the stream other than base flow averages 1.5 inches per year. Evapotranspiration in the Black Hills region is estimated to range from 13 to 15 inches per year (Orr 1959; Wyoming State Engineer's Office 1976). Therefore the upper bound on average annual recharge to the Madison aquifer in the Black Hills is calculated as 400,000 acre-feet.

The lower bound on the recharge rate can be determined by measuring known point sources of discharge from the Madison aquifer. Rahn and Gries (1973) measured all of the known springs and seeps in the Black Hills region. They estimated total recharge to the Madison aquifer on the basis of this work as being a minimum of 139,000 acre-feet per year. Their work underestimated total recharge because they acknowledged that some springs were probably overlooked, and because only springs near the outcrop area were surveyed. On the basis of the work by Rahn and Gries and calculated potential recharge, recharge to the Madison aquifer in the Black Hills can be stated to be in the range of 140,000 to 400,000 acre-feet per year.

<u>Hartville Uplift</u>

The recharge to the Madison aquifer in the Hartville uplift area has been estimated to be 2800 acre-feet per year by the Wyoming State Engineer's Office

Source: Old West Regional Commission, 1976

Figure 3-6. AVERAGE ANNUAL PRECIPITATION IN THE BLACK HILLS REGION (inches)

TABLE 3-1

QUANTITY OF PRECIPITATION THAT FALLS ON THE PRECAMBRIAN CORE, MADISON GROUP, AND MINNELUSA FORMATION OUTCROP AREAS IN THE BLACK HILLS REGION

Geologic Unit	County	Outcrop Area (mi^2) West of Precambrian Core	Outcrop Area (mi^2) East of Precambrian Core	Average Annual Precipitation[a] (inches)	Total Precipitation on Outcrop Area[a] (acre-feet)	Precipitation Available for Stream Flow and Runoff (acre-feet)[a,b]
Minnelusa Formation	Crook, WY	231	--	20	246,000	62,000
	Weston, WY	114	--	20	122,000	30,000
	Lawrence and Meade, SD	104	63	21 21	116,000 71,000	33,000 20,000
	Pennington, SD	64	43	21 19	72,000 44,000	20,000 9,000
	Custer, SD	275	41	18 18	264,000 39,000	44,000 7,000
	Fall River, SD	28	--	18	27,000	4,000
Total		816	147	--	999,000	229,000
Madison Group	Crook, WY	20	--	20	21,000	5,000
	Lawrence and Meade, SD	95 --	57 --	21 21	106,000 64,000	30,000 18,000
	Pennington, SD	160	27	22 19	188,000 27,000	60,000 6,000
	Custer, SD	80	27	18 18	77,000 26,000	13,000 4,000
Total		355	111	--	509,000	136,000
Precambrian Core	Lawrence and Meade, SD	305		23	374,000	13,000
	Pennington, SD	450		22	528,000	168,000
	Custer, SD	290		18	278,000	46,000
Total		1045		--	1,180,000	227,000

[a] Where two numbers are shown, the upper value is for west of the Precambrian core, and the lower value is for east of the Precambrian core.

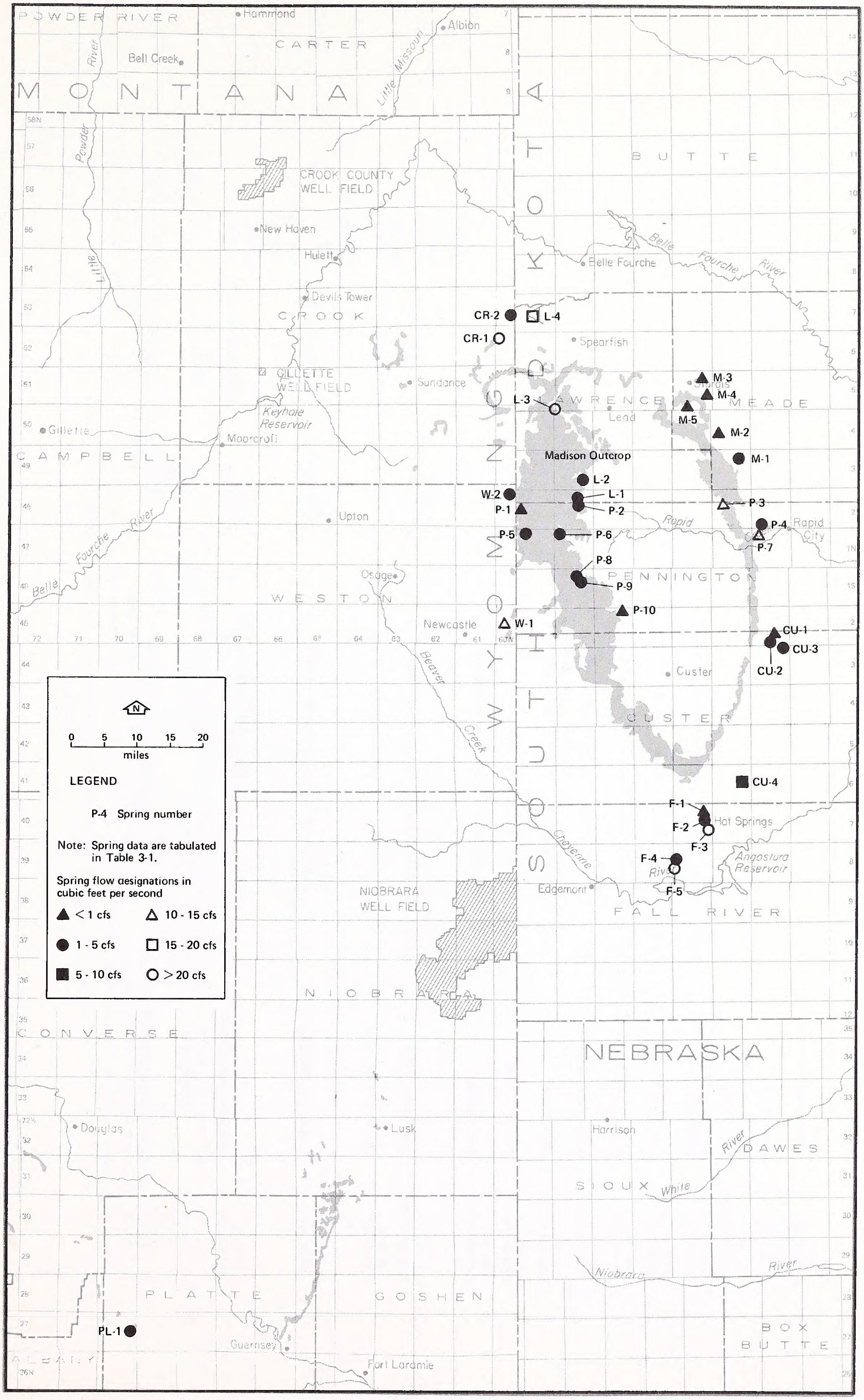
[b] Assuming 15 inches of evapotranspiration per year.

(1976). This estimate is based on an outcrop area of 12.5 square miles and evapotranspiration rates calculated by the Thornwaite method. Actual recharge may be as much as two to three times larger than that estimated by the Wyoming State Engineer's Office, because recharge to the Madison aquifer can occur both at the Madison outcrop area in the Hartville uplift and by infiltration through the Arikaree Formation, a rock unit that directly overlies the Madison Group in parts of the Hartville uplift.

3.B.3 DISCHARGE FROM THE MADISON AQUIFER SYSTEM: SPRING FLOW AND STREAM FLOW

Ground water discharges from the Madison aquifer in the Black Hills region (the Black Hills region is rigorously defined for this section as the area encompassed by the grid on Figure 4-4) as springs and seeps located in or near the streams that drain the region. In addition, ground water flows out of the Black Hills region in the Madison aquifer to the east and northeast. The locations and discharges of the major springs and seeps in the Black Hills were measured by Rahn and Gries (1973) (Figure 3-7). On the basis of their measurements, they calculated the total ground-water discharge from the Madison aquifer to be approximately 190 cubic feet per second (cfs). Thirty-two percent of the total discharge (62 cfs) occurs as springs and seeps on or near the central Madison Group plateau located west of the Precambrian core of the Black Hills. Eighteen percent of the discharge (37 cfs) occurs as springs and seeps located where the Madison Group and Minnelusa Formation outcrop in stream channels north, east, and south of the Precambrian core; and 50 percent of the discharge (93 cfs) occurs as springs and seeps in the Goose Egg, Spearfish, and Sundance formations (Table 3-2; Appendix C).

All of the springs measured by Rahn and Gries (1973) are located within the Madison Group or Minnelusa Formation outcrop areas, or within 6 miles of the Minnelusa Formation outcrop areas. A review of the literature uncovered no references to springs in the Black Hills region located outside this narrow band near the Madison Group outcrop areas in the Black Hills discharging more than 1 cfs. From this review, the study team concluded that most of the ground water discharge to the land surface from the Madison and Minnelusa aquifers in



Source: Cox, 1962;
Rahn and Gries, 1973;
Stockdale, 1974.

Figure 3-7. SPRINGS IN THE BLACK HILLS AND EASTERN POWDER RIVER BASIN

TABLE 3-2

SPRINGS OF THE BLACK HILLS REGION AS THEY RELATE TO REGIONAL GEOLOGY AND GEOGRAPHY

Springs That Occur at the Minnekahta-Spearfish Contact or in the Spearfish or Sundance Formation			Springs on or near the Central Black Hills Madison Limestone Plateau			Springs That Are Not in the Central Plateau and That Occur in the Madison or Minnelusa Formation			
Spring Location (No.)*	Spring Name	Discharge (cfs)	Spring Location (No.)*	Spring Name	Discharge (cfs)	Spring Location (No.)*	Spring Name	Comment	Discharge (cfs)
Custer Co. (CU-1)	Deadman Gulch Spring	0.8	Lawrence Co. (L-1)	Headquarters Spring on South Fork of Rapid Creek	3	Custer Co. (CU-1)	Battle Creek Springs	At Madison-Minnelusa contact east of Black Hills	1
Custer Co. (CU-3)	Grace Coolidge Springs	1	Lawrence Co. (L-2)	Tilson Creek Springs	2	Fall River Co. (F-2)	Hot Brook Springs	Madison outcrop in stream channel	2
Custer Co. (CU-4)	Beaver Creek Spring	9	Lawrence Co. (L-3)	Spearfish Creek Springs	40	Pennington Co. (P-7)	Cleghorn Spring	Minnelusa outcrop	10
Fall River Co. (F-1)	Cold Brook Spring	0.7	Pennington Co. (P-5)	Beaver Creek Spring	2	Crook Co. (CR-1)	Sand Creek Springs	Madison outcrop in stream channel	24
Fall River Co. (F-3)	Hot Springs	23	Pennington Co. (P-6)	Castle Creek Spring	4				
Fall River Co. (F-5)	Cascade Spring	23	Pennington Co. (P-2)	Rhoads' Fork Spring	4				
Fall River Co. (F-4)	Cold Spring	1	Pennington Co. (P-8)	South Fork of Castle Spring and Pole Creek Springs	1				
Lawrence Co. (L-4)	Crow Creek Springs	17	Pennington Co. (P-9)	Ditch Creek Springs	3				
Meade Co. (M-1)	Elk Creek at Piedmont Spring	2	Pennington Co. (P-10)	Spring Creek Springs	0.2				
Meade Co. (M-3)	Bear Butte Spring	0.6	Pennington Co. (P-1)	Soldier Creek Springs	0.4				
Meade Co. (M-4)	Alkali Creek near Black Hills Cemetery	0.6	Weston Co. (W-2)	Cold Spring Creek Springs	2				
Pennington Co. (P-4)	City Spring	1							
Crook Co. (CR-2)	Montana Lake								
Weston Co. (W-1)	Stockdale-Beaver Creek Springs	13							
	Total Discharge:	92.7		Total Discharge:	61.6			Total Discharge:	37

Data source: Rahn and Gries 1973.

*See Figure 3-7 for locations of springs.

the Black Hills region takes place near the Madison Group and Minnelusa Formation outcrop areas.

The actual amount of ground water that discharges between the Precambrian core and 6 miles beyond the outcrops of the Minnelusa Formation in the Black Hills is likely to be greater than that measured by Rahn and Gries (1973). This contention is supported by: (1) small springs in the lower part of the Spearfish Creek valley and small springs in the Redwater Creek valley, mentioned by Cox (1962), were not measured by Rahn and Gries; (2) Rahn and Gries acknowledged that some springs could have been overlooked; and (3) evapotranspiration losses upstream of the stream gaging sites used by Rahn and Gries caused measured flows to be less than actual ground-water discharges. However, actual ground-water discharges from the Madison Group in the Black Hills are not likely to be significantly greater than those that were measured by Rahn and Gries in 1973.

The springs and seeps measured by Rahn and Gries sustain the base flow of all major streams that drain the Black Hills. These major streams in the Black Hills, which are fed by spring flow from the Madison Group, are:

- Spearfish Creek, Sand Creek, and Crow Creek, all tributaries of the Redwater River that drain the northeastern part of the Black Hills and have a total base flow of approximately 80 cfs
- Elk Creek, Rapid Creek, Boxelder Creek, Spring Creek, and Battle Creek, all tributaries of the Cheyenne River that drain the eastern side of the Black Hills and have a total base flow of approximately 47 cfs
- Stockade-Beaver Creek, which drains part of the western side of the Black Hills and has a base flow of 13 cfs
- Cascade Springs Creek and the Fall River south of the Black Hills, which are fed by the large Cascade Spring and Hot Springs, respectively, which have a total base flow of approximately 50 cfs

Upward leakage from the Madison aquifer also accounts for part of the base flow of streams in the study area that do not directly drain from the Black Hills. Streams which probably contain a Madison aquifer base-flow component include the Belle Fourche River, the Little Missouri River, Inyan Kara Creek, and the Cheyenne River. The base-flow contributions from the Madison aquifer to these streams are not generally recognized because: (1) the upward leakage from the Madison aquifer discharges as seeps through younger strata, (2) the total contribution to base flow from upward leakage from the Madison aquifer is not large, and (3) part of the base flow of these streams comes from ground-water discharge from local flow systems contained in strata overlying the Minnelusa Formation. The quantity of base flow that potentially may be contributed to these streams from upward leakage from the Madison aquifer was calculated using a steady-state model of the Madison aquifer system (this model is discussed in Section 4). The calculated ground-water discharges from the Madison aquifer to the major stream valleys located near the Madison Group and Minnelusa Formation outcrop areas in the Black Hills region using this steady-state model are:

River Reach	Discharge (cfs) from Madison Aquifer to the Stream
Little Missouri River above Alzada, Montana	1
Belle Fourche River between Keyhole Reservoir and the Belle Fourche Reservoir, Wyoming and South Dakota	9
Cheyenne River between mouth of Stockade-Beaver Creek and Angostura Reservoir, Wyoming and South Dakota	4
Inyan Kara Creek, Wyoming	2

These calculated ground-water discharges are small compared with the measured ground-water discharge from the Madison aquifer near the Madison Group outcrop areas.

Ground water in the Madison aquifer system flows out of the Black Hills region to the east-northeast and to the northwest. Ground-water discharge to the east-northeast was calculated to be 54 cfs, using the steady-state model of the Madison aquifer system. Ground-water flow to the northwest could not be accurately calculated with the steady-state model because the total flux is very small.

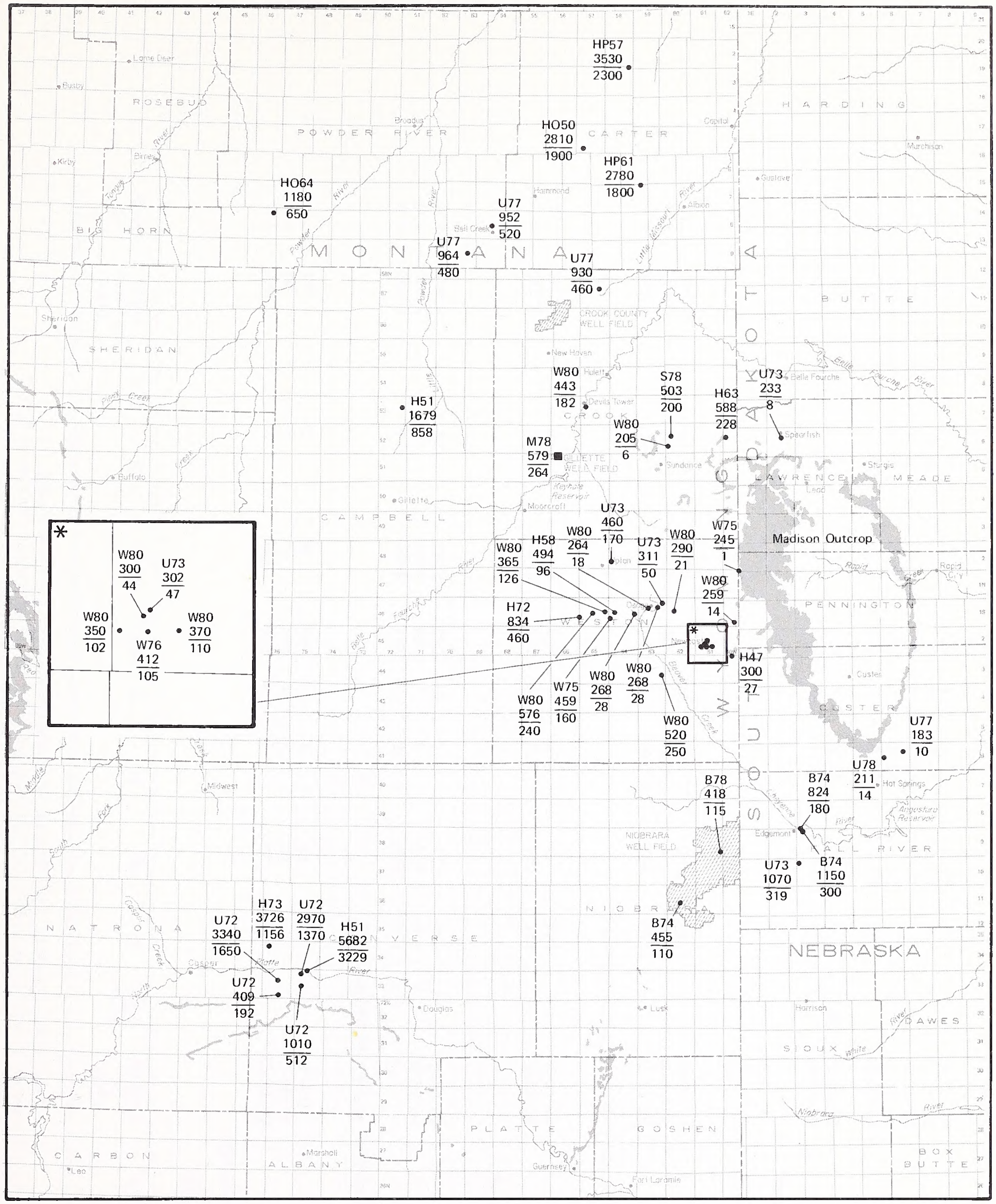
3.B.4 WATER QUALITY

Madison Group and Red River Formation

Ground water in the Madison aquifer in the Black Hills region has total dissolved solids (TDS) concentrations generally less than 1000 milligrams per liter (mg/l) (Figure 3-8; Table 3-3; Appendix D). The principal cations in the ground water are calcium and magnesium, and the principal anions are bicarbonate and sulfate. The quality of Madison ground water is generally best near Madison outcrop areas, where TDS concentrations are less than 300 mg/l and sulfate concentrations are less than 10 mg/l. Total dissolved solids and sulfate concentrations in the Madison aquifer increase with distance from the outcrop areas. At the Niobrara well field, which is located approximately 24 miles north of Madison Group outcrops in the Hartville uplift, TDS and sulfate concentrations average approximately 450 and 110 mg/l, respectively. At the Gillette well field, which is located approximately 35 miles west of the Madison Group outcrop in the Black Hills, TDS concentrations range from 480 to 700 mg/l and sulfate concentrations range from 195 to 335 mg/l. At the Crook County well field, which is located approximately 60 miles northwest of the Madison Group outcrops in the Black Hills, TDS concentrations range from 500 to 900 mg/l and sulfate concentrations range from 200 to 460 mg/l.

The major chemical characteristics of the Madison ground water and the spatial variations in major chemical characteristics can be explained with a simple chemical model of the Madison carbonate aquifer system (Hanshaw and others 1978). The salient features of the model are explained below.

The waters that recharge the Madison aquifer in the outcrop areas have a high total carbon dioxide concentration and relatively low TDS concentrations. As the ground water moves through the aquifer, calcite, dolomite, gypsum, and anhydrite are dissolved. Near the outcrop areas, equilibrium is established with respect to calcite. Once the ground water is saturated with calcite, the calcite begins to precipitate, but dolomite, gypsum, and anhydrite continue to dissolve. Eventually, saturation with respect to dolomite occurs. In the Black Hills region, saturation with respect to dolomite also occurs near the Madison Group outcrop areas. Gypsum and anhydrite continue to dissolve, with the concurrent precip-



LEGEND

N

0 5 10 15 20
miles

H78 — Source code (see sources)
H78 — Year collected
1120 — Total dissolved solids, mg/l
400 — Sulfate ion concentration, mg/l

Source:
- B - Bechtel, undated
- H - Hodson, 1974
- HO - Hopkins, 1976
- M - Montgomery Engineers, 1979
- U - U.S. Geological Survey data bank, collected by USGS, all U73 samples collected by Back
- W - Eisen and others, 1980

Figure 3-8. WATER QUALITY IN THE MADISON GROUP, BLACK HILLS, AND EASTERN POWDER RIVER BASIN

TABLE 3-3

REPRESENTATIVE WATER QUALITY ANALYSES OF THE MINNELUSA FORMATION, MADISON GROUP, AND RED RIVER FORMATION IN THE VICINITY OF THE NIOBRARA COUNTY, CROOK COUNTY, AND GILLETTE WELL-FIELD SITES (in milligrams per liter, except as noted)

Well No. (Township-Range-Section)	Date of Sample	Temp (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	Total Dissolved Solids	pH (units)
MINNELUSA FORMATION												
Near Minnelusa Outcrop Areas												
54N-64W-7bc, Wyo.	06-04-68	-	110	36	3	2	286	180	2	-	485	7.7
47N-60W-30aa, Wyo.	06-03-69	-	68	24	1	1	305	12	1	-	280	7.9
6N-2F-10da, S. Dak.	11——54	-	63	21	7	-	296	8	4	-	247	-
Near the Black Hills Monocline, Crook County, Wyoming												
51N-66W-09db	-	-	620	220	130	-	293	2200	16	-	3,300	8.0
52N-67W-19cc	01-22-58	-	740	230	5	-	330	2400	14	-	3,580	7.0
52N-68W-20dd	08-04-64	-	580	190	30	68	232	2000	40	-	3,040	8.4
Niobrara County, Wyoming												
35N-63W-15bd	02-14-65	-	600	240	250	-	709	2100	160	-	3,710	7.3
36N-64W-26ada	09-14-65	-	240	37	750	-	185	2000	130	-	3,210	7.2
West of Black Hills Monocline, Campbell County, Wyoming												
52N-69W-11cc	06-10-70	-	2400	650	76,000	-	131	2200	120,000	-	202,000	6.0
52N-69W-28db	01-07-63	-	610	230	1,100	-	378	2200	1,600	-	5,920	7.3
52N-70W-15da	07-10-63	-	1700	750	20,000	35	488	3300	34,000	-	60,500	8.1
MADISON GROUP												
Niobrara County, Wyoming												
36N-62W-28 aba	04-15-74	-	114	30.9	36.4	5.9	256	122	110.0	1.56	704	7.80
	04-26-74	46.0	110	35.0	36.0	6.1	242	120	130.0	3.60	584	7.00
36N-62W-28 baa	05-22-74	-	88	51.0	29.2	4.2	232	98	125.0	2.20	661	7.50
	05-24-74	54.0	98	35.0	28.0	6.1	219	110	110.0	3.00	526	7.00
	06-02-74	-	84	29.0	30.3	5.8	207	120	72.5	1.44	579	7.65
	06-08-74	-	78	25.5	29.8	4.8	207	104	70.0	1.28	556	7.65
	06-12-74	-	80	23.0	29.6	6.3	201	109	57.5	1.20	536	7.65
	06-13-74	-	90	24.0	27.8	4.2	207	108	62.5	1.20	554	7.50
	06-20-74	-	85	24.0	42.0	6.0	232	110	74.0	-	-	7.30
38N-61W 35d	09-30-78	-	80	17.0	44.0	7.0	256	115	32.0	0.57	414	8.10

TABLE 3-3 Concluded

Well No. (Township-Range-Section)	Date of Sample	Temp (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	Total Dissolved Solids	pH (units)
MADISON GROUP (cont.)												
Crook County, Wyoming												
51-66-6 cab	12-12-79	22.0	148	56	11.0	2.0	272	335	28	2.65	707	7.5
51-66-6 bc	02-20-80	23.0	104	40	4.0	1.0	281	195	4	0.66	488	6.8
52-61-24 aac	12-21-63	-	140	29	2.0	1.9	274	228	3.1	0	588	7.7
52-62-18 c	07-27-78	12.0	120	30	2.6	1.4	270	200	1.4	-	503	7.3
52-63-25 dc	03-16-73	-	65	16	2.1	1.2	268	7.4	1.7	0.6	-	8.3
	12-13-79	9.0	52	17	3.0	1.0	250	4	2	0.36	204	7.6
	02-15-80	10.0	50	16	1.0	1.0	229	0	3	-	182	7.6
	03-13-80	-	57	16	3.0	1.0	244	6	4	-	205	7.8
	04-12-80	-	55	16	2.0	1.0	244	8	2	-	205	7.1
	05-13-80	-	63	14	3.0	1.0	254	10	4	-	221	7.8
53-65-18 bbd	07-11-62	-	112	43	4.0	1.0	264	275	1.5	0.5	579	7.2
	04-28-70	15.0	112	35	3.3	1.5	261	210	3.4	1.2	504	7.9
	09-27-73	-	112	36	3.0	2.0	194	185	1.5	0.3	500	7.5
	08-30-75	17.0	110	38	3.7	1.5	273	210	2.6	0.5	512	7.6
	08-30-75	10.0	66	24	1.9	1.2	307	15	1.7	0.2	273	7.6
	12-12-79	15.0	115	42	4.0	1.0	264	240	5	0.52	539	7.8
	02-15-80	13.0	98	35	2.0	1.0	220	194	6	0.56	442	7.9
	03-13-80	-	101	34	4.0	1.0	244	182	4	0.54	443	7.5
	04-12-80	-	110	39	3.0	2.0	278	200	4	0.58	494	7.1
	05-13-80	-	115	36	2.0	1.0	273	200	5	0.58	493	7.9
57-65-15da	08-05-77	47.6	180	48	35	8	190	450	51	-	902	-
RED RIVER FORMATION												
57-65-15da	08-12-71	50.0	84	39	5	2	220	190	3	-	460	-

itation of calcite and dolomite as the ground water flows farther away from the outcrop areas. Saturation with respect to gypsum and anhydrite is not reached in the ground water of the Madison aquifer in the vicinity of the Black Hills except north of the trend of the Lake Basin fault zone, where anhydrite beds are interbedded with the carbonates of the Madison Group, and perhaps in the central and southern part of the Powder River Basin, where ground-water velocities in the Madison aquifer may be very slow.

The irreversible dissolution of gypsum and anhydrite are the major reactions that drive the evolution of ground-water quality in the Madison aquifer in the vicinity of the Black Hills. These are the major reactions because saturation with respect to dolomite and calcite occurs near the Madison Group outcrop area, and because saturation with respect to gypsum and anhydrite does not occur in most of the region. As a result, sulfate concentrations in the Madison aquifer gradually increase with distance traveled from the Madison Group outcrop area (Figure 3-8). This gradual increase in sulfate concentrations with distance from the outcrop area is well illustrated by the trilinear plot of Madison aquifer water quality analyses shown in Figure 3-9. The velocity of the ground water and the concentrations of gypsum and anhydrite in the aquifer matrix vary spatially within the Madison aquifer. As a result, the correlations between distance from the outcrop area and sulfate concentration are not perfect.

Concurrent with the dissolution of gypsum and anhydrite is the dissolution of high-solubility trace aquifer matrix constituents. The distribution of these trace constituents, such as halite, is erratic; as a result, ground water in the Madison aquifer can locally contain relatively high concentrations of chloride, fluoride, and sodium. The presence of minor amounts of gypsum and anhydrite and trace quantities of halite in the carbonate matrix is consistent with the shallow reef depositional environment of the Madison Group.

The nonuniform distribution of ground-water velocities and matrix constituents in the Madison aquifer within a vertical section results in marked differences in water quality between adjacent Madison Group water wells. At the Gillette well field and at Newcastle, Madison wells that draw ground water from an upper karstic or high-transmissivity zone in the Madison aquifer contain

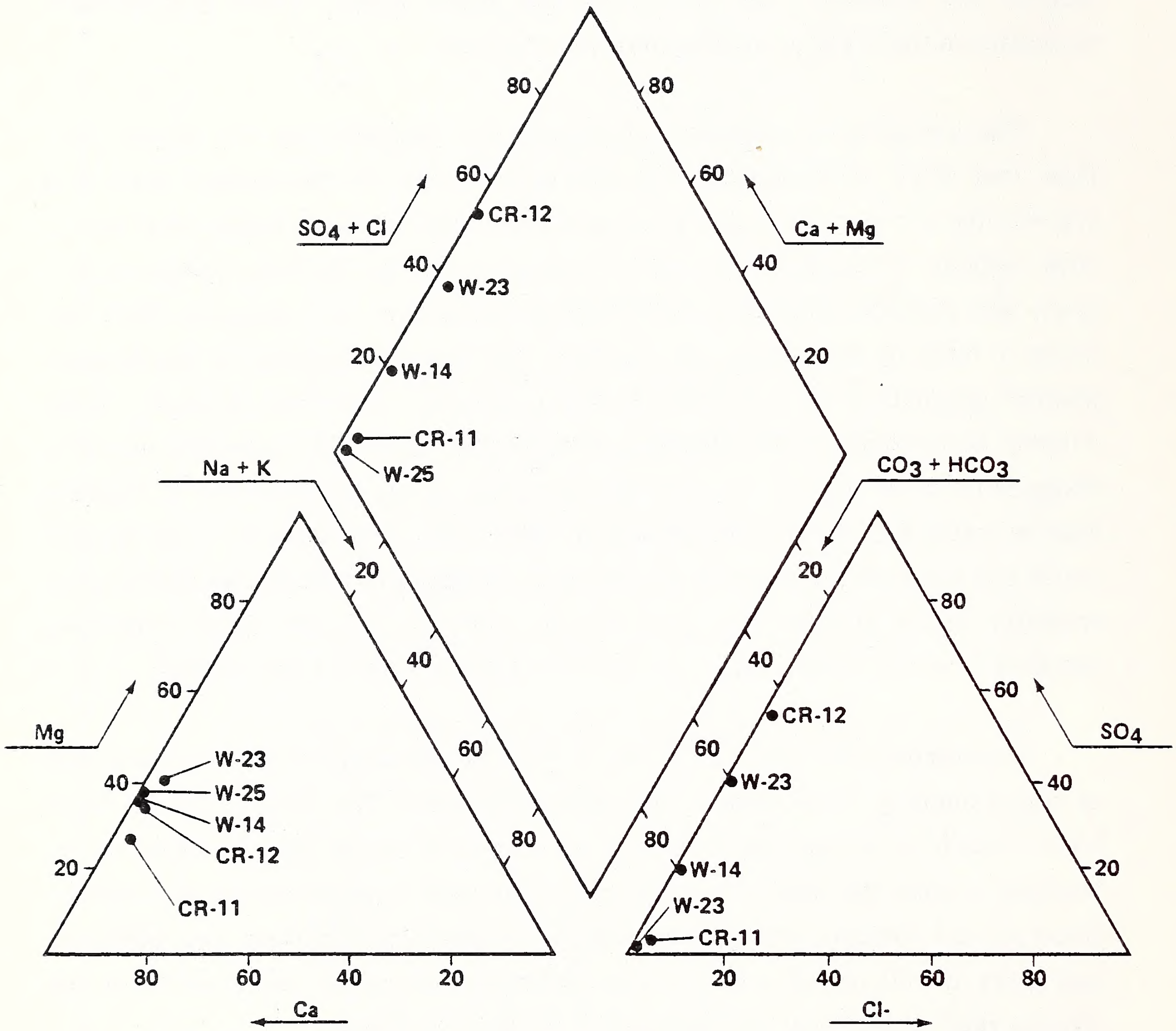


Figure 3-9. TRILINEAR PLOT OF SELECTED MADISON AQUIFER WATER QUALITY ANALYSES

lower concentrations of sulfate, TDS and chloride than do Madison wells that draw ground water only from the low-transmissivity zone in the Madison aquifer (Table 3-4). Sulfate, TDS, and chloride concentrations in ground water from the Madison wells at the Gillette well field completed in the karstic zone are lower (by an average of 140, 219, and 24 mg/l, respectively) than in ground water from Madison wells not completed in the karstic zone.

Total dissolved solids, sulfate, and chloride concentrations were much higher in the upper part of the Madison aquifer than in the lower part of the Madison aquifer at the USGS Madison test well No. 1 near Hulett, Wyoming (Table 3-3). Total dissolved solids, sulfate, and chloride concentrations averaged approximately 910, 450, and 53 mg/l, respectively, in the upper part of the Madison aquifer and 525, 210, and 3 mg/l, respectively, in the lower part of the Madison aquifer (Table 3-5). The water quality in the lower part of the Madison aquifer is very similar to that in the Red River Formation. Drill stem and flow tests conducted at Madison test well No. 1 suggest that the transmissivities of the lower part of the Madison Group and of the Red River Formation may be greater than the transmissivity of the upper part of the Madison Group. The differences in water quality are probably a result of faster ground-water velocities and lower matrix concentrations of gypsum, anhydrite, and halite in the lower part of the Madison Group and in the Red River Formation.

Relatively high concentrations of uranium, radium-226, and strontium-90 are found in some Madison aquifer ground water. Ground water from an ETSI test well (38N-61W-35) in Niobrara County had a radium-226 concentration of 8 picocuries per liter (pCi/l) when sampled in September 1978 (Bechtel 1979). This concentration exceeds the EPA mandatory drinking water criterion for 5 pCi/l of radium-226. Radium-226 levels in Madison ground water at the towns of Philip and Midland, South Dakota, are 100 and 15 pCi/l, respectively (Wilson 1979). The high concentrations of uranium and uranium decay products that are found in Madison ground water are probably related to the uranium mineralization that occurs in the Inyan Kara Group in the Black Hills region. The origin of the uranium is not known, but Gott, Wolcott, and Bowles (1974) suggested that the uranium reached the Inyan Kara Group by upward migration from deeper strata. Regardless of the mechanism of origin, the data available imply only

TABLE 3-4

VARIATIONS IN GROUND-WATER QUALITY BETWEEN THE HIGH-TRANSMISSIVITY AND LOW-TRANSMISSIVITY ZONES IN THE MADISON AQUIFER AT GILLETTE AND NEWCASTLE, WYOMING

Well Name	Well Location (Township-Range-Section)	Well Completed in High-Transmissivity or Low-Transmissivity Zone	Water Quality* TDS (mg/l)	SO_4 (mg/l)	Cl (mg/l)	Date Water Sample Collected
Gillette No. M-2	51N-66W-6	High	488	195	4	02/20/80
Gillette No. M-3	51N-66W-6	Low	707	335	28	12/12/79
Fountain Motor Motel (Newcastle)	45N-61W-20d	High	295	45	5	05/13/75
Newcastle No. 4	45N-61W-28ab	Low	364	104	4	05/13/80

*TDS = total dissolved solids
SO_4 = sulfate
Cl = chloride

TABLE 3-5

WATER QUALITY SUMMARY--MADISON TEST WELL NO. 1
(milligrams per liter, except as noted)

Formation	Sampling Depth (Feet)	Date of Sample	°C	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS (calculated)
Charles	2260-2435	8-8-77	46.5	180	47	35	8	210	460	55	934
Charles	2260-2435	8-9-77	40.5	180	47	35	8	210	450	54	919
Mission Canyon	2425-2600	8-8-77	46	180	44	36	8	210	460	54	930
Mission Canyon	2425-2600	8-8-79	46.2	180	44	36	8	210	460	55	929
Mission Canyon	2425-2600	8-6-77	48.5	170	44	36	9	200	450	51	893
Mission Canyon	2600-2835	8-5-77	47.6	180	48	35	8	190	450	51	902
Mission Canyon	2760	10-21-76	35.5	180	40	70	9	214	470	66	973
Lodgepole	2805-2955	08-02-77	50	92	38	7	3	200	210	5	487
Lodgepole	2805-2955	08-02-77	50	94	37	7	3	210	210	5	589
Lodgepole	2835-2945	08-11-77	47.5	110	38	12	5	190	270	11	574
Lodgepole	2945-3095	08-01-77	50	97	40	7	3	200	220	6	503
Red River	3095-3305	8-12-77	50	84	39	5	2	220	190	3	460
Red River	3100-3280	7-29-77	50.5	86	40	5	3	220	190	3	461
Red River	3100-3290	7-30-77	49.5	87	40	5	3	210	190	3	459
Red River	3290-3480	7-29-77	51.5	81	39	88	3	110	200	3	468
Red River	3290-3480	7-28-77	46.5	83	39	7	3	220	190	3	461
Flathead	4290	10-18-76	47	70	15	180	23	224	74	290	802
Flathead	4299	10-24-76	-	95	35	82	5	251	280	37	688

Source: U.S. Geological Survey data bank.

that, locally, relatively high concentrations of radioactive elements are found in Madison ground water.

Minnelusa Formation

The chemical quality of ground water in the Minnelusa Formation differs markedly from that in the Madison Group (Table 3-3). The lithology of the Minnelusa Formation is highly variable; as a result, ground-water quality variations in the Minnelusa Formation section are significant. Generally, three distinct lithologic units can be defined: (1) a basal clastic unit, called the Bell Sand; (2) a middle unit, consisting of carbonates with interbedded sandstones, shales, and evaporites; and (3) an upper sandy unit that is often interbedded with evaporites (see Appendix B). Each of these lithologic units functions as a separate hydrologic unit; the upper and lower units locally yield large quantities of water to wells and the middle unit typically does not; therefore the water quality in each of these units is discussed separately.

Upper Minnelusa Unit. Water quality in the sandy upper Minnelusa unit, though it is quite variable (Figure 3-10, Table 3-6), can be divided into three distinct types:

- Calcium bicarbonate and calcium bicarbonate sulfate-type ground water with TDS concentrations of less than 1000 mg/l. This water type occurs near outcrop areas of the Minnelusa Formation.

- Calcium sulfate-type ground water with TDS concentrations of greater than 4000 mg/l. This water type occurs in the upper Minnelusa unit in the Black Hills region away from the outcrop areas. Anhydrite and gypsum in the upper Minnelusa unit are the source of the calcium and sulfate. Calcium sulfate ground water with TDS concentrations ranging from 2000 to 4000 mg/l are found in the upper Minnelusa unit in most of the Black Hills region.

- Sodium chloride-type ground water with TDS concentrations ranging from 1000 to over 200,000 mg/l west of the Black Hills monocline and possibly west of the Fanny Peak monocline. Near the Black Hills monocline in Crook County, Wyoming, sodium chloride waters are found in stratigraphic traps with oil; calcium sulfate waters occur away from these stratigraphic traps. Calcium sulfate-type water cannot be found more than a few miles west of the Black Hills monocline, except near the Montana-Wyoming border where the monocline flattens out [Figure 3-10]. The high concentrations of sodium chloride in the ground water west of the Black Hills and Fanny Peak monoclines are probably the result of very slow ground-water movement.

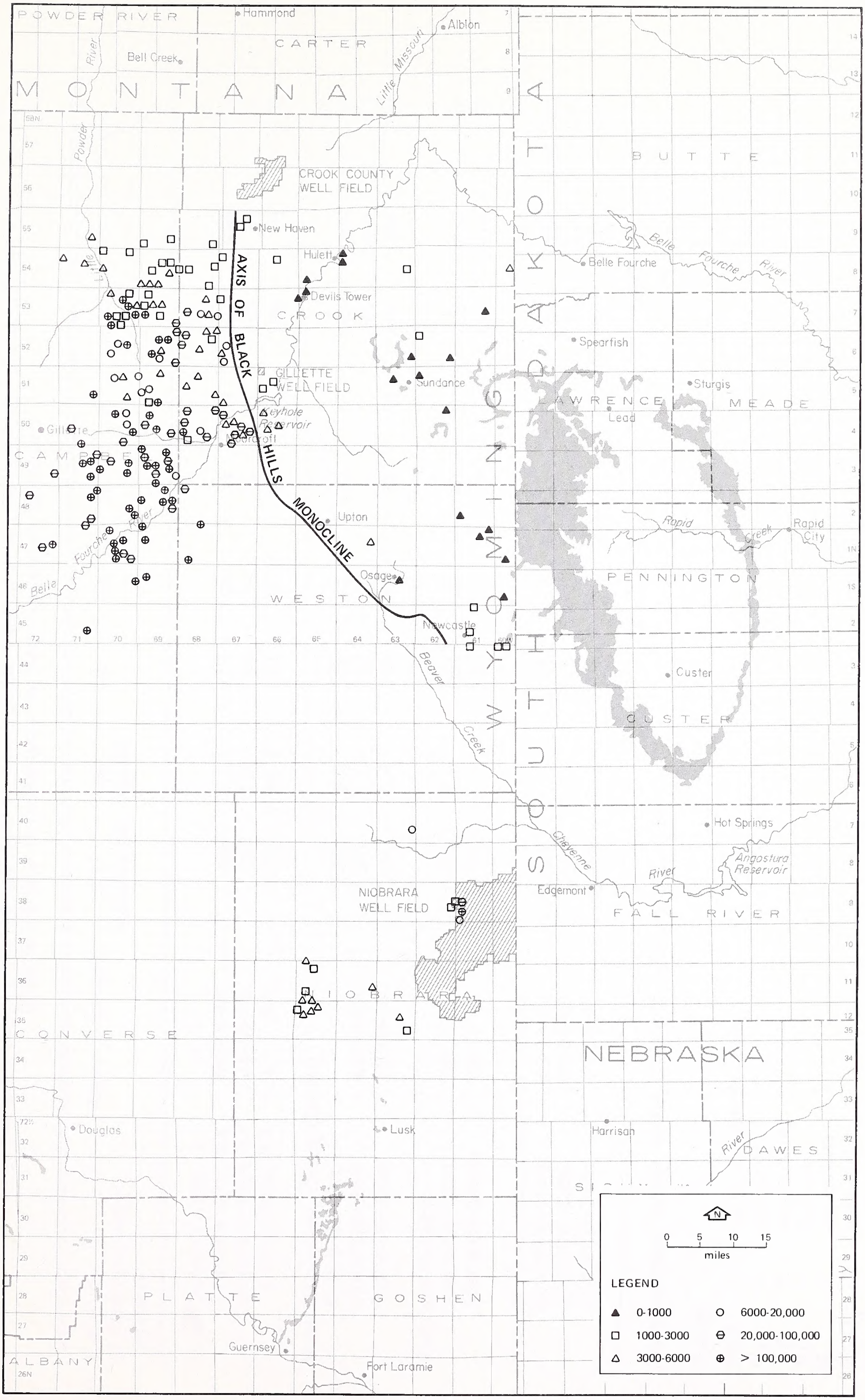


Figure 3-10. WATER QUALITY IN THE MINNELUSA FORMATION
(Total dissolved solids in mg/l)

TABLE 3-6

REPRESENTATIVE WATER QUALITY ANALYSES FROM THE MINNELUSA FORMATION
(Concentrations in milligrams per liter, except as indicated)

Location (township-range-section)	Date of Sample	TDS (calculated)	pH (units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl
Near Outcrop Area										
54N-64W-7bc, WY	06-04-68	485	7.7	110	36	3	2	286	180	2
47N-60W-30aa, WY	06-03-69	280	7.9	68	24	1	1	305	12	1
6 N-2E-10da, SD	11- -54	247	--	63	21	7	--	296	8	4
Near Monocline, Crook County										
51N-66W-09db		3,300	8.0	620	220	130		293	2200	16
52N-67W-19cc	01-22-58	3,580	7.0	740	230	5		330	2400	14
52N-68W-20dd	08-04-64	3,040	8.4	580	190	30	68	232	200	40
Niobrara County										
35N-63W-15bd	02-14-65	3,710	7.3	600	240	250		709	2100	160
36N-64W-26ada	09-14-65	3,210	7.2	240	37	750		185	2000	130
West of Monocline, Campbell County										
52N-69W-11cc	06-10-70	202,000	6.0	2400	650	76,000		131	2200	120,000
52N-69W-28db	01-07-63	5,920	7.3	610	230	1,100		378	2200	1,600
52N-70W-15da	07-10-63	60,500	8.1	1700	750	20,000	35	488	3300	34,000

Data sources: Busby, Wells, and Glover (1979); Cox (1962).

Notes:

TDS = total dissolved solids
Ca = calcium
Mg = magnesium
Na = sodium
K = potassium
HCO_3 = carbonate
SO_4 = sulfate
Cl = chloride

Middle Minnelusa Unit. The few water quality samples that have been taken from the middle Minnelusa unit east of the Black Hills monocline suggest that water quality in the middle Minnelusa is similar to that in the upper Minnelusa Formation (Table 3-7).

Basal Clastic Unit. The basal clastic unit usually contains calcium carbonate-type ground water with TDS concentrations of less than 1000 mg/l. The water quality in this unit is similar to that in the Madison aquifer and differs markedly from water quality in the upper and middle units of the Minnelusa Formation (Eisen and others 1980). Only one well is known to be completed solely in this unit, but several wells are completed both in this clastic unit and in the Madison Group. These wells, with a tabulation of selected chemical parameters, are listed in Table 3-8.

3.C HISTORICAL USE OF THE MADISON AQUIFER SYSTEM

3.C.1 LOCATIONS OF WELLS AND QUANTITY PUMPED

The first uses of ground water from the Madison aquifer in the eastern Powder River Basin and Black Hills area began in the early 1900s with the drilling of the Cambria well near Newcastle, Wyoming, and the Chicago, Burlington & Quincy (CB&Q) railroad well in Edgemont, South Dakota (Appendix E). Since that time, more than 130 Madison wells are known to have been drilled and developed. Most of these wells have been drilled since 1950 and are located near Madison Group outcrop areas (Figure 3-11). In the Black Hills region, current annual production exceeds 10,000 acre-feet per year. Almost all of this production occurs in four small areas: Bell Creek, Montana; Osage and Newcastle, Wyoming; and Edgemont, South Dakota. Significant amounts of Madison ground water may also be produced in Pennington County, South Dakota, where more than 40 Madison wells exist, but production data from these wells were not available. The ground water is produced for oil field water flooding operations and municipal uses, or flows to waste. Total ground-water production from the Madison aquifer in the western Black Hills region since 1900 is estimated to be approximately 300,000 acre-feet (Table 3-9).

TABLE 3-7

MINNELUSA WATER QUALITY AT THE COLTHARP AND DEVILS TOWER WELLS

Coltharp No. 1 Well (51N-66W-sec 18 bd)[a]		Devils Tower Well (53N-65W-18bbd)[b]	
Sample Depth Below Top of Minnelusa (feet)	Total Dissolved Solids (mg/l)	Sample Depth Below Top of Minnelusa (feet)	Total Dissolved Solids (mg/l)
0 - 12	3300	97 - 200	2270
107 - 158	4070	242 - 320	2428
831	2710	518 - 620	2220
837 - 844	914		
(848 - total thickness of Minnelusa)		(719 - total thickness of Minnelusa)	

Data sources:

[a]Busby, Wells, and Glover 1979.

[b]Whitcomb and Gordon 1964.

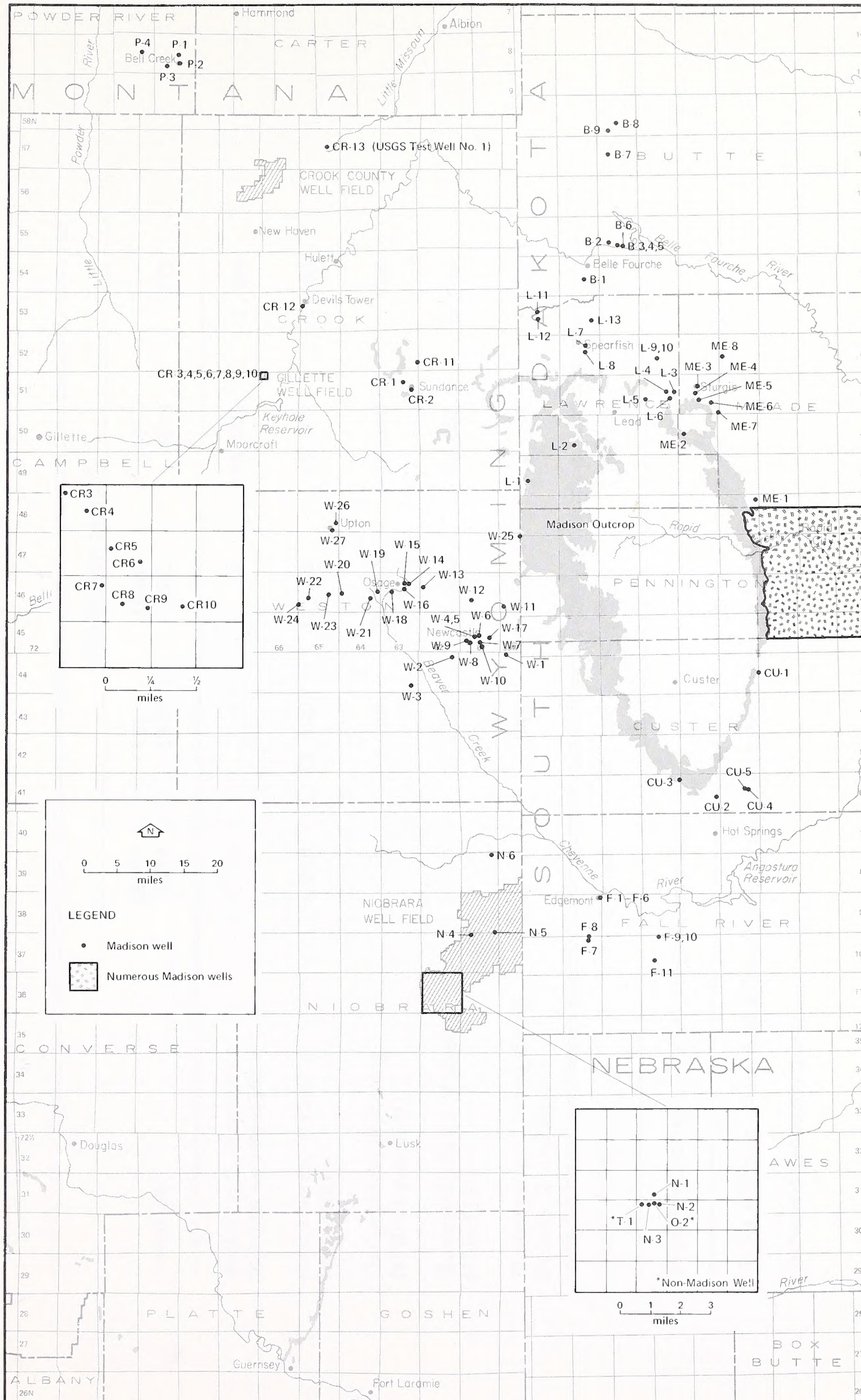
TABLE 3-8

WELLS FINISHED IN THE BASAL CLASTIC UNIT OF THE MINNELUSA FORMATION
(Concentrations in milligrams per liter)

Well Location (Township-range-section)	Owner	Comments	Date Analyzed	TDS	SO_4	HCO_3	Cl	Source
1. 46N-60W-31aa	Martens	Open only in lower Minnelusa	12-10-47	290	16	306	2	Whitcomb, 1963
2. 52N-63W-25dc	Sundance	Open to Madison also	3-16-73	236	7	268	2	Eisen, 1980
3. 46N-64W-23ccb	Osage-West Field	Open to Madison also	6-15-72	279	33	275	2	Eisen, 1980
4. 46N-63W-10dca	Black Hills Power	Open to Madison also	7-11-72	315	51	295	1	Eisen, 1980
5. 44N-60W-5bbd	LAK Ranch	Open to Madison also	12-10-47	300	27	300	3	Eisen, 1980
6. 45N-61W-28ab	Carlsen	Open to Madison also	3-16-62	280	37	289	1.4	Whitcomb, 1963
WELLS FINISHED IN UPPER MINNELUSA NEAR THE ABOVE - LISTED WELLS								
1. 45N-61W-2bab	Martens		03-14-62	2870	2000	127	19	Busby et al., 1979
3. 47N-64W-12c	East of Upton		?	3910	2760	110	36	Crawford, 1940
5. 44N-60W-5bbd	LAK Ranch		12-10-47	2020	1300	222	11	Busby et al., 1979
6. 45N-61W-28ab	Carlsen		3-16-62	3220	1980	127	19	Whitcomb, 1963

Note: The LAK Ranch well and the Carlsen wells are constructed such that water is yielded from the Minnelusa Formation through the annulus between the surface casing and an inner casing which yields water from the Madison Group and the Bell Sand. The LAK well in 1960 yielded 2 gpm from the Madison Group and 41 gpm from the Minnelusa Formation, and the Carlson well yielded 1150 gpm from the Madison Group and 300 gpm from the Minnelusa Formation.

TDS = total dissolved solids
SO_4 = sulfate
HCO_3 = carbonate
Cl = chloride



Note: More detailed information on these wells is provided in Appendix E.

Figure 3-11. MADISON WELLS IN THE BLACK HILLS AND EASTERN POWDER RIVER BASIN

TABLE 3-9

HISTORICAL USE OF MADISON WATER AT MAJOR PUMPING CENTERS IN THE EASTERN POWDER RIVER BASIN AND THE WESTERN AND SOUTHERN BLACK HILLS

	Production Period*				
Location	1900-1949	1950-1959	1960-1969	1970-1979	1979
Bell Creek, Montana (8S-54E and 95-53E)	0	0	0	25,000	1,400
Osage Area, Wyoming (46N-63E)	9,000	12,000	12,000	13,000	1,300
Osage Area, Wyoming (46N-64 and 65W)	0	1,200	15,000	11,000	800
Newcastle Area, Wyoming (45N-61W)	0	16,000	46,000	52,000	5,700
Edgemont and Provo, South Dakota (8 and 9S-2E)	35,000	18,000	18,000	18,000	1,800
Yearly Totals	44,000	47,200	91,000	119,000	11,000

Total Production to 1979: 301,200 acre-feet

Data sources: Eisen and others 1980; Hodson 1974; M. Brown 1979.

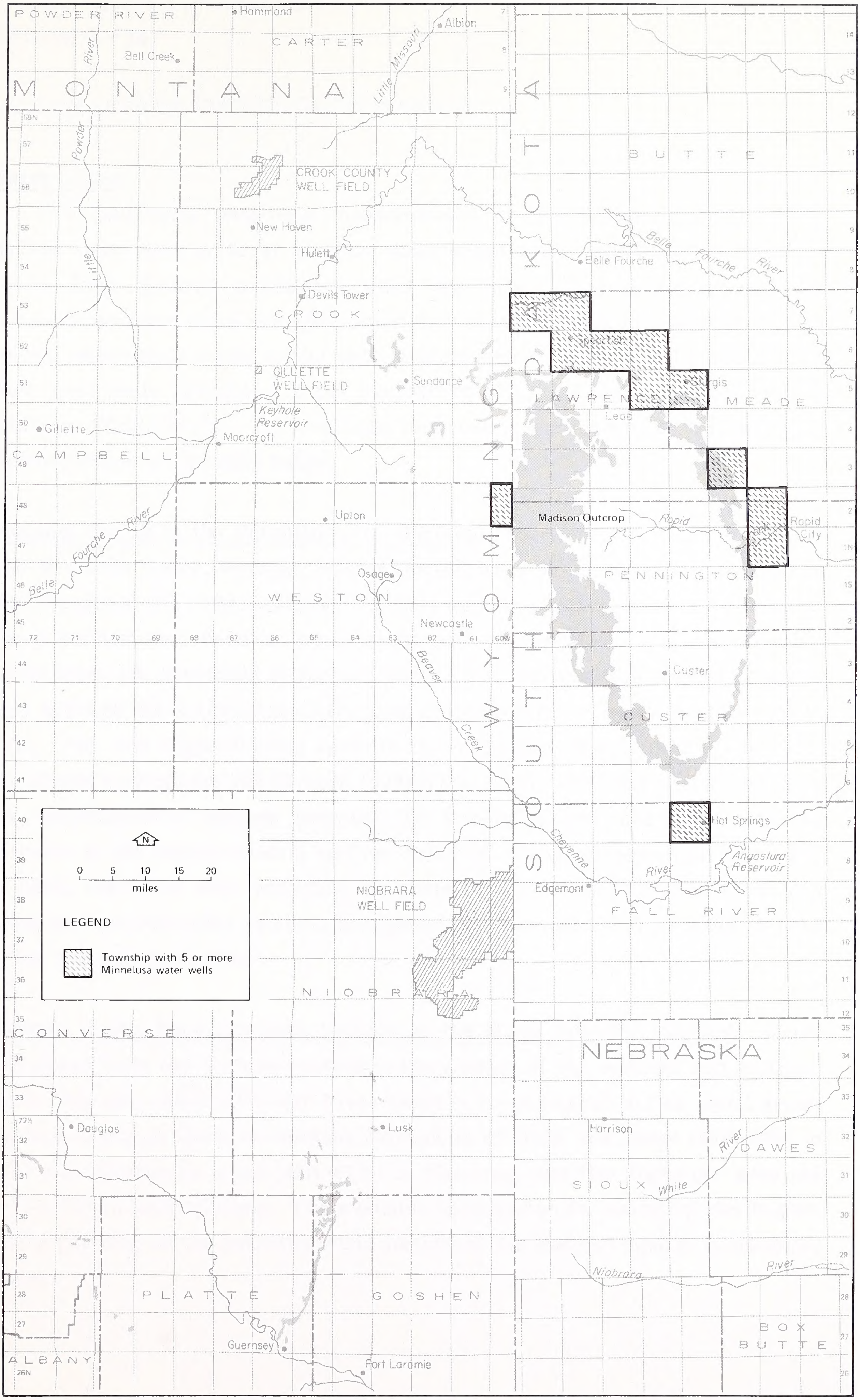
*Amounts produced are in acre-feet.

The use of Madison ground water is expected to increase with the addition of at least two new developments. The city of Gillette is currently developing a well field near Moorcroft, Wyoming, and plans to produce an annual average of about 5400 acre-feet of ground water for 50 years from the Madison aquifer for municipal uses (James M. Montgomery, Consulting Engineers 1979). Black Hills Power and Light is also developing a Madison aquifer water supply system for a new electric power plant near Osage, Wyoming. This well field is expected to supply 1450 acre-feet of water per year for cooling beginning in the 1990s (Kelly 1980a). No operating Madison water, oil, or gas wells exist in northwestern Nebraska (Ginsberg 1980; Souders 1980).

Ground-water production in the Black Hills region from the Minnelusa Formation is largely concentrated in the Spearfish-Belle Fourche area of South Dakota (Figure 3-12). Cox (1962) estimated that about 10,000 acre-feet of ground water from the Minnelusa Formation was being produced in this area for irrigation needs.

Besides Cox (1962), no other published inventory of Minnelusa wells or water use has been made for the Black Hills region. Except in the Spearfish-Belle Fourche area, near Hulett, Wyoming, and possibly near the Minnelusa Formation outcrop areas in the Black Hills, little use is made of the Minnelusa Formation for ground-water supply because of its relatively poor quality. No operating Minnelusa water, oil, or gas wells exist in northwestern Nebraska (Ginsberg 1980; Souders 1980).

The Inyan Kara Group is the only other major aquifer below the Cretaceous shales that supplies ground water to wells in the western Black Hills area. There are numerous wells completed in this rock unit, but well yields are generally less than 10 gallons per minute (Whitcomb 1965; Whitcomb and Morris 1964). The water is produced mainly for oil field water flooding and for domestic and stock uses. No published inventory of Inyan Kara Group wells is known to exist.



Source: Howells, 1980.
Eisen and others, 1980.

Figure 3-12. MINNELUSA WATER WELLS IN THE BLACK HILLS AND EASTERN POWDER RIVER BASIN

3.C.2 EFFECTS OF HISTORIC WITHDRAWALS

Water Levels

No continuous long-term measurements of the Madison potentiometric surface have been made at Madison observation wells, and periodic measurements from Madison production wells are rare. The available data for documenting water-level changes consist only of water-level measurements from several observation wells, initial shut-in pressures or water-level measurements from most wells completed in the Madison aquifer, and postcompletion shut-in pressures (Table 3-10). The available information on changes in the potentiometric surface is discussed below.

Regional Trends in the Potentiometric Surface. The water level in the Madison well at Devils Tower, Wyoming (53N-65W-18), has been monitored from 1962 to 1980 (Figure 3-13). The water level in this well rose 19 feet from 1964 to 1976. The potentiometric head in the Martens well (46N-60W-31) also rose significantly from the mid 1960s to the mid 1970s. The Martens well flowed 0.3 cfs in 1941 and 0.02 cfs in 1960; the water level dropped to 8 feet below land surface in 1962. The well began flowing again in the mid-1960s, flowed 0.08 cfs in 1973, and flowed 0.13 cfs in 1980 (Hodson 1974; Eisen 1980). The observed increases in the potentiometric surface between the mid-1960s and mid-1970s, and the decrease in the potentiometric surface observed at the Martens well from 1941 to 1962, correlate with variations in annual precipitation. Precipitation was below normal from 1959 to 1961, and generally above normal from 1962 to 1978 in the western Black Hills.

Changes in the Potentiometric Surface at the Major Pumping Centers. Water production from the Madison aquifer in the vicinity of the western and southern Black Hills and eastern Powder River Basin is concentrated in four small areas: the Bell Creek oil fields in Montana (8S-54E to 9S-53E), the Osage (46N-63W to 65W) and Newcastle areas (45N-61W) in Wyoming, and the Edgemont area (8S and 9S-2E) in South Dakota. The available information for assessing the impact of this pumping on the potentiometric surface of the Madison aquifer is discussed below.

TABLE 3-10

WATER WELLS COMPLETED IN THE MADISON GROUP WITH DATA ON THE POTENTIOMETRIC SURFACE AND FLOW RATES FROM MORE THAN ONE TIME PERIOD

Well Name	Well Location	Year Well Drilled	Initial Well Measurements: Flow (cfs)	Initial Well Measurements: Pressure (psi)	Initial Well Measurements: Depth to Water (feet)	Later Measurements (date)	Well Production	Data Sources
Powder River County, Montana								
Bell Creek Madison Well No. 1	8S-54E-27	1969	-	12.2[a]	-	18 psi (5/12/80)	Data available only for Madison wells 1 & 2 combined; 1970-1979 production: 15,500 ac-ft	1
Bell Creek Madison Well No. 3	8S-54E-29	1972	-	56	-	38 psi (5/12/80)	1970-1979 production: 5500 ac-ft	1
Bell Creek Ranch Well No. 1	9S-53E-22	1971	-	90	-	94 psi (5/12/80)	1971-1979 production: 4400 ac-ft	1
Crook County, Wyoming								
Devils Tower	53N-65W-18	1962	-	-	-	Measurements of water levels taken frequently	Total production small	
Weston County, Wyoming								
LAK Ranch	44N-60W-5	1945	.04	-	-	3 gpm (1960)	-	2
Newcastle, City No. 1[b]	45N-61W-20	1949	3.57	200	-	180 psi (3/62); 3.34 cfs (1974); 171 psi (6/20/78)	Current production: about 22 cfs	3,4
Newcastle, City No. 4	45N-61W-20	1978	1.31	164.5	-	163 psi (10/16/78)	Current production: about 0.50 cfs	4,5
Tesoro Petroleum Co. (Wyoming Refinery)	45N-61W-29	1960	-	200	-	150 psi, 120 gpm (1973); 90 psi (2/1980)	Production data not available	3,6
Coronado Oil Co.[c]	45N-61W-33ab	1964	-	-	-	146 psi (10/76); 149 psi (11/75); 145 psi (10/76); 150 psi (3/77); 151 psi (3/78)	-	7
Martens Well[d]	46N-60W-31ba	1941	.33	-	-	8 gpm (8/60); 8.60 ft to water (5/62); 7.41 ft to water (9/62); 59 gpm (1980)	-	2,8
Cambria Mine	46N-61W-29	1900(?)	.45	-	-	37 ft to water (9/60); 27 to 36 ft to water (1969-1978); frequent water level measurements, 1969-1978	Well abandoned	2,6
Black Hills Power and Light No. 1	46N-63W-10dca	1941	1.78	-	-	1.60 cfs (1946); 1.29 cfs (1960); 6.99 cfs (1974); 171 psi (1978); 1.16 cfs gpm (1980)	Flow uncontrolled 1949-1960 but controlled in 1980 at 1.16 cfs	2,6,9
Black Hills Power and Light No. 2	46N-63W-15	1951	1.11	-	-	0.45 cfs (1980); 170 psi (1973?); 160 and 170 psi (1979)	Flows 0.45 cfs continuously	3,6,9
Black Hills Power and Light No. 3	46N-63W-11ca	1979	-	-	-	130 psi (1979); 125.5 psi (1980)		9

TABLE 3-10 Concluded

Well Name	Well Location	Year Well Drilled	Initial Well Measurements: Flow (cfs)	Pressure (psi)	Depth to Water (feet)	Later Measurements (date)	Well Production	Data Sources
Butte Oil and Gas	46N-63W-17	1969	-	280	-	185 psi (8/73); 161 psi (2/80)	1979-1973 production: 600 ac-ft; 1970-1979 production: 1100 ac-ft	3,6
Butte Oil and Gas	46N-64W-23	1965	-	-	223	370 ft to water after shutting off pumps for 2 hours (8/73)	1965-1973 production: 2375 ac-ft; 1965-1979 production: 4650 ac-ft	3,6
Terra Resources	46N-65W-20	1960	-	-	530	650 ft to water in 1973 when pump was removed and well was not used	No more than 9744 ac-ft produced 1960-1972; production records grouped with well 46N-66W-25	3,6
Terra Resources	46N-65W-23	1959	-	-	395	420 ft to water (1973?)	No more than 7000 ac-ft produced 1956-1973; 1956-1963 includes production from well 46N-64W-19	3,6
Terra Resources	46N-66W-25	1962	-	-	800	880 ft to water (1973?)	See well 46N-65W-20	3
Mallow Camp Well	47N-60W-4da	1965	-	-	-	Feet to water: 194 (1973); 218 (5/75); 190 (1/76); 180 (6/76); 150 (1/77); 122 (4/77); 180 (1/78)	-	7
City of Upton	48N-65W-35ccb	1961	-	18?	-	Frequent measurements 1970-1972, 1976-1980; less than 10 ft to water when not pumping	-	7
Fall River County, South Dakota								
CB&Q No. 1	9S-2E-1aaa	1908	.67	-	-	Does not flow (1979)	-	
City of Edgemont No. 2	9S-2E-1	1911	1.28	94.5	-	0.22 cfs (1979); Howells measured 0.32 cfs (1975)	-	
City of Edgemont No. 3	9S-2E-1	1936	1.56	39	-	0.33 cfs (1979); 37 psi (6/24/75)	-	
Provo Well No. 1	10S-2E-3	1942	0.37	-	-	0.19 cfs (1979)	Only Edgemont well No. 8 is pumped; all other wells flow free; average flow in 1979 was 2.4 cfs	10,11
Provo Well No. 2	10S-2E-3	1943	0.562	-	-	0.28 cfs (1979)	-	
CB&Q No. 2	9S-2E-1aaa	1946	2.23	110	-	87 psi (spring 1979); 0.45 cfs (1979); 90.5 psi (6/24/75)	-	
Mine Development	9S-2E-1	1962	1.00	86	-	0.60 cfs (1979)		
City of Edgemont No. 8	9S-2E-1	1962	0.61	33	-	0.33 cfs	-	

[a] Original psi measurements taken from bottom of hole; later psi measurements made using surface gage.
[b] Discharge measurements probably not accurate.
[c] Abandoned 1966.
[d] Owner reported well began flowing in 1960s.
[e] Initial 0.45-cfs flow may have been obtained with a pump.

Data Sources:

1. Belden, 1980.
2. Whitcomb, 1963.
3. Hodson, 1974.
4. Eisen, 1980.
5. Anderson and Kelly, 1978.
6. Eisen and others, 1980.
7. Stevens, 1978.
8. Wyoming State Engineer, 1974.
9. Kelly, 1980.
10. M. Brown, 1979.
11. West, 1975.

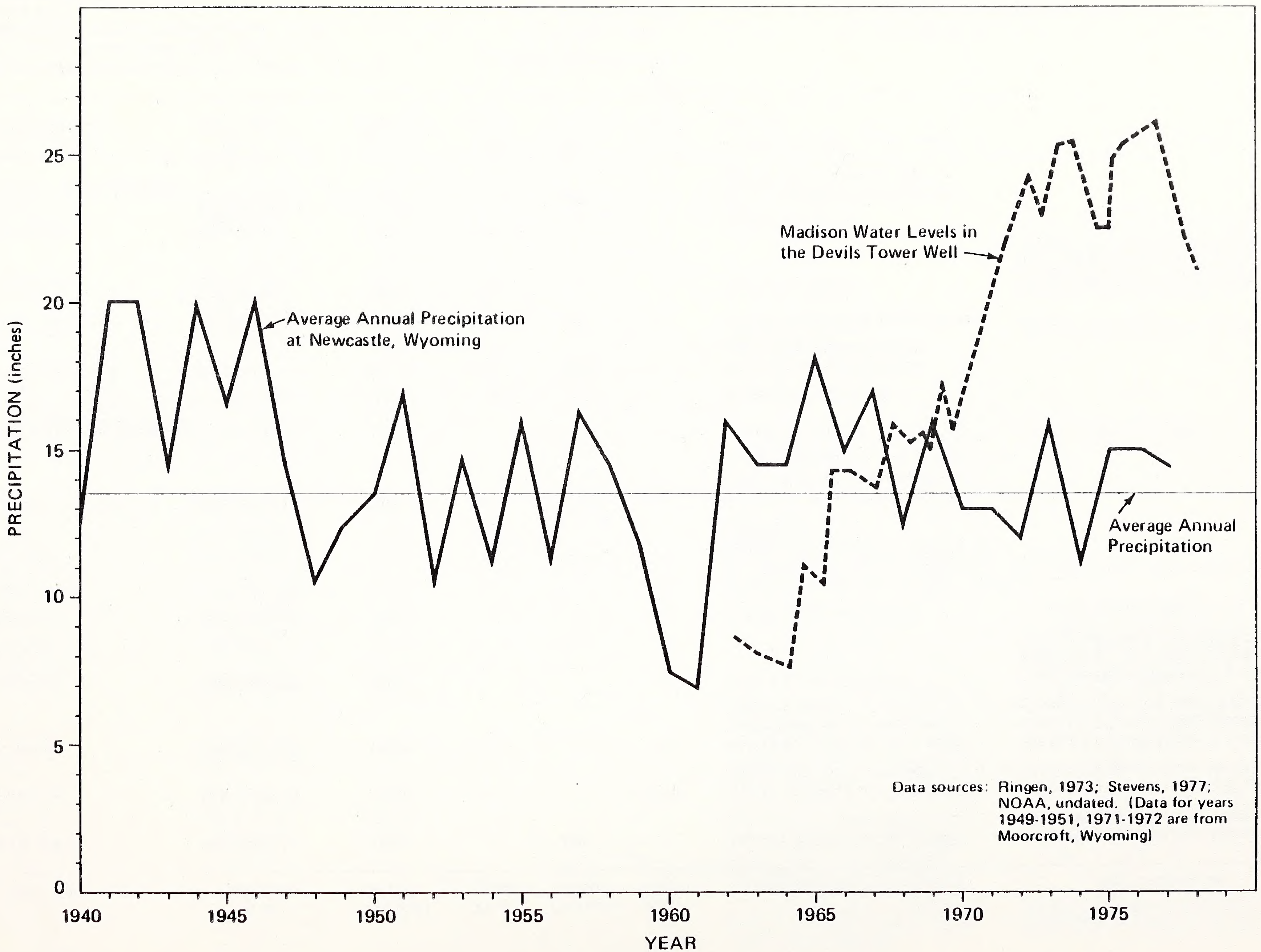


Figure 3-13. MADISON WATER LEVELS IN THE DEVILS TOWER WELL (53N-65W-18bbd) AND AVERAGE ANNUAL PRECIPITATION AT NEWCASTLE, WYOMING

Bell Creek, Montana (8S-54E to 9S-53E). Production from the four Bell Creek Madison wells has totaled 25,000 acre-feet over the past decade. All four wells are flowing wells. Initial shut-in pressures when the wells were completed (1969 to 1972) and shut-in pressures for 1980 are available for three of the four Madison wells at the Bell Creek field (Belden 1980). The accuracy of the initial measurements is probably poor. Shut-in pressures increased 4 to 6 psi (9 and 14 feet) at two of the three wells from initial well completion to 1980. Shut-in pressure at the third well showed a decline of 18 psi (42 feet) from 1972 to 1980.

Osage Area, Wyoming (46N-63E). Five Madison wells were drilled in the Osage area from 1941 to 1979. All five wells flow. Total production from these wells has been approximately 39,000 acre-feet. The initial potentiometric surface at the wells ranged from 4694 to 4818 feet (Figure 3-14). The shut-in pressure at Black Hills Power and Light well No. 2 in 1978 was the same as the original shut-in pressure in 1951 (Hodson 1974; Kelly 1980b). Initial and later shut-in pressures were not taken at the other wells.

The flow of Black Hills Power and Light well No. 1 (46N-63W-18) has been measured several times. The flow decreased from 1.6 cfs in 1946 to 1.0 cfs in 1974, then increased to 1.2 cfs in 1980. Since the accuracy of the flow measurements and the changes in well efficiency are unknown, nothing conclusive can be stated about changes in the potentiometric surface.

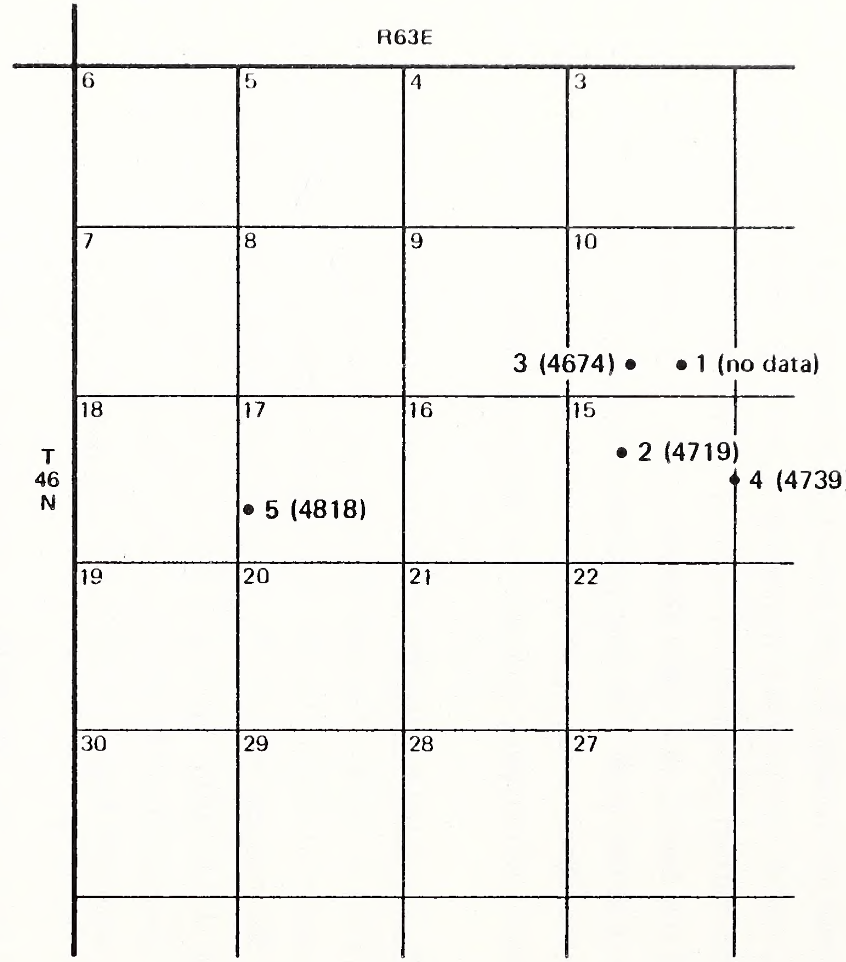
Osage Area, Wyoming (46N-64W and 65W). Six Madison water wells were completed west of township 46 north, range 63 east, west of Osage, Wyoming, between 1956 and 1965. Total production from these wells has been approximately 29,000 acre-feet (Eisen 1980). The primary use of this water is for oil field water flooding. Only one well flows. The water level at the Terra Resources well (46N-65W-20) was 530 feet below land surface when the well was drilled in 1960. This water level had decreased 120 feet to 650 feet below land surface when measured by the U.S. Geological Survey in 1973. This well was not being used when this water-level measurement was made (Hodson 1974). The water level in the Buttes Oil and Gas well (46N-64W-23) was 223 feet below land surface when the well was completed in 1965, and was 370 feet below land surface in 1973 after the pumps were shut off for two hours (Hodson 1974). Smaller water-level declines were reported at the four other wells in the area.

Well No.	Well Name	Date Drilled
1	Black Hills Power & Light 1, W-14	1941
2	Black Hills Power & Light 2, W-16	1951
3	Black Hills Power & Light 3, W-15	1979
4	Black Hills Power & Light 4, W-17	1979
5	Butte Gas and Oil, W-18	1969

LEGEND

•5 Well location and number

(4818) Water level elevation above MSL (in feet)



Data sources: Kelly, 1980b; Hodson, 1974

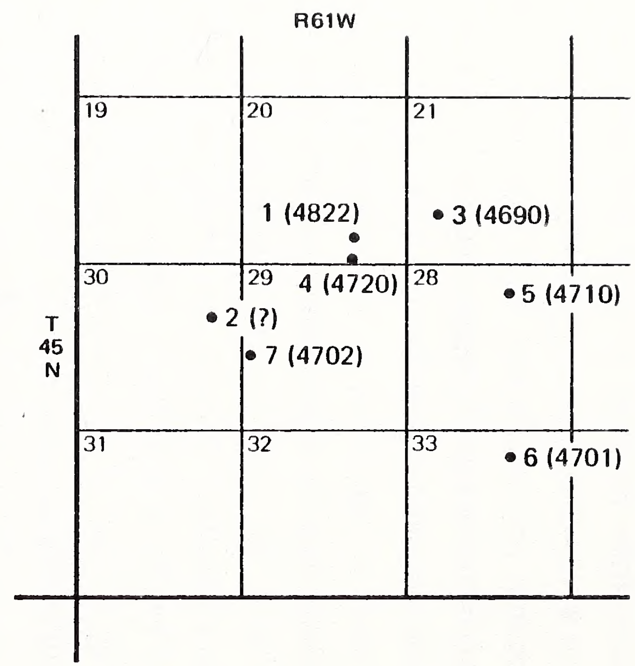
Figure 3-14. OSAGE AREA SHOWING WELL LOCATION AND POTENTIOMETRIC SURFACE ELEVATIONS, AS DERIVED FROM INITIAL WATER LEVEL OR SHUT-IN PRESSURE READINGS

Newcastle Area, Wyoming (45N-61W). Seven Madison wells were drilled near the city of Newcastle from 1949 to 1978. Total production from the 6-square-mile area in which the wells are located has totaled over 100,000 acre-feet. The original potentiometric head at each of the wells and the well locations are shown in Figure 3-15. The shut-in pressure at Newcastle well No. 1 (45N-61W-20) declined 20 pounds per square inch (psi) from 1949 to 1962. The shut-in pressure at the Tesoro Petroleum Company well (45N-61W-29) declined 50 psi from 1960 to 1973 and declined 60 psi from 1973 to 1980. The original potentiometric data from each of the wells in the Newcastle area, which are plotted versus time in Figure 3-16, also suggest that the potentiometric surface has declined in the Newcastle area. The observed change in the potentiometric surface of almost 100 feet from the 1940s to the 1960s, as calculated from initial shut-in pressures at Newcastle well No. 1, may be the result of a decline in the potentiometric surface caused by variations in precipitation. The observation that the potentiometric surface in the Newcastle area, as calculated from the initial shut-in pressure at Newcastle well No. 4 in 1980, was higher than that calculated from initial shut-in pressures at wells drilled in the early 1960s, suggests that small declines have occurred in the potentiometric surface at Newcastle.

Edgemont, South Dakota (8S and 9S-2E). Six flowing Madison wells were completed within a 1-square-mile area in Edgemont, South Dakota, between 1907 and 1962. Total production from the wells is estimated to be about 73,000 acre-feet. Initial and later potentiometric surface elevations, calculated from shut-in pressures, are plotted versus time in Figure 3-17. The potentiometric surface remained fairly constant from 1911 to 1979, even though current production exceeds 2.2 cfs and all the wells are located within a very small area.

Salt Creek Oil Field Wells (southern Johnson and northern Natrona counties) near Midwest, Wyoming. The largest withdrawals of ground water from the Madison aquifer have occurred outside the Black Hills region in the southwestern Powder River Basin near Midwest, Wyoming. Production from the Madison aquifer during the period 1955 to 1973 was reported to have been 245,000 acre-feet (Wyoming State Engineer's Office 1974). Some of this production has come from the Tensleep Sandstone member of the Minnelusa

Well No.	Well Name	Date Drilled
1	City of Newcastle 1, W-4	1949
2	City of Newcastle 2, W-9	1961
3	City of Newcastle 3, W-6	1965
4	City of Newcastle 4, W-5	1978
5	Carlson Well (Fountain Motel), W-7	1962
6	Coronado Oil Company, W-10	1964
7	Tesoro Petroleum Company, W-8	1960



LEGEND

• 7 Well location and number

(4702) Water level elevation (in feet)

Data sources: Burnham, 1978; Hodson, 1974

Figure 3-15. NEWCASTLE AREA SHOWING WELL LOCATIONS AND POTENTIOMETRIC SURFACE, AS DERIVED FROM INITIAL SHUT-IN PRESSURES

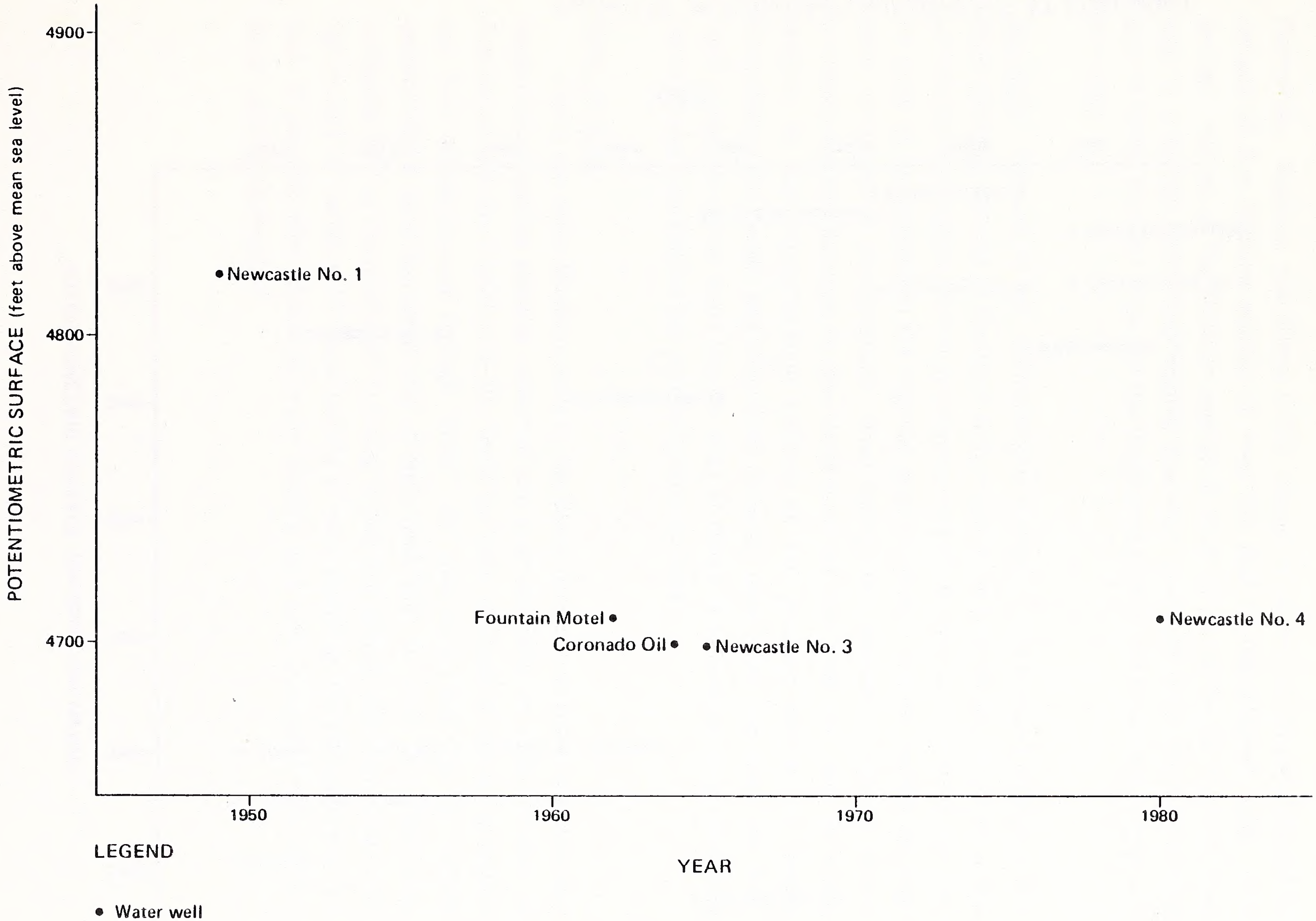


Figure 3-16. POTENTIOMETRIC SURFACE AT THE NEWCASTLE WELLS, AS DETERMINED FROM INITIAL SHUT-IN PRESSURES

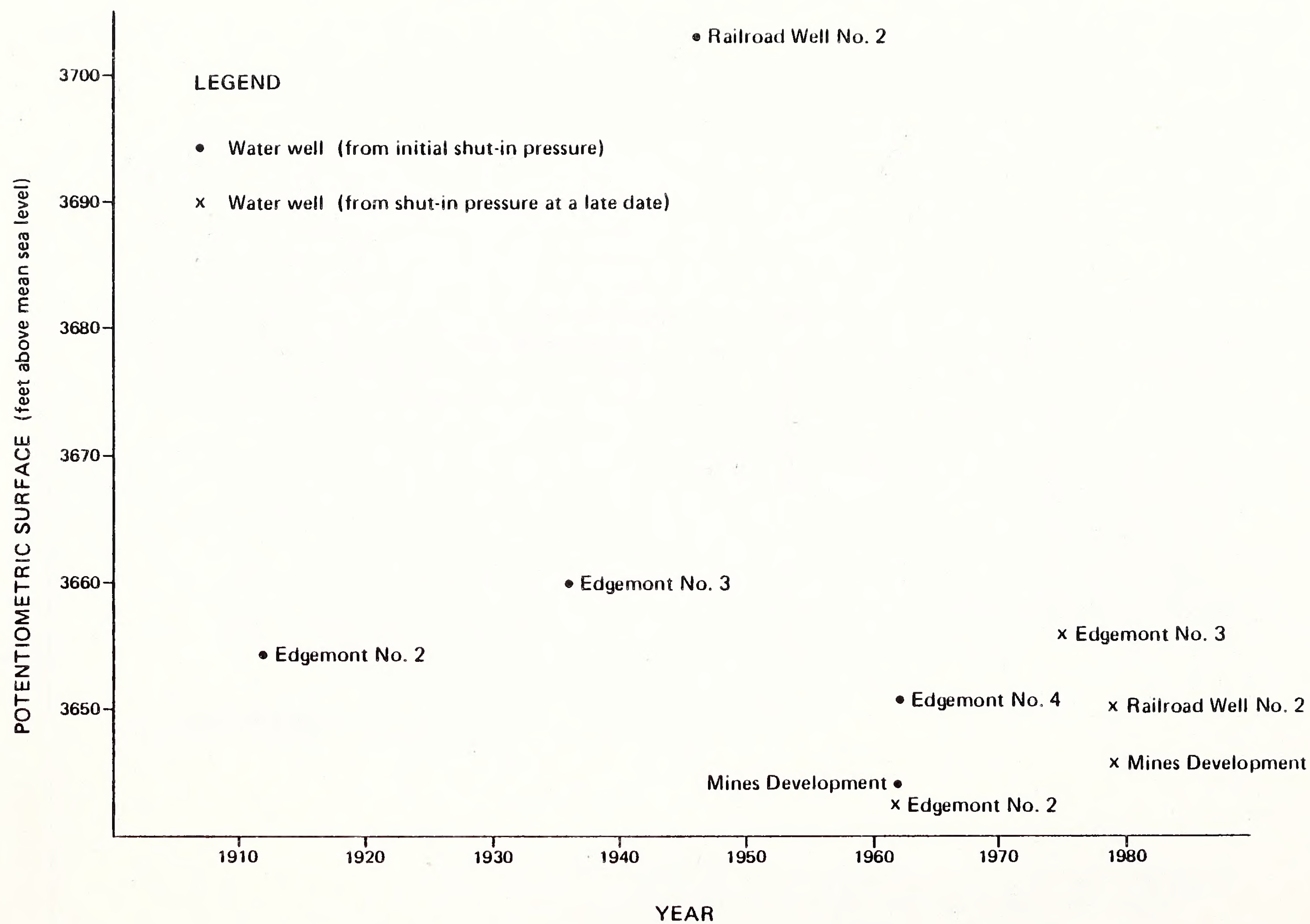


Figure 3-17. POTENTIOMETRIC SURFACE AT EDGEMONT, AS DETERMINED FROM INITIAL SHUT-IN PRESSURES AND LATER SHUT-IN PRESSURES

Formation. Swenson and others (1976) mapped a decline in the potentiometric surface of the Madison aquifer of over 400 feet in the Midwest area. The geologic setting of the Madison aquifer is much different in the Midwest area than it is in the Black Hills region; therefore analogies between the Madison aquifer in the Midwest area and the Madison aquifer in the Black Hills region are not valid.

Summary. Declines in the potentiometric surface of the Madison aquifer at the major pumping centers in the Black Hills region have been small. Declines in the potentiometric surface caused by pumping may have been masked during the past 15 years by an increase in the regional potentiometric surface caused by long-term variations in precipitation. Even taking into account a regional potentiometric surface increase in the Madison of 20 feet over the past 15 years, declines in the potentiometric surface at the pumping centers of Osage, Newcastle, Bell Creek, and Edgemont probably have been less than 100 feet. Only in Madison water wells located west of Osage have declines of greater than 100 feet been recorded in the potentiometric surface.

Water Quality

There are eight Madison wells in the Black Hills region with multiple time-spaced water quality samples collected and analyzed prior to 1980. Except at Newcastle well No. 1 (45N-61W-20), there has been no trend of increasing sulfate and TDS concentrations through time. At Newcastle well No. 1, sulfate concentrations have increased only 17 mg/l from 1941 to 1980. A recent study conducted by the University of Wyoming (Eisen and others 1980) concluded that the amount of variation in water quality at each sampling site was generally less than 20 percent when historical water quality data were compared with current water quality information.

4. NUMERICAL MODEL OF THE MADISON AQUIFER SYSTEM

The impacts that would occur as a result of pumping from the proposed ETSI well-field sites were calculated by simulating the Madison aquifer system as a multilayer aquifer system using a digital model. The Madison aquifer system was conceptualized as a five-layer aquifer system that was numerically modeled using the program for simulation of three-dimensional ground-water flow by Trescott and Larson (1976). This approach was undertaken after a review was made of earlier attempts to simulate the impacts of ETSI ground-water withdrawals (see Section 2). None of the previous approaches were found suitable for evaluating impacts that could be caused by ETSI, given the current state of knowledge about the Madison aquifer. The review of previous studies suggested that the multilayer numerical approach used in this study is the best approach for simulating withdrawals from the Madison aquifer. Other techniques could have been used to calculate drawdowns of the potentiometric surface of the Madison aquifer, but the deterministic approach used in this study represents the most comprehensive and thorough approach that could be used with available data to model the aquifer system and simulate system response to pumping.

This study is not the first to model the Madison aquifer system as a multi-dimensional aquifer system using the numerical model by Trescott and Larson (1976). The model of the Madison aquifer system in the northern Great Plains region that is currently being developed by the U.S. Geological Survey also uses this approach. The USGS study, which is to include an assessment of impacts caused by pumping from the proposed ETSI well-field sites, to date has been documented only by release of the preliminary data set used to model steady-state conditions in the aquifer system (Downey and Weiss 1980). The study is expected to be completed in the fall of 1980.

The USGS numerical model of the Madison aquifer system is composed of three layers: the Red River aquifer unit, the Madison aquifer unit, and the Inyan Kara (Lower Cretaceous) aquifer unit. Data specified in the preliminary data release were transmissivities of the Madison and Red River aquifers, vertical hydraulic conductivities for the confining beds, and the fresh-water potentiometric surface of the Inyan Kara Group. The transmissivities specified in the Madison aquifer in the Black Hills region ranged from zero at the boundary of the Madison aquifer to 0.476 ft^2/sec northeast of the Crook County well field; and transmissivities specified in the Red River ranged from zero at the boundaries of the Red River aquifer to 0.872 ft^2/sec northeast of the Crook County site. Transmissivities in both the Red River and Madison aquifers were specified as being 16 times greater in a northeast-southwest direction than in the northwest-southeast direction. Leakage coefficients specified between the Red River aquifer and the Madison aquifer ranged from 9×10^{-13} to 6×10^{-10} sec^{-1}, and leakage coefficients specified between the Madison aquifer and the Inyan Kara Group ranged between 7.8×10^{-14} and 1.6×10^{-13} sec^{-1}. The data set did not include estimates of storage coefficients.

Estimates of the storage coefficients were made, using Konikow (1976) as the basis for these estimates, in order to conduct transient simulations of ETSI's ground-water withdrawals using the USGS model. The leakage coefficients, specified by Downey and Weiss (1980), between the Madison and Red River aquifer units were also adjusted to correct for errors in the connection between the Madison and the Red River layers.

Several transient simulations were made of the withdrawal of 20,500 acre-feet per year from the proposed ETSI Niobrara well-field site using values for the storage coefficent of the Madison and Red River aquifer units in the range of 5×10^{-5} to 2×10^{-4}. After 50 years of pumping, the simulated drawdowns are not very sensitive to the specified storage coefficients. The drawdowns calculated when a storage coefficient of 10^{-4} was specified in both the Red River and Madison aquifer units are shown in Figure 4-1. The asymmetric cone of depression with drawdowns of 90 feet at the Gillette well field, Wyoming, 110 miles north of the specified pumping center, and 75 feet at Edgemont, 30 miles east of the specified pumping center, is a result of the anisotropic transmissivity distribution used in the model.

The USGS model was not used in this study to calculate impacts because the data set was released only as preliminary version, because the model was designed to simulate a very large region, and because the drawdowns calculated

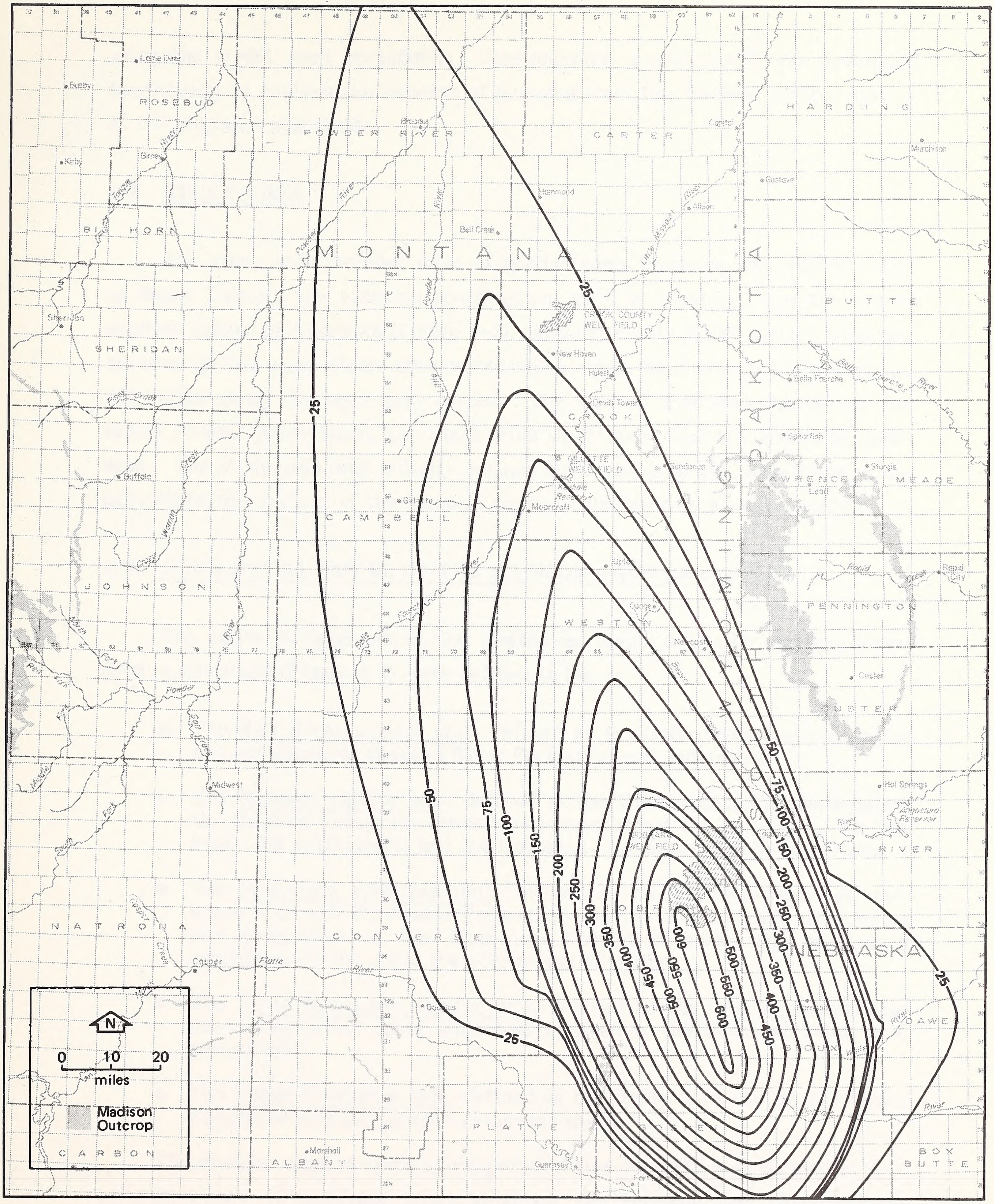


Figure 4-1. DRAWDOWNS (in feet) IN THE MADISON POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985 - 2035) OF PUMPING FROM THE NIOBRARA COUNTY WELL FIELD (PLAN 1) USING THE U.S. GEOLOGICAL SURVEY PRELIMINARY DATA SET (Downey and Weiss, June 1980)

using the model were unrealistic. Consequently, a new model was developed specifically to analyze the impacts of pumping from the Madison aquifer system at the proposed well fields.

4.A STUDY AREA

The study area includes most of northeastern Wyoming, the western edge of South Dakota, the extreme southeastern part of Montana, and the northwestern corner of Nebraska (Figure 4-2). Approximately 50,000 square miles are covered by this area, which extends 240 miles along the north-south borders and 200 miles along the east-west border. The studied area includes almost the entire Powder River Basin, the Black Hills Uplift area, and the Hartville uplift area. The study area was initially defined on the basis of the drawdowns in the potentiometric surface of the Madison aquifer calculated by Konikow (1976).

4.B CONCEPTUAL MODEL OF THE MADISON AQUIFER SYSTEM

The major components in the multilayer Madison aquifer system model used in this study (Figure 4-3) were defined to be:

- The Red River aquifer unit, defined as the Ordovician-age carbonates and consisting of the Red River Formation and equivalents
- The Madison aquifer unit, defined as the Mississippian-age carbonates; the Madison Group; the lower clastic member of the Minnelusa, the Bell Sand, and equivalents; and the Devonian- and Silurian- age carbonates
- The Minnelusa confining unit, defined as the Pennsylvanian-age carbonates of the Minnelusa Formation and the Permian-age carbonates and evaporites of the Minnelusa Formation below the continuous sandstones of the upper member of the Minnelusa.
- The upper Minnelusa aquifer unit, defined as the laterally continuous sandstones of the upper Minnelusa Formation, the Converse Sands, and equivalents
- The Upper Confining unit, defined as the strata between the Minnelusa Formation and the Lower Cretaceous shales

The Madison aquifer system, composed of five subunits, was defined after a careful review of available information on the geologic and hydrogeologic characteristics of the strata in the study area. The aquifer system was

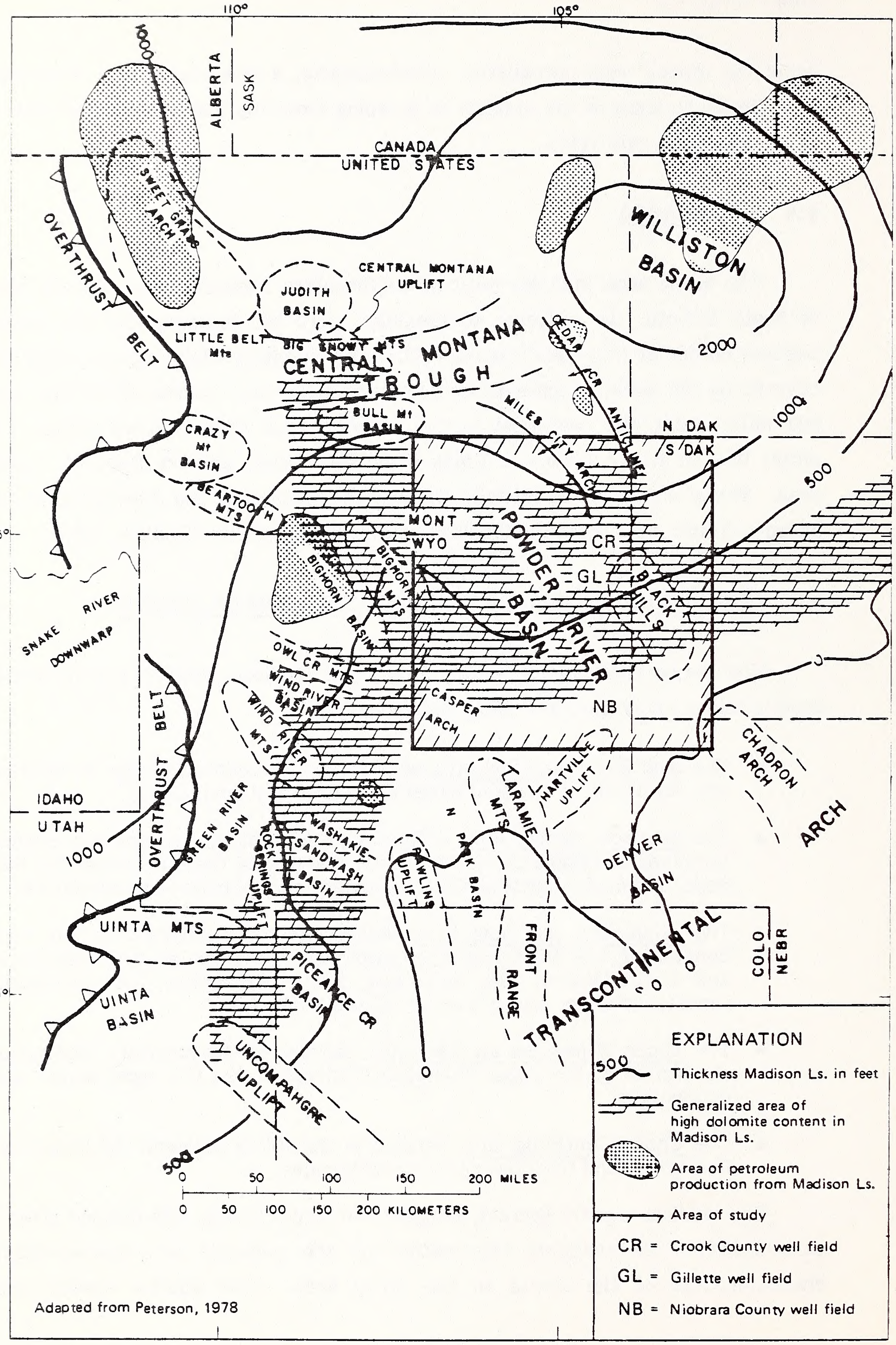


Figure 4-2. RELATIONSHIP BETWEEN STUDY AREA AND GENERAL GEOLOGIC FEATURES IN SURROUNDING REGION

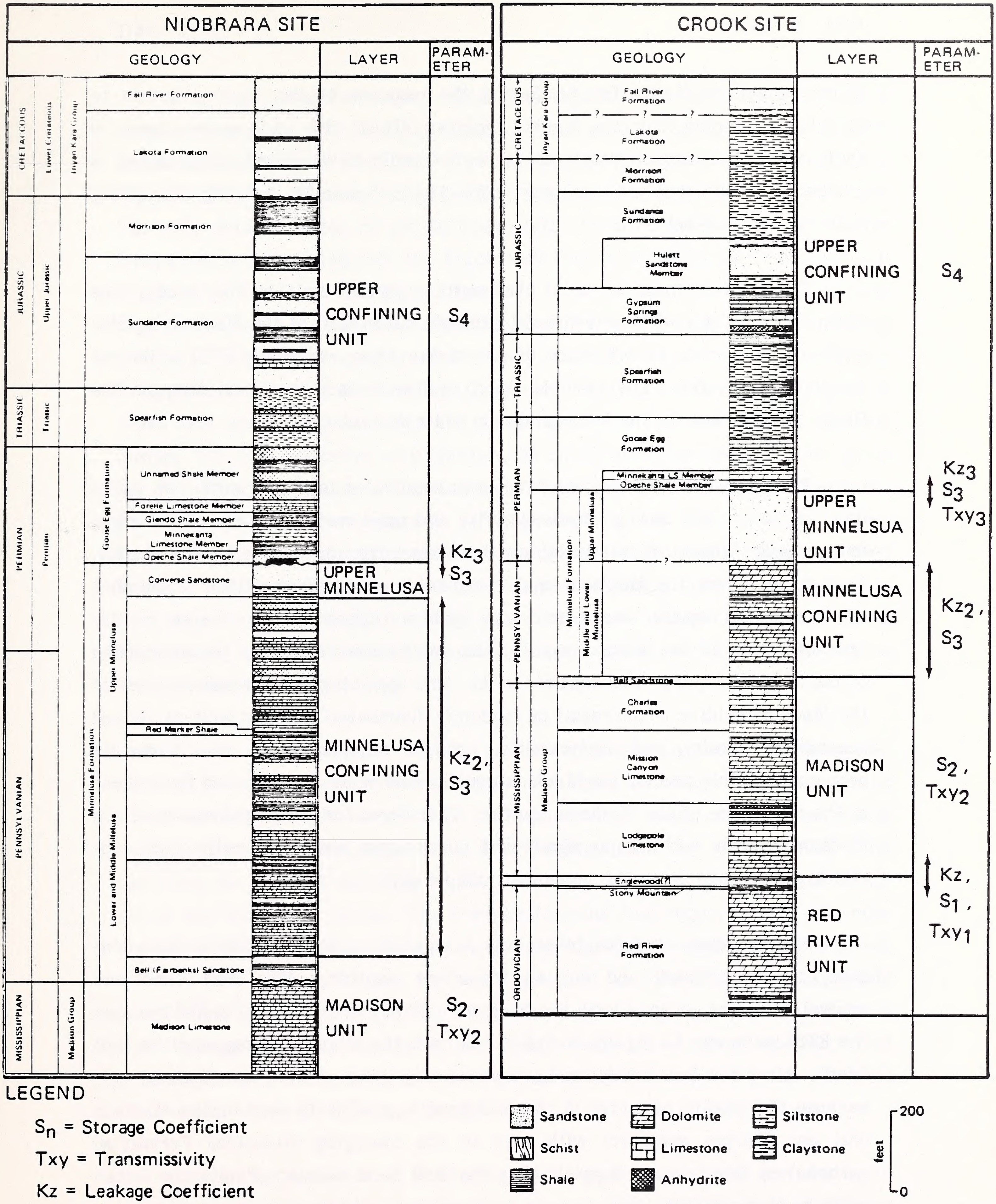


Figure 4-3. RELATIONSHIPS BETWEEN THE GEOLOGY, THE CORRESPONDING LAYERS, AND PARAMETERS USED IN THE NUMERICAL MODEL AT THE NIOBRARA AND CROOK COUNTY WELL FIELDS

characterized explicitly for simulating the response of the aquifer system to long-term pumping from the Madison aquifer. These five units were chosen so that interformational movements of water could be analyzed when water is pumped from the Madison aquifer by ETSI. The rationale for defining the aquifer units is described below.

The Madison aquifer unit, the most important unit in this study, was defined to conform with conventional geologic definitions of the Madison aquifer and with the political definition of the strata from which the ETSI wells can legally pump water. The term Madison aquifer is used in the vicinity of the Black Hills to refer to the Madison Group or its equivalents.

The Madison aquifer could have been subdivided into two units: an upper unit, characterized by high transmissivity and good water quality; and a lower unit, characterized by relatively low transmissivity and poorer water quality. Test results from the Madison aquifer can best be explained with a model that represents the aquifer as a two-unit system (Appendix H). Water quality characteristics of the Madison aquifer also can be used to support the subdivision of the Madison aquifer into multiple units. The upper high-transmissivity part of the Madison aquifer is the result of randomly distributed zones of well-developed secondary porosity and permeability. On a regional scale, the hydraulic properties of this part of the Madison aquifer cannot be distinguished from those in the remainder of the Madison aquifer. Therefore, for a regional model of the Madison aquifer system, no significant advantages would be realized by subdividing the Madison aquifer unit into multiple units.

The Bell Sand was not treated as a separate unit because it is discontinuous, poorly defined, and not an important aquifer. The Bell Sand and equivalents were grouped with the Madison unit in the conceptual model because the ETSI wells can be legally completed in both the Madison Group and the Bell Sand. Also, the Bell Sand can be conveniently grouped with the Madison unit because the quality of water in the Bell Sand is similar to that in the Madison unit and sharply contrasts with that in the overlying Minnelusa Formation carbonates; this feature suggests that the Bell Sand is hydraulically connected with the Madison unit.

The Red River Formation, which underlies the Madison Group, is also a carbonate aquifer. The Red River unit was not included with the Madison unit because Downey and Weiss (1980) modeled the Red River as a separate unit, and because of the legal constraints specified for the completion of the ETSI wells. The only data available on the hydrogeologic characteristics of the Red River Formation in the vicinity of the Black Hills are from USGS Madison test well No. 1. The Red River can be distinguished from the Madison Group at the test well on the basis of flow characteristics, but not on the basis of water quality analyses. The water quality of the Red River Formation and the overlying Lodgepole Member of the Madison Group are similar, but the water quality in these two units contrasts with the water quality in the rest of the Madison Group. The thin Devonian- and Silurian-age carbonates that occur at the top of the Red River Formation in the vicinity of the Black Hills were grouped with the Red River unit for completeness. The geologic strata below the Red River Formation are ignored in the numerical and conceptual models. This was done because the characteristics of the strata are very poorly known, the strata are thin or absent in much of the study area, little or no economic use is made of these units, and inclusion of these strata in the model would function only to reduce calculated drawdown.

The units overlying the Madison unit were included in the conceptual model because the hydrogeologic characteristics of these units are such that if the potentiometric head is decreased in the Madison unit, water could be derived by leakage from the overlying units. The starting point for defining the units overlying the Madison unit was to exclude from the conceptual model all strata above the Inyan Kara Group. The several-thousand-foot sequence of Cretaceous shales overlying the Inyan Kara Group, which includes the massive Pierre Shale, have a very low effective vertical hydraulic conductivity (approximately 2×10^{-10} ft^2/sec; Neuzil 1980). These shales are assumed to act as a barrier that hydrogeologically separates the strata below from those above. This boundary is also being used as a similar barrier by Downey and Weiss (1980) in their model of the Madison aquifer system.

The entire sequence of strata between the Madison Group and the Inyan Kara Group could have been considered as a single confining unit, as was done by

Downey and Weiss (1980). This approach was not adopted because the lithologic characteristics and inferred hydrogeologic properties of the Minnelusa Formation differ markedly from those of the other formations in this sequence; therefore these units were treated as separate units. The leakage coefficients that will determine the quantity of leakage to the Madison unit during a 50-year period were believed, a priori, to be predominantly a function of effective vertical hydraulic conductivity of the Minnelusa Formation and not a function of the average effective vertical hydraulic conductivity of the entire Minnelusa Formation to Inyan Kara Group sequence.

The Minnelusa Formation was subdivided into two units on the basis of water-yielding characteristics and lithology. The upper part of the Minnelusa Formation was defined as one of these units. In the northern part of the Black Hills, many wells yielding large quantities of water or economic amounts of oil are finished in the upper Minnelusa sands. The water-yielding characteristics of the upper Minnelusa, though, diminish toward the southern part of the Black Hills region, where the unit becomes poorly defined. The definition of the upper Minnelusa unit resulted in the specification of the Minnelusa Formation carbonate sequence as a confining unit between the upper Minnelusa unit and the Madison unit. The water-yielding characteristics of the Minnelusa Formation carbonates differ markedly from those in the overlying Minnelusa sandstones and the underlying Madison Group.

Overlying the Minnelusa Formation are the Goose Egg, Spearfish, and Sundance formations, and the Inyan Kara Group, a sequence composed predominantly of shale, siltstones, and evaporites. Some minor water-bearing units are found in the sequence (the Minnekahta Limestone, the Hulett and Fall River Sandstones), but these were ignored in the conceptual model. These formations were grouped as one unit on the basis of similar lithologies and lack of information to support any separation of the sequence into more than one unit.

4.C NUMERICAL METHODS

The USGS finite-difference computer model for simulation of three-dimensional ground-water flow was used to represent the response of the aquifer system to pumping stresses from the three proposed ETSI well fields (Trescott 1975; Trescott and Larson 1976). This model allows for variable grid spacing and uses the strongly implicit procedure for simultaneous solution of the difference equations.

The numerical model of Trescott and Larson (1976) was modified so that the water quality changes that would occur in the Madison aquifer as a result of pumping from the ETSI well fields could also be simulated. This modification consisted of constructing a simple mixing model which was then incorporated into the numerical model. The mixing model assumes that TDS concentrations are conservative, that convection is the only transport process for chemical species, and that chemical concentrations are uniform within each grid cell block. The mixing model was written as a subroutine to the USGS program for the simulation of three-dimensional ground-water flow (Trescott and Larson 1976).

The governing equation for the mixing model is:

$$C_{i,t+1} = \frac{\left[\sum_{n=1}^{6} a F_n C_{n,t} + C_{i,t}\left(V_t - \sum_{n=1}^{6} b F_n\right)\right]}{V_{t+1}}$$

where:
- $C_{i,t}$ = the concentration in grid cell block i at time step t, in mg/l;
- F_n = flow into grid cell block i during time step t, in ft^3
- n = counter for the six grid blocks adjoining block i
- V = the volume of water in grid block i in ft^3
- t = time step
- a = 1 if $F_n > 0$; 0 if $F_n < 0$
- b = 1 if $F_n < 0$; 0 if $F_n > 0$

TABLE 4-1

PARAMETER ESTIMATES USED IN THE MADISON AQUIFER MODEL

Layer	Parameter[a]	Estimated Value[b]	Probable Range in Parameter Estimates	Supporting Evidence
Upper Confining Unit	Transmissivity	0.00015 ft^2/sec	---	The parameter was arbitrarily set at a very low value.
	Storage coefficient	3.3×10^{-4}	---	The estimate is based on an idealized unit thickness of 1000 feet, and a storage coefficient of $b \times 10^{-7}$.
	Leakage coefficient	$4 \times 10^{-12} sec^{-1}$	4×10^{-11} to $4 \times 10^{-13} sec^{-1}$	The estimate is derived from the steady-state model. The range was defined on the basis of reasonable aquifer response.
Upper Minnelusa	Transmissivity[a]	0.003 ft^2/sec where upper Minnelusa contains >50% clastics 0.0003 ft^2/sec where upper Minnelusa contains <50% clastics	10^{-4} to 10^{-2} ft^2/sec	The estimates of transmissivity are derived from USGS Madison test well No. 1 test data, flow and specific capacity data from Whitcomb and Morris (1964), permeability data from Eisen and others (1980), and lithologic considerations.
	Storage coefficient[c]	$b \times 3.3 \times 10^{-7}$	$b \times 3.3 \times 10^{-7}$ to $b \times 10^{-6}$	The parameter estimate is based on Lohman's (1972) estimates of storage coefficients for a typical confined aquifer.
	Leakage coefficient	$10^{-10} sec^{-1}$ where the upper member of the Minnelusa Formation contains >50% clastics $10^{-11} sec^{-1}$ where the upper member of the Minnelusa Formation contains <50% clastics	10^{-10} to $4 \times 10^{-12} sec^{-1}$	The estimates are based on the steady-state model and on lithologic considerations.

TABLE 4-1 Concluded

Layer	Parameter[a]	Estimated Value[b]	Probable Range in Parameter Estimates	Supporting Evidence
Madison	Transmissivity[a]	0.03 ft^2/sec	0.015 to 0.09 ft^2/sec	The estimate is based on our model of aquifer tests at Gillette and Niobrara well fields, pump tests at many wells in western Black Hills region, long-term response of aquifer to pumping in western Black Hills region, and steady-state model.
	Storage coefficient[c]	b x 3.3 x 10^{7}	b x 3.3 x 10^{-7} to b x 10^{-6}	Refer to discussion of Red River storage coefficient estimate.
	Leakage coefficient	10^{-9} sec^{-1}	10^{-9} to 10^{-11} sec^{-1}	The estimate is based upon an effective vertical hydraulic conductivity of 5 x 10^{-7} ft/sec and a thickness of 500 feet between the midpoints of the Madison and Red River units.
Red River	Transmissivity[a]	b x 0.00375 ft/sec	b x 0.001 to b x 0.01 ft/sec	The estimate is based on test data from USGS test well No. 1.
	Storage coefficient	b x 3.3 x 10^{-7}	b x 10^{-7} to b x 10^{-6}	The estimate is based on a porosity of 10% and a matrix compressibility of 1.1 x 10^{-11} M^2/N. The matrix compressibility may be larger.

[a] Along the Black Hills monocline, the Fanny Peak monocline and lineament, the Shawnee flexure, the Rawhide fault, and the Cascade monocline, transmissivity in all layers (except the Upper Confining unit) was reduced by 0.01. The basis for this reduction was the model calibration procedure and geologic and water quality data that suggest a low-transmissivity zone along the structures. North of the Lake Basin fault zone, transmissivity was reduced by 0.1 in all layers except the upper. The basis for this reduction was the low transmissivity reported at USGS test well No. 2 and specific capacity data and water quality data in Miller (1976).

[b] b=thickness of unit, as determined from the isopachous maps presented in Appendix A.

[c] The storage coefficient in outcrop areas of the Madison and upper Minnelusa were specified as 0.1.

The mass balance routines in the numerical model were also modified. The modification consisted of a routine that computes a mass balance for each layer at each time step, a routine that prints out vertical flows by grid blocks, and a routine that calculates changes in storage at each outcrop block at each time step.

The use of the numerical model requires that the region of interest be subdivided into a finite-difference grid, that parameter values be specified at each grid block for each aquifer layer, and that the appropriate boundary conditions be specified. For reasons of computational efficiency, separate grids were used for the steady-state model, for the calculation of drawdowns at the Crook County and Gillette well fields, and for the calculation of drawdowns at the Niobrara County well field. The methods used to estimate the parameters used in the numerical model are discussed in the following section.

4.C.1 PARAMETER ESTIMATES

The five-layer conceptual model of the Madison aquifer system was translated into a four-layer numerical model (Figure 4-3). The four layers in the numerical model are: (1) the Red River aquifer unit, (2) the Madison aquifer unit, (3) the upper Minnelusa aquifer unit, and (4) the Upper Confining unit. The input parameters to the numerical model are transmissivity and storage coefficients for each layer, and a leakage coefficient for each set of adjacent layers. The leakage coefficients are specified between each set of layers as a function of the vertical hydraulic conductivities of the adjacent layers if no confining bed separates the layers, or as a function of the confining bed properties. The estimated values of the aquifer parameters that were assumed to characterize the Madison aquifer system within the study region, and the methods used to derive these estimates are described in this section. A summary of these parameters is listed in Table 4-1.

Transmissivity

Madison Unit. The regional transmissivity of the Madison aquifer in the vicinity of the Black Hills is assumed to be a function of well-developed zones of secondary porosity and permeability in the Madison aquifer. These zones are assumed to be randomly distributed within the modeled area. The records in well logs of bit drops and lost circulation in the Madison Group along the western and southern flanks of the Black Hills, and the solution features observed in Madison Group outcrop areas all around the Black Hills, support this assumption. The persistence of solution features in the center of the basin is unknown, but solution features are common in the Big Horn Mountains (Sando 1972). These features probably persist from the Black Hills, through the Powder River Basin, to the Big Horn Mountains, although they may be collapsed, sealed, or filled in parts of the basin. The persistence of well-developed secondary porosity and permeabiity toward the north is unknown, but these zones are probably not as persistent north of the Lake Basin fault zone where the Wyoming shelf becomes the Montana Trough and Williston Basin. This observation is based on the lithologic changes that occur in the Madison (Andrichuk 1955).

Reported transmissivities of the Madison aquifer, as determined by conventional analyses of aquifer and pump tests, range between 0.0015 and 0.46 ft^2/sec (Eisen and others 1980). Aquifer tests with multiple observation wells have been conducted in the Madison aquifer in the Black Hills region at the Niobrara and Gillette well fields. Analyses of these tests by conventional methods have produced puzzling results.

The Niobrara well-field aquifer tests conducted in 1976 and 1978 were characterized by a stabilization of drawdowns within 24 hours of the start of pumping. The time-drawdown behavior during all of the Niobrara aquifer tests was typical of leaky aquifers that conform with the Hantush-Jacob (1955) prototype (see Figures H-1 and H-2 in Appendix H). Analysis of the test data by leaky-aquifer theory results in the calculation of transmissivities in the range of 0.0015 to 0.003 ft^2/sec and a leakage coefficient of approximately 5×10^{-4} sec^{-1} that is not consistent with the geologic character of overlying strata. Alternative explanations involving a region of high transmissivity, possibly along the Old Woman fault, cannot reproduce the observed stabilization without having the region of high transmissivity specified as a perfect recharge boundary.

Several aquifer tests were conducted at the Gillette well field during 1979 and 1980. Analyses of these tests produced estimates of transmissivity that ranged between 0.0077 and 0.46 ft^2/sec. Analyses of the early part of the observation well data result in calculated transmissivities that increase with distance from the pumped well. Two of the eight wells at the site were completed in the upper part of the Madison aquifer where drill bit drops and circulation losses occurred; the six other wells at the site were completed through much of the aquifer section and did not encounter bit drops or circulation losses near the top of the Madison aquifer.

These observations led to the development of the following conceptual model that explains the hydraulic behavior of the Madison aquifer and, on a regional scale, the effective capacity of the two zones in the Madison to transmit water (see Appendix H, page H-32). The rock comprising the bulk of the Madison Formation has a moderate transmissivity on the order of 0.005 ft^2/sec. Well-developed zones of secondary porosity and permeability in the upper part of the Madison Group create local zones of high transmissivity ranging up to 1.5 ft^2/sec or more. These zones are randomly distributed areally--that is, they are not present everywhere; however, they are assumed to be areally continuous from the hydraulic viewpoint. The high leakage properties obtained from the analyses of pumping test data are a relative measure of the hydraulic connection between the high-transmissivity zone and the main bulk of the Madison aquifer. This conceptual model is consistent with the geology and water quality characteristics in the aquifer, and explains the wide range of reported transmissivities, and the anomalous aquifer test results. The aquifer tests and numerical simulations of the Gillette aquifer tests are discussed in detail in Appendix H.

The actual distribution of these well-developed zones of secondary porosity and permeability cannot be specified, even on a local scale. Also, on a regional scale, the important factor is the effective capacity of the two zones to transmit water (see Appendix H, page H-32). Two approaches were used to estimate the effective regional transmissivity of the Madison aquifer. The first approach was to determine what range of values produced reasonable aquifer recharge rates when used in a steady-state model. Transmissivities in the range of 0.015 to 0.030 ft^2/sec produced reasonable aquifer recharge rates (150,000 to 300,000 acre-feet per year in the Black Hills region). The second approach was to determine what range of values produced reasonable calculations of historic drawdown. Transmissivities in the range of 0.030 to 0.045 ft^2/sec produced a reasonable match between calculated and observed declines at historic pumping centers in the Black Hills region. Spatial variation in the transmissivity of the Madison aquifer may explain why the transmissivity value that best reproduces historical drawdown produces estimates of recharge that are too large. However, because no firm basis could be formulated for varying transmissivity spatially near the Black Hills, a uniform transmissivity value of 0.03 ft^2/sec was used.

The geologic structures of the Black Hills region, especially the steep monoclines west and south of the Black Hills uplift on the edges of the Powder River Basin, are likely zones of lower transmissivity. Sharp water quality differences in the Minnelusa Formation on either side of the Black Hills monocline, and suggested water quality differences in the Madison Group on either side of the Black Hills and Fanny Peak monoclines (Eisen and others 1980), as well as abrupt changes in the Madison potentiometric surface along the Black Hills monocline suggest that a low-transmissivity zone occurs along this zone of folding on the eastern margin of the Powder River Basin. Changes in structural relief of 6000 feet within a few miles along the monoclines and possible faulting of the Madison Group along these monoclines are the cause of these transmissivity reductions. The steady-state model of the Madison aquifer system was used to determine that the effective transmissivity along the Black Hills and Fanny Peak monoclines is on the order of 0.01 of the transmissivity in the rest of the aquifer. Since structural relief along the Cascade anticline is similar to that along the Black Hills and Fanny Peak monoclines, a similar transmissivity reduction of 0.01 was specified along the Cascade anticline.

Abrupt changes in the quality of the ground water in the Madison aquifer, approximately on the trend of the Lake Basin fault zone north of the Black Hills, and the low transmissivity of the Madison aquifer reported for the Madison Group at USGS test well No. 2 (Brown and others 1977) suggest that transmissivity decreases north of the trend of the Lake Basin fault zone. Therefore a transmissivity of 0.003 ft^2/sec was specified in this area.

The regional transmissivity of the Madison specified in this study differs somewhat from those used by Konikow (1976) and by Downey and Weiss (1980). Konikow (1976) specified a spatially variant transmissivity distribution for the Madison in which the transmissivity varied between 0.01 and 0.03 ft^2/sec. The variations in transmissivity were specified by Konikow on the basis of temperature variations in the Madison aquifer. Downey and Weiss (1980) specified the transmissivity of the Madison aquifer as a function of thickness and temperature. Values of transmissivity between 0.015 and 0.06 ft^2/sec were specified along the western flanks of the Black Hills in their model.

Transmissivities in this study were not specified as a function of temperature because data are not available to support a gradual increase in transmissivity with aquifer depth within the Black Hills region. The transmissivity of the Madison was also not specified as a function of aquifer thickness because the model of Madison transmissivity used in this study is assumed to be a function of the persistence of well-developed zones of secondary porosity and permeability and thus not directly affected by the total thickness of the formation.

To summarize, the transmissivity of the Madison unit was specified as 0.03 ft^2/sec in the study area, except north of the trend of the Lake Basin fault zone, where the transmissivity was specified as 0.003 ft^2/sec, and along some major geologic structures. Along the Black Hills monocline, the Fanny Peak monocline, the Rawhide fault, and the Cascade anticline, the transmissivity of the Madison unit was reduced to 0.0003 ft^2/sec.

Red River Unit. The transmissivity of the Red River unit was specified as 0.00375 ft^2/sec per 100 feet of aquifer thickness, except along the Black Hills monocline where the transmissivity was specified as being reduced by two orders of magnitude, and north of the trend of the Lake Basin fault zone where transmissivity was specified as being reduced by one order of magnitude.

The transmissivity value for the Red River unit was based solely on data collected during testing of USGS Madison test well No. 1 near Hulett, Wyoming. The transmissivity of the Red River unit was estimated from a drill stem test to be 0.01 ft^2/sec over a 180-foot-thick section. The total thickness of the Red

River Formation at the well is 460 feet. Spinner data from a flow test conducted in the well in August 1977 indicated that flow contributions per unit thickness were similar. Therefore the Red River Formation may have a transmissivity of 0.025 ft^2/sec at this location (0.0054 ft^2/sec per 100 feet of aquifer thickness). The transmissivity of the Red River aquifer unit was specified lower than that calculated at USGS test well No. 1 because the transmissivity at test well No. 1 may be partially the result of fracturing associated with the Little Missouri fault zone. The transmissivity of the Red River aquifer unit was specified as a function of thickness because the transmissivity of the Red River Formation is apparently the result of secondary porosity development within the entire Red River section, and because the Red River Formation thins rapidly south of USGS Madison test well No. 1.

Minnelusa. The transmissivity of the upper Minnelusa unit was specified as 0.003 ft^2/sec where the upper member of the Minnelusa Formation has been mapped by Tenney (1966) as consisting of more than 50 percent clastics, and as 0.0003 ft^2/sec where the upper member of the Minnelusa Formation has been mapped as consisting of less than 50 percent clastics. Exceptions to this were that the transmissivity of the upper Minnelusa aquifer unit was specified as being two orders of magnitude less along the Black Hills monocline, the Fanny Peak monocline, the Rawhide fault, and the Cascade anticline.

The hydraulic conductivity of upper Minnelusa sands in oil fields in eastern Wyoming is reported by Eisen and others (1980) to be in the range of 2×10^{-6} to 3×10^{-5} ft/sec. Where the aquifer is 200 feet thick, this translates to a transmissivity of 0.0004 to 0.006 ft^2/sec. The hydraulic conductivity of the upper Minnelusa unit was calculated as 8×10^{-6} ft/sec at USGS Madison test well No. 1 from drill stem test data (Blankennagel and others 1977). The upper Minnelusa sands are 300 feet thick at this well; therefore, the transmissivity calculated from the drill stem test data is 0.002 ft^2/sec. Whitcomb (1963) reported specific capacities of 0.01 and 0.003 ft^2/sec (4.7 and 1.4 gal/ft) for two upper Minnelusa wells in Crook County, Wyoming. The transmissivities calculated from these specific capacity data are approximately 0.014 and 0.004 ft^2/sec. Based on this information, and the high yields reported from the upper Minnelusa wells in Crook County, Wyoming, and Lawrence and Butte counties, South Dakota (Whitcomb and Morris 1964; Cox 1962), the transmissivity of 0.003 ft^2/sec was specified for the upper Minnelusa where the upper member of the Minnelusa Formation contains greater than 50 percent clastics. The transmissivity of the upper Minnelusa, where the upper member of the Minnelusa Formation as mapped by Tenney (1966) is less than 50 percent clastics, was specified as 0.003 ft^2/sec solely on the basis of lithologic characteristics.

The transmissivity of the upper Minnelusa unit was reduced by two orders of magnitude along the Black Hills and Fanny Peak monoclines and the Cascade anticline because water quality data suggest that flow in the upper Minnelusa is sluggish west of the Black Hills monocline. Since the reduction in transmissivity could not be calculated from available data, it was specified as 0.01 because that value was used for the Madison aquifer unit.

Upper Confining Unit. The transmissivity of the Upper Confining unit was specified to be 1.5×10^{-4} ft^2/sec everywhere, though locally some zones of relatively high transmissivity exist within this unit, such as the Minnekahta Limestone and the Hulett Sandstone. The conceptual model is structured such that almost all water movement in this unit will be vertical when the Madison unit is stressed by pumping. Horizontal movement of water will be specifically restricted by the use of a transmissivity of 1.5×10^{-4} ft^2/sec.

Storage Coefficients

The storage coefficient was specified in the Madison, Red River, Minnelusa, and Upper Confining units as a function of aquifer thickness and location in the flow system. The storage coefficient in all the units was specified as 3.3×10^{-7} per foot of aquifer thickness where the aquifers are confined. The storage coefficient where the Madison, Red River, and Minnelusa are unconfined, namely in the outcrop areas, was specified as 0.1.

The storage coefficient of a confined aquifer can be computed if the porosity and the matrix compressibility and aquifer thickness are known. The average porosity of the Madison aquifer near the flanks of the Black Hills, where the Madison aquifer is composed mainly of dolomite, is about 10 percent (Head and Merkel 1976; Blankennagel 1977). The aquifer matrix compressibility is unknown, but the average compressibility of solid rock is 1.1×10^{-11} pascals (Pa) (Freeze and Cherry 1979). The storage coefficient per foot of aquifer thickness computed with a porosity of 10 percent and a matrix compressibility of 1.1×10^{-11} Pa is 3.3×10^{-7}. A storage coefficient of 3.3×10^{-7} per foot is lower than the typical storage coefficient of a confined aquifer, which is approximately 1×10^{-6} per foot of aquifer thickness (Lohman 1972).

The storage coefficients calculated at the Niobrara and Gillette well fields for the Madison aquifer using a porosity of 10 percent and a matrix compressibility of 1.1×10^{-11} Pa are 8×10^{-5} and 2×10^{-4}, respectively. These values compare favorably with estimates of storage coefficients made at the two sites from aquifer test data. Storage coefficients in the range of 10^{-5} to 10^{-4} were calculated at the Niobrara well field from aquifer test data, and storage coefficients in the range of 10^{-4} to 2×10^{-4} were calculated at the Gillette site.

The storage coefficient of the confined Red River aquifer unit was calculated in a manner analogous to that for the Madison aquifer unit. The Red River Formation at Madison well No. 1 in the Bell Creek oil field and at USGS test well No. 1 had a porosity of approximately 10 percent (Blankennagel and others 1977; Montana Oil and Gas Commission 1969).

The storage coefficient (specific yield) in the outcrop areas where the Red River and Madison aquifers are unconfined is unknown. The value of 0.1 was chosen on the basis of the average porosity of the rocks and recognition of the fact that fracturing and weathering enhance porosity in outcrop areas.

The storage coefficient in the upper Minnelusa unit and the Upper Confining unit were specified as 3.3×10^{-7} per foot of aquifer thickness for consistency since no data are available to determine the actual storage coefficients. The thickness of the entire Minnelusa Formation section, not the thickness of the upper Minnelusa unit, was used in calculating the storage coefficient of the upper Minnelusa unit. The total thickness of the Minnelusa Formation was used so that the water released from storage from the Minnelusa confining unit would not be ignored. A uniform thickness of 1000 feet was used for calculating the storage coefficient of the Upper Confining unit.

Leakage Coefficients

The interactions between the four units used in the Madison aquifer system model are defined by the vertical hydraulic conductivities of the units, or if a confining unit separates aquifer units, by a leakage coefficient. The numerical model treats the interactions between all units analogously. Where a confining layer exists, the leakage coefficient is specified. Where no confining layers exist, a parameter that reflects the net vertical hydraulic conductivity between the two aquifer units is specified (Trescott and Larson 1976, p. XIII). In either case, the parameter is called the leakage coefficient (K'/b').

Red River Unit to Madison Unit. The leakage coefficients between the Red River unit and the Madison unit were specified as 10^{-9} sec^{-1} everywhere the two units exist. This value was determined by assuming that the vertical hydraulic conductivity of the Red River unit and Madison unit is approximately equal to about 5×10^{-7} ft/sec (1 to 2 percent of the horizontal hydraulic conductivity) and by assuming that the distance between the midpoint of the Madison and Red River units is about 500 feet. The leakage coefficient computed from these values is four times less than the leakage coefficient calculated from aquifer test data between the low-transmissivity and high-transmissivity zones in the Madison aquifer at the Niobrara well field, and two times less than that calculated between the low-transmissivity and high-transmissivity zones at the Gillette well field. However, the leakage coefficients derived from these tests may not be a good measure of the connection to adjacent aquifers (see Appendix H).

Minnelusa Confining Unit (Madison Unit to Upper Minnelusa Unit). The leakage coefficient between the Madison unit and the upper Minnelusa unit, which represents the vertical hydraulic conductivity of the Minnelusa confining unit divided by the thickness of the confining unit, was specified as:

- 10^{-10} sec^{-1} where the upper member of the Minnelusa Formation is composed of greater than 50 percent clastics, as mapped by Tenney (1966) (Figure B-7 in Appendix B)

- $10^{-11}sec^{-1}$ where the upper member of the Minnelusa Formation is composed of less than 50 percent clastics

The vertical hydraulic conductivity of the Minnelusa confining unit could not be defined from aquifer pump tests results or from recorded potentiometric declines near wells which have been pumping from the Madison for long periods of time. The Minnelusa confining unit has not been stressed enough by the short-term withdrawals, and the necessary data have not been collected near pumping wells to permit the calculation of the leakage coefficient. The aquifer tests conducted at the Niobrara and Gillette well fields were initially thought to contain information on leakage from the Minnelusa Formation to the Madison Group, but the numerical model used in this study to explain the aquifer test behavior was unable to clearly discern the magnitude of leakage from the Minnelusa Formation.

The leakage coefficient between the Madison unit and the upper Minnelusa unit was defined to be less than the leakage coefficient between the Madison unit and Red River unit, and greater than that of the Upper Confining unit. Near the Black Hills, where the upper member of the Minnelusa Formation generally contains greater than 50 percent clastics, the leakage coefficient of $10^{-10}sec^{-1}$ produced a reasonable aquifer response when used in the steady-state model in terms of recharge to and discharge from the upper Minnelusa unit. The vertical hydraulic conductivity of 5×10^{-8} ft/sec for the Minnelusa confining unit, which was used to compute the leakage coefficient of $10^{-10}sec^{-1}$, is reasonable for clastic-rich carbonates (Freeze and Cherry 1979). The leakage coefficient was defined as one order of magnitude less where the upper member of the Minnelusa Formation contains less than 50 percent nonclastics on the basis of lithologic considerations. Thick evaporite beds generally exist in the lower part of the upper member, where the upper member contains less than 50 percent clastics. These evaporite beds are at the top of what is defined as the Minnelusa confining unit.

<u>Upper Confining Unit</u>. The leakage coefficient for the Upper Confining unit was specified as $4 \times 10^{-12}sec^{-1}$ everywhere the Upper Confining unit exists. A vertical hydraulic conductivity of 4×10^{-9} ft/sec, which is only 20 times greater

than the calculated vertical hydraulic conductivity of the Pierre Shale (Neuzil 1980), was used in calculating the leakage coefficient in the Upper Confining unit. The leakage coefficient in the Upper Confining unit was defined on the basis of aquifer system response observed by Konikow (1976) in his model of the Madison aquifer, and aquifer system response observed in the steady-state model of the Madison aquifer system developed in this study. Data were not available to calculate this coefficient by other methods.

The starting point for defining the leakage coefficient was $10^{-12}sec^{-1}$, which is the midpoint value (on a logarithmic scale) in the range of leakage values (10^{-11} to $10^{-13}sec^{-1}$) that Konikow (1976) found produced reasonable aquifer responses in his model of the Madison aquifer. In the steady state model developed in this study, the observed potentiometric surface of the Madison aquifer could best be reproduced when the leakage coefficient of the Upper Confining unit was varied between 10^{-11} and 10^{-12} sec^{-1}.

4.C.2. COMPARISON BETWEEN THE OBSERVED AND COMPUTED MADISON POTENTIOMETRIC SURFACE

A steady-state model of the Madison aquifer system in the vicinity of the Black Hills was developed to determine if the calculated potentiometric surface would approximate the observed irregular potentiometric surface in the vicinity of the Black Hills when the model parameters were defined as listed on Table 4-2.

Grid

The area modeled in the steady-state model covered approximately 22,000 square miles, subdivided into a 24-mile by 18-mile grid (Figure 4-4). This region was chosen on the basis of the potentiometric map by Miller and Strausz (1980) such that the modeled region contains the area in which the observed potentiometric surface changes rapidly in the vicinity of the Black Hills. The grid boundary on the east was chosen so that the boundary was approximately parallel to equipotential lines, and the northern and southern boundaries were chosen so as to be approximately normal to equipotential lines.

TABLE 4-2

CALCULATED POTENTIOMETRIC HEADS IN THE MADISON AQUIFER USING THE STEADY-STATE MODEL

Location (Township-Range-Section)	Observed Potentiometric Head, Earliest Available Measurement	Steady-State Base Run	Sensitivity Runs			
		$TK_1=4x10^{-12}$ MF = 0.01	$TK_2=10^{-12}$ MF = 0.01	$TK_2=10^{-11}$ MF = 0.01	$TK_1=4x10^{-12}$ MF = 0.1	$TK_1=4x10^{-12}$ MF = 0.05
Crook County, Wyoming						
USGS test well No. 1 (57N-65W-15)	3700	3646	3732	3626	3664	3659
Devils Tower (52N-63W-25)	3850	3872	3941	3864	3884	3880
Gillette well field (51N-66W-6)	3850	4067	4149	4036	4066	4064
Sundance (52N-63W-25)	4330	4333	4339	4345	4332	4332
Niobrara County, Wyoming						
ETSI Well No. O-1 (36N-62W-28)	3725	3767	3976	3686	4675	4700
Weston County, Wyoming						
Osage (46N-63W-15)	4740	4745	4972	4558	4215	4022
Terra Resources (46N-65W-23 and 46N-65W-20)	3896 3915	3900	4063	3845	4364	4376
Upton (48N-66W-35)	4150-4200	4408	4584	4285	4930	4953
Newcastle (45N-61W-20)	4820	4990	5160	4818	3879	3825

TABLE 4-2 Concluded

Location (Township-Range-Section)	Observed Potentiometric Head, Earliest Available	Steady-State Base Run	Sensitivity Runs			
		$TK_1=4x10^{-12}$ MF = 0.01 Measurement	$TK_2=10^{-12}$ MF = 0.01	$TK_2=10^{-11}$ MF = 0.01	$TK_1=4x10^{-12}$ MF = 0.1	$TK_1=4x10^{-12}$ MF = 0.05
Fall River County, South Dakota						
Edgemont (9S-2E-2)	3668	3643	3900	3527	3673	3660
Lawrence County, South Dakota						
Spearfish (6N-2E-15)	3670	3670	3730	3663	3699	3693
Butte County, South Dakota						
Delzner (12N-3E-28)	3210+ (flows 1000 gpm)	3249	3319	3236	3250	3250

Notes: The following parameter distributions were used:

In all computer runs, transmissivity in the Madison unit was set equal to 0.0225 ft^2/sec, transmissivity in the Minnelusa unit was set equal to 0.003 ft^2/sec, and the leakage coefficient between the Madison unit and Minnelusa unit was set equal to 10^{-10} sec^{-1}.

TK_1 = Leakage coefficient between Minnelusa unit and Upper Confining unit.

MF = Factor by which transmissivities were reduced along the Fanny Peak monocline, the Black Hills monocline, and the Cascade anticline.

Boundary Conditions

Constant-head boundaries were specified at outcrop areas and along the boundaries of the grid (Figure 4-4). This specification is consistent with that used by Konikow (1976) and Downey and Weiss (1980). The values of the constant heads in outcrop areas were defined by using the lowest topographic point within a cell block or by available water level data. Constant-head values at the grid boundaries were based on the potentiometric maps of Miller and Strausz (1980). Ground-water flow across the northern, southern, and western boundaries was calculated to be insignificant in proportion to the total flow in the system; these boundary conditions have no effect on the results of these simulations and were therefore specified as no-flow boundaries.

Parameters

The initial parameter distributions used in the steady-state run are listed in Table 4-1, except that the transmissivity of the Madison aquifer unit was specified as 0.0225 ft^2/sec. This transmissivity value produced the most reasonable recharge rates. The Red River unit was not used in the simulations because the inclusion or deletion of this layer had no significant effect on the calculated potentiometric surface.

Results

Close agreement was obtained at most points between observed and computed potentiometric heads (Table 4-2). The leakage coefficient that represents the vertical hydraulic conductivity of the Upper Confining unit was varied between 10^{-12} and 10^{-11} to determine the sensitivity of the system to this parameter. In varying this leakage coefficient between the extremes of 10^{-11} and 10^{-12} sec^{-1}, the observed potentiometric heads were bracketed at all locations except at Sundance and at the Gillette well field where calculated potentiometric heads were always greater than the observed heads. The potentiometric heads may have been consistently overpredicted at these two locations because of: (1) incorrect spatial specification of the transmissivity reduction associated with the Black Hills monocline, or (2) a zone of low transmissivity in the Madison aquifer trends northeast-southwest and passes between Osage and Upton.

The monocline transmissivity reduction factor was varied between 0.1 and 0.01 to determine the aquifer system's sensitivity to this parameter. The computed potentiometric gradient along the Black Hills monocline is very sensitive to the value used for this factor. Computed potentiometric heads west of Osage and Newcastle agreed best with observed potentiometric heads when a value of 0.01 was specified.

A recharge rate of 230 cfs was calculated for the Madison aquifer with the steady-state model (Table 4-3). This recharge value is a reasonable value based on measured recharge and discharge to the aquifer (see Section 3.B.2). The computed spring flows agree well with observed spring flows (Table 4-4).

Conclusions

Close agreement was obtained between the calculated and observed potentiometric heads and between known and calculated recharge and discharge from the Madison aquifer system. However, the model and the parameter distributions that were used do not represent a unique solution for the steady-state potentiometric surface. Outside the region in which Jurassic-age and older strata outcrop, leakage coefficients could be varied within a large range without significantly affecting the calculated potentiometric surface. The transmissivity of the Madison unit outside the Madison outcrop area can also be varied within a large range and result in only minor changes in the calculated potentiometric surface.

The steady-state model illustrated several important features about how the Madison aquifer system functions: (1) The system is driven by recharge at the outcrop area in the Black Hills and by discharge near the outcrop areas; (2) ground-water flow in the system away from the outcrop area of Jurassic age and older strata is very small relative to total recharge to the system; (3) recharge to the Madison aquifer system from the Hartville uplift and flow out of the system to the northwest are small; (4) transmissivity along the Black Hills-Fanny

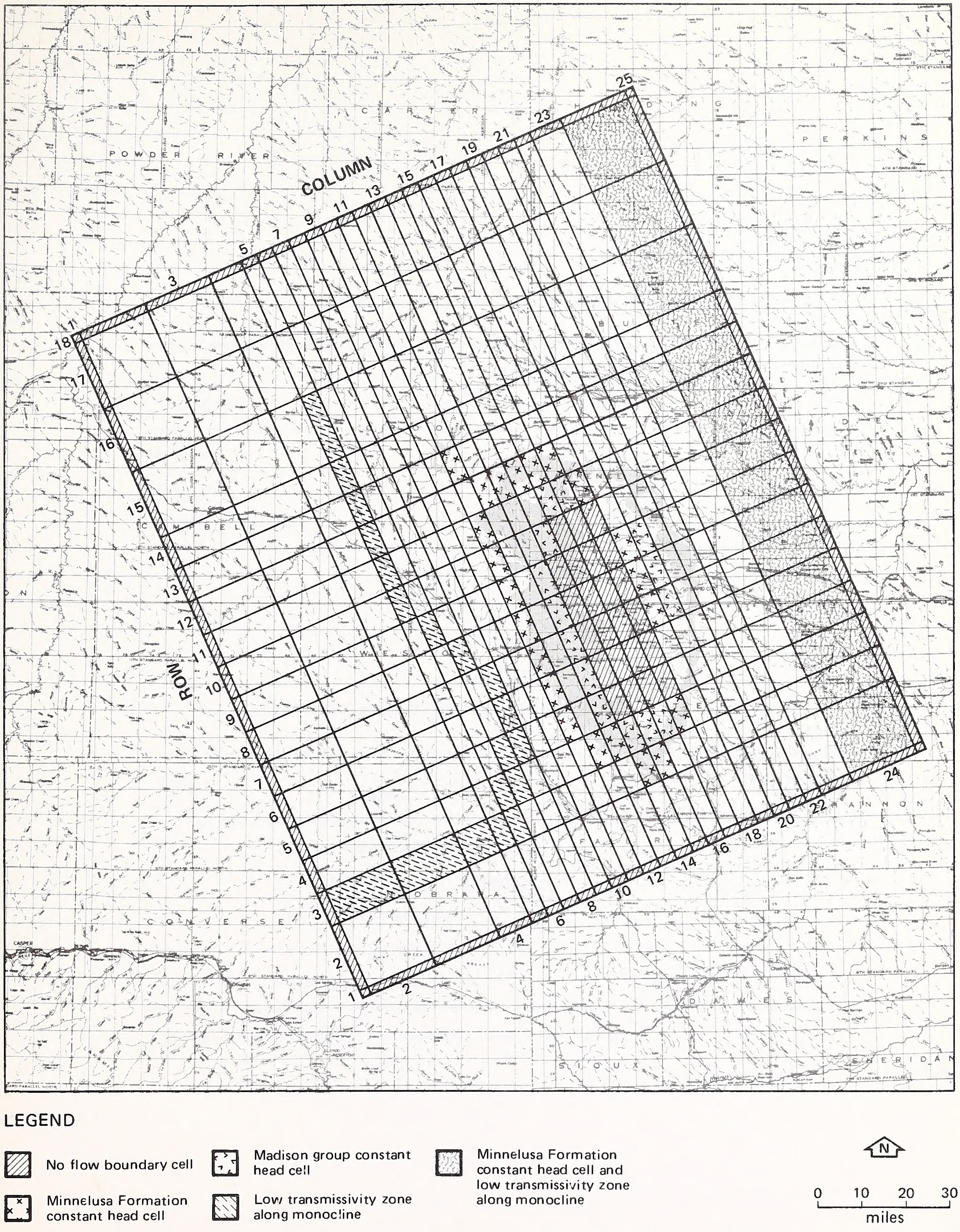


Figure 4-4. FINITE-DIFFERENCE GRID USED IN STEADY-STATE MODEL

TABLE 4-3

CALCULATED RECHARGE-DISCHARGE RATES USING STEADY-STATE MODEL

Layer	At Outcrop Recharge (cfs)	At Outcrop Discharge (cfs)	Flow out of modeled region to the east (cfs)
Madison	230	6	48
Minnelusa	52	113	5
Upper Confining Unit	15	124	-

TABLE 4-4

CALCULATED DISCHARGE OF MAJOR SPRINGS USING STEADY-STATE MODEL

Spring No.*	Spring	Calculated Flow (cfs)	Observed Flow (cfs)
WI	Stockade-Beaver Creek, WY	16	13
F3, F5	Cascade Spring and Hot Springs, SD	35	46
L4	Crow Creek Springs, SD	16	17
CR1	Sand Creek Springs, WY	12	24
P7	Cleghan Springs, SD	13	10

* Spring numbers correspond to numbers on Table 3-2.

Peak monoclines west of the Black Hills is much lower than transmissivity on either side of the monocline.

4.C.3 METHOD USED TO SIMULATE WITHDRAWALS FROM THE NIOBRARA COUNTY WELL FIELD

Design of Finite-Difference Grid

The finite-difference grid used to simulate pumping from the Madison aquifer at the Niobrara well field covers an area of approximately 21,000 square miles (Figure 4-5). The grid is centered over the proposed Niobrara well field, is oriented north-northeast, and extends 132 miles in the east-west direction and 162 miles in the north-south direction. The grid was designed so that minimal drawdown would occur at the boundaries of the grid, except at the southeastern boundary where the boundary is near the erosional limits of the Madison Group. The grid was oriented parallel to the strike of the major structural features. The grid utilizes variable-sized grid blocks and is divided into 19 rows and 14 columns. At the center of the grid, blocks 6 miles on a side were used.

Pumping Locations and Pumping Rates

Pumping from the Niobrara County well-field area was simulated by distributing the pumping equally over five grid cell blocks, those with row-column coordinates of (11,7), (11,8), (17,7), (13,7), and (13,8), which correspond to the well locations within the proposed well field.

The pumping rates used to simulate ETSI's proposed withdrawals for plan 1 and plan 2 are listed in Tables 4-5 and 4-6. The proposed ETSI withdrawals from the Gillette well field for plan 2 were simulated using the grid developed for simulating pumping from the Gillette and Crook County well fields. Water-level recovery was simulated for the 50-year period following the 50 years of pumping.

4.C.4 METHOD USED TO SIMULATE WITHDRAWALS FROM THE CROOK COUNTY AND GILLETTE WELL FIELDS

TABLE 4-5

PUMPING SCHEDULES FOR THE VARIOUS WELL-FIELD COMBINATIONS: PLANS 1, 2, 3, AND 4

Plan Number and Name		Time Period (years)	Pumping Rate in cfs (acre-feet per year)
Plan 1:	Niobrara Well Field Only	1985-2035	28.31 (20,500)
Plan 2:*	Niobrara Well Field	1985-1995	16.90 (12,240)
		1995-2005	18.62 (13,480)
		2005-2015	19.48 (14,100)
		2015-2025	19.94 (14,440)
		2025-2035	20.17 (14,610)
	City of Gillette Well Field	1985-1995	11.41 (8,260)
		1995-2005	9.69 (7,020)
		2005-2015	8.83 (6,390)
		2015-2025	8.37 (6,060)
		2025-2035	8.14 (5,890)
Plan 3:	Crook Well Field Only	1985-2035	28.31 (20,500)
Plan 4:*	Crook Well Field	1985-1995	16.90 (12,240)
		1995-2005	18.62 (13,480)
		2005-2015	19.48 (14,100)
		2015-2025	19.94 (14,440)
		2025-2035	20.17 (14,610)
	City of Gillette Well Field	1985-1995	11.41 (8,260)
		1995-2005	9.69 (7,020)
		2005-2015	8.83 (6,390)
		2015-2025	8.37 (6,060)
		2025-2035	8.14 (5,890)

*Average annual rates for 50 years (acre-feet):

Niobrara - 13,700, Gillette - 6800
Crook - 13,700, Gillette - 6800

TABLE 4-6

PUMPING SCHEDULE FOR CITY OF GILLETTE WELL FIELD NEAR MOORCROFT, WYOMING

Time Period (years)	Total Pumping Rate: cfs (acre-feet per year)	Amount Supplied to City of Gillette: cfs (acre-feet per year)	Maximum Amount That Could Be Available to ETSI: cfs (acre-feet per year)
1985-1995	15.60 (11,300)	4.19 (3040)	11.41 (8260)
1995-2005	15.60 (11,300)	5.91 (4280)	9.69 (7020)
2005-2015	15.60 (11,300)	6.77 (4910)	8.83 (6390)
2015-2025	15.60 (11,300)	7.23 (5240)	8.37 (6060)
2025-2035	15.60 (11,300)	7.46 (5410)	8.14 (5890)

Source: James M. Montgomery Consulting Engineers 1979.

*Equivalent to 10 million gallons per day.

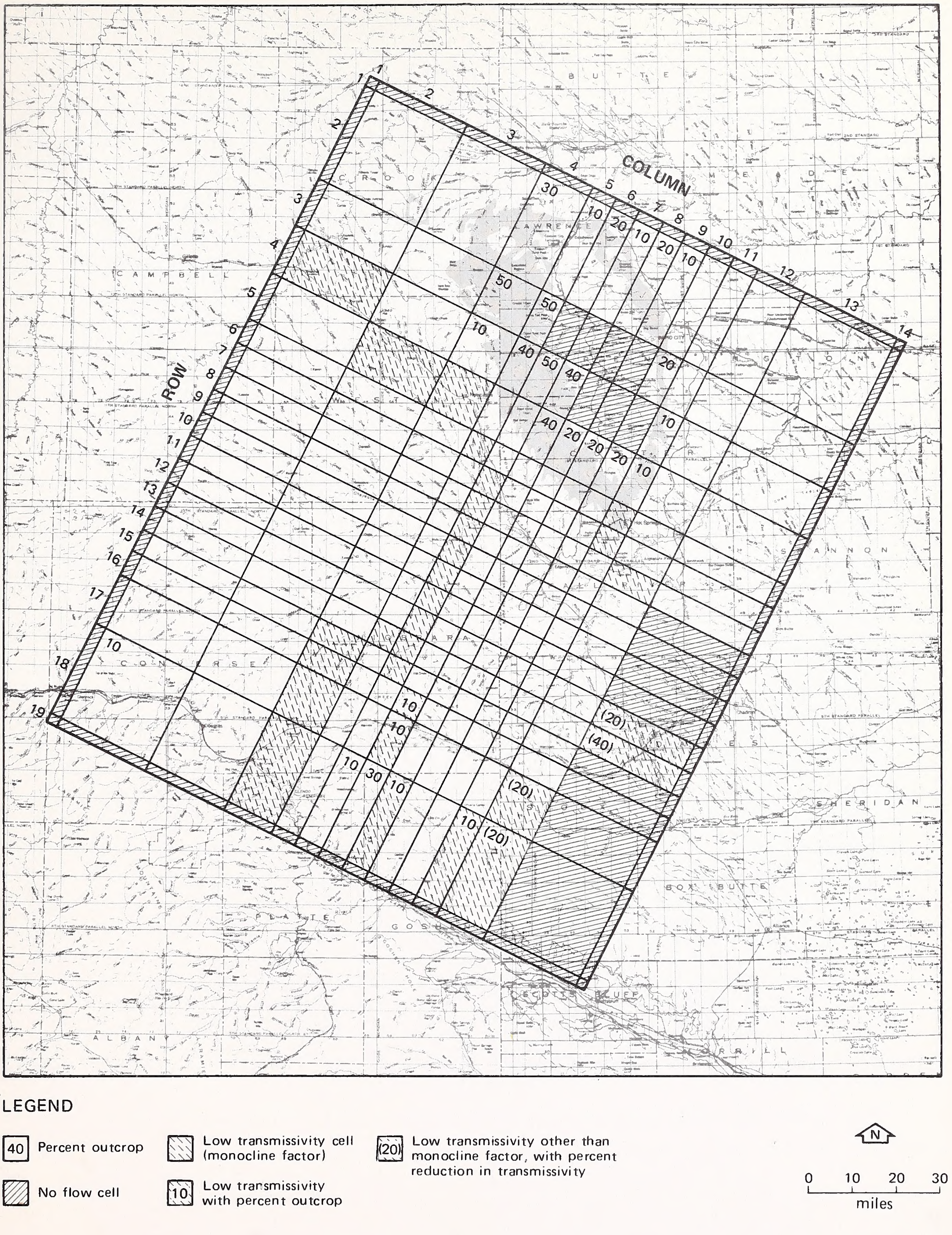


Figure 4-5a. FINITE-DIFFERENCE GRID USED IN SIMULATING PUMPING FROM THE NIOBRARA COUNTY WELL FIELD (Madison aquifer layer)

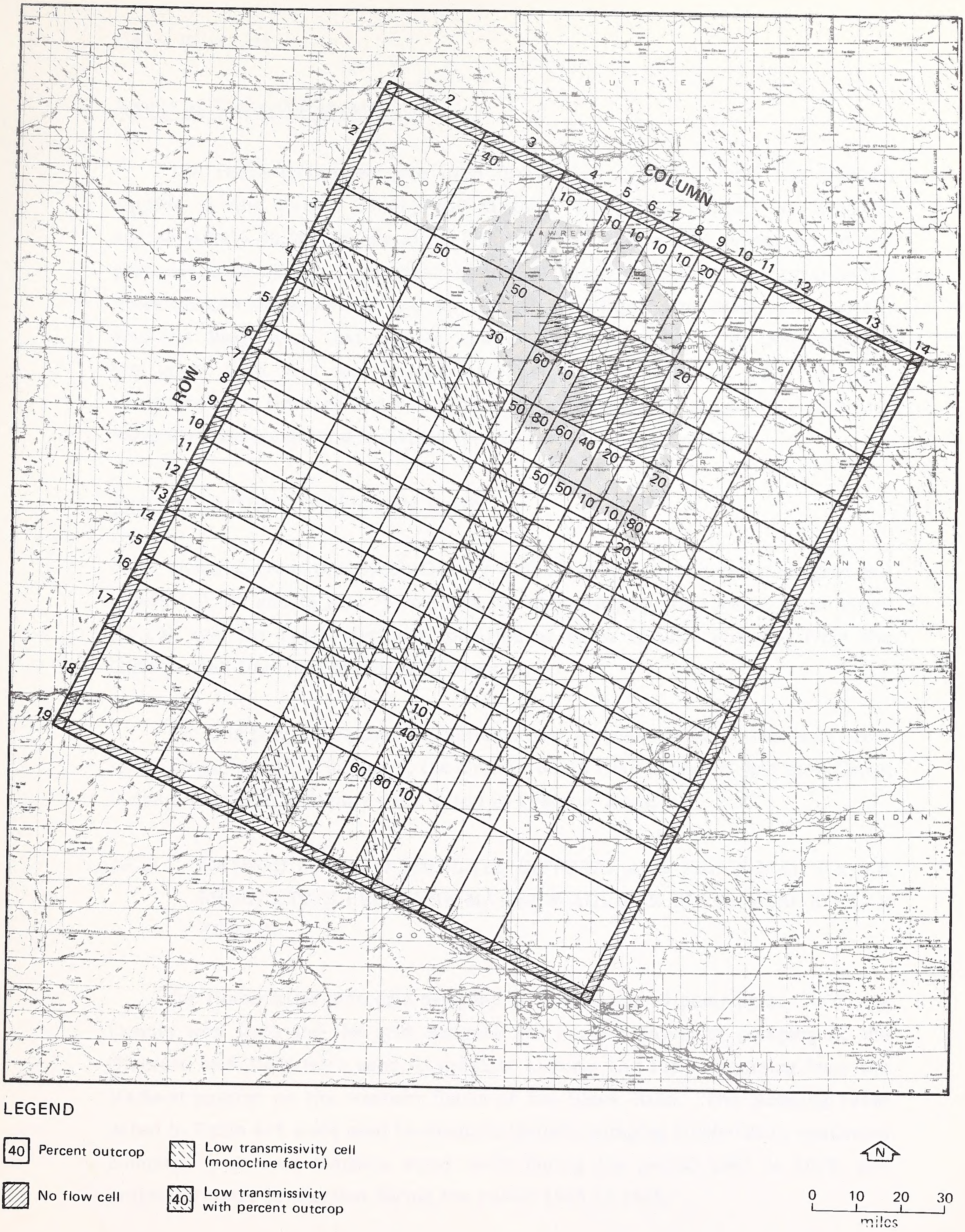


Figure 4-5b. FINITE-DIFFERENCE GRID USED IN SIMULATING PUMPING FROM THE NIOBRARA COUNTY WELL FIELD (Minnelusa aquifer layer)

Design of Finite-Difference Grid

The finite-difference grid used to simulate pumping from the Madison aquifer at the Crook County and Gillette well fields covers an area of approximately 40,000 square miles (Figure 4-6). The grid is centered over the proposed Crook County well field, is oriented north-northwest, and extends 200 miles in both the east-west and north-south directions. The areal extent of the grid was designed so that minimal drawdown would occur at the boundaries of the grid. The grid was oriented parallel to the strike of major geologic structures near the well fields and parallel to the outcrop areas. The grid uses variable-sized blocks and is divided into 20 rows and 17 columns.

Pumping Locations and Pumping Rates

Pumping from the Crook County well field was distributed over grid cell blocks (10,10) and (9,10). Two-thirds of the pumping was specified at block (10,10), and the remainder was specified at block (9,10). Pumping from the Gillette well field was specified at block (8,7).

The pumping rates used to simulate the proposed ETSI withdrawals from the Gillette well field in plan 2, the Crook County field in plan 3, and both Crook County and Gillette in plan 4 are listed in Tables 4-5 and 4-6.

4.C.5 METHOD USED TO SIMULATE HISTORIC AND PROJECTED WATER PRODUCTION FROM THE MADISON AQUIFER IN THE BLACK HILLS REGION

The finite-difference grid designed for simulation of pumping at the Crook County well field and the grid designed for the simulation of pumping at the Niobrara well field were used to simulate historic and future pumping from the Madison aquifer on the western flanks of the Black Hills. The pumping rates listed in Table 4-7 were used to simulate historic pumping (1900-1980), continued pumping by present Madison water users during the period 1980 to 2035, and projected water production during the period 1985 to 2035.

TABLE 4-7

PUMPING SCHEDULES USED FOR SIMULATING HISTORICAL AND FUTURE PRODUCTION FROM THE MADISON AQUIFER SYSTEM

Location	Simulated Historical Pumping Schedule	Simulated Future Pumping Schedules: Continued Production By Existing Producers	Simulated Future Pumping Schedules: Projected Production
Bell Creek, Montana (8S-54E and 9S-53E)	4.3 cfs (1970-1977); 2.1 cfs (1978-1980)	2.1 cfs (1981-2035)	2.1 cfs (1981-2035)
Edgemont, South Dakota (8S-2E and 9S-2E)	1.1 cfs (1907-1945); 2.5 cfs (1946-1980)	2.5 cfs (1981-2035)	2.5 cfs (1981-2035)
Gillette Well Field, Wyoming (51N-66E-6)	—	—	2.1cfs(1981-1985); 4.1cfs(1986-1995); 5.8cfs(1996-2005); 6.6cfs(2006-2015); 7.1cfs(2016-2025); 7.3 cfs (2026-2035)
Marten's Well, Wyoming (46N-60E-31ba)	0.1 cfs (1942-1980)	0.1 cfs (1981-2035)	0.1 cfs (1981-2035)
Newcastle, Wyoming (45N-61E)	2.2 cfs (1949-1962); 7.1 cfs (1962-1977); 7.8 cfs (1978-1980)	7.8 cfs (1981-2035)	7.8 cfs (1981-2035)
Osage, Wyoming (46N-63E)	1.2 cfs (1941-1951); 1.7 cfs (1950-1980)	1.7 cfs (1981-2035)	1.7cfs(1981-1995); 3.7 cfs (1996-2035)
West Osage Area, Wyoming (46N-64W and 46N-65W)	2.1 cfs (1960-1969); 1.5 cfs (1970-1980)	1.5 cfs (1981-2035)	1.5 cfs (1981-2035)
Sundance, Wyoming (51N-63W)	0.1 cfs (1971-1980)	0.1 cfs (1981-2035)	0.1 cfs (1981-2035)
Upton, Wyoming (48N-65W)	0.2 cfs (1949-1975); 0.3 cfs (1976-1980)	0.3 cfs (1981-2035)	0.3 cfs (1981-2035)

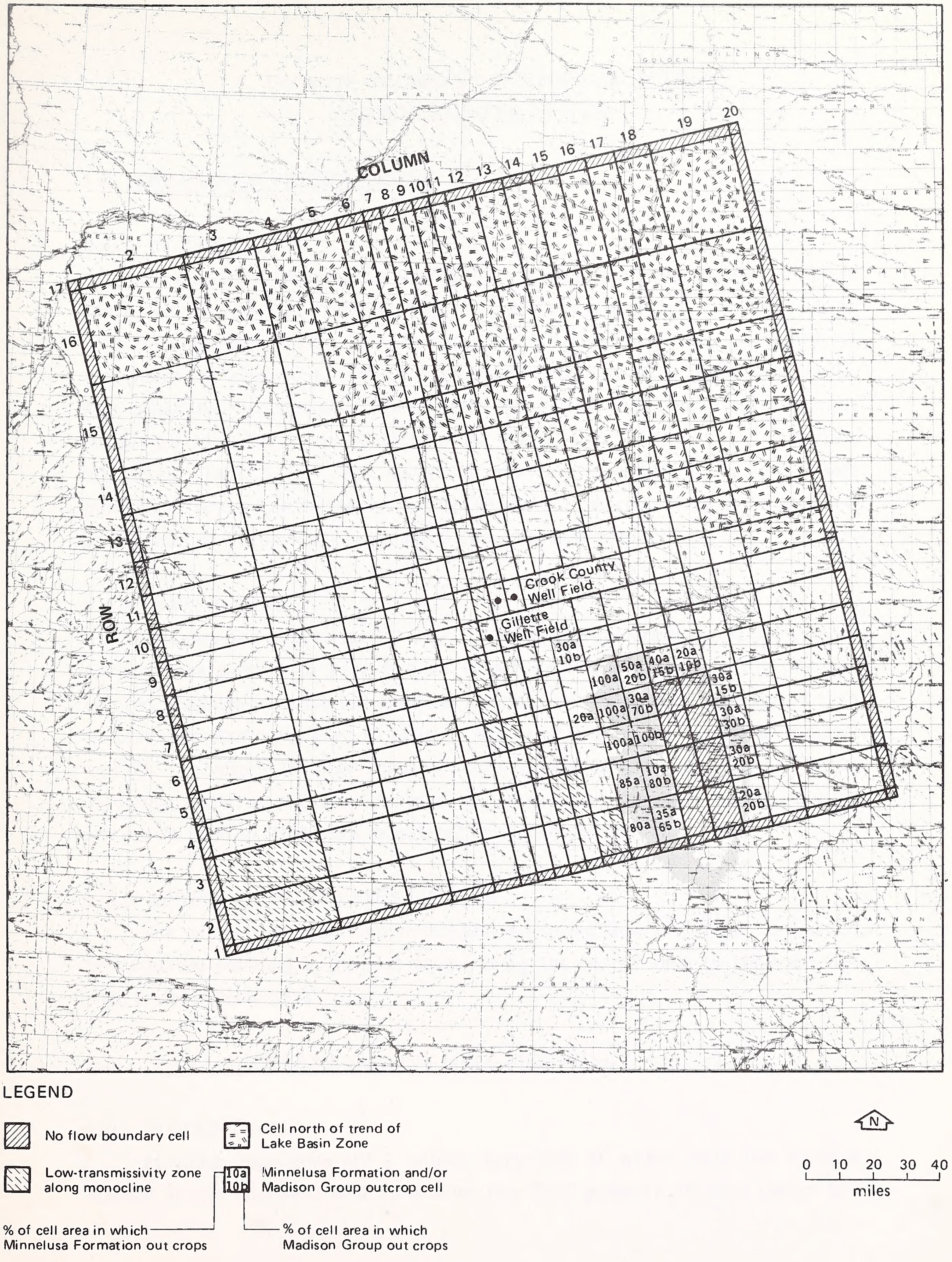


Figure 4-6. FINITE-DIFFERENCE GRID USED IN SIMULATING PUMPING FROM THE CROOK COUNTY AND GILLETTE WELL FIELDS

5. IMPACTS CAUSED BY PUMPING FROM THE MADISON AQUIFER SYSTEM

5.A IMPACTS OF PRESENT USERS

5.A.1 WATER LEVELS

Calculated changes in the potentiometric surface of the Madison aquifer in the Black Hills region, from the beginning of production in the early 1900s to 1980, are shown in Figure 5-1. Drawdowns of more than 25 feet occur only in the vicinity of Edgemont, Provo, Osage, Newcastle, and Bell Creek (Table 5-1). The calculated additional drawdowns that occur from the simulation of current production rates from the Madison during the 50-year life of the ETSI project are small (Table 5-1). The additional drawdowns caused by current users pumping at present rates for the period 1985 to 2035 were calculated to be 8, 14, and 18 feet at Edgemont, Osage, and Newcastle, respectively.

5.A.2 WATER QUALITY

The pumping at Newcastle, Osage, and Edgemont during the period 1900 to 1980 was calculated to have had no effect on water quality in the Madison aquifer. Similarly, simulated pumping at these locations during the period 1985 to 2035 was also calculated to have no effect on water quality in the Madison aquifer. Changes in TDS concentrations in the Madison aquifer at Osage, Wyoming, and at Bell Creek, Montana, as the result of simulated pumping during the period 1950 to 1980 were calculated to be less than 10 mg/l.

5.A.3 SPRING FLOW AND STREAM FLOW

The calculated reductions in stream and spring flow that occur as a result of simulated pumping by current users during the period 1985 to 2035 are less than 0.5 cfs (Table 5-2).

5.B PLAN 1: NIOBRARA COUNTY WELL FIELD ONLY

5.B.1 WATER LEVELS

Pumping approximately 1 million acre-feet of water from the Madison aquifer at the Niobrara well field over the ETSI project's 50-year design life

TABLE 5-1

DRAWDOWNS IN THE MADISON POTENTIOMETRIC SURFACE[a]

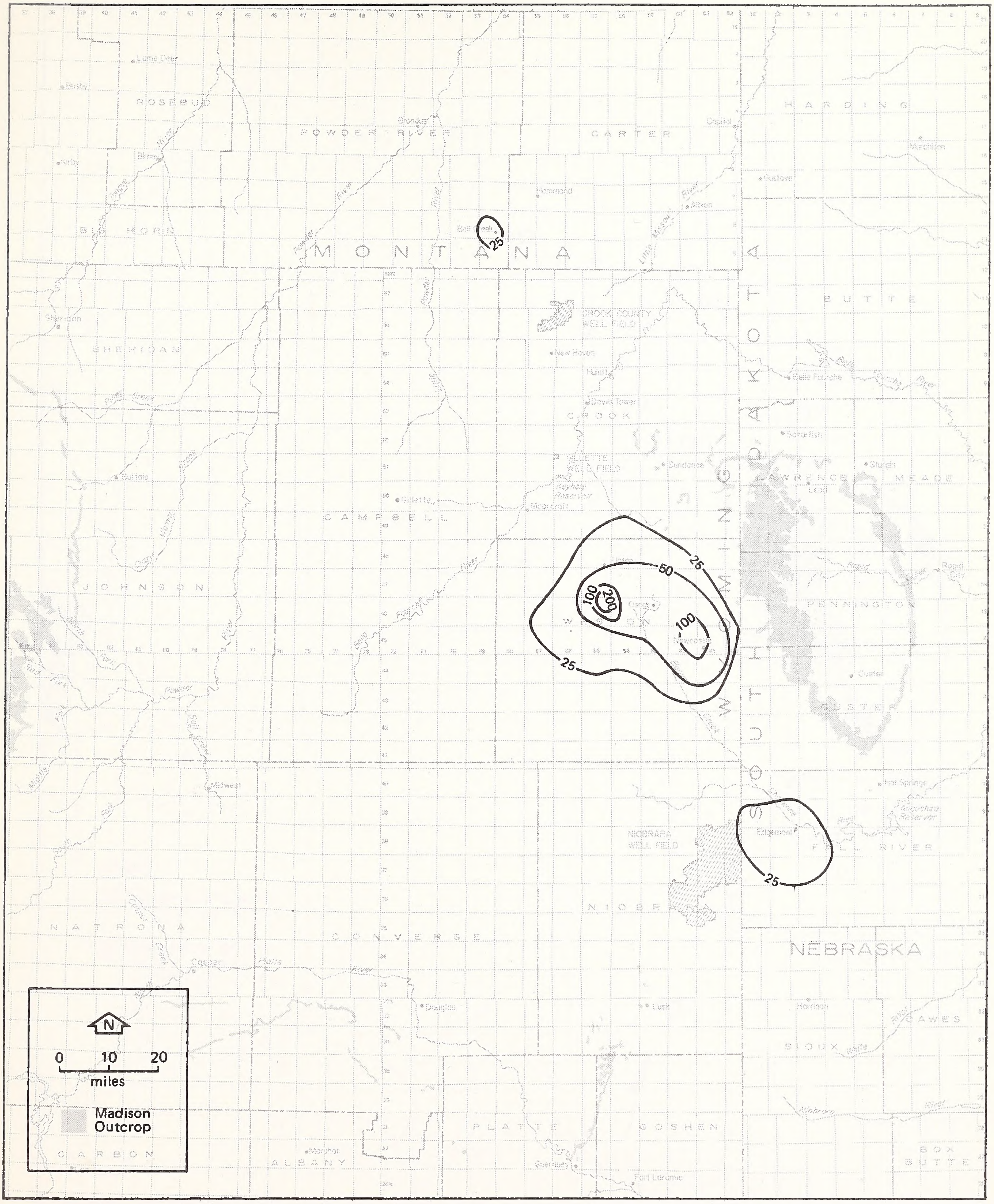
Approximate Location[a]	Location No. (See Figure 5-2)	Calculated Drawdowns (feet)[b]														
		Current Use Only		Current Use Plus Planned Use	Plan 1: Niobrara Site Only			Plan 2: Niobrara Site Plus Gillette Site			Plan 3: Crook Site Only			Plan 4: Crook Site Plus Gillette Site		
		1900-1980 Time Period	(Column A) 1985-2035 Time Period	(Column B) 1985-2035 Time Period	ETSI only	ETSI Plus Col. A	ETSI Plus Col. B	ETSI only	ETSI Plus Col. A	ETSI Plus Col. B	ETSI only	ETSI Plus Col. A	ETSI Plus Col. B	ETSI only	ETSI Plus Col. A	ETSI Plus Col. B
Niobrara County Site, Wyo.	1	18	9	9	666	675	675	464	473	473	-	9	9	-	9	9
Edgemont, S. Dak.	2	44	8	8	295	303	303	203	211	211	-	8	8	-	8	8
Provo, S. Dak.	3	31	8	8	335	343	343	230	237	237	-	8	8	-	8	8
Hot Springs, S. Dak.	4	1	1	1	7	8	8	5	6	6	-	1	1	-	1	1
Cascade Springs, S. Dak.	5	3	3	3	32	35	35	22	25	25	-	3	3	-	3	3
Lusk, Wyo.	6	-	1	1	6	7	7	4	5	5	-	1	1	-	1	1
Newcastle, Wyo.	7	128	18	29	2	21	31	1	20	30	4	23	33	7	26	36
Osage, Wyo.	8	68	14	76	-	14	76	24	38	100	17	31	93	36	50	112
Upton, Wyo.	9	32	13	66	-	13	66	56	69	122	38	51	104	82	95	148
Sundance, Wyo.	10	5	8	35	-	8	35	34	42	69	47	55	82	66	74	101
Gillette Well Field, Wyo.	11	11	10	132	-	10	132	191	202	224	91	101	223	254	264	384
Devils Tower, Wyo.	12	8	10	64	-	10	64	77	87	141	134	144	198	169	179	233
Hulett, Wyo.[c]	13	7	9	53	-	9	53	60	69	113	125	134	178	147	156	200
Crook County Site, Wyo.	14	10	10	32	-	10	32	30	40	62	366	376	398	286	296	318
Bell Creek, Mont.	15	30	10	22	-	11	22	15	26	37	151	162	173	117	127	139
Belle Fourche, S. Dak.	16	2	4	13	-	4	13	11	15	24	49	53	62	44	48	57
Spearfish, S. Dak.	17	1	4	12	-	4	12	11	15	23	38	42	50	36	40	18

Note: The numbers in the columns have been rounded to the nearest whole number and may not add exactly in the rows because of this rounding.

[a] Exact locations are shown on Figure 5-2.

[b] Pumping schedules used in drawdown calculations are listed in Tables 4-5, 4-6, and 4-7.

[c] Drawdowns calculated for the Minnelusa aquifer unit only.



Note: Pumping rates used in simulation are listed in Table 4-7.

Figure 5-1. DRAWDOWNS (in feet) IN THE MADISON POTENTIOMETRIC SURFACE IN THE BLACK HILLS REGION IN 1980 CAUSED BY PUMPING BY PRESENT MADISON GROUP WATER USERS

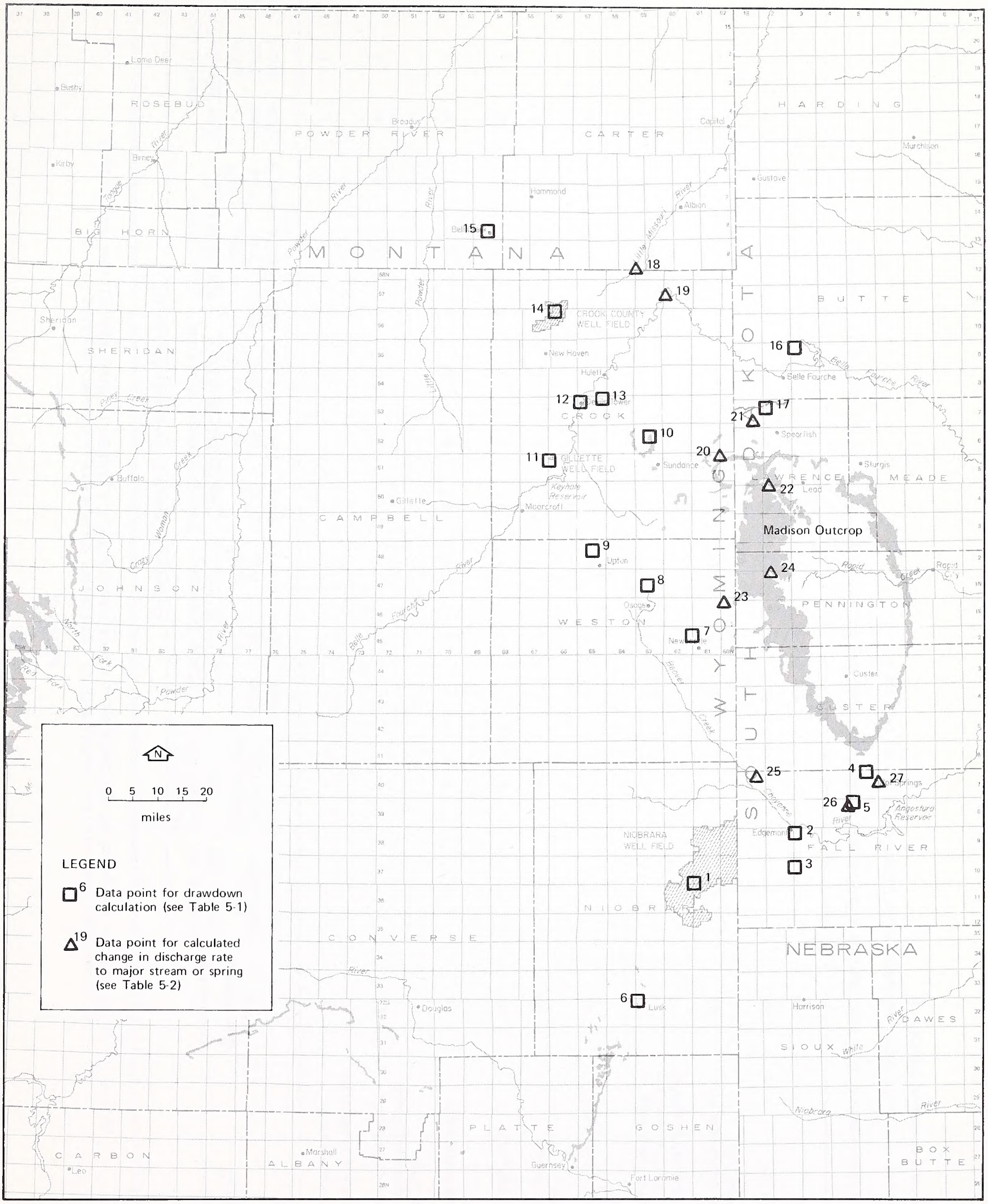


Figure 5-2. LOCATIONS OF DATA POINTS FOR TABLE 5-1 AND 5-2 WHERE DRAWDOWNS FOR THE VARIOUS WELL FIELD PUMPING COMBINATIONS AND CHANGES IN DISCHARGE RATES TO MAJOR STREAMS AND SPRINGS ARE SHOWN

TABLE 5-2

CHANGES IN GROUND-WATER DISCHARGE RATES TO THE MAJOR STREAMS AND SPRINGS IN THE BLACK HILLS REGION AS A RESULT OF WITHDRAWALS FROM THE MADISON AQUIFER DURING THE PERIOD 1985 TO 2035

Approximate Location[b]	Location No. (See Figure 5-2)	Calculated Change in Discharge Rate (cfs)[a]													
		(Column A) Current Use Only, 1985-2035 Time Period	(Column B) Current Use Plus Planned Use, 1985-2035 Time Period	Plan 1: Niobrara Well Field Only			Plan 2: Niobrara Well Field Plus Gillette Well Field			Plan 3: Crook Well Field Only			Plan 4: Crook Plus Gillette Well Field		
				ETSI Only	ETSI Plus Col. A	ETSI[b] Plus Col. B[c]	ETSI Only	ETSI Plus Col. A	ETSI[b] Plus Col. B[c]	ETSI Only	ETSI Plus Col. A	ETSI[b] Plus Col. B	ETSI Only	ETSI Plus Col. A	ETSI[b] Plus Col. B[c]
Little Missouri River at the Montana-Wyoming State Line	18	-	-	-	-	-	-	-	-	1	1	1	1	1	1
Belle Fourche River (Keyhole Reservoir to Wyoming-South Dakota State Line	19	-	1	-	-	-	1	1	2	4	4	4	4	4	4
Sand Creek (entire drainage basin)	20	-	3	-	-	-	2	2	5	3	4	7	4	4	7
Crow Creek Springs, SD	21	-	1	-	-	-	1	1	1	2	2	3	2	2	3
Spearfish Creek (entire drainage basin)	22	-	1	-	-	-	1	1	2	1	1	2	1	1	2
Stockade-Beaver Creek (entire drainage basin)	23	-	-	-	-	-	-	-	-	-	-	-	1	1	1
Rapid Creek (entire drainage basin west of the Precambrian core of the Black Hills uplift)	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cheyenne River (upstream of Angostura Reservoir)	25	-	-	1	1	1	1	1	1	-	-	-	-	-	-
Cascade Springs, SD	26	-	-	4	4	4	3	3	3	-	-	-	-	-	-
Hot Springs, SD	27	-	-	2	2	2	1	1	1	-	-	-	-	-	-

Note: Numbers in the columns have been rounded to the nearest whole number and may not add exactly in the rows because of this rounding.

[a]Pumping schedules used in drawdown calculations are listed in Tables 4-5, 4-6, and 4-7.

[b]Exact locations are shown on Figure 5-2.

(1985-2035) would result in large declines in the potentiometric surface of the Madison aquifer system (Figure 5-3 and Table 5-1). Drawdowns greater than 25 feet in the Madison potentiometric surface were calculated to occur after 50 years of pumping within a region of about 5300 square miles extending north, south, and east from the Niobrara County site. The region over which drawdowns of greater than 25 feet were calculated due to pumping would encompass the western half of Fall River and Custer counties, South Dakota; the northern portion of Sioux and Dawes counties, Nebraska; and the eastern half of Niobrara County, the extreme southeastern half of Weston County, and the northern half of Goshen County, Wyoming. Drawdowns of greater than 100 feet were calculated in a region of more than 3800 square miles in Niobrara, Goshen, Sioux, and Fall River counties. Drawdowns greater than 200 feet were calculated in a region of more than 2000 square miles in Sioux, Niobrara, and Fall River counties; and drawdowns greater than 400 feet were calculated only within a radius of 15 miles north, south, and east of the Niobrara well field.

The cone of depression is asymmetrical due to variations in the hydrogeologic properties within the Madison aquifer system (Figure 5-3). The extent of the cone of depression is limited to the west by the low-transmissivity zones associated with the Black Hills monocline, the Fanny Peak monocline, and the Rawhide fault. The Precambrian core of the Black Hills uplift and the surrounding Madison aquifer outcrop areas form the northern boundary of the cone of depression, while the Cascade anticline and the erosional limit of the Madison Group act as the northeastern and southeastern boundaries to the spread of drawdown from pumping.

Several existing Madison and Minnelusa water users would be likely to have increased pumping lifts as a result of the declines in the potentiometric surface (Table 5-1). Only at the Madison wells located near Edgemont, South Dakota, are drawdowns in the potentiometric surface predicted to exceed 25 feet. Water levels at the seven Madison wells used for municipal water supply at Edgemont were calculated to decline by 295 feet, from their current level of 200 feet above land surface to 95 feet below land surface during the 50-year life of the project (Figure 5-3). This would result in the gradual lessening and eventual cessation of flow from these wells. Water levels at Madison wells at Provo,

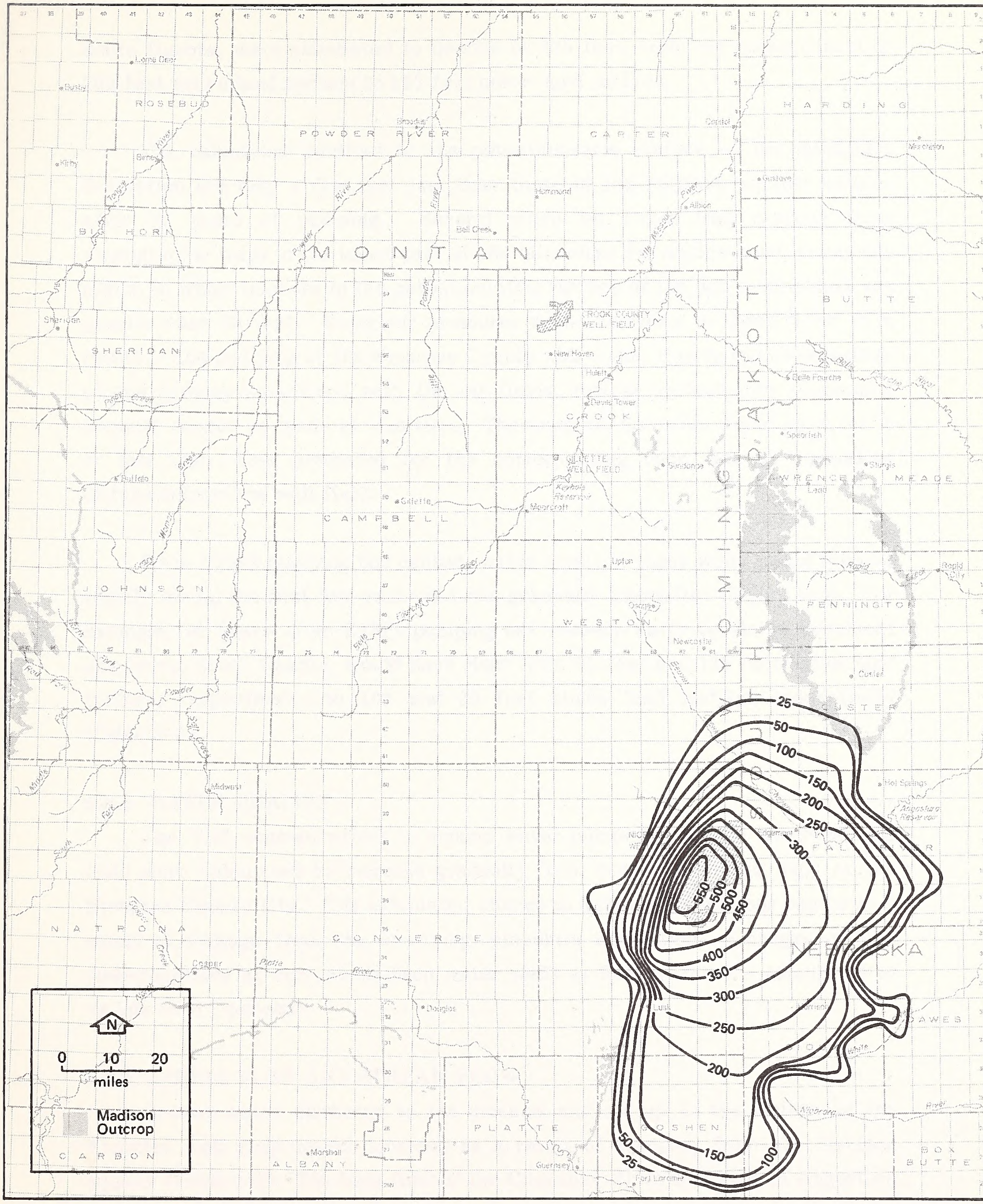


Figure 5-3. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING FROM NIOBRARA COUNTY WELL FIELD ONLY (PLAN 1)

South Dakota, were calculated to decline by 335 feet, from the present level of 200 feet above land surface to 135 feet below land surface.

The calculated declines in the potentiometric surface of the Minnelusa Formation are only a few feet less than those in the Madison aquifer surface after 50 years of pumping. Several small oil fields that produce from stratigraphic traps in the upper part of the Minnelusa Formation exist within the region in which declines in the potentiometric surface of the upper Minnelusa are greater than 25 feet. Reservoir pressures would decrease in these fields as a result of the pumping at the Niobrara County well field. Due to the complexities of the geology associated with the oil fields, further refinements concerning impacts cannot be made at this time. The impacts, however, would be equal to or less than those predicted for the corresponding rock unit at equivalent distances from the well field.

Once ETSI's pumping has ceased, water levels in these wells would recover rapidly during the first few years and rise gradually thereafter (Figure 5-4). For example, 50 years after ETSI's pumping has ceased, water levels at Edgemont and Provo, South Dakota, would have risen from 95 feet and 135 feet below land surface, respectively, to 102 and 90 feet above land surface, respectively (Table 5-3).

5.B.2 WATER QUALITY

The TDS concentrations in ground water pumped from the Niobrara well field were calculated to increase gradually from 500 mg/l to 560 mg/l at the Niobrara County site. The calculated change in TDS concentrations occurs as a result of leakage from the overlying Minnelusa Formation. Changes in TDS concentrations at current Madison water wells at Edgemont were calculated to be less than 1 percent.

5.B.3 SPRING FLOW AND STREAM FLOW

Ground-water discharge to the streams and springs in the vicinity of the Niobrara well field would decrease as a result of pumping from the Madison aquifer (Table 5-2). The base flow of the Cheyenne River upstream of Angostura Reservoir in Fall River County, South Dakota, was calculated to decrease by

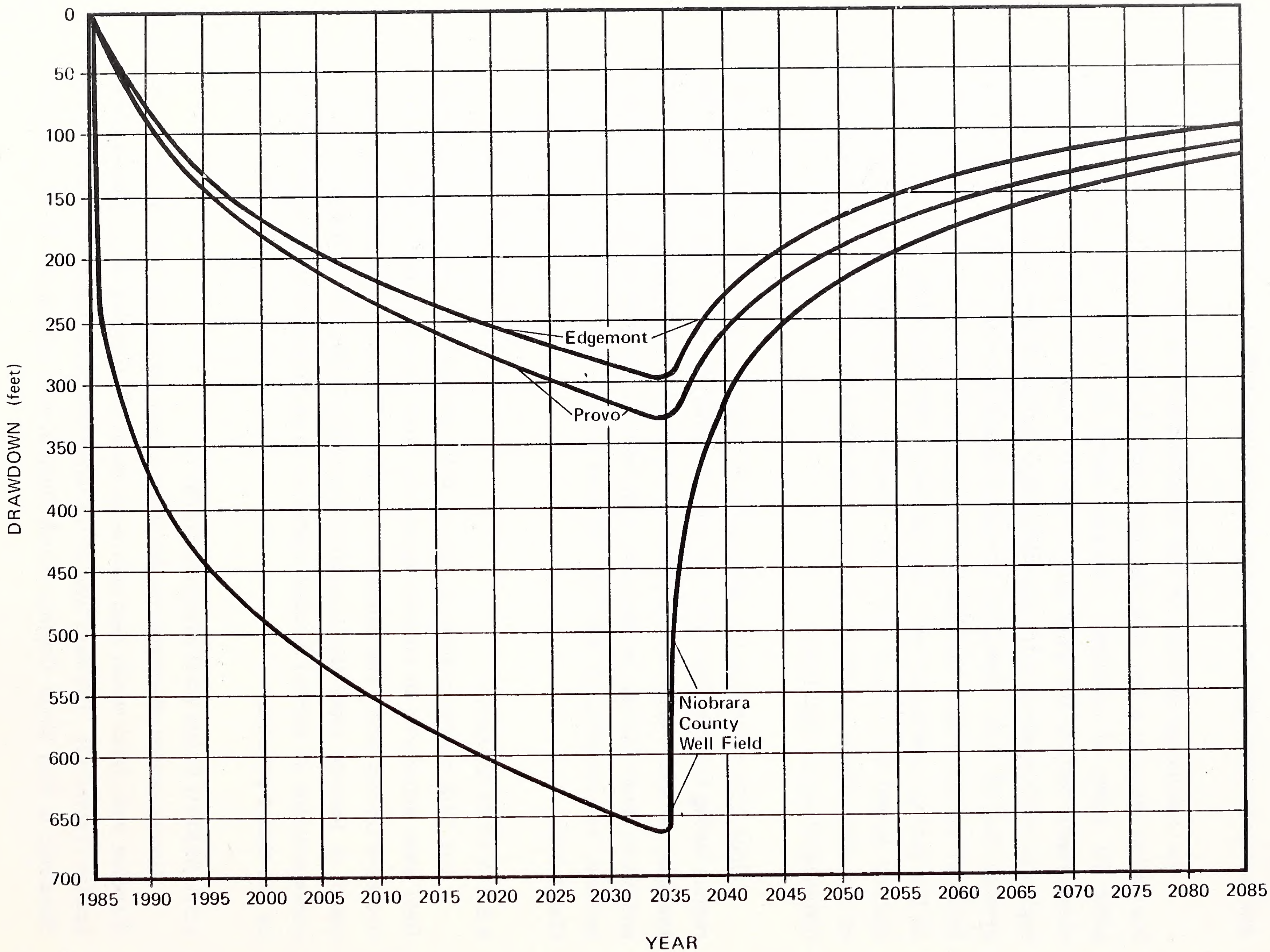


Figure 5-4. TIME-DRAWDOWN PLOT WITH PUMPING FROM NIOBRARA COUNTY WELL FIELD ONLY (PLAN 1)

TABLE 5-3

DRAWDOWNS IN THE MADISON POTENTIOMETRIC SURFACE 50 YEARS AFTER ETSI STOPS PUMPING (1985 to 2085)

Approximate Location[b]	Location No. (see Figure 5-2)	Calculated Drawdown (feet)[a]	
		Plan 1: Niobrara County Well Field Only (ETSI pumping only)	Plan 3: Crook County Well Field Only (ETSI pumping only)
Niobrara County Site, WY	1	122	—
Edgemont, SD	2	98	—
Provo, SD	3	110	—
Hot Springs, SD	4	7	—
Cascade Springs, SD	5	29	—
Lusk, WY	6	6	—
Newcastle, WY	7	5	4
Osage, WY	8	—	14
Upton, WY	9	—	27
Sundance, WY	10	—	37
Gillette Well Field, WY	11	—	40
Devils Tower, WY	12	—	15
Hulett, WY[c]	13	—	44
Crook County Site, WY	14	—	56
Bell Creek, WY	15	—	58
Belle Fourche, SD	16	—	32
Spearfish, SD	17	—	27

[a] Change in the Madison potentiometric surface between the start of ETSI's pumping (1985) and 50 years after ETSI's pumping ceases (2085).

[b] Exact locations as shown on Figure 5-2.

[c] Drawdown calculated in the Minnelusa aquifer unit.

approximately 1 cfs after 50 years of pumping. The average flow of Cascade Springs and of the springs in the Hot Springs area, in Fall River County, South Dakota, were calculated to decline by 4 cfs and 2 cfs, respectively, from their present levels of 22 cfs and 25 cfs.

5.C PLAN 2: NIOBRARA AND GILLETTE WELL FIELDS

5.C.1 WATER LEVELS

Pumping of approximately 1 million acre-feet of water from the Madison aquifer at the Niobrara and Gillette well fields over the ETSI project's 50-year design life (1985-2035) would result in large declines in the potentiometric surface of the Madison aquifer system (Figure 5-5). These declines would immediately begin to lessen at most locations once pumping ceases.

The calculated declines in the potentiometric surface in the Madison aquifer system would consist of two separate cones of depression, one centered over the Niobrara site and another centered over the Gillette site. The cone of depression at the Niobrara site would be very similar to that previously described for plan 1, with drawdowns reduced in magnitude by approximately 30 percent (Table 5-1). Pumping from the Gillette site was calculated to produce declines of over 25 feet in the Madison potentiometric surface in an area of approximately 1650 square miles around the Gillette well field after 50 years of pumping. Drawdowns greater than 100 feet were calculated within a 10-mile radius of the Gillette site.

Many existing Madison and Minnelusa water users are calculated to have increased pumping lifts as a result of the declines in the potentiometric surface around the Gillette well field (Figure 5-6). The potentiometric heads at the seven Madison wells used for mnicipal water supply at Edgemont were calculated to decline by 203 feet; at Provo the heads were calculated to decline by 230 feet. Water levels at Madison wells used for water flooding at the Bell Creek oil field in Montana, which are currently 40 to 200 feet above land surface, were calculated to decline by 15 feet. The water level in the Madison water well at Devils Tower National Monument, which is now within 20 feet of land surface, was calculated to decline by 77 feet after 50 years of pumping from the Gillette

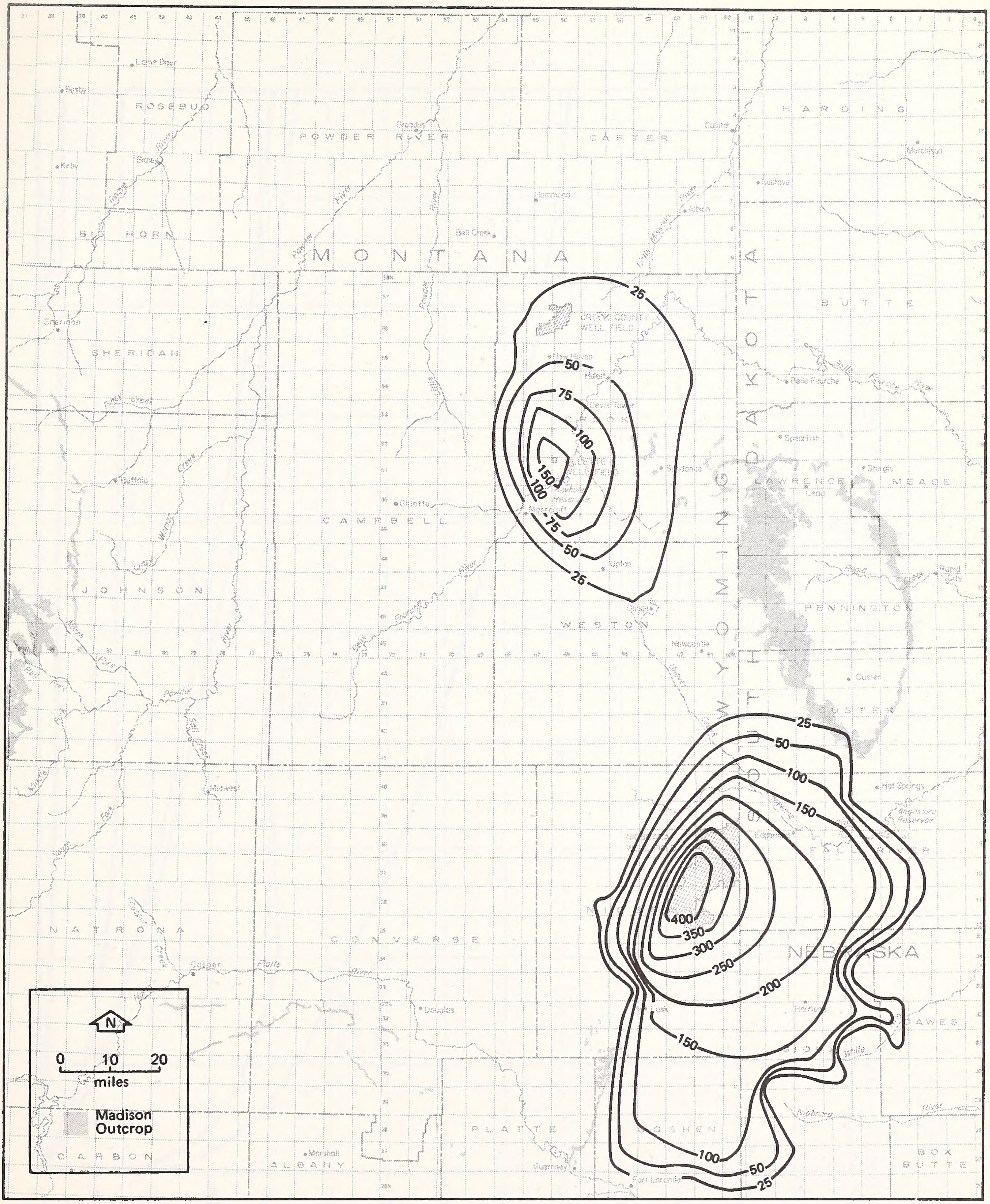


Figure 5-5. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING FROM NIOBRARA COUNTY AND GILLETTE WELL FIELDS (PLAN 2)

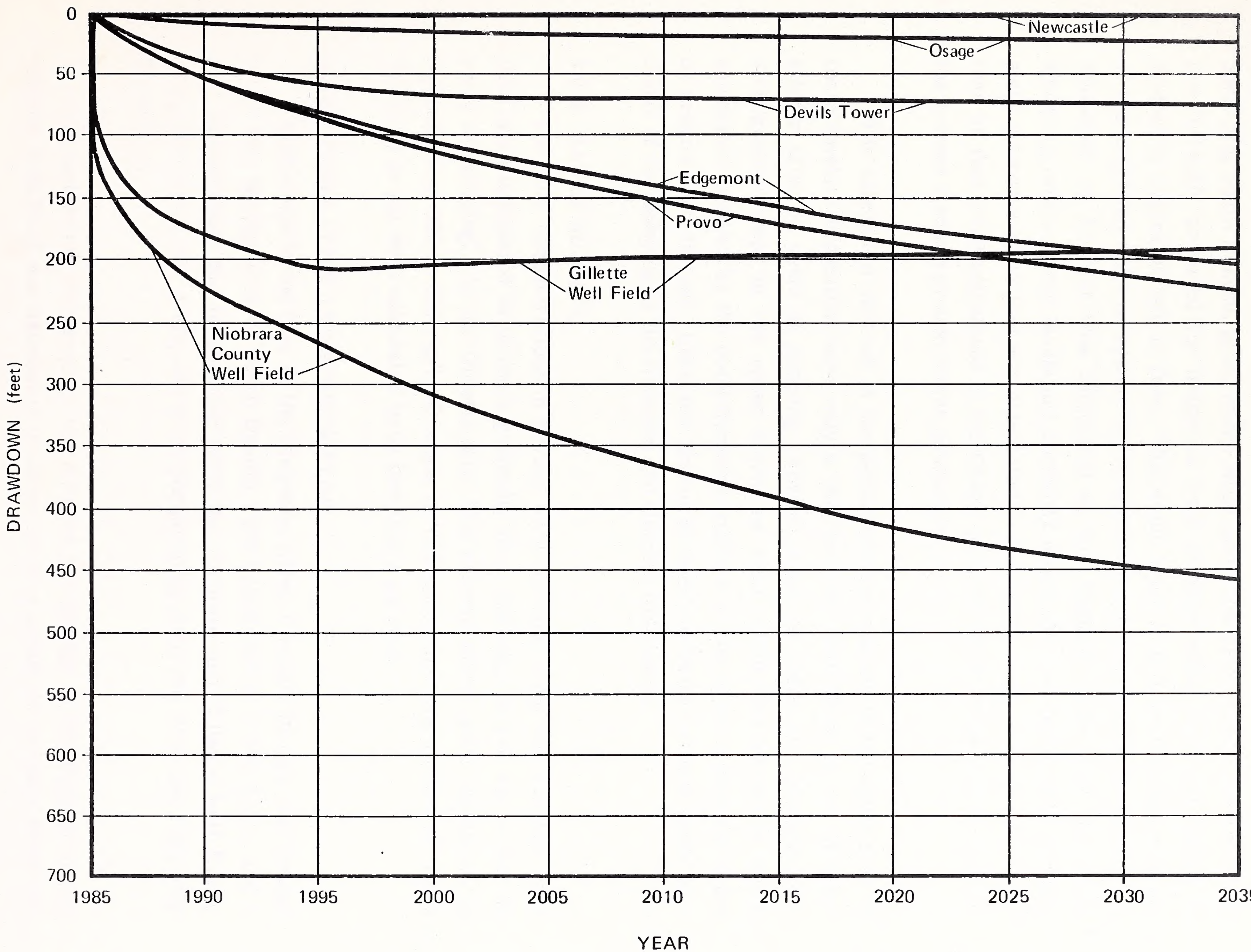


Figure 5-6. TIME-DRAWDOWN PLOT WITH PUMPING FROM NIOBRARA COUNTY AND GILLETTE WELL FIELDS (PLAN 2)

well field. Madison Group and Minnelusa Formation water levels in the Spearfish, South Dakota, area, where large quantities of Minnelusa ground water are currently produced for irrigation from artesian wells, were calculated to decline by approximately 11 feet. This would result in a flow reduction in many of the irrigation wells in western Butte and Lawrence counties, South Dakota. A drawdown of 34 feet was calculated at the Madison wells near Sundance, Wyoming, where water levels are currently about 400 feet below land surface, and a drawdown of 56 feet was calculated at the Upton wells. Drawdowns of less than 25 feet were calculated in the Osage and Newcastle areas, where most of the current Madison ground-water production occurs.

The calculated declines in the potentiometric surface in the upper part of the Minnelusa Formation were only a few feet less than those in the Madison aquifer after 50 years of pumping. Several small oil fields that produce from stratigraphic traps in the upper Minnelusa exist within the region in which calculated declines in the potentiometric surface of the upper Minnelusa would be greater than 25 feet. Reservoir pressures would decrease in these fields as a result of the pumping at the Niobrara and Gillette well fields.

5.C.2 WATER QUALITY

The TDS concentrations in ground water pumped from the Niobrara well field were calculated to increase gradually from 500 mg/l to 540 mg/l after 50 years of pumping. At the Gillette site, TDS concentrations were calculated to increase from 600 to 620 mg/l. Changes in TDS concentrations at Madison wells currently in use were calculated to be less than 1 percent.

5.C.3 SPRING FLOW AND STREAM FLOW

Reductions in the flow of the Cheyenne River, Cascade Springs, and springs in the Hot Springs area of South Dakota were calculated as 1 cfs, 3 cfs, and 1 cfs, respectively, due to pumping from the Niobrara and Gillette well fields, compared with 1 cfs, 4 cfs, and 2 cfs for pumping from the Niobrara field only (Table 5-2).

Ground-water discharge to the streams and springs in the vicinity of the Gillette well field was calculated to decrease as a result of pumping from the

Madison aquifer. The base flow of Sand Creek in eastern Crook County, Wyoming, was calculated to decrease by 2 cfs. The base flow of Spearfish Creek was calculated to decrease by 1 cfs. The total discharge of Crow Creek Springs, near the McNenny Fish Hatchery in Lawrence County, South Dakota, was calculated to decrease by 1 cfs. The base flow of the Belle Fourche River between Keyhole Reservoir and the Wyoming-South Dakota state line was calculated to decrease by 1 cfs.

5.D PLAN 3: CROOK COUNTY WELL FIELD ONLY

5.D.1 WATER LEVELS

Pumping of approximately 1 million acre-feet of water from the Madison aquifer at the Crook County well field over the ETSI project's 50-year design life (1985-2035) would result in large declines in the potentiometric surface of the Madison aquifer system (Figure 5-7, Table 5-1). Drawdowns greater than 25 feet in the Madison potentiometric surface were calculated within a region of about 16,700 square miles centered on the Crook County site after 50 years of pumping. This region encompasses parts of Crook, Campbell, Johnson, Sheridan, and Weston counties in Wyoming; Carter, Powder River, and Rosebud counties in Montana; and Butte, Harding, and Lawrence counties in South Dakota. Drawdowns greater than 100 feet due to pumping were calculated in a region of more than 3000 square miles in Weston, Powder River, and Carter counties. Drawdowns greater than 200 feet due to pumping were calculated only within a radius of 10 miles from the Crook County field.

The cone of depression is asymmetrical due to variations in the hydrogeologic properties within the Madison aquifer system (Figure 5-7). The extent of the cone of depression is limited southeast of the Crook County site by the Madison aquifer recharge areas in the Black Hills region. The recharge areas and the low-transmissivity zone along the Black Hills monocline are the cause of the irregular shape of the contours south and southeast of the well field. The steeper contours northeast of the Crook County site are the result of the low transmissivity in the Madison aquifer system north of the trend of the Lake Basin fault zone.

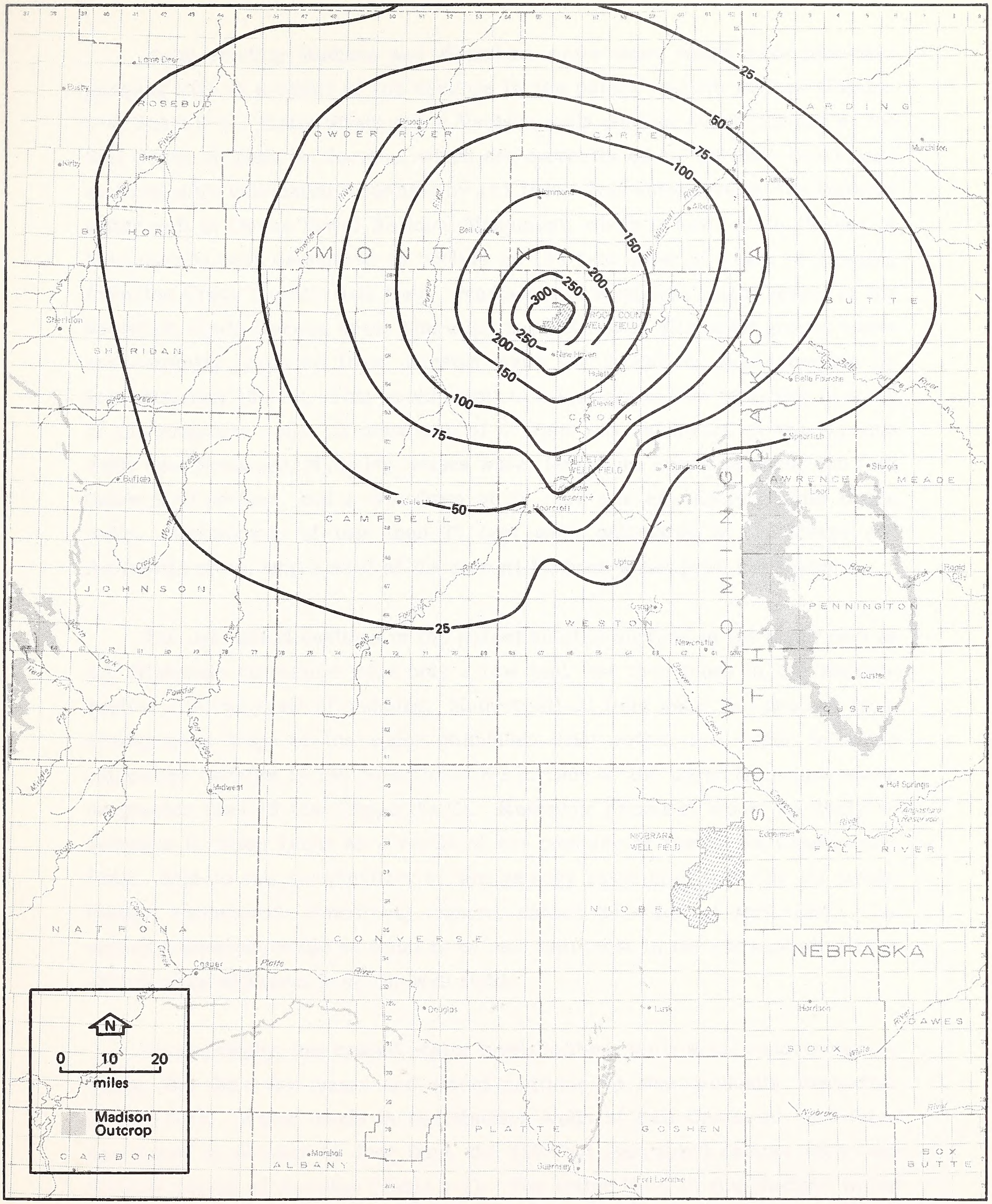


Figure 5-7. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING FROM CROOK COUNTY WELL FIELD ONLY (PLAN 3)

Many existing Madison and Minnelusa water users would have increased pumping lifts as a result of the declines in the potentiometric surface (Figure 5-8, Table 5-1). Water levels at the Madison wells used for water flooding at the Bell Creek oil field in Montana, which are currently 40 to 200 feet above land surface, were calculated to decline by 151 feet. The water level in the Madison water well at Devils Tower National Monument, which is now within 20 feet of land surface, was calculated to decline by 134 feet after 50 years of pumping from the Crook County well field. Madison and Minnelusa water levels in the Spearfish, South Dakota, area, where large quantities of Minnelusa ground water are currently produced from artesian wells for irrigation, would decline by approximately 40 feet. This would result in a substantial flow reduction in many of the irrigation wells. A drawdown of 47 feet was calculated at the Madison wells near Sundance, Wyoming, where water levels are currently about 400 feet below land surface, and a drawdown of 38 feet was calculated at the Upton wells. Drawdowns of less than 25 feet were calculated in the Osage and Newcastle areas, where most of the current Madison water production occurs.

The calculated declines in the potentiometric surface in the upper part of the Minnelusa Formation were only a few feet less than those in the Madison aquifer after 50 years of pumping. Many small oil field wells that produce from stratigraphic traps in the upper Minnelusa exist within the region in which calculated declines in the potentiometric surface of the upper Minnelusa would be greater than 25 feet (Appendix G). Reservoir pressures would be likely to decrease in these fields as a result of the pumping at the Crook County well field. Due to the complexities of the geology associated with the oil fields, further refinements concerning impacts cannot be made at this time. The impacts, however, would be equal to or less than those in the corresponding rock unit at equal distances from the well field.

Once pumping has ceased, water levels in these wells would recover rapidly during the first few years and would continue to rise gradually thereafter (Figure 5-8). Water levels in the Madison wells at Bell Creek oil field were calculated to recover 92 feet from the 150-foot calculated decline after the 50-year period of pumping (Table 5-3). The water level in the Madison water well at Devils Tower National Monument was calculated to recover approxi-

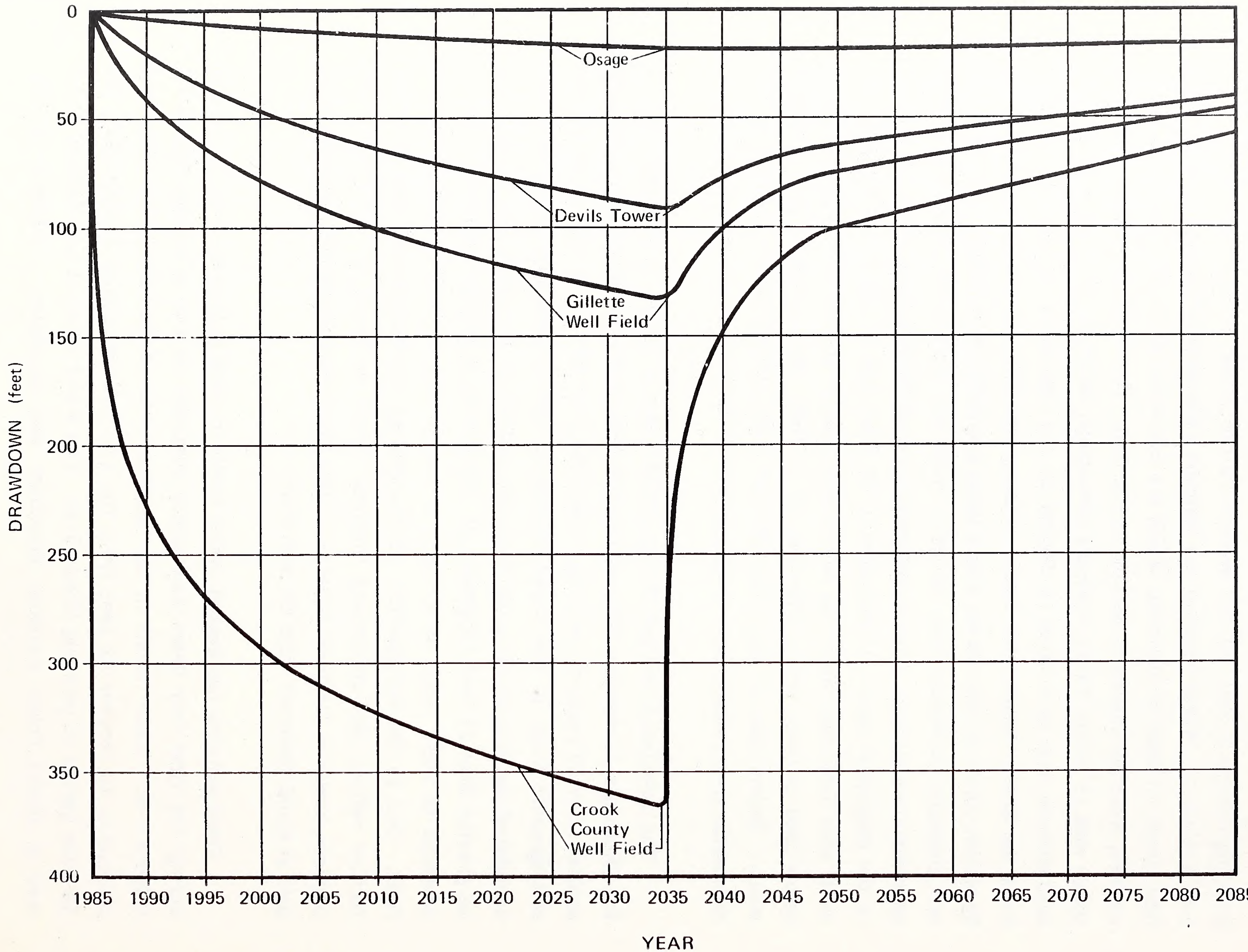


Figure 5-8. TIME-DRAWDOWN PLOT WITH PUMPING FROM CROOK COUNTY WELL FIELD ONLY (PLAN 3)

mately 119 feet after 50 years. Madison and Minnelusa water levels in the Spearfish area were calculated to rise 13 feet during the 50-year recovery period. Madison wells near Sundance and Upton, Wyoming, were calculated to recover 10 feet and 14 feet, respectively, from their respective 47-foot and 38-foot pumping declines.

5.D.2 WATER QUALITY

The water quality in the well field was calculated to increase gradually in TDS concentration over the life of the project, from 900 mg/l to 910 mg/l. Changes in TDS concentrations at Madison water wells currently in use were calculated to be less than 1 percent.

5.D.3 SPRING FLOW AND STREAM FLOW

Ground-water discharge to the streams and springs in the vicinity of the Crook County well field would decrease as a result of pumping from the Madison aquifer (Table 5-2). The base flow of Sand Creek in eastern Crook County was calculated to decrease by 3 cfs. The base flow of Spearfish Creek was calculated to decrease by 1 cfs. The total discharge of Crow Creek Springs, near the McNenny Fish Hatchery in Lawrence County, South Dakota, was calculated to decrease by 2 cfs. The base flow of the Belle Fourche River between Keyhole Reservoir and the Wyoming-South Dakota state line was calculated to decrease by 4 cfs. The base flow of the Little Missouri River above the state line in Wyoming was calculated to decrease by approximately 1 cfs.

5.E PLAN 4: CROOK COUNTY AND GILLETTE WELL FIELDS

5.E.1 WATER LEVELS

Pumping 1 million acre-feet of ground water from the Madison aquifer system during the period 1985-2035 would cause large drawdowns in the potentiometric surface of the Madison (Figure 5-9). The calculated cone of depression in the Madison aquifer system and the calculated spring flow and stream flow reductions are similar to those calculated for pumping from the proposed Crook County well field alone, except that the cone of depression is more asymmetrical. The pronounced asymmetry is the result of the low-transmissivity zone along the Black Hills monocline, which is located west of the Gillette site.

With both the Crook County and Gillette well fields pumping simultaneously, calculated drawdowns are somewhat greater than those calculated for plan 3 at Osage, Upton, Sundance, and Devils Tower. Drawdowns of 36 feet, 82 feet, 66 feet, and 169 feet were calculated at Osage, Upton, Sundance, and Devils Tower, respectively, after 50 years of pumping (Table 5-1, Figure 5-10). Calculated drawdowns at the Bell Creek, Montana, wells are 117 feet; this is 34 feet less than that calculated for plan 3. Drawdowns in the Belle Fourche and Spearfish areas of South Dakota are similar to drawdowns calculated for plan 3.

5.E.2 WATER QUALITY CHANGES

The TDS concentrations of the ground water were calculated to increase gradually from 900 to less than 910 mg/l at the Crook County well field over the life of the project, and TDS concentrations were calculated to increase gradually from 600 to 620 mg/l at the Gillette field over the life of the project.

5.E.3 SPRING FLOW AND STREAM FLOW

Calculated stream and spring flow reductions are the same as those calculated for plan 3, except that the base flow of Sand Creek was calculated to decrease by 4 cfs, instead of 3 cfs (Table 5-2).

5.F CUMULATIVE IMPACTS

The proposed ETSI withdrawals from the Madison aquifer would not be the only production that occurs from the Madison aquifer in the western part of the Black Hills region during the period 1985 to 2035. Existing Madison water users will continue to produce ground water, and new water supply systems will be developed to produce ground water from the Madison aquifer. Only two water supply systems, besides ETSI's, are planned to begin operation between 1980 and 2035. The city of Gillette plans to begin producing ground water from the Madison aquifer at a well field near Moorcroft in 1981, and Black Hills Power and Light plans to begin producing ground water from the Madison aquifer for a new power plant near Osage in the 1980s. Ground water produced for these two new projects is projected to average 6.2 cfs (4500 acre-feet per year) and 2.0 cfs (1200 acre-feet per year), respectively.

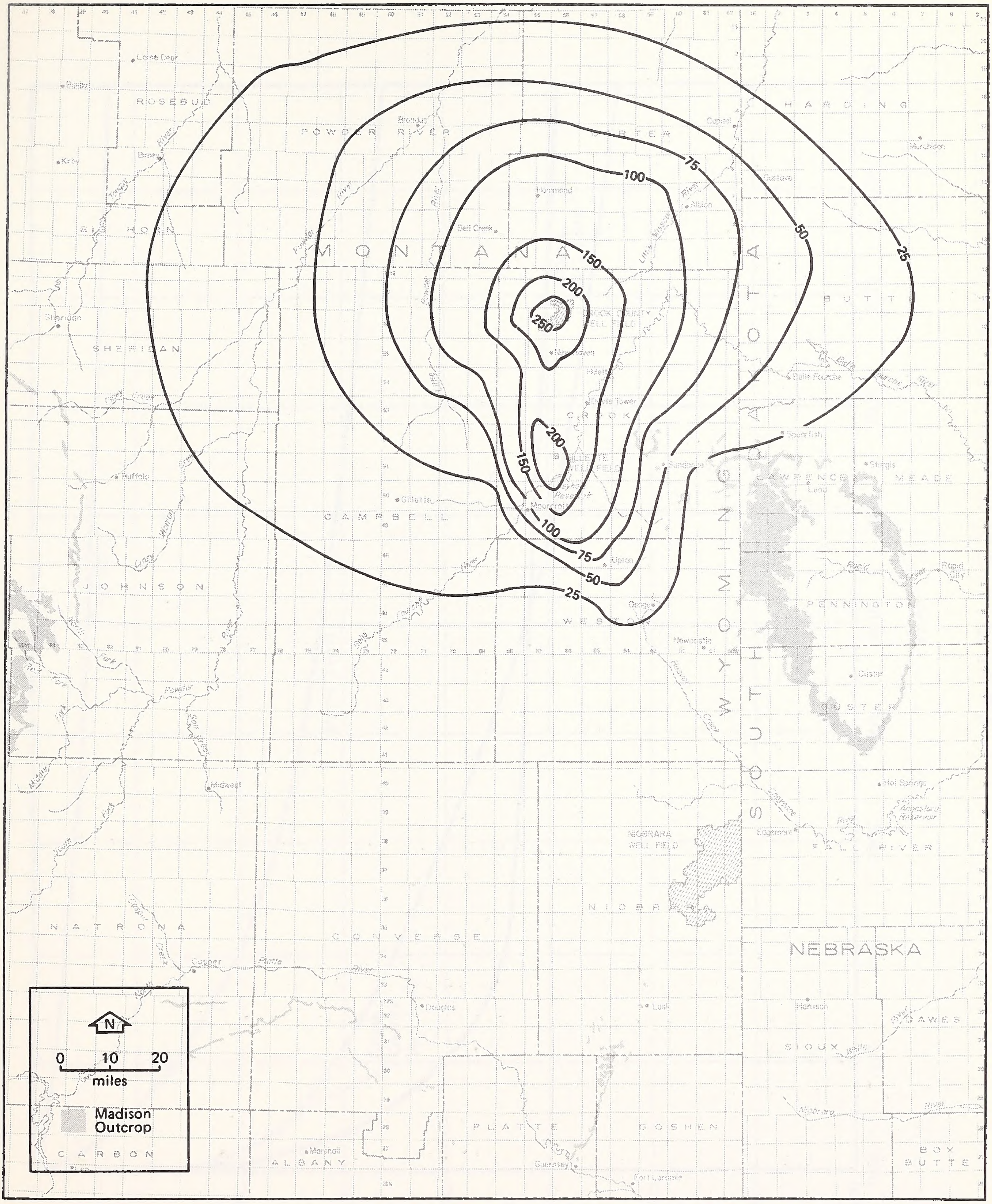


Figure 5-9. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING FROM CROOK COUNTY AND GILLETTE WELL FIELDS (PLAN 4)

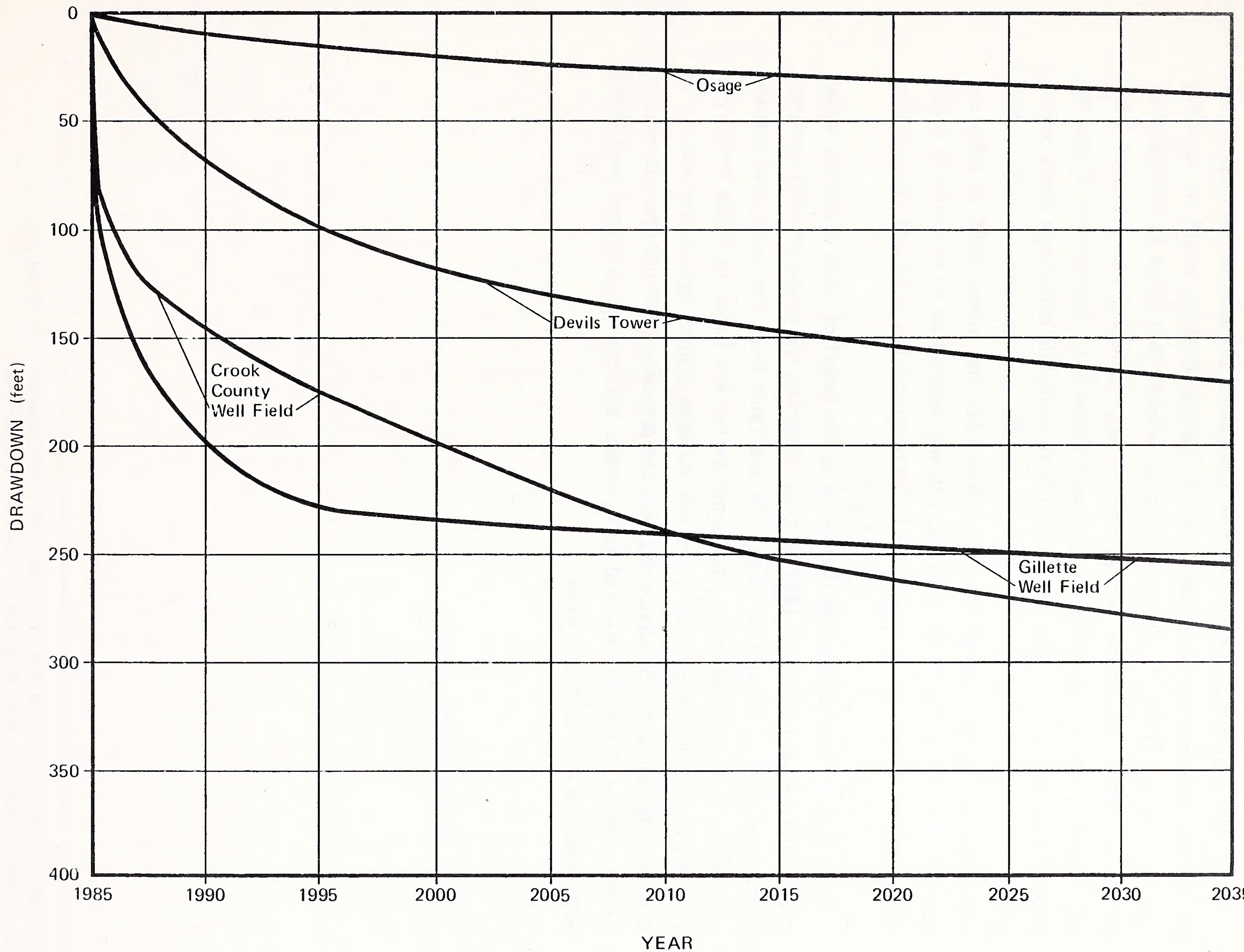


Figure 5-10. TIME-DRAWDOWN PLOT WITH PUMPING FROM THE CROOK COUNTY AND GILLETTE WELL FIELDS (PLAN 4)

The projected water production from the Madison aquifer during the period 1985 to 2035 was simulated so that the cumulative impacts of Madison water production, defined as all present and planned production, could be assessed (Tables 4-5, 4-6, and 4-7). The calculated drawdowns that occur as the result of simulated water production during this period, excluding the proposed ETSI development, are shown in Figure 5-11 and Table 5-1. Drawdowns of greater than 50 feet would occur only near the Gillette well field and Osage areas, where simulated production rates increase during the period 1985 to 2035. The calculated spring and stream flow reductions for the period 1985 to 2035 are listed in Table 5-2. The flow of Sand Creek was calculated to decrease by 3 cfs, but base-flow reductions in other streams were calculated to be less than 0.5 cfs.

The calculated drawdowns that occur as the result of total projected water production during the period 1985 to 2035, including the proposed ETSI developments, are shown in Figures 5-12 to 5-19 and Table 5-1. The calculated stream and spring flow reductions for this same period are listed in Table 5-2. The cumulative impacts of pumping from the Madison aquifer system are similar to the impacts calculated by simulating only the proposed ETSI withdrawals, except in the vicinity of the Gillette well field, where drawdowns are larger than those simulated for ETSI pumping alone.

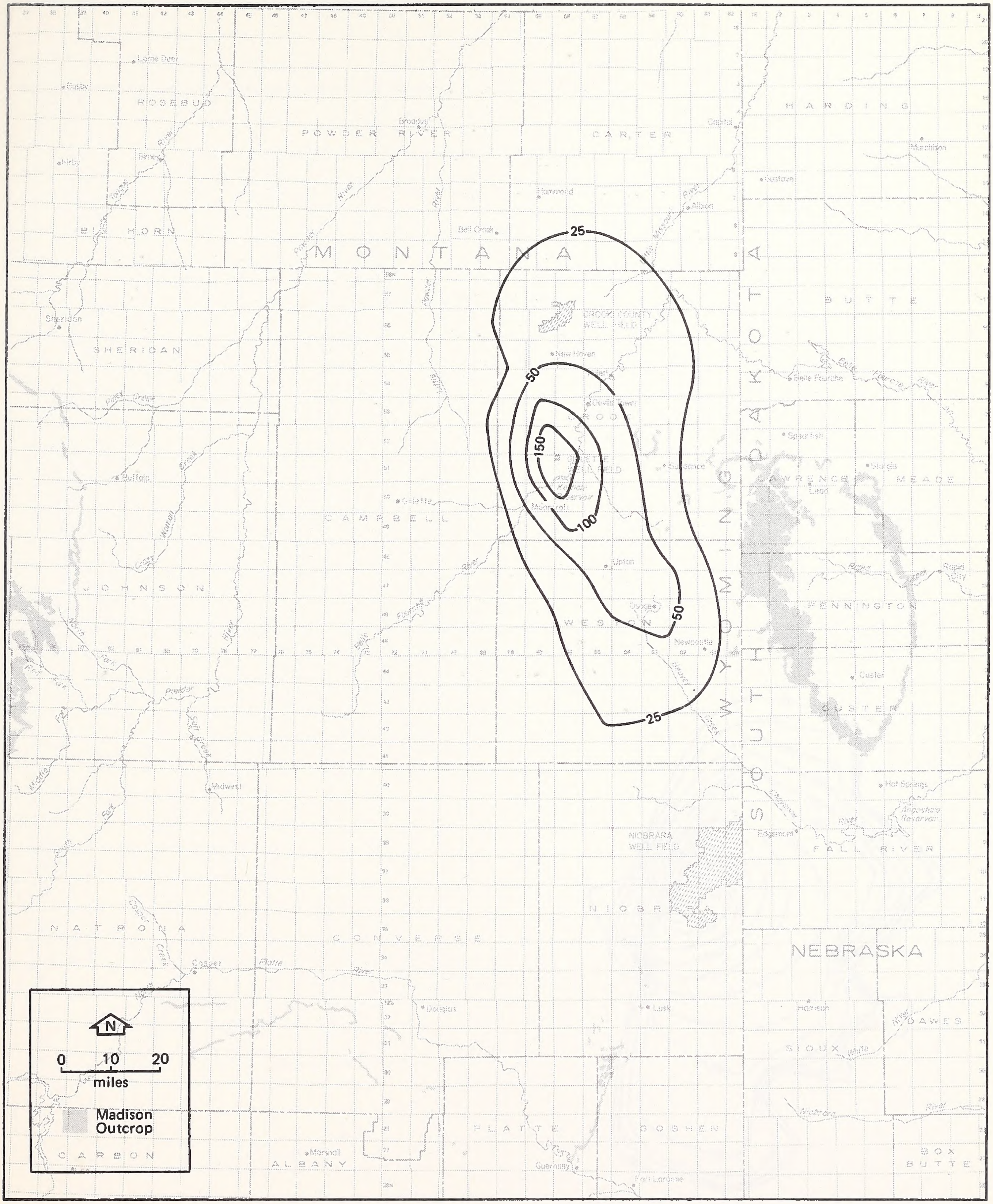


Figure 5-11. DRAWDOWNS (in feet) IN THE MADISON POTENTIOMETRIC SURFACE FOR THE YEAR 2035 WITH PUMPING BY CURRENT AND PLANNED MADISON WATER USERS ONLY

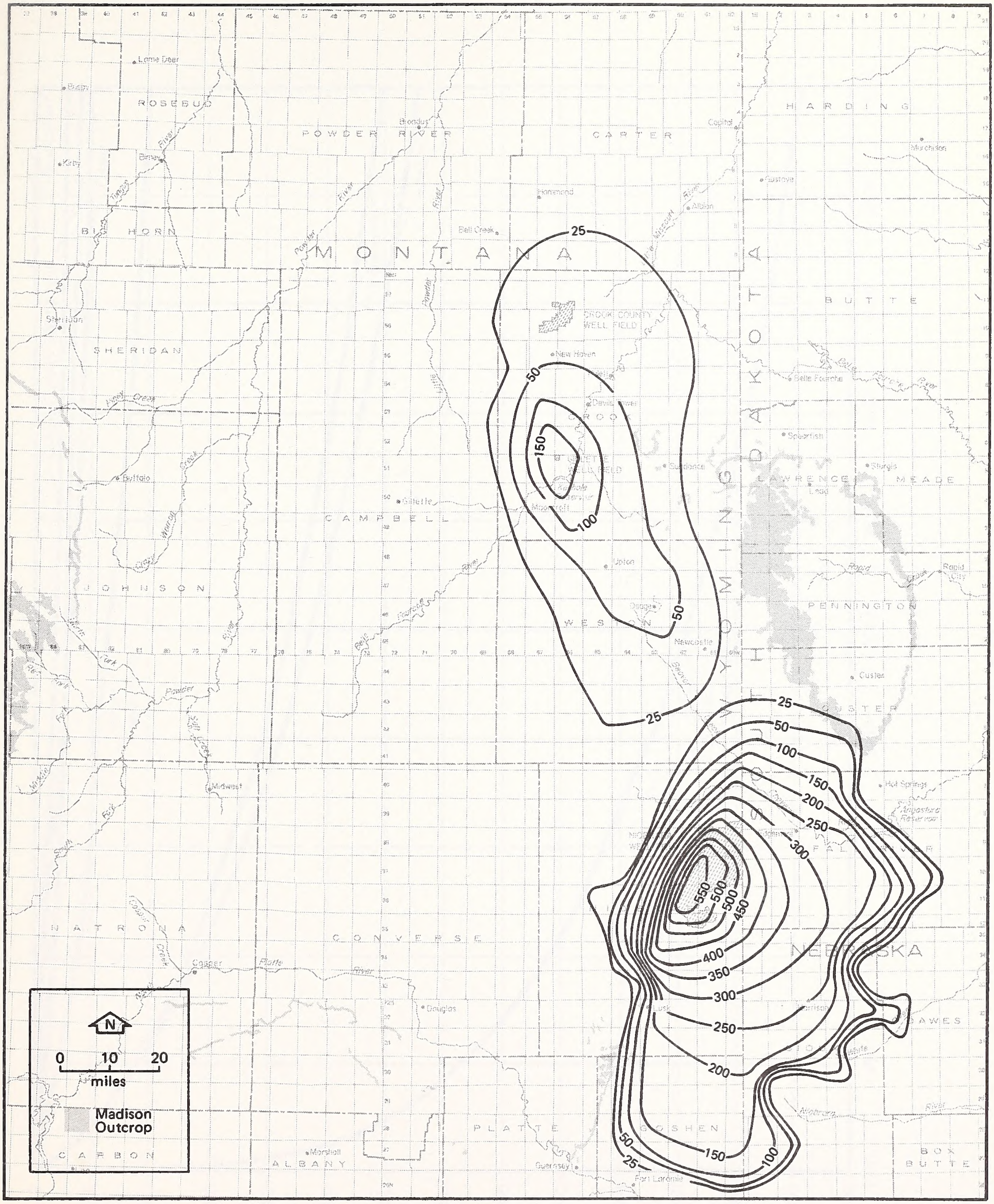


Figure 5-12. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING BY EXISTING AND PLANNED MADISON USERS, WITH ETSI PUMPING FROM NIOBRARA COUNTY WELL FIELD ONLY (PLAN 1)

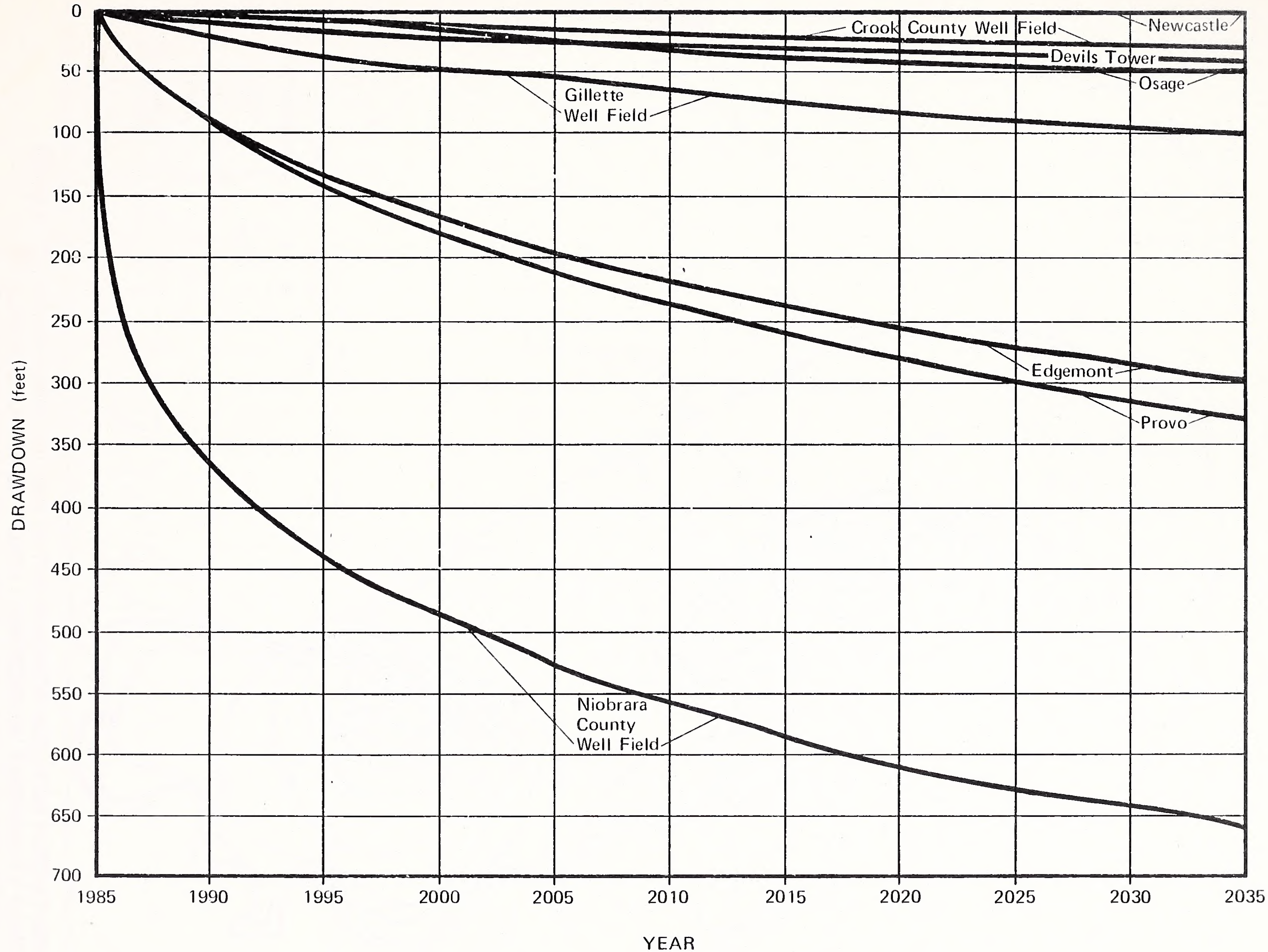


Figure 5-13. TIME-DRAWDOWN PLOT FOR PUMPING BY EXISTING AND PLANNED USERS, WITH ETSI PUMPING FROM NIOBRARA COUNTY WELL FIELD ONLY (PLAN 1)

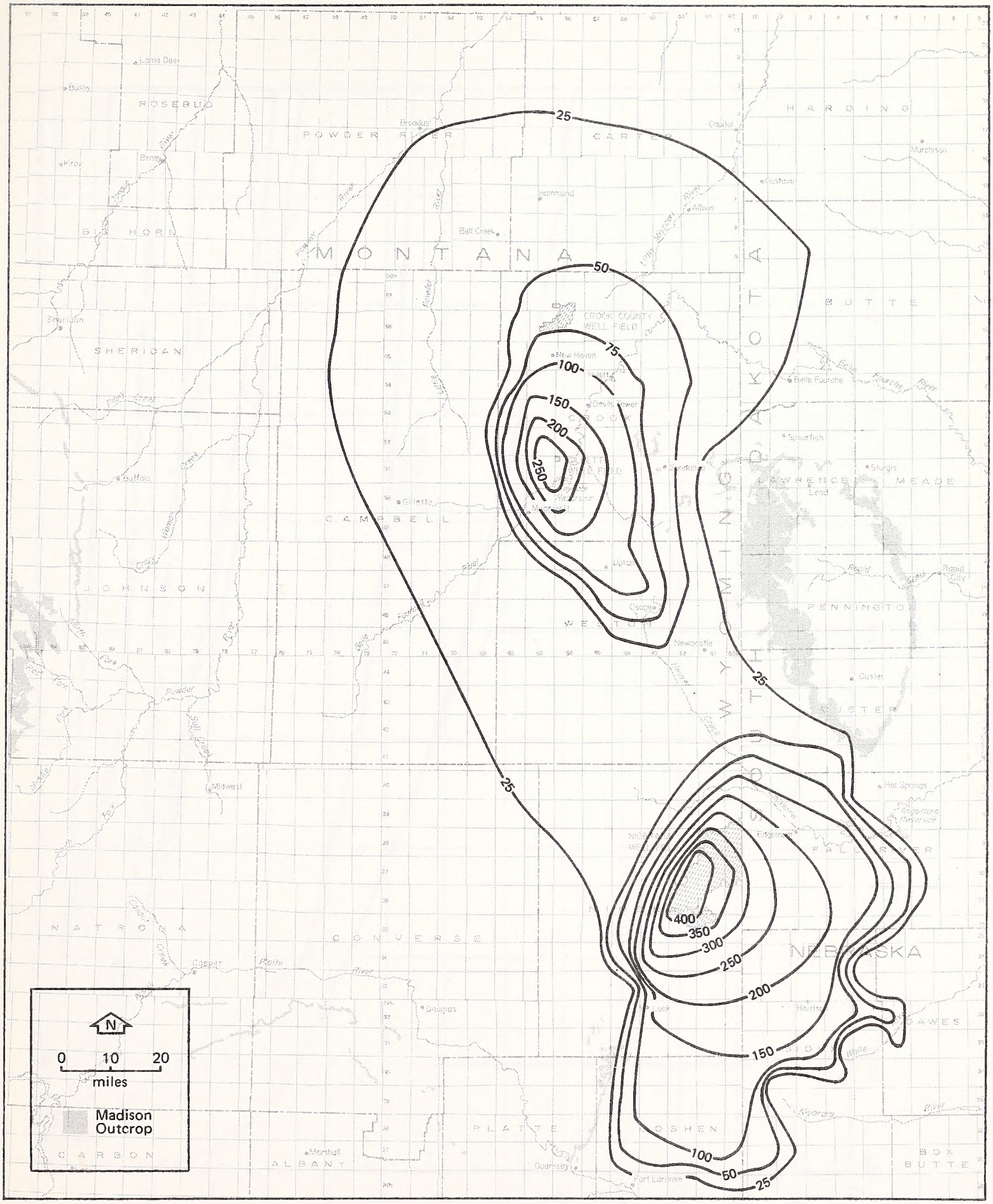


Figure 5-14. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING BY EXISTING AND PLANNED MADISON USERS, WITH ETSI PUMPING FROM NIOBRARA COUNTY AND GILLETTE WELL FIELDS (PLAN 2)

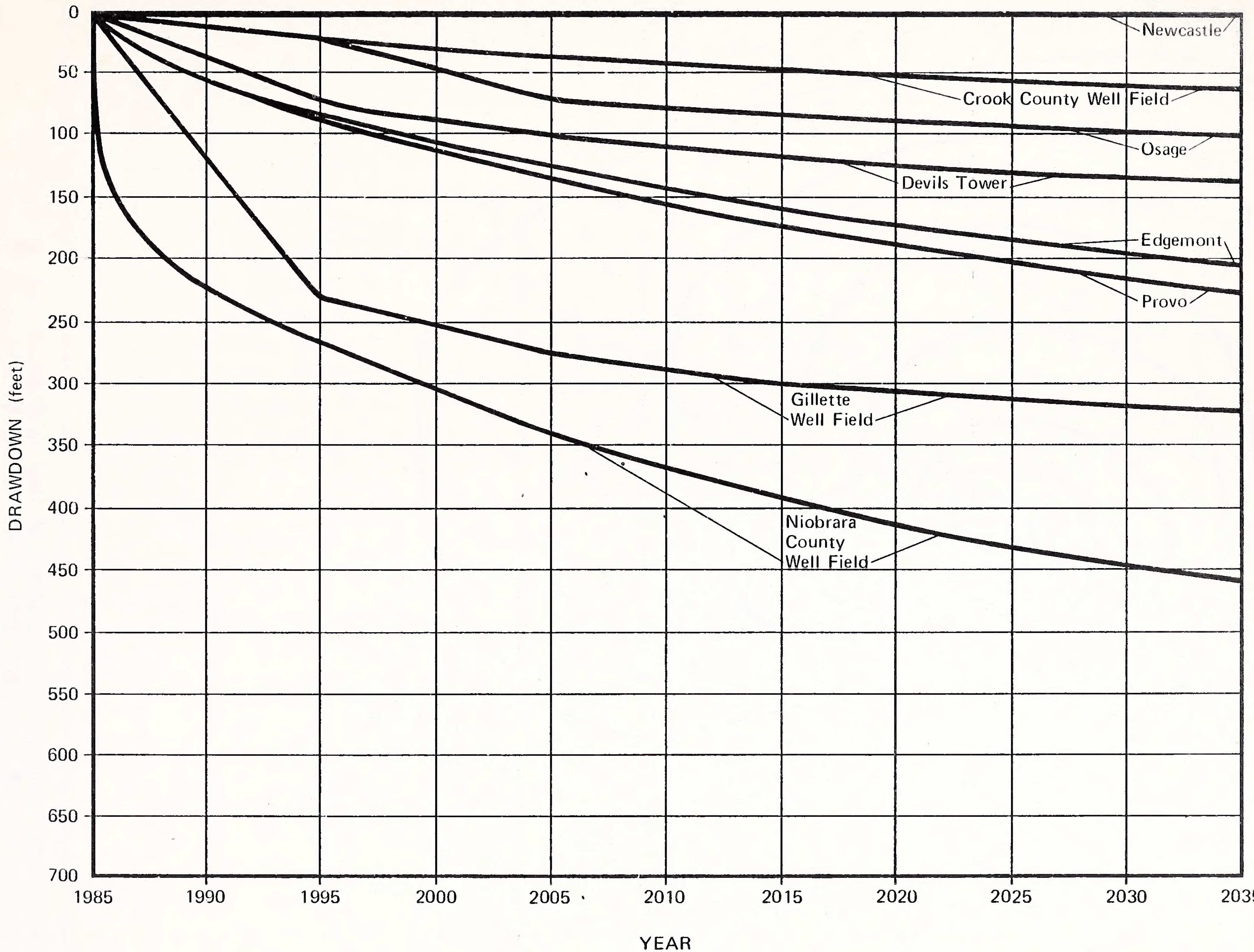


Figure 5-15. TIME-DRAWDOWN PLOT FOR PUMPING BY EXISTING AND PLANNED USERS, WITH ETSI PUMPING FROM BOTH NIOBRARA COUNTY AND GILLETTE WELL FIELDS (PLAN 2)

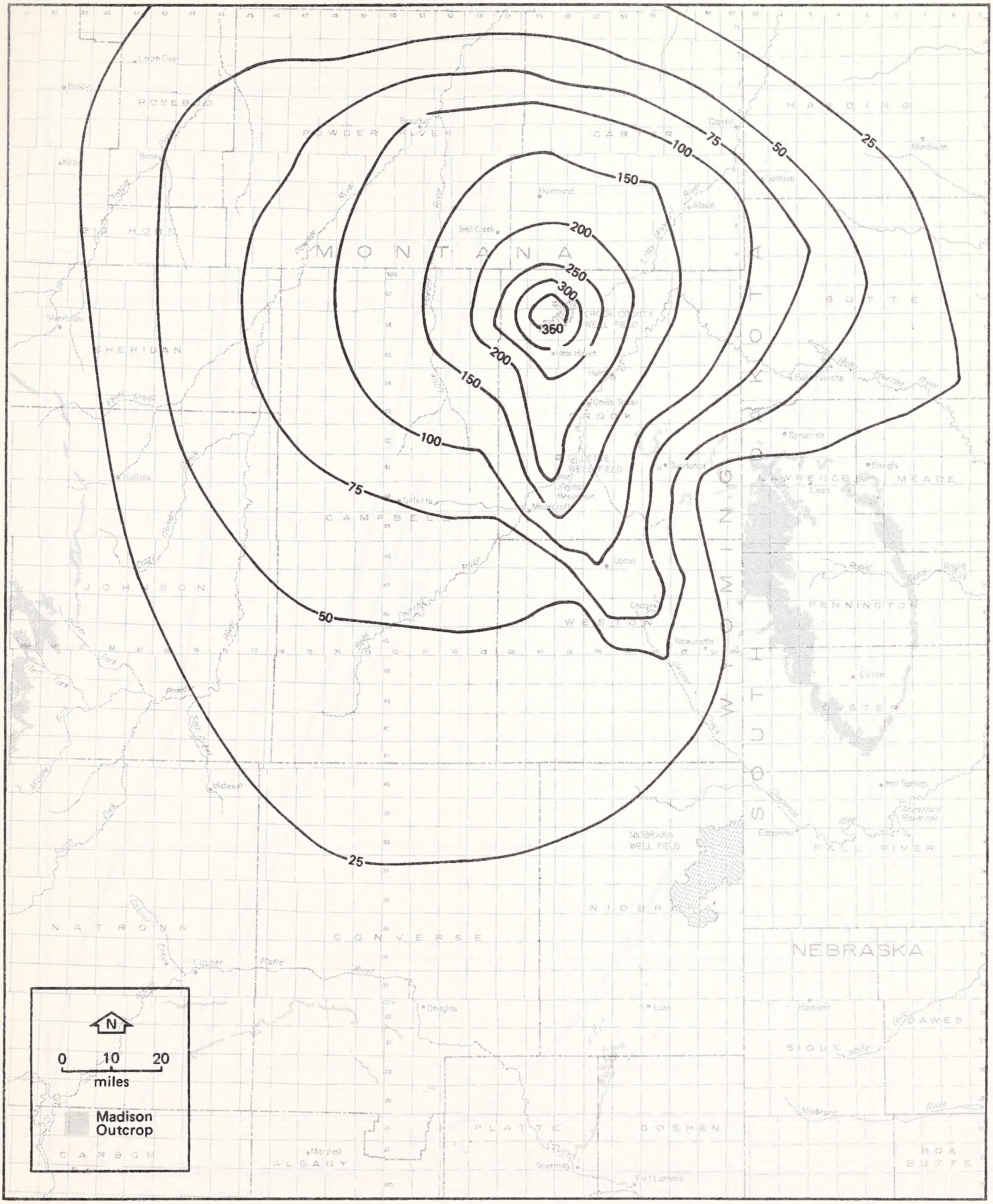


Figure 5-16. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING BY EXISTING AND PLANNED MADISON USERS, WITH ETSI PUMPING FROM CROOK COUNTY WELL FIELD ONLY (PLAN 3)

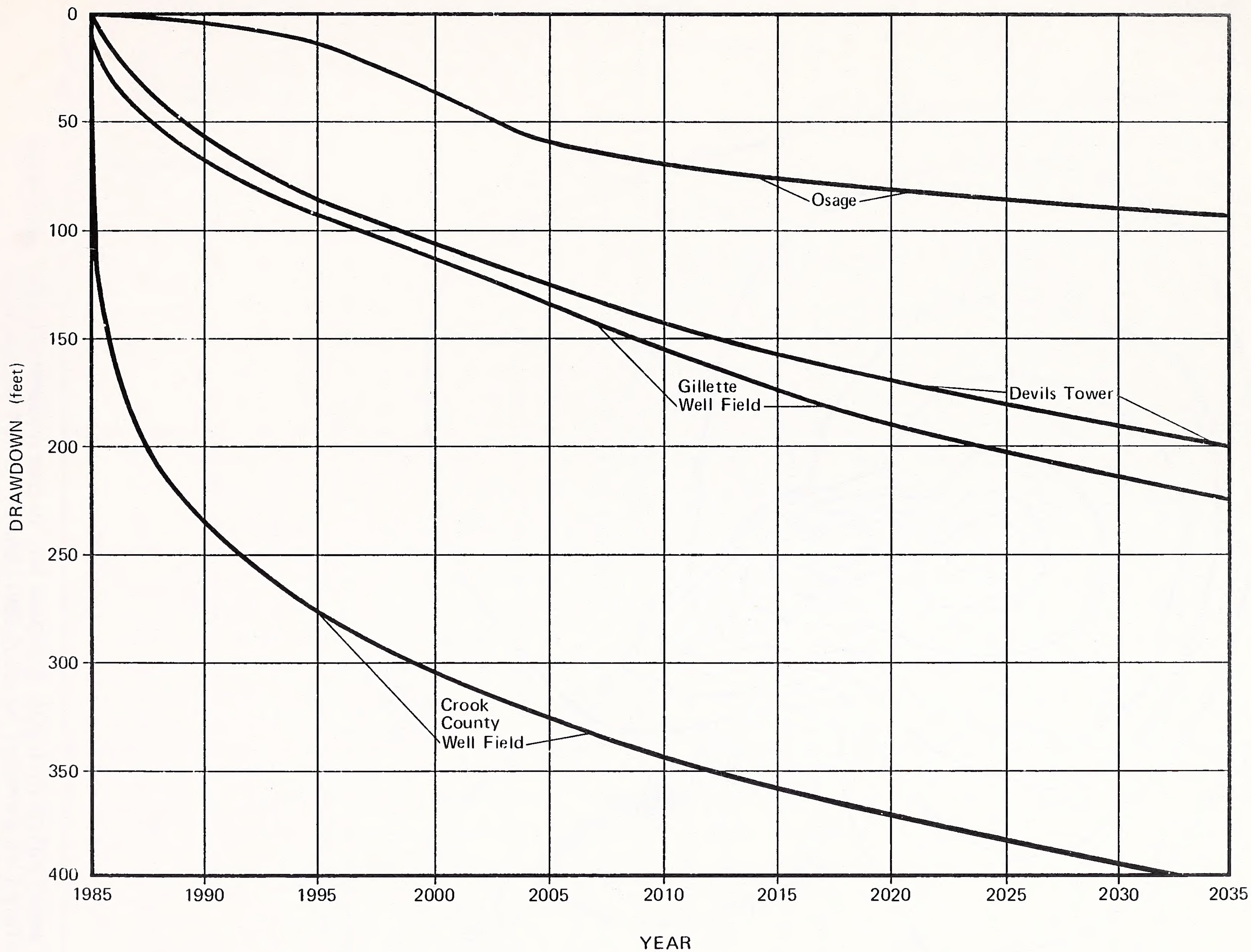


Figure 5-17. TIME-DRAWDOWN PLOT FOR PUMPING BY EXISTING AND PLANNED USERS, WITH ETSI PUMPING FROM CROOK COUNTY WELL FIELD ONLY (PLAN 3)

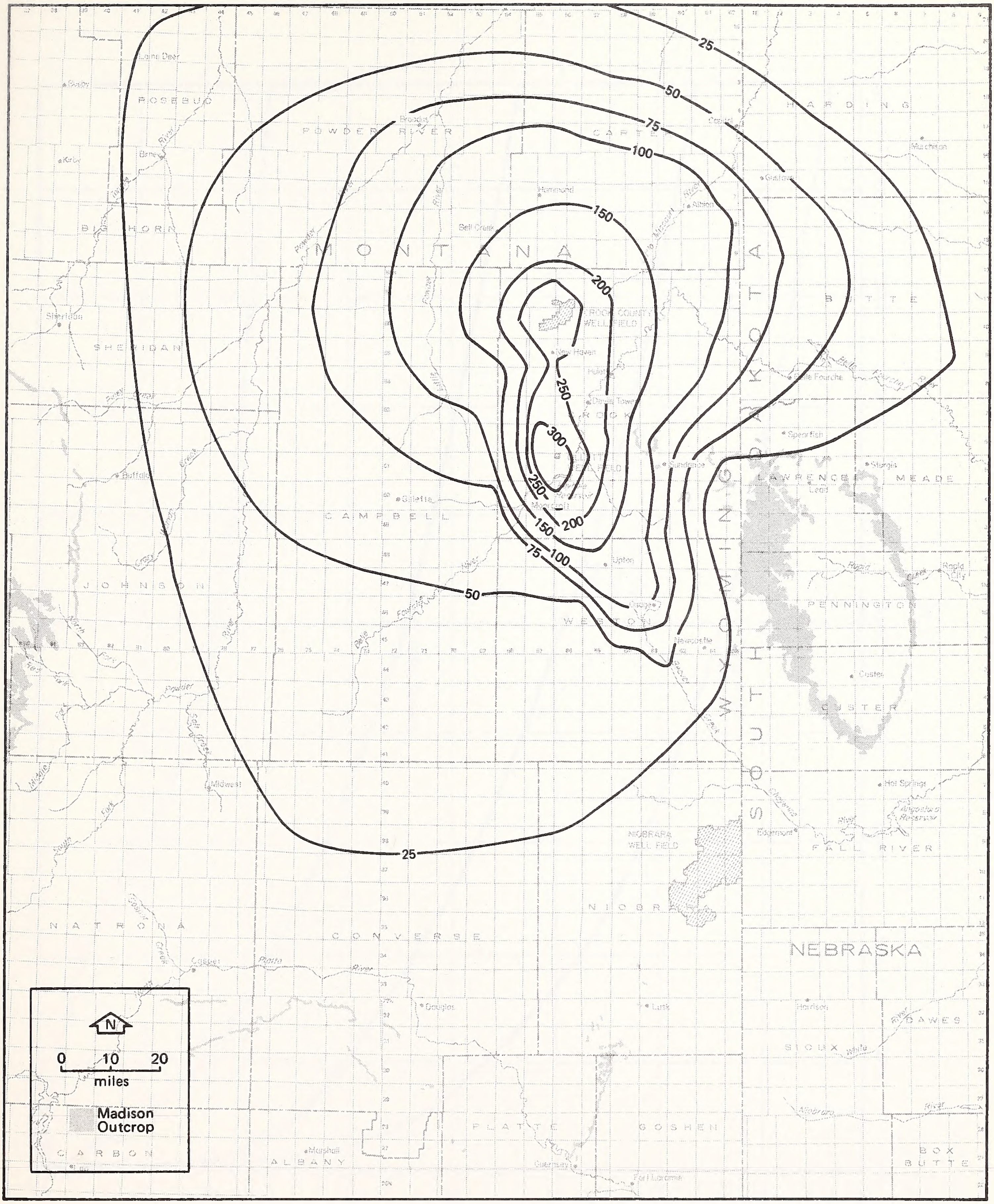


Figure 5-18. DRAWDOWNS (in feet) IN THE MADISON AQUIFER POTENTIOMETRIC SURFACE AFTER 50 YEARS (1985-2035) OF PUMPING BY EXISTING AND PLANNED MADISON USERS, WITH ETSI PUMPING FROM CROOK COUNTY AND GILLETTE WELL FIELDS (PLAN 4)

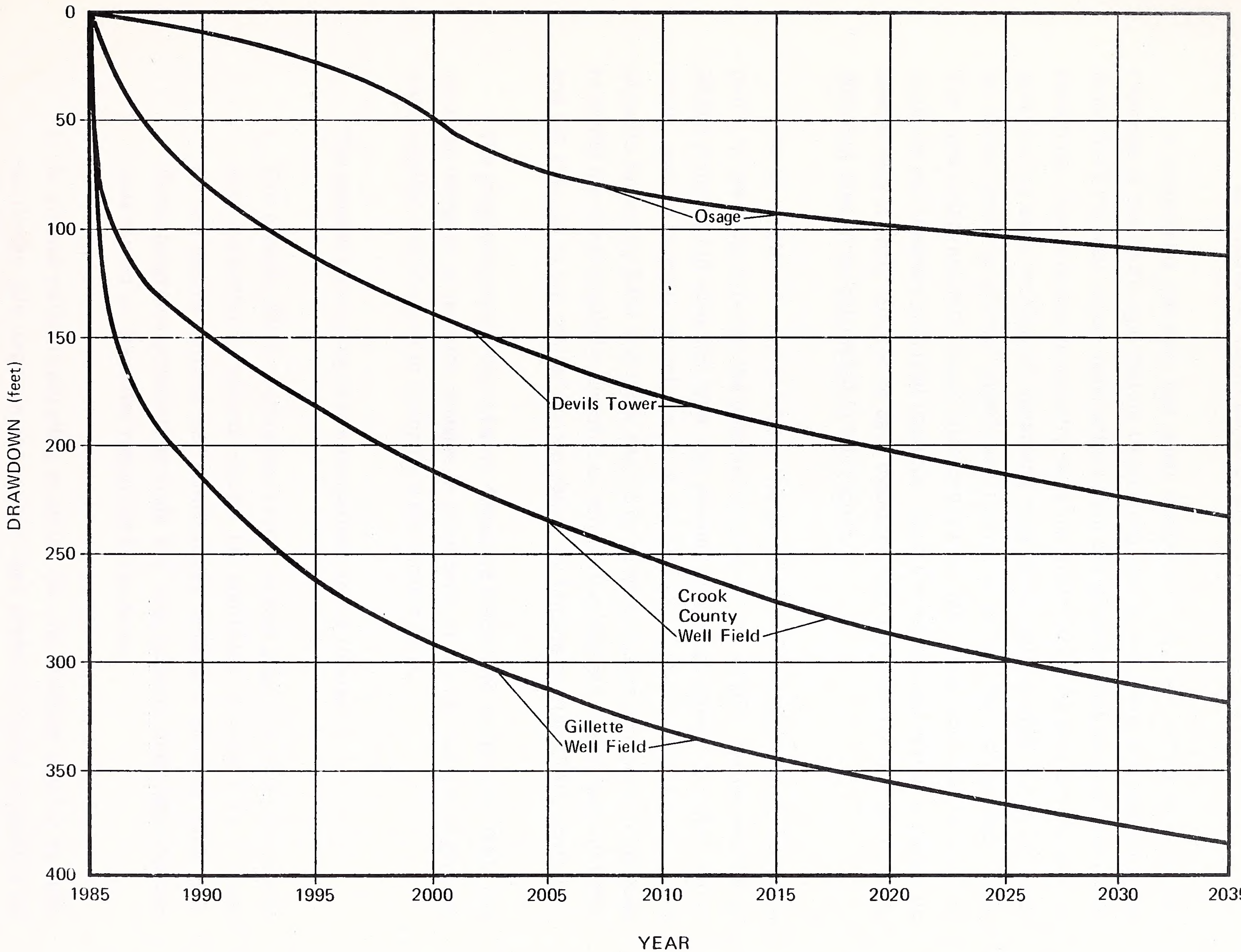


Figure 5-19. TIME-DRAWDOWN PLOT FOR PUMPING BY EXISTING AND PLANNED USERS, WITH ETSI PUMPING FROM BOTH CROOK COUNTY AND GILLETTE WELL FIELDS (PLAN 4)

6. MADISON AQUIFER SYSTEM MONITORING NETWORK

A monitoring network has been designed to provide information on the response of the hydrologic system to pumping stress, since the proposed pumping from the ETSI well fields would affect both the ground-water and surface-water resources. This proposed monitoring network would serve the primary purpose of providing an early warning of impending impacts so that remedial measures could be implemented to prevent significant impact to water users other than ETSI. The monitoring network would also provide a data base that can be used to evaluate and reassess potential impacts. Such a reassessment would probably be needed only if early monitoring data indicated that the impacts are significantly different than those calculated in this report.

As an additional consideration, the proposed monitoring network would be useful in assessing not only the possible impacts on the aquifer system caused by ETSI's pumping but also the type and amount of change caused by other water users, and by natural conditions such as climate. The distinction between impacts caused by ETSI and those caused by outside factors is important because remedial measures should be directed at mitigating impacts caused only by ETSI, and not changes to the aquifer system caused by factors outside ETSI's control.

The proposed monitoring network discussed below and outlined in Table 6-1 has been designed to monitor changes in ground-water levels, changes in ground-water quality, and changes in spring flow and stream flow.

The general monitoring recommendations are as follows:

1. The present USGS continuous-record stream gage and observation well data collection programs should be continued (Figure 6-1). These stream gaging stations and observations wells are listed in Table 6-2. These programs presently provide the only reliable long-term continuous record on the water resources in the area.

2. A ground-water monitoring program for the Madison aquifer system, similar to but larger in scope than that presently being conducted by

TABLE 6-1

OUTLINE OF MONITORING RECOMMENDATIONS

- Continue USGS stream gage and observation well program (Table 6-2).

- Monitor Madison ground-water users in northeastern Wyoming and western South Dakota for water levels (potentiometric head), water quality, and water use.

- A Minnelusa water well monitoring program should be designed and implemented near the selected ETSI well-field site after an inventory of these wells is completed.

- Install one Madison Group well and one Minnelusa Formation well between the Gillette well field and Upton, Wyoming.

- After the ETSI well field has been constructed and is in operation, monitor all ETSI production wells for rate of production, water levels, and water quality.

- A person or group, designated by mutual agreement with ETSI and state and federal agencies, should be established to collect, analyze, and report on the information collected by this monitoring network. A responsible authority, not associated with this person or group and having an understanding of the well-field operation and the Madison aquifer system, should be designated to review the data and analyses from the above-named person or group and to respond to any problems that could occur as a result of ETSI's well-field development.

TABLE 6-1 Continued

- These general recommendations should be implemented regardless of which individual plan is followed. Except for the recommendations directly pertaining to ETSI's development, these recommendations should be implemented in order to establish more complete hydrologic baseline conditions in the area and to assess impacts that are likely to be occurring as a result of present use of the water resources. The stress on the hydrologic system in this area, both present and future, is significant enough to warrant such a program, regardless of whether ETSI's project is approved. Programs by the U.S. Geological Survey, the U.S. Environmental Protection Agency, the University of Wyoming Water Resources Research Institute, and others that are inventorying and monitoring the water resources in the area should be continued.

Plan 1: Niobrara County Well Field Only

- All Madison (Pahasapa-Englewood Formation) and Minnelusa ground-water users in the Edgemont area should be monitored for water levels, water quality, and water use.

- Observation wells should be installed at or near locations OW-5 through OW-8 (Figure 6-1). Wells OW-5 through OW-7 should be completed in the Madison Group, and Well OW-8 should be completed in the Minnelusa Formation. Periodic water-level measurements should be made from these wells. Except when initially installed, no water quality samples need to be collected from these wells.

Plan 2: Niobrara County and Gillette Well Fields

- The recommendations as outlined under Plan 1 should be implemented.

- Production from the Gillette well field should be measured to account for the amount of water supplied to ETSI.

TABLE 6-1 Concluded

Plan 3: Crook County Well Field Only

- All Madison ground-water users in the well-field area should be monitored (Bell Creek, Montana; western Butte and Lawrence Counties, South Dakota; Crook County, Wyoming) for water levels and water quality.

- Observation wells should be installed at or near locations OW-9 through OW-11 (see Figure 6-1). Wells OW-9 and OW-10 should be completed in the Madison Group, and well OW-11 should be completed in the Minnelusa Formation. Periodic water-level measurements should be made from these wells. Except when initially completed, no water quality samples need to be collected from these wells.

- A stream gage, measuring daily stream flow and similar to those used by the U.S. Geological Survey, should be installed on the Belle Fourche River near Township 57 North and Range 63 West in Wyoming.

Plan 4: Crook County and Gillette Well Fields

- The recommendations outlined under Plan 3 should be implemented.

- Production from the Gillette well field should be measured to account for the amount of water supplied to ETSI.

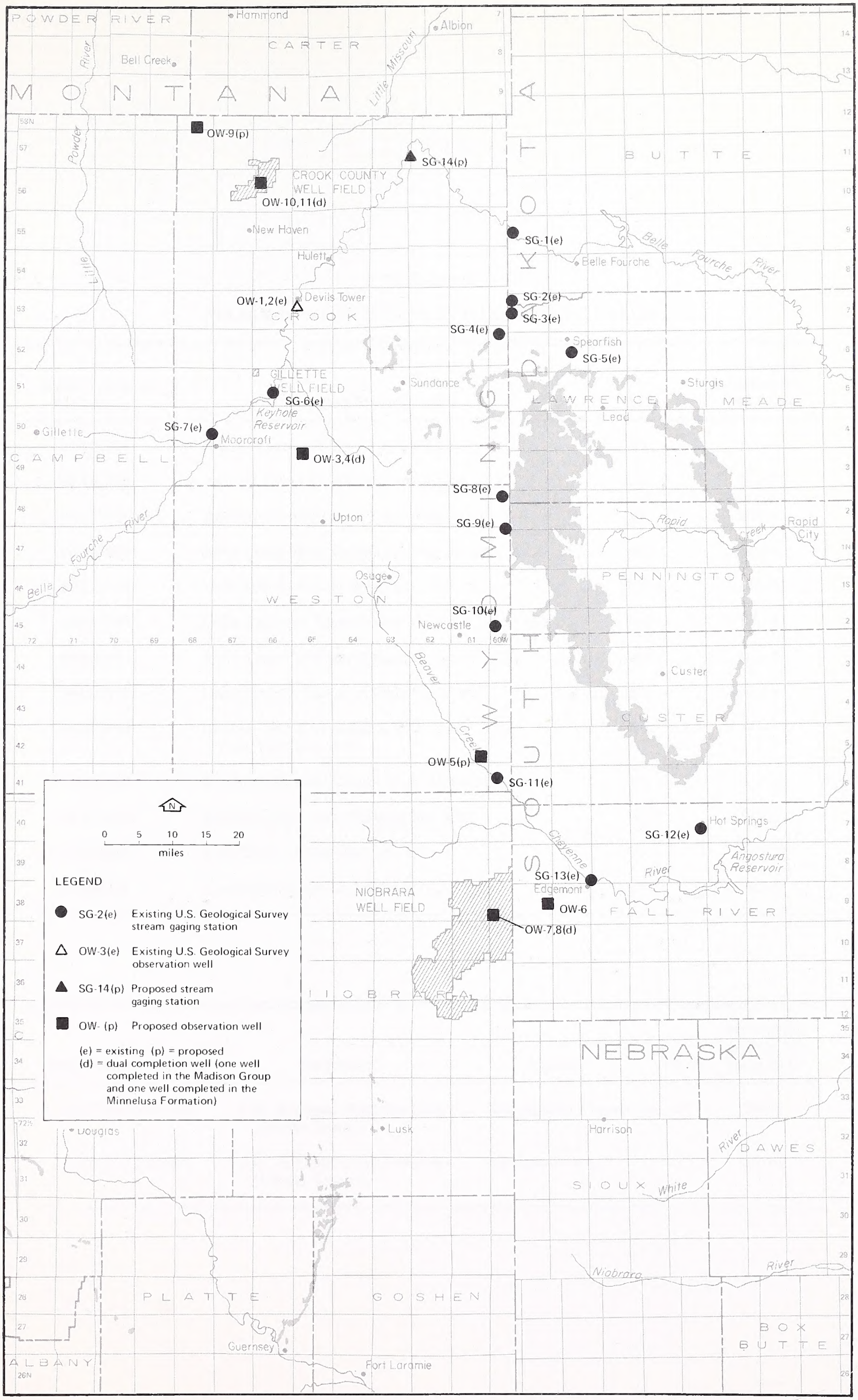


Figure 6-1. LOCATION OF EXISTING AND PROPOSED STREAM GAGES AND OBSERVATION WELLS FOR THE ETSI MONITORING NETWORK

TABLE 6-2

STREAM GAGING STATIONS AND MONITORING WELLS

Stream Gaging Station No.	Gaging Station Name	State	Monitoring Location No. (Map 6-1)
06428500	Belle Fourche River at WY-SD state line	SD	SG-1
06430000	Murray Ditch at WY-SD state line	SD	SG-2
06430500	Redwater Creek at WY-SD state line	SD	SG-3
06429905	Sand Creek near Ranch A, near Beulah, WY	WY	SG-4
06431500	Spearfish Creek at Spearfish, SD	SD	SG-5
06427500	Belle Fourche River below Keyhole Reservoir	WY	SG-6
06426500	Belle Fourche River below Moorcroft, WY	WY	SG-7
06429500	Cold Springs Creek at Buckhorn, WY	WY	SG-8
06392900	Beaver Creek at Mallo Camp, near Four Corners, WY	WY	SG-9
06392950	Stockade Beaver Creek near Newcastle, WY	WY	SG-10
06394000	Beaver Creek near Newcastle, WY	WY	SG-11
06402000	Fall River at Hot Springs, SD	SD	SG-12
06395000	Cheyenne River at Edgemont, SD	SD	SG-13

Observation Well No.	Well Name	Aquifer	State	Monitoring Location No. (Map 6-1)
443503104425101	U.S. National Park Service (Devils Tower)	Minnekahta Limestone	WY	OW-1
443459104425601	U.S. National Park Service (Devils Tower)	Madison Group	WY	OW-2

the University of Wyoming Water Resources Research Institute, should be conducted. This program should include the collection of data on water levels (potentiometric head), water quality, and amount of water produced from each Madison well at Bell Creek, Montana; in Crook, Weston, and Niobrara counties in Wyoming; and in Butte, Custer, Fall River, and Lawrence counties in South Dakota. This monitoring program should be placed in effect at least one year prior to, and continue at least one year after, any ETSI well field begins operation. This program is needed to develop baseline conditions on water levels, water quality, water use, and seasonal fluctuations before the ETSI well field begins operation. This program is also needed to assess the impact which these users are presently having and will have on the aquifer system. The scope of this program can be adjusted after one year of well-field operation, depending upon the response of the system to stress and seasonal change. During this baseline time period, the monitoring program should follow the schedule outlined below:

- Water-level measurements: monthly
- Water quality samples: quarterly
- Total volume of water withdrawn: monthly

The water quality parameters that should be analyzed include:

Field Measurements

pH
Temperature
Conductivity

Laboratory Measurements

Total suspended solids
Total dissolved solids
Conductivity
Total alkalinity as calcium carbonate
Total hardness as calcium carbonate
Sodium

Potassium
Calcium
Magnesium
Sulfate
Chloride
Carbonate
Bicarbonate
pH
Gross alpha
Gross beta

After a well site is chosen, monitoring requirements can be reduced to encompass only the area potentially affected by ETSI's ground- water withdrawals.

3. The University of Wyoming Water Resources Research Institute is presently making a Minnelusa water-well inventory in northeastern Wyoming. After this well inventory has been completed, a representative number of wells near the chosen ETSI well site should be selected for the monitoring network to observe Minnelusa water levels and water quality. The monitoring procedures and schedule should follow the procedure outlined for the Madison wells above. These Minnelusa Formation wells will be useful in helping to measure impact on the Minnelusa aquifer system and in observing the amount of leakage that may be induced by ETSI's well-field development.

4. A similar inventory should be made of Minnelusa wells near the selected well-field site in Butte, Custer, Fall River, and Lawrence counties, South Dakota. Data collected should be similar to data collected on the Madison and Minnelusa wells in Wyoming. From this inventory, a monitoring network should be designed for measuring potential impacts.

5. Two observation wells, one completed only in the Madison Group and one completed only in the Minnelusa Formation, should be installed between the Gillette well field and Upton, Wyoming. Depending upon

the accessibility of the proposed site, land status, and other economic factors, these wells should be located in or near township 49 north and range 65 west in Wyoming (see Wells OW-3 and OW-4 on Figure 6-1). These wells may be installed as individual wells, as dual completion wells, or in another similar manner. The wells should be constructed so that data collected from each well reflect the most representative aquifer characteristics of the formation to which the well is open, screened, or perforated, and not rock formations above or below. The Madison well should be open to the entire Madison interval. The Minnelusa well should be open, screened, or perforated to the more permeable part of the Minnelusa and to the interval that yields the most water to wells in the area surrounding this well field. The frequency and type of measurements to be made from these wells should be the same as those measurements outlined above. The data from these wells are needed to separate the amount of impact the Gillette well field will have on the aquifer system from those impacts caused by other Madison wells to the south (Upton, Osage, and Newcastle).

6. Once the ETSI well field has been constructed, all of the ETSI Madison production wells should be monitored in the following manner:

   a. Water-level measurements and water quality samples should be taken from each well before any ETSI well field is placed into operation. This should be done after the well has been developed. This monitoring process should continue on a monthly basis until all of the wells are drilled and the well field begins operation in order to establish baseline conditions at the well field.

   b. After the ETSI well field is placed into operation, water-level measurements should be taken from any unused production wells in the ETSI well field on a weekly basis for the first full year of operation and on a monthly basis thereafter. Depending on the response of the aquifer system to stress, the frequency of these measurements can be adjusted.

c. Water quality samples should be collected from each ETSI production well on a monthly basis for the first year and on a quarterly basis thereafter. The frequency of sampling and the number of wells sampled can be reduced or increased after one year of operation. At least four wells, one each near the northern, southern, eastern, and western borders of the well field, should be sampled on a quarterly basis after one year of operation.

d. Ground-water production at all of ETSI's production wells should be continuously monitored.

7. One person or group of people needs to be assigned to collect, analyze, and report the data from this monitoring network. This authority should understand all aspects of ETSI's well-field operation, the hydrogeology and use made of the Madison aquifer system, and should have the capability of identifying and implementing any actions necessary to remedy any problems caused by ETSI's ground-water development and affecting water users other than ETSI.

At the present time, a number of federal, state and university programs are studying, inventorying, and monitoring the ground- and surface-water resources in the Powder River Basin and Black Hills area. Programs by the U.S. Geological Survey, the U.S. Environmental Protection Agency, and the University of Wyoming's Water Resources Research Institute should be continued. These studies will establish important hydrologic baseline conditions in the area which will enable the assessment of impacts that are likely to occur as a result of present use of the water resource. In this regard, ETSI's monitoring network should be designed to complement, and not substitute for, a comprehensive program which can be used to provide information on the water resource as the Madison aquifer becomes more fully developed. With the development of the Gillette well field near Moorcroft and any additional development near Osage or Newcastle, additional impact will likely occur to the Madison aquifer system, regardless of ETSI's well-field development.

One of the following monitoring programs should be implemented to complement the general monitoring network described above if a decision is made to select one of the well fields. The monitoring network described below is specifically tailored to apply to one of ETSI's proposed development plans.

6.A PLAN 1: NIOBRARA COUNTY WELL FIELD ONLY

The following recommendations should be implemented to monitor ground-water levels, water quality, water use, and spring and stream flows in the vicinity of the Niobrara County well field if plan 1 is adopted:

1. All Madison and Minnelusa ground-water wells in the vicinity of the well-field should be monitored. These include the Madison and Minnelusa wells at Edgemont and Provo, South Dakota (Madison wells numbered F-1 through F-7 in Figure 3-11). Madison wells F-9, F-10, and F-11 should be monitored if they are in use or are accessible for measurement. Where practical, these wells should be monitored for water levels (potentiometric head), water quality, and amount of water produced in the same manner and schedule as the Madison wells discussed above. If any additional Minnelusa wells are identified from the well inventory described above, a representative number of these wells in the vicinity of the well site should also be monitored.

2. Observation wells should be installed in or near locations OW-5, OW-6, OW-7, and OW-8 shown on Figure 6-1. Wells OW-5 through OW-7 should be completed in the Madison Group and well OW-8 in the Minnelusa Formation in the same manner and for the same purposes as described earlier for the Madison and Minnelusa wells at observation well sites OW-3 and OW-4. Although permits from the Wyoming State Engineer state that five wells in specific locations should be constructed as observation wells for the Niobrara County well field, it is felt by the study team that the monitoring network as described here will adequately serve the monitoring purpose. The water-level monitoring schedule should follow the same schedule as that described for the Madison wells. No water quality samples need to be collected from these wells, except at initial installation.

6.B PLAN 2: NIOBRARA AND GILLETTE WELL FIELDS

A monitoring program for both the Niobrara and Gillette well fields should be implemented if plan 2 is adopted. The monitoring program for plan 1 should be established for the Niobrara field. In addition, each of the Gillette wells should be monitored for discharge rates in the manner and schedule outlined in plan 1 to account for the amount of water pumped by ETSI, as well as the amount pumped by Gillette. Water-level measurements should also be made in any unpumped Gillette wells on a monthly basis.

6.C PLAN 3: CROOK COUNTY WELL FIELD ONLY

A program to monitor ground-water levels, water quality, and spring and stream flows at the Crook County well field should be implemented if plan 3 is adopted. The following recommendations should be implemented:

1. All Madison ground-water wells in the well-field area should be monitored. These include the Madison wells at Bell Creek, Montana, Crook County, Wyoming, and Butte and Lawrence counties in South Dakota (wells numbered P-1 through P-4, B-1 through B-9, and L-7, L-8, L-11, L-12, and L-13 in Appendix E). Where practical, these wells should be monitored for water level (potentiometric head), water quality, and amount of water produced in the same manner and schedule outlined for the Madison wells described earlier. After the Minnelusa well inventory has been completed, a representative number of these wells in the vicinity of the well site should be monitored in the same manner as the Madison wells.

2. Observation wells should be installed in or near locations OW-9, OW-10, and OW-11 shown in Figure 6-1. Wells OW-9 and OW-10 should be completed in the Madison Group and well OW-11 in the Minnelusa Formation in the manner and for the same purposes as described earlier for the Madison and Minnelusa wells at observation well sites OW-3 and OW-4. The water-level monitoring schedule should follow the same schedule as that described above for the Madison wells. No water

quality samples need to be collected from these wells, except at initial installation.

3. A continuously recording stream gage should be installed on the Belle Fourche River in northeastern Crook County near monitoring site SG-14 (Figure 6-1). This stream gage should be installed and maintained in the same manner as the other USGS stream gaging stations in the area. The purpose of this additional stream gage is to better define the relationship between ground water and stream flow and to help identify and quantify potential impacts on the Belle Fourche River between Keyhole Reservoir and the Wyoming-South Dakota state line that might be caused by ETSI's pumping from the Crook County well field.

6.D PLAN 4: CROOK COUNTY AND GILLETTE WELL FIELDS

A monitoring program for both the Crook County and Gillette well fields should be implemented if plan 4 is adopted. The monitoring program for plan 3 should be established. In addition, each of the Gillette wells should be monitored for discharge rates in the manner and schedule outlined in plan 3 to account for the amount of water pumped by ETSI, as well as the amount pumped by Gillette. Water levels should also be monitored in any unpumped Gillette well on a monthly basis.

7. RELIABILITY OF IMPACT PREDICTIONS

The aquifer parameters used in the numerical models developed for predicting the drawdowns from the proposed ETSI withdrawals are the best estimates of these parameters on the basis of available data. Data on these parameter estimates, especially on those pertaining to the hydraulic connection between the Madison aquifer and adjacent formations, were very limited. Consequently, uncertainty is associated with each of these parameter estimates. In an attempt to evaluate the effect of this uncertainty on the predicted drawdowns, Monte Carlo simulations were used to calculate the likelihood that drawdowns would be greater than or less than those drawdowns calculated (Section 5) when the best estimates of the aquifer parameters (Section 4) were used. In this report, Monte Carlo simulations refer to a set of repetitive simulations with a mathmatical model and the associated statistical analyses of the results.

Separate Monte Carlo simulations were performed only for plan 1 (Niobrara well field only) and plan 3 (Crook County well field only). Monte Carlo simulations for plans 2 and 4 (plans 1 and 3 with Gillette supplemental water) would produce results similar to those for plans 1 and 3.

7.A METHOD

The following steps were taken in assessing the reliability of the calculated drawdowns:

1. A log-normal probability distribution was specified for each of the model parameters.

2. One hundred sets of parameter combinations were randomly generated from the specified log-normal distributions.

3. Transient simulations of the ETSI withdrawals for a 50-year period were made for each of the 100 combinations generated in step 2.

4. The drawdowns calculated in the 100 simulation runs were statistically analyzed to calculate the probability that a specified drawdown will be exceeded.

A probability distribution was specified for each parameter that describes the uncertainty associated with the parameter estimates (Table 7-1). The starting point for defining the probability distributions was to assume that the distributions were log-normal (Freeze 1975; Baker and others 1978; Smith and Freeze 1979). The distributions were then defined by specifying a median value and extreme values on the basis of known information about the parameters.

7.A.1 STORAGE COEFFICIENT

The median value for the storage coefficient in all layers was specified as 3.3×10^{-7} per foot of aquifer thickness; this is consistent with the values derived in Section 4 (Figure 7-1). The storage coefficient in all layers was specified as having a 98 percent probability of being greater than 10^{-7} per foot of aquifer thickness. A storage coefficient of 10^{-7} per foot of aquifer thickness corresponds to an aquifer with no matrix compressibility and a porosity of 7 percent.

7.A.2 LEAKAGE COEFFICIENT

The median value for the leakage coefficient between all sets of adjacent aquifer units was specified as equal to the value listed in Table 4-1, which were used in transient simulations. The extremes of the leakage coefficient distributions were specified by assuming that there is a 98 percent probability that the actual leakage coefficient is greater than a value one order of magnitude less than the median value (Figure 7-2).

7.A.3 TRANSMISSIVITY

The median value of the transmissivity of the Madison aquifer unit in the vicinity of the Niobrara well field was specified as 0.03 ft^2/sec. This transmissivity was specified as having a 98 percent probability of being greater

TABLE 7-1

PROBABILITY DISTRIBUTIONS USED IN MONTE CARLO SIMULATIONS

Parameter	Original Value Used in Numerical Simulations	Median Value	Value With 2 Percent Exceedence Probability	Value With 98 Percent Exceedence Probability
Madison Transmissivity (ft^2/sec)	0.030 (Niobrara) 0.034 (Crook)	0.030 (Niobrara) 0.030 (Crook)	0.09 (Niobrara) 0.16 (Crook)	0.01 (Niobrara) 0.01 (Crook)
Red River Hydraulic Conductivity (ft/sec)	0.00375	0.0054	0.015	0.002
Specific Storage for All Units	$3.3x10^{-7}$	$3.3x10^{-7}$	10^{-7}	10^{-6}
Leakage Coefficient (sec^{-1}) Red River to Madison	10^{-9}	10^{-9}	10^{-8}	10^{-10}
Leakage Coefficient (sec^{-1}) Madison to Minnelusa*	10^{-10}	10^{-10}	10^{-9}	10^{-11}
Leakage Coefficient (sec^{-1}) Minnelusa to Upper Unit	$4x10^{-12}$	$4x10^{-12}$	$4x10^{-11}$	$4x10^{-13}$
Monocline Transmissivity Reduction Factor	0.010	0.018	0.62	0.005

* Where the Minnelusa Formation was composed of less than 50 percent clastics, the values shown were reduced by one order of magnitude.

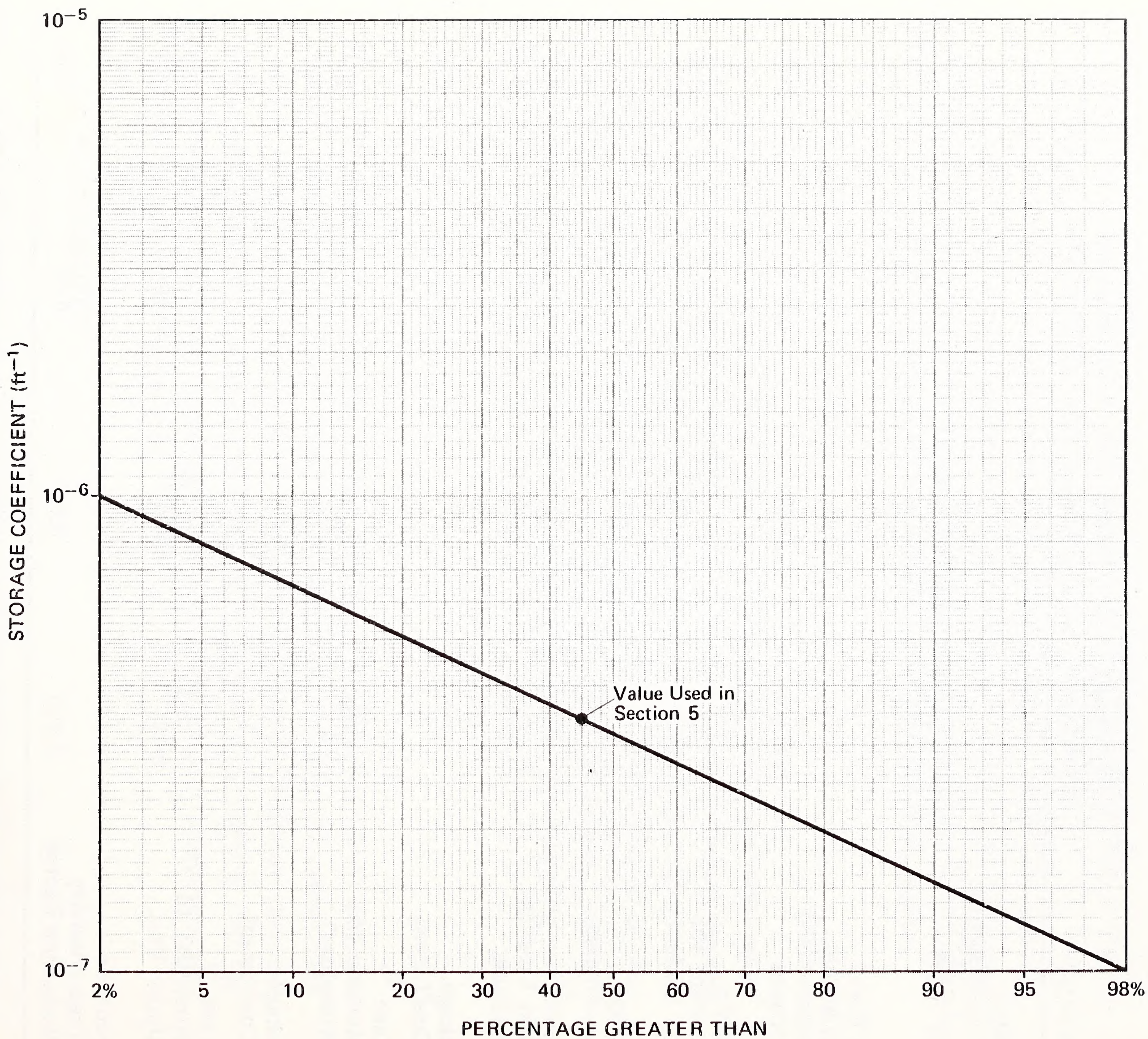


Figure 7-1. PROBABILITY DISTRIBUTION SPECIFIED FOR THE STORAGE COEFFICIENTS (SPECIFIC STORAGE) IN ALL UNITS

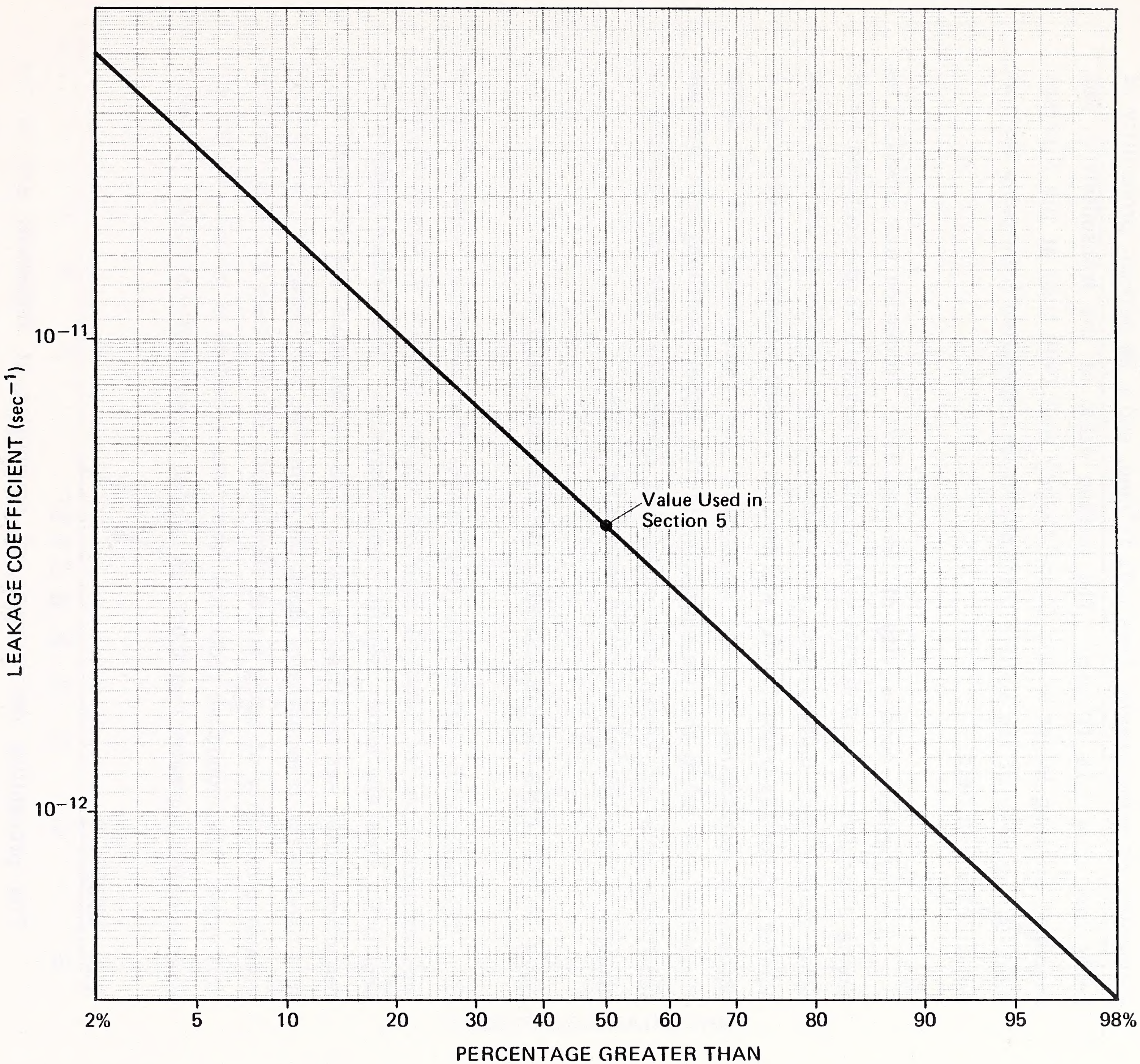


Figure 7-2. PROBABILITY DISTRIBUTION SPECIFIED BY THE LEAKAGE COEFFICIENT IN THE UPPER CONFINING UNIT

than 0.01 ft^2/sec (Figure 7-3). The median value of the transmissivity of the Madison aquifer unit in the vicinity of the Crook County well field was specified as 0.034 ft^2/sec. This transmissivity was specified as having a 98 percent probability of being greater than 0.01 ft^2/sec, and a 98 percent probability of being less than 1.16 ft^2/sec. The median value of the transmissivity was specified as being larger at the Crook County well field than at the Niobrara field, on the basis of the aquifer transmissivities calculated from pump tests at the Gillette well field.

The hydraulic conductivity of the Red River Formation was specified as having a median value of 0.0055 ft/sec, and as having a 98 percent chance of being greater than 0.002 ft/sec. The hydraulic conductivity of the Red River aquifer and not the transmissivity was used for reasons discussed in Section 4. A probability distribution was not assigned to the transmissivity of the upper Minnelusa unit or to the transmissivity of the Upper Confining unit because sensitivity runs had shown that calculated drawdowns were not sensitive to changes in these parameters within reasonable limits.

7.A.4 MONOCLINE TRANSMISSIVITY REDUCTION FACTOR

The probability distribution function for the monocline reduction factor was estimated on the basis of observed aquifer behavior in the steady-state sensitivity runs and known aquifer transmissivities. The median value of the reduction factor was specified as 0.018. The median value was not specified as 0.01 because the transmissivity along the monocline was thought to have a much greater probability of being larger than 0.0003 ft^2/sec than of being less than this value. The monocline reduction factor was specified as having a 98 percent chance of being greater than 0.005 (an implied transmissivity of 0.0002 ft^2/sec).

7.B RESULTS

The probability distributions of drawdowns at Edgemont and at the Niobrara well field as calculated from the Monte Carlo simulations of pumping 20,500 acre-feet per year for 50 years from the Niobrara field are shown on Figures 7-4 and 7-5. The calculated probability distribution of drawdowns at

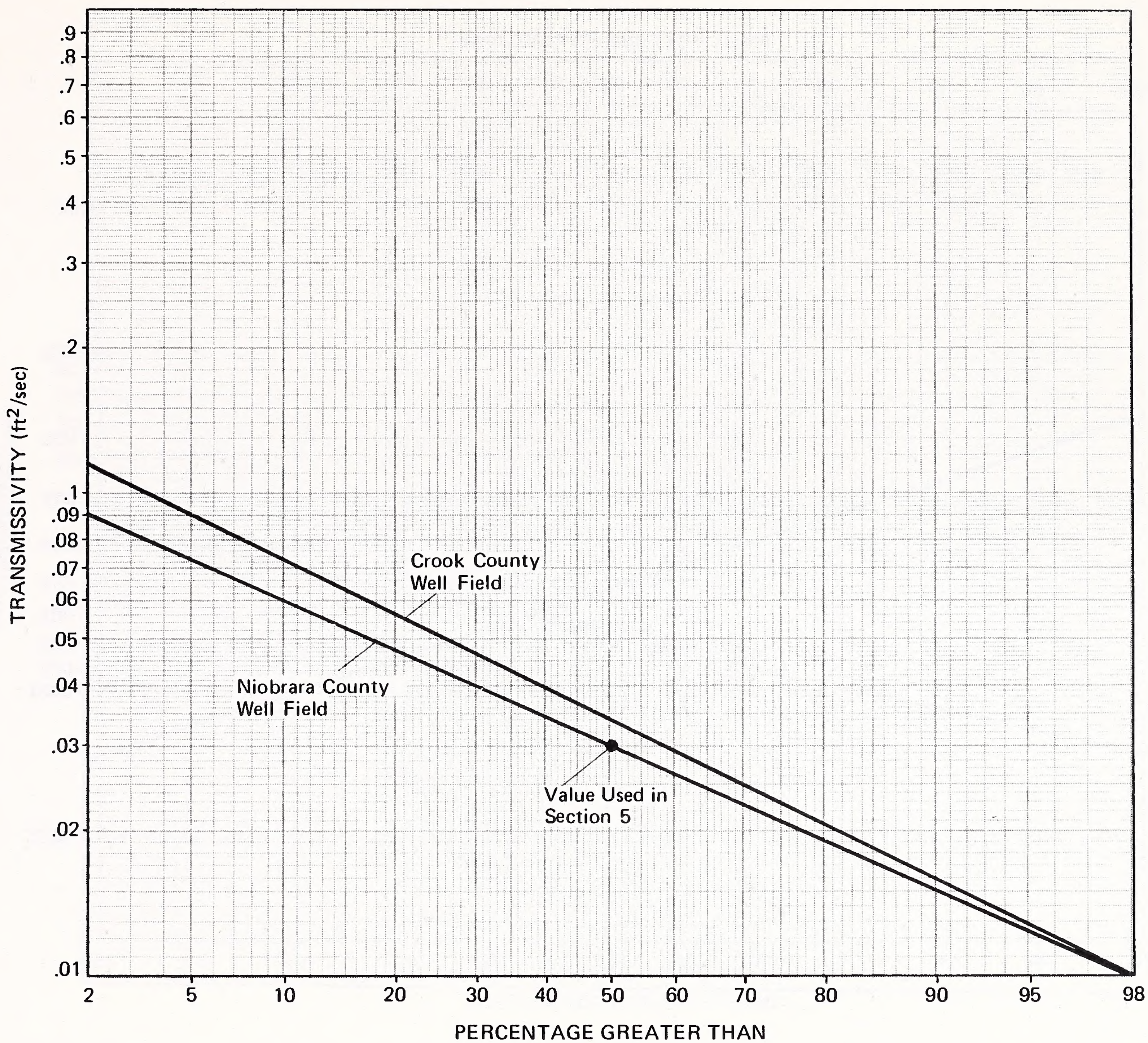


Figure 7-3. PROBABILITY DISTRIBUTION SPECIFIED FOR THE TRANSMISSIVITY OF THE MADISON UNIT

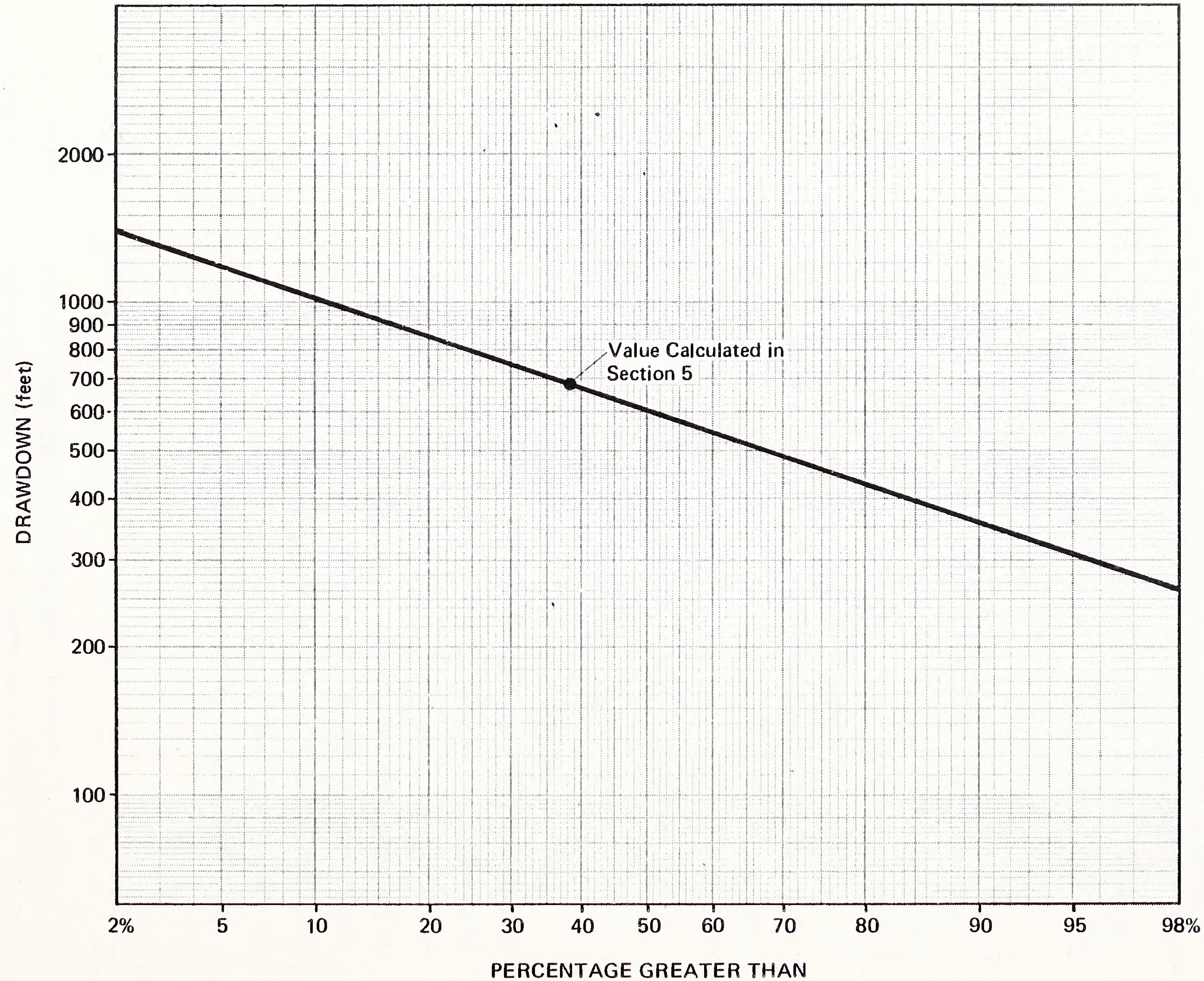


Figure 7-4. CALCULATED PROBABILITY DISTRIBUTION OF DRAWDOWNS AT THE NIOBRARA WELL FIELD (Plan 1)

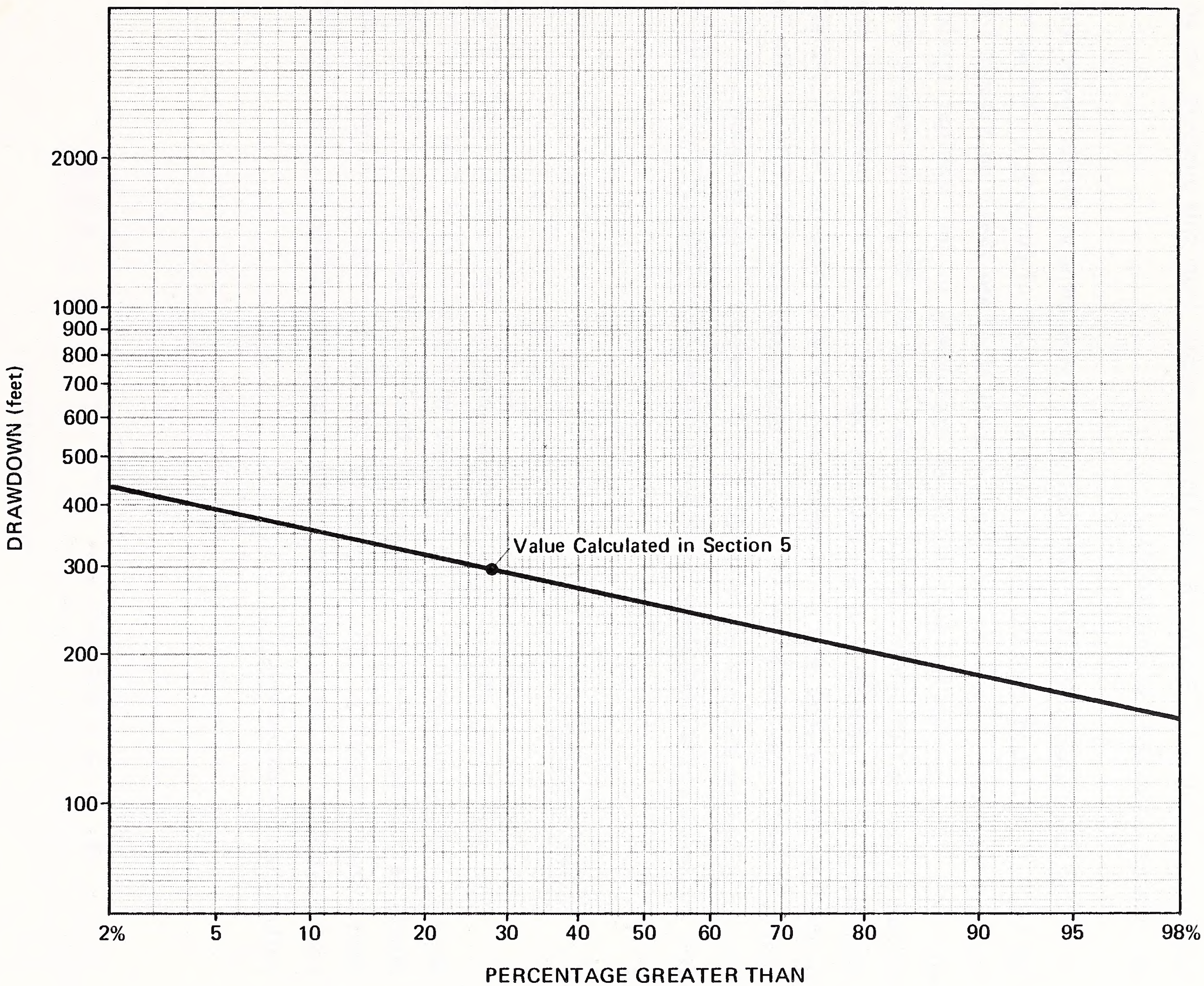


Figure 7-5. CALCULATED PROBABILITY DISTRIBUTION OF DRAWDOWNS AT EDGEMONT WITH PUMPING FROM NIOBRARA COUNTY WELL FIELD ONLY (PLAN 1)

Edgemont show that there is a 98 percent chance that drawdowns will be greater than 150 feet, a 50 percent chance that drawdowns will be greater than 260 feet, and a 2 percent chance that drawdowns will be greater than 440 feet. The drawdown calculated in Section 5 was 295 feet, which, from this analysis, has an exceedance probability of 28 percent.

The calculated probability distributions of drawdowns at Devils Tower and the Gillette well field from the Monte Carlo simulations of pumping 20,500 acre-feet per year for 50 years at the Crook County field are shown on Figures 7-6 and 7-7. The probability distribution of drawdowns in the Madison aquifer calculated at the Gillette well field show that there is a 98 percent chance that drawdowns will be greater than 46 feet, a 50 percent chance that drawdowns will be greater than 76 feet, and a 2 percent chance that drawdowns will be greater than 120 feet. The drawdown of 91 feet calculated for the Gillette site in Section 5 has an exceedance probability of 21 percent. The drawdown of 134 feet at Devils Tower calculated in Section 5 has an exceedance probability of 25 percent.

7.C CONCLUSIONS

The probability distributions of drawdowns in the Madison aquifer from Monte Carlo simulations of ETSI's proposed withdrawals show that the drawdowns calculated in Section 5 are greater than the values having a 50 percent exceedance probability. This suggests that the values computed in Section 5 are conservative in the sense that they have a smaller probability of being exceeded rather than not exceeded.

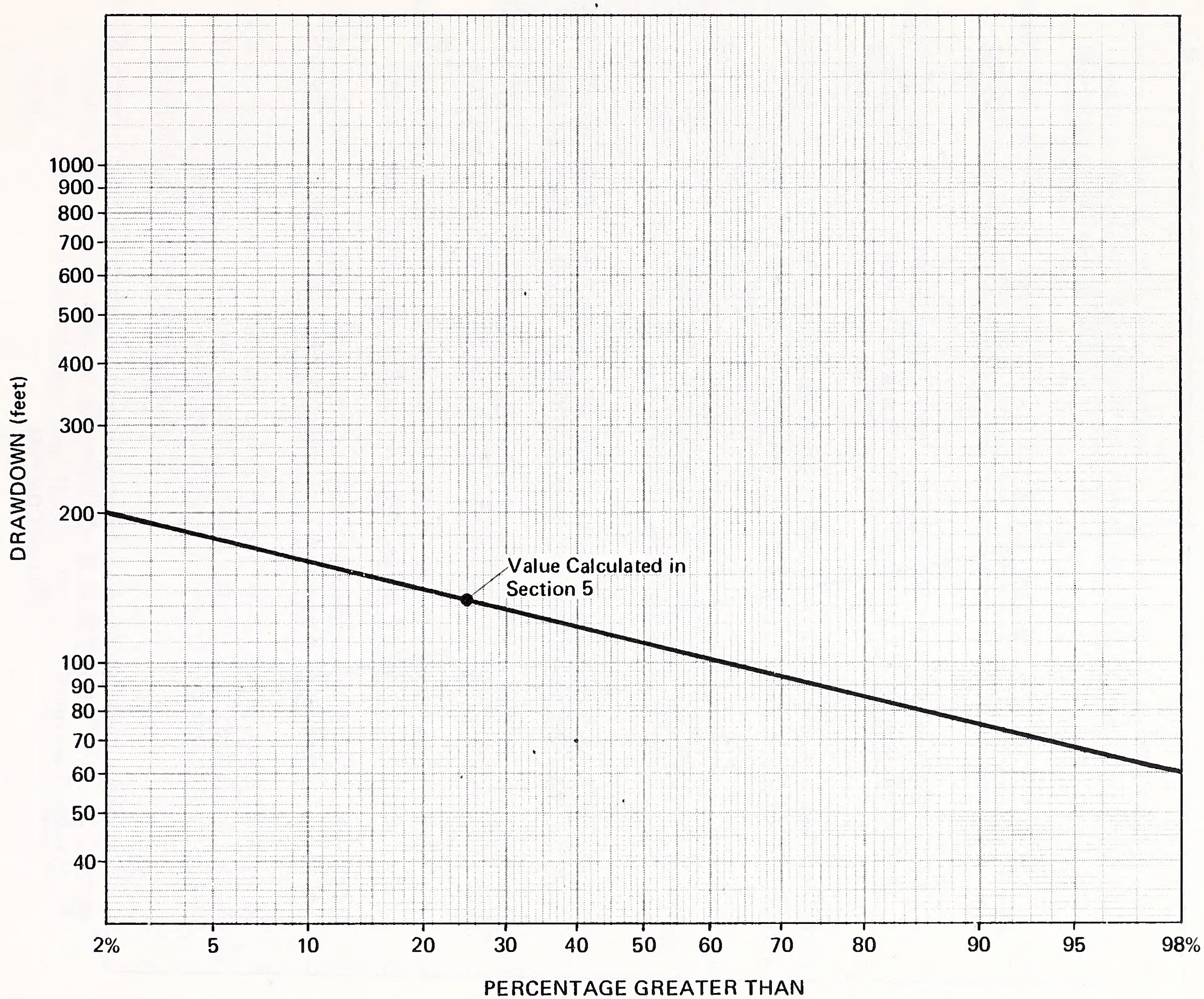


Figure 7-6 CALCULATED PROBABILITY DISTRIBUTION OF DRAWDOWNS AT DEVILS TOWER (Plan 3)

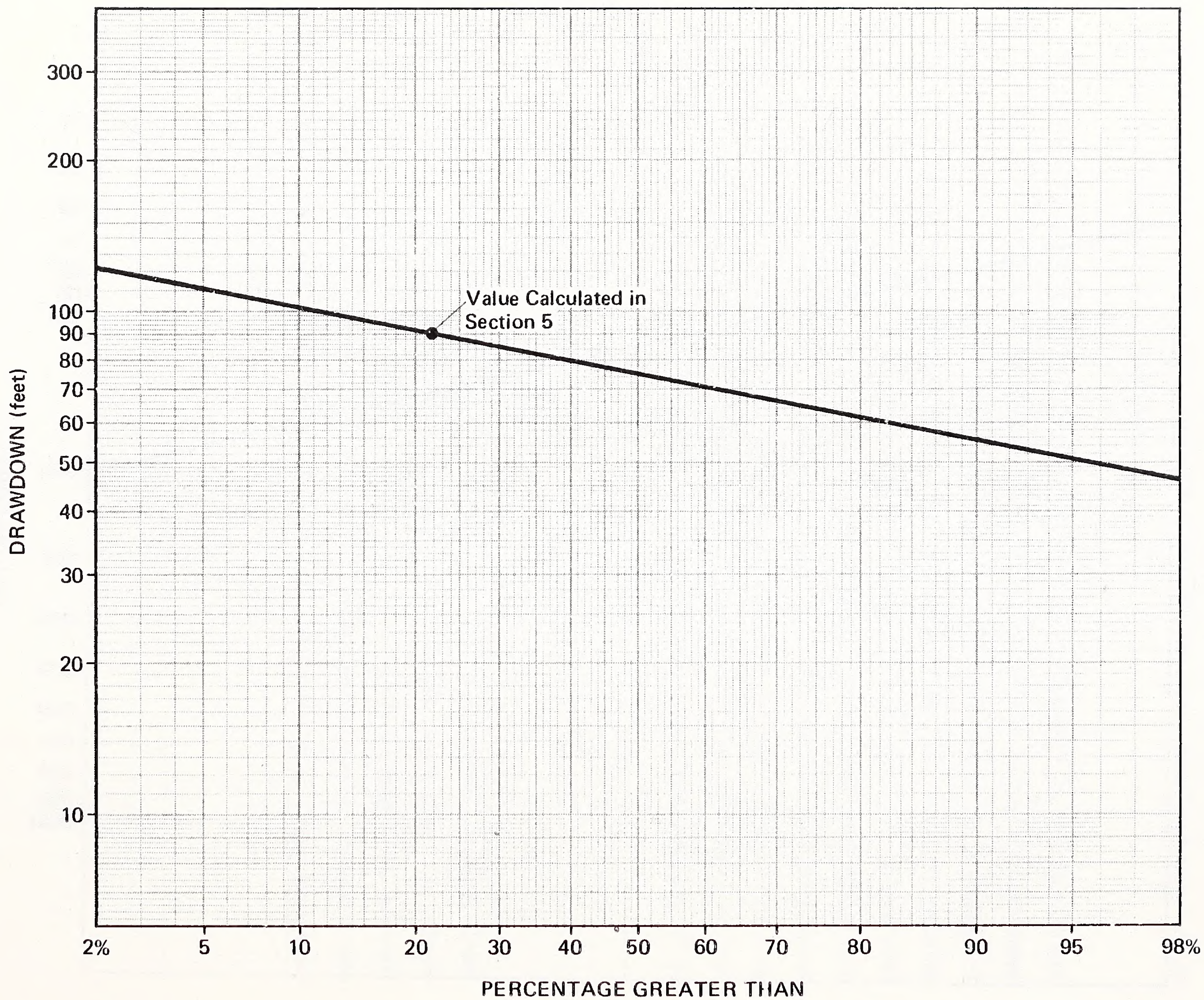


Figure 7-7. CALCULATED PROBABILITY DISTRIBUTION OF DRAWDOWNS AT GILLETTE WELL FIELD (Plan 3)

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APPENDIX A
WELL PERMITS

Appendix A

This appendix contains the following material:

A.1. Typical Well Permit. All 40 permits (27854 through 27893) are the same except for the specific location and depth of the well. Included with the permit is a list of 19 limitations which apply to each permit.

A.2 Enrolled Act 10, Senate Forty-Second Legislature of the State of Wyoming, 1974 Session.

A.3. Third-Party Beneficiary Agreement between the Office of the Wyoming State Engineer and ETSI, dated September 24, 1974

A.1

TYPICAL WELL PERMIT

Form U.W. 5

NOTE: Do not fold this form. Use typewriter or ball point pen.

STATE OF WYOMING

OFFICE OF THE STATE ENGINEER

APPLICATION FOR PERMIT TO APPROPRIATE GROUND WATER

Temporary Filing No. U.W. 8-12-297

FILING FEE $2.00

PERMIT NO. U.W. 27867

NAME AND NUMBER OF WELL

WATER DIVISION NO. 2 DISTRICT 1

ETSI-P-1

U.W. DISTRICT Niobrara Co.

1. Name of applicant(s) Energy Transportation Systems, Inc. Phone: (415) 764-5787
2. Address of applicant(s) P. O. Box 3965, San Francisco, California Zip: 94119
3. Name & address of agent to receive correspondence and notices Mr. Lawrence Materi, P. O. Box 151 Upton, Wyoming 82730
4. Use to which the water will be applied: Irrigation ☐ Municipal ☐ Industrial ☒ Commercial ☐ Domestic ☐ Stock Watering ☐ Other
5. Location of the well: Niobrara County, Center of NW 1/4 of Sec. 21, T. 36 N., R. 62 W., or Lot ___ Block ___ of the ___ Subdivision (or Add'n) of ___ Sec. ___ T. ___ N., R. ___ W., of the 6th P.M. (or W.R.M.), Wyoming.
6. Estimated depth of the well is 3500 feet.
7. MAXIMUM quantity of water to be developed and beneficially used: 1000 gallons per minute. Note: If for domestic or stock use, this application will be processed for a maximum of 25 gallons per minute.
8. If for irrigation use,
   ☐ Land will be irrigated from this well only.
   ☐ Land is irrigated from existing water right(s) to be supplemented by this well. Describe existing water right(s) under REMARKS.
9. If for irrigation use, describe MAXIMUM acreage to be irrigated. Show number of acres to be irrigated in each 40-acre subdivision.

Township	Range	Sec.	NE¼ NE¼	NE¼ NW¼	NE¼ SW¼	NE¼ SE¼	NW¼ NE¼	NW¼ NW¼	NW¼ SW¼	NW¼ SE¼	SW¼ NE¼	SW¼ NW¼	SW¼ SW¼	SW¼ SE¼	SE¼ NE¼	SE¼ NW¼	SE¼ SW¼	SE¼ SE¼	TOTALS

WATER WILL BE UTILIZED FOR INDUSTRIAL PURPOSES IN CAMPBELL COUNTY, WYOMING, IN A LOCATION NOT YET FINALLY DETERMINED

REMARKS:

Permit No. U.W 27867

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Book No. 141 Page No. 98

The well is to be constructed on lands owned by John E. DeGering and Kay DeGering (husband & wife) and Leonard L. DeGering and Helen L. DeGering (husband & wife) (The granting of a permit does not constitute the granting of right of way. If any easement or right of way is necessary in connection with this application, it should be understood that the responsibility is the applicant's. A copy of the agreement should accompany this application, if the land is privately owned and the owner is not a co-applicant.)

The water is to be used ~~xxxxxxxxxxxx~~ for the industrial purposes of the applicant.
(If landowner is not the applicant, a copy of the agreement relating to usage of appropriated water on the land should be submitted to this office. If the landowner is included as a co-applicant on the application, this procedure need not be followed.) A memorandum of lease dated September 7, 1973, between the Owner and applicant is on file as an attachment to application ETSI-T-1 of applicant and is incorporated herein by reference thereto.

THE LEGALLY REQUIRED FILING FEE MUST ACCOMPANY THIS APPLICATION.

Under penalties of perjury, I declare that I have examined this application and to the best of my knowledge and belief it is true, correct and complete.

John Hunke, Vice President — Signature of Applicant or Authorized Agent
Energy Transportation Systems, Inc.

Date: September 7, 19 73

THIS SECTION IS NOT TO BE FILLED IN BY APPLICANT

THE STATE OF WYOMING }
STATE ENGINEER'S OFFICE } ss.

This instrument was received and filed for record on the 7 day of Sept. A. D. 19 73 at 4:00 o'clock P. M.

Permit No. U.W. 27867

Karen L. Armour for State Engineer

THIS IS TO CERTIFY that I have examined the foregoing application and do hereby grant the same subject to the following limitations and conditions:

This application is approved subject to the condition that the proposed use shall not interfere with any existing rights to ground water from the same source of supply and is subject to regulation and correlation with surface water rights, if the ground and surface waters are interconnected. The use of water hereunder is subject to the further provisions of Chapter 169, Session Laws of Wyoming, 1957, and any subsequent amendments thereto.

Granting of a permit does not guarantee the right to have the water level or artesian pressure in the well maintained at any specific level. The well should be constructed to a depth adequate to allow for the maximum devlopment and beneficial use of ground water in the source of supply.

If the well is a flowing artesian well, it shall be so constructed and equipped that the flow may be shut off when not in use, without loss of water into surface formations or at the surface.

Approval of this application may be considered as authorization to proceed with construction of the proposed well.

Construction of well will begin within one (1) year from date of approval. A Statement of Completion will be filed within thirty (30) days of completion of construction, including pump installation.

Completion of construction and completion of the beneficial use of water for the purposes specified in Item 4 of this application will be made by December 31, 19 76.

The amount of appropriation shall be limited to the quantity to which permittee is entitled as determined at time of proof of application of water to beneficial use.

Witness my hand this 24th day of Sept. A. D. 19 74

Floyd A. Bishop, State Engineer.

FOR ADDITIONAL LIMITATIONS SEE THE FOLLOWING PAGES OF THIS PERMIT.

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The following conditions and limitations are applicable to Permit Nos. U. W. 27854 through U. W. 27893 issued to Energy Transportation Systems, Inc. (ETSI):

1. ETSI has on file with the State Engineer applications numbered ETSI P-1 through ETSI P-26 and ETSI P-31 through ETSI P-98 to appropriate ground water for processing coal, transporting coal in a coal slurry pipeline, and for related and appurtenant purposes, and these permits are issued subject only to application numbers 1, 19, 31, 33, 34, 35, 37, 39, 41, 43, 44, 46, 48, 50, 52, 53, 55, 56, 60, 64, 66, 68, 69, 71, 73, 76, 77, 78, 79, 83, 84, 85, 86, 88, 90, 91, 92, 94, 95, and 98, and the remainder of said applications are subject to further consideration by the State Engineer as hereinafter provided. These permits are designed to permit ETSI to pump 15,000 acre-feet of water on an average annual basis, and no more than 20,000 acre-feet of water per year. Such average annual pumping shall be computed on the basis of 20 consecutive years commencing with the year the water is first used. Said average shall be computed annually for each 20-year period following the year the water is first pumped by ETSI, and ETSI shall pump no more than 300,000 acre-feet of water in any such 20-year period; provided, however, that the State Engineer may, pursuant to application by ETSI, and upon a showing that additional water may be withdrawn and used from the Madison Formation without interference, permit ETSI to take no more than 20,000 acre-feet of water on a average annual basis. Accordingly, and subject to the approval of the State Engineer, ETSI may be granted additional permits to enable it to pump the quantities of water permitted herein.

2. Neither ETSI, its agents and employees, nor any independent contractor with whom ETSI, its agents or employees may contract or subcontract shall initiate construction or cause to be drilled, dug, or constructed any production well pursuant to any permit until such time as:

(a) The design of a monitoring and observation well system, consisting of five observation wells, one to be located in each of the following townships:

Section 28, T36N, R62W, West of the 6th P.M.
Section 16, T39N, R64W, West of the 6th P.M.
Section 16, T42N, R61W, West of the 6th P.M.
Section 4, T38N, R61W, West of the 6th P.M.
Section 8, T38N, R60W, West of the 6th P.M.

shall have been approved by the State Engineer, provided, the location(s) of any such well(s), as set forth above, may, prior to commencement of construction of any such well(s) and upon written notice from the State Engineer, be changed to any other location as the State Engineer may require; and

(b) ETSI has applied for and the State Engineer has granted permits for each of the said five monitoring and observation wells, and the State Engineer has endorsed on each such permit his approval of the monitoring and observation system. Provided that in no event shall water be produced from any production well under these permits within a period of one year from the date of completion of the final observation well, exclusive of such amounts as the State Engineer may allow to be produced for testing purposes during such period.

3. ETSI shall, at its own expense, install and maintain on each production well such monitoring or other measuring devices as may be required and approved by the State Engineer.

4. ETSI shall, at its own expense, purchase and install metering devices acceptable to the State Engineer on any or all of six wells to be designated by the State Engineer.

5. As a condition of continuing these permits in full force and effect, ETSI shall submit to the State Engineer monthly reports for a period of five years following the date water is first produced under any production well permit(s) indicating the quantity of water withdrawn from each operating well, as well as the cumulative withdrawals from all said wells in operation at any time during the reporting period, and the drawdown of the well levels, if any, on the five monitoring and observation wells required by Condition 2 hereof. Said reports shall be submitted on the first day of each month following commencement of the production of water by ETSI or on the first working day after the first day of each month if the filing date should fall on an official holiday or on a Saturday or Sunday.

If at any time during or prior to the expiration of the five-year reporting period the State Engineer should determine and ETSI and the State Engineer should mutually agree that a monthly reporting period is no longer necessary, ETSI may report to the State Engineer on a semi-annual basis, and said reports shall be submitted to the State Engineer on the second day of January of the year following the commencement of the production of water by ETSI, and the reports shall be filed on the first day of July and the second day of January semi-annually thereafter, or on the first working day after either said date if the filing date should fall on an official holiday or on a Saturday or Sunday. If the State Engineer so elects, he may engage a ground water hydrologist approved by ETSI to examine the data collection process and analyze the data itself for the benefit of the State Engineer, all of the costs of which shall be borne by ETSI.

6. ETSI shall test each production well drilled, dug, or constructed by it and at such times and in such manner as the State Engineer may require and the results of such testing shall be submitted to the State Engineer on a continuing basis, and in no event shall any test results be submitted later than seven days following completion of such tests as may be required.

7. All costs of data processing involved in testing the production wells during or following construction shall be borne by ETSI, and such test data shall include a cement bond log and such other geophysical logs and data as the State Engineer may require.

8. The State Engineer and any of his duly authorized agents or employees shall have the right at any and all times during the life of these permits and at the State's own expense, to run or conduct such independent tests and inspections of any or all of ETSI's wells as the State Engineer may require.

9. Each production well shall be cemented from the surface of the ground to the top of the Madison Formation and in no case shall any well be cased or cemented to a depth of less than 2500 feet below the ground surface.

10. In no case shall any production well constructed pursuant to these permits withdraw water from any formation or formations other than the Madison Formation and the Bell Sand unit of the Minnelusa Formation, provided that in no event shall any water be withdrawn from the Madison Formation or Bell Sand unit of the Minnelusa Formation where said formations shall occur at depths of less than 2500 feet below the ground surface.

11. In no case shall the total withdrawals by ETSI from all production wells exceed the maximum quantity set forth in Condition 1 hereof. Water withdrawn under these permits shall be used to process coal, transport coal in a coal slurry pipeline, and for related and appurtenant purposes, and no other use shall be made of such water without the express prior approval of the State Engineer or the Wyoming State Legislature, or both, if necessary.

12. If at any time ETSI so operates its wells as to lower the water table so as to endanger the water supply of any domestic, municipal, stockwatering or irrigation use, or other beneficial use of appropriated water within the State of Wyoming existing at the time the applications underlying these permits were filed, ETSI may be required by the State Engineer, at ETSI's own expense, to either:

(a) Deepen the well and pay the additional costs of pumping water for any person whose water supply has been endangered by reason of ETSI's pumping operation so that it is equal to the supply available prior to ETSI's pumping; or

(b) Provide any person whose water supply is endangered that quantity of suitable water required to equal the amount available prior to ETSI's pumping operation; or

(c) Obtain its water from another source that will not significantly affect or endanger the supply of water available to the beneficial users herein described.

13. In the event that ETSI should desire to abandon any production well, ETSI shall so inform and notify the State Engineer and state the reason or reasons for such proposed abandonment, and if such abandonment is thereafter allowed, ETSI shall comply with all requirements of the State Engineer in regard to the abandonment of any such well.

14. If and when ETSI, its successors, or assigns should desire to terminate the use of water under these permits for processing coal, transporting coal in a coal slurry pipeline, and related and appurtenant purposes, the State Engineer shall be so notified, and the State of Wyoming, through its duly authorized and appointed officers, shall succeed to ownership of these permits.

15. ETSI and the Office of the State Engineer of the State of Wyoming have entered into an agreement dated September 24, 1974, said agreement being intended to protect the third party beneficiaries named in Section 3 thereof. And in the event that a proper bond or line of credit is not established pursuant to Section 6 of said agreement, the permits herein granted may be cancelled or their operation suspended until such time as an arrangement or new agreement satisfactory to the State Engineer may be entered into or agreed upon between ETSI and the Office of the State Engineer of the State of Wyoming.

16. ETSI shall notify the State Engineer of the specific point(s) of injection of water produced under these permits into the pipeline operated by said ETSI.

17. The conditions and limitations of these permits are binding upon any and all successors and assigns of ETSI.

18. The permits granted herein shall be subject to cancellation at the end of the fifty-year period following the first production of water from the ETSI production wells, provided that ETSI and the State Engineer may mutually agree to extend such cancellation date.

19. The permits granted herein are subject to all other applicable requirements of State law not herein specifically stated.

A.2

ENROLLED ACT 10

(ORIGINAL SIGNED BY
P[illegible]SIDENT AND SPEAKER)

SIGNED BY GOVERNOR

DATE: 2-21-74

CHAPTER NO: 25

ORIGINAL SENATE
FILE NO. 14

ENROLLED ACT NO. 10, SENATE

FORTY-SECOND LEGISLATURE OF THE STATE OF WYOMING
1974 SESSION

AN ACT to create section 41-10.5 and to repeal sections 41-1.4 and 41-151 of the statutes relating to use of Wyoming water outside of Wyoming; approving the proposal of Energy Transportation Systems Inc. to appropriate underground water subject to the approval of the state engineer; providing criteria upon which the approval of the state engineer is to be predicated; providing certain limitations on approving applications for permits for use of underground water; providing certain conditions on use to be stated in any permit issued; prohibiting the appropriation or transfer of water or water rights outside Wyoming without prior legislative approval; providing for a legislative study; providing for severability; and providing an immediate effective date.

Be It Enacted by the Legislature of the State of Wyoming.

Section 1. Section 41-10.5 of the statutes is created to read:

41-10.5. Applications for use of water outside the state.

(a) All water being the property of the state and part of the natural resources of the state shall be controlled and managed by the state for the purpose of protecting and assuring the maximum permanent beneficial use of waters within the state.

(b) None of the water of the state either surface or underground may be appropriated, stored or diverted for use outside of the state or for use as a medium of transportation of mineral, chemical or other products to another state without the specific prior approval of the legislature on the advice of the state engineer.

(c) No holder of either a permit to appropriate water or a certificate to appropriate water, nor any applicant for a right to appropriate the unappropriated water of this state, may transfer or use the water so appropriated, certificated or applied for outside the state of Wyoming without prior approval of the legislature of Wyoming, provided further, that as a prerequisite to any use or transfer any adjoining state in which any such water is used shall grant reciprocal rights for the use of water in Wyoming.

(d) Subject to the approval of the state engineer, and notwithstanding the provisions of section 41-10.5(b) of the statutes, the legislature hereby approves the proposal of Energy Transporation Systems, Inc., a Delaware corporation, to appropriate no more than twenty thousand (20,000) acre feet annually of the unappropriated underground waters of the state for use in a coal slurry pipeline extending from Wyoming to Arkansas. The state engineer, may in his discretion, issue permits to appropriate such underground water to the extent necessary not to exceed twenty thousand (20,000) acre feet annually to meet the requirements of that project and subject to such conditions as the state engineer may require, and provided that the state engineer determines to his satisfaction that such appropriations of the project meet his requirements, which requirements shall include, but are not limited to the following:

(i) That the water to be used is underground water, from the Madison or Bell Sand formations;

(ii) That such use will not interfere with domestic, municipal, stock watering or irrigation uses or other existing beneficial uses within Wyoming;

(iii) That the water is withdrawn from a source of supply located at a minimum of two thousand five hundred (2,500) feet below the ground surface, from wells constructed to a depth of more than two thousand five hundred (2,500) feet beneath the ground surface; and

(iv) That the wells are cemented or otherwise sealed off from the surface of the ground to the top of the formation or formations from which the water is withdrawn, in order to prevent any movement of water in the well outside the casing and to prevent the entry of water from overlying aquifers into said wells, and that the water so withdrawn will be used to develop other resources of Wyoming.

(e) Nothing in subsection (d) shall be construed as a directive for the state engineer to grant his approval.

(f) The permits shall contain the following requirements and provisions, and any others deemed necessary or desirable, for protection of Wyoming's water and other resources, ecology and environment, by the state engineer and environmental quality agency after mutual consultation:

(i) If at any time the permittee so operates his wells as to lower the water table so as to endanger the water supply of any domestic, municipal, stockwatering or irrigation use or other beneficial use of appropriated water within the state of Wyoming existing at the time the application underlying this permit was filed, permittee may be required by the state engineer at permittees own expense to either:

(A) Deepen the well and pay the additional costs of pumping water for any person whose water supply has been endangered by reason of permittee's pumping operation so that it is equal to the supply available prior to permittee's pumping; or

(B) Provide any person whose water supply is endangered that quantity of suitable water required to equal the amount available prior to permittee's pumping operation; or

(C) Obtain its water from another source that will not significantly affect or endanger the supply of water available to the beneficial users herein described.

(ii) Permittee will pay the costs of court and reasonable fees of attorneys and experts of any person who is required to enforce the terms of this permit by legal action, provided said person is successful in obtaining a final judgment in his favor and against permittee, and provided said fees are found by a court of competent jurisdiction to be both reasonable and necessary. Any such action must be brought in the courts of the state of Wyoming.

(iii) If the state engineer finds reasonable cause to believe the permittee has endangered or is about to endanger the existing water table, an order to show cause why the permit should not be terminated or suspended may be issued. Any hearing held under this section shall conform with the provisions of the Wyoming Administrative Procedures Act.

Section 2. Sections 41-1.4 and 41-151 are hereby repealed.

Section 3. Excluding the applications referred to in subsection 41-10.5(d) of the statutes, and also excluding applications for permits to appropriate underground water for secondary recovery by water flooding of oil and gas fields, and also excluding test wells, no application or applications for the appropriation of undergound water in any one county for industrial purposes totalling more than six thousand (6000) acre feet per year, shall be approved by the State Engineer until April 1, 1975, unless authorized by the Legislature.

Section 4. The Joint Interim Mines, Minerals, and Industrial Development Committee and the Joint Interim Agricultural Public Lands and Water Resources Committee of the 42nd Legislature are hereby directed in conjunction with The Department of Economic Planning and Development, and the Office of the State Engineer to conduct a study of the use of underground water in Wyoming and report back to the 43rd session of the Wyoming Legislature in January 1975.

Section 5. If any provision of this act is held to be unconstitutional, such a ruling shall not affect other provisions of the act which can be given effect without the unconsititutional provision, and to this end the provisions of this act are severable.

ORIGINAL SENATE
FILE NO. 14

ENROLLED ACT NO. 10, SENATE

FORTY-SECOND LEGISLATURE OF THE STATE OF WYOMING
1974 SESSION

Section 6. This act is effective immediately upon passage.

(END)

President of the Senate	Speaker of the House

(ORIGINAL SIGNED BY PRESIDENT AND SPEAKER)

SIGNED BY GOVERNOR

DATE: 2-21-74

CHAPTER NO: 25

A.3

THIRD-PARTY BENEFICIARY AGREEMENT

AGREEMENT

This Agreement between the Office of the State Engineer of the State of Wyoming (State) and Energy Transportation Systems, Inc., a Delaware corporation qualified to do business in Wyoming (ETSI), dated September 24, 1974,

W I T N E S S E T H:

WHEREAS, ETSI has filed applications numbered ETSI P-1 through -26 and ETSI P-31 through -98 with the State Engineer of the State of Wyoming for permits to appropriate groundwater from certain lands in Niobrara County, Wyoming; and

WHEREAS, ETSI has entered into leases with the owners of land in Niobrara County giving ETSI the privilege of entering upon such land for the purpose of pumping water from the Madison Formation, memoranda of said leases being filed with the office of the County Clerk of Niobrara County, and also filed with the State Engineer of Wyoming as exhibits to the aforementioned applications; and

WHEREAS, ETSI has, in addition to its applications for permits to appropriate groundwater, applied for and received permits from the Wyoming State Engineer to construct test wells on lands leased by ETSI in Niobrara County, and pursuant to which said permits ETSI has constructed test and observation wells into the Madison Formation, and has filed the results of its said testing program with the State Engineer; and

WHEREAS, the State Engineer conducted a public meeting in Lusk, Wyoming, on July 15, 1974, at which time ETSI publicly described how it intended to use the pumped groundwater for its coal slurry project, and at which meeting ETSI also described its geologic and hydrologic findings which were based on core drillings, test wells, and other available data; and

WHEREAS, ETSI has advised the State Engineer of Wyoming, as well as the public, that in the opinion of ETSI and on the basis of all the information ETSI has obtained concerning the effects of pumping water for its coal slurry project there will be no interference with the pumping of any preferred or existing user in the State of Wyoming; and

WHEREAS, ETSI intends to protect and the State intends to defend all preferred and existing users in the State of Wyoming against any interference resulting from ETSI's pumping, and to that end ETSI and the State have determined that this purpose can best be accomplished by an agreement between said parties made expressly for the benefit of such persons;

NOW, THEREFORE, in consideration of the promises herein contained, the parties do hereby agree as follows:

1. Definitions. As used in this Agreement, the following terms have the meanings ascribed to them, unless otherwise indicated:

(a) "Person" means a natural person, partnership, association, corporation, municipality, including those specific municipalities named herein, irrigation district, and the State of Wyoming or a political subdivision thereof.

(b) "Groundwater" means any water under the surface of the land or under the bed of any stream, lake, reservoir, or other body of surface water.

(c) "Madison Formation" means the underground geologic structure or formation in the Mississippian System having boundaries that may be ascertained or reasonably inferred and in which water stands, flows, or percolates, and for the purpose of this definition, includes the Bell Sand unit of the Minnelusa Formation.

(d) "Existing User" means any person having a permit to appropriate groundwater senior to any ETSI permit or any person who utilizes groundwater for domestic and stock watering purposes in Wyoming.

(e) "Preferred Users" means the Cities of Newcastle, Upton, Moorcroft, and Osage to the extent of their pumping for preferred uses from the Madison Formation in Weston County, the Cities of Gillette and Sundance and the Devil's Tower National Monument to the extent of their pumping for preferred uses from the Madison Formation in either Weston, Crook, or Campbell County, and one "new city" to be designated by the State Engineer and located within the general vicinity of southeastern Campbell County, to the extent of its pumping for preferred uses from the Madison Formation in either Converse, Campbell, or Weston County.

(f) "Preferred Uses" means all of the existing and future use of groundwater pumped from the Madison by preferred users within their respective counties, but does not include industrial or irrigation use.

(g) "Interference" means such reduction in the quantity of water or degredation in quality of water so as to endanger the utilization of water by any preferred or existing user.

(h) "Pumping" means all withdrawals of water from the Madison Formation for beneficial uses for which said water was appropriated.

(i) "Project" or "Coal Slurry Project" means the coal slurry pipeline system owned and operated by ETSI, and which system will utilize 15,000 acre-feet of water on an average annual basis, and no more than

20,000 acre-feet of water per year. Such average annual use shall be computed on a basis of twenty consecutive years commencing with the year water is first used. Said average shall be computed annually for each twenty-year period following the year water is first used by ETSI, and ETSI shall use no more than 300,000 acre-feet of water in any such twenty-year period. Provided, however, that the State Engineer may, pursuant to application by ETSI and upon showing that additional water may be withdrawn and used from the Madison Formation without interference, permit ETSI to take no more than 20,000 acre-feet of water on an average annual basis.

2. Effective Date and Term.

This Agreement will become effective if and when the State Engineer issues permits to ETSI for the appropriation of groundwater for the coal slurry project, and will remain in effect until such time as the project is terminated or ETSI's permits are canceled from the records of the office of the Wyoming State Engineer.

3. Third-Party Beneficiaries.

All existing and preferred users as herein defined are hereby designated the beneficiaries of this contract.

4. <u>Covenant of ETSI to Protect Beneficial Uses.</u>

In the event ETSI's pumping from the Madison Formation causes interference with the pumping of any existing or preferred user, the State Engineer may on the basis of a valid complaint by any such user, hold a public hearing and investigate and determine whether and to what extent ETSI has caused interference with such user's pumping. If the State Engineer shall determine that any such complaint should be investigated, he shall first undertake any such investigation with his own staff. Should the State Engineer determine that such investigation requires independent consultants to assist in the investigation, the State Engineer shall notify ETSI in writing, and together the State Engineer and ETSI shall select consultants qualified to investigate the complaint. In the event the parties cannot agree on the consultants so to be engaged, the extent of the investigation or the reasonableness of the cost of said investigation, the issue shall be submitted to arbitration. In such event, the State Engineer and ETSI shall each appoint an arbitrator, and the two appointees shall select a third arbitrator. The three arbitrators shall decide whatever issues cannot be agreed to between the parties, and a decision by a majority of the arbitrators shall be conclusive and binding upon the parties. If either the State Engineer or ETSI refuses to appoint an arbitrator, or the two so appointed cannot agree on a third arbitrator, then either party to this Agreement may request a Court of competent jurisdiction to enforce the provisions of this paragraph. The cost of arbitration as well as the cost of any investigation shall be paid for by ETSI. The State Engineer or the arbitrators shall utilize all relevant data, including available monitoring data provided by the United States Geological Survey, in making their findings and determination. If, after a public hearing and investigation, the State Engineer determines that interference with the complainant's pumping has been caused by ETSI, he shall find and determine what corrective measures shall be taken by ETSI, which measures shall include the following, or any combination thereof:

(a) An order requiring restoration of complainant's pumping so that complainant can extract from the Madison Formation a quantity of water equal to the amount pumped before such interference. If the complainant's pumps must be lowered, his well(s) deepened, or a new well or wells constructed in order to enable complainant to pump such equivalent quantity of water from the Madison Formation, ETSI shall pay any and all costs of deepening such well(s) and lowering the pump(s) or constructing a new well or wells and providing new pumps, and ETSI shall also pay such additional pumping costs as may be required by order of the State Engineer.

(b) An order requiring ETSI to supply to said complainant, in the event complainant's pump(s) cannot be lowered, his well(s) deepened, or a substitute well or wells and pumping plant constructed, substantially the same quantity and quality of water enjoyed by complainant prior to interference by ETSI pumping and at a cost to said complainant equivalent to the operation and maintenance costs paid by complainant prior to interference with his pumping. In the case of preferred users, ETSI may at its option, and with the concurrence of the State Engineer, appropriate the wastewater of any such preferred user and either (1) spread or inject said preferred user's wastewater into the underground in order to satisfy ETSI's substitute water supply requirement in whole or in part, or (2) utilize said preferred user's wastewater for ETSI's own benefit and use.

(c) In the event that ETSI's interference with any complainant's pumping cannot be corrected by any of the measures prescribed in Subsections (a) or (b) hereof, the State Engineer shall, before invoking the provisions of Subsection (d) hereof, permit ETSI to correct such interference by whatever supplies, means, or technology available at that time, subject, however to the approval of the State Engineer.

(d) An order of the State Engineer requiring ETSI to cease and desist all its pumping from the Madison, in the event that ETSI's interference with any person's pumping cannot be corrected by any of the measures prescribed in Subsections (a), (b), or (c) hereof. ETSI shall comply with such order to cease and desist no later than twenty-four months after receipt of said order.

5. Potential Interference.

The State Engineer may, on the basis of information developed by his office, the U. S. Geological Survey, or any other reliable source, investigate the possibility that ETSI's pumping will interfere with the rights of existing or preferred users. In such event, the State Engineer shall notify ETSI in writing of his proposed investigation and allow ETSI ninety days in which to submit evidence to the effect that either (1) no interference is threatened, (2) any possible interference can be corrected by any of the measures made available to it under the provisions of Subdivisions (a), (b), and (c) of Section 4, or (3) that any possible interference can be corrected by reduced pumping. The State Engineer will make a final determination that no interference will occur or issue an order requiring ETSI either to take any one or a combination of the corrective measures provided in Subdivisions (a), (b), and (c) of

Section 4, reduce pumping, or issue a cease and desist order as provided in Subdivision (d) of Section 4. Any order of the State Engineer under this Section shall be appealable to the Board of Control, and the final order of the Board of Control shall, in turn, be appealable in the manner provided in Section 41-216 of the Laws of Wyoming.

6. Guaranty.

Within thirty days after written demand by the State Engineer, ETSI shall post a bond in the face amount of One Million Dollars to guarantee compliance with the provisions of Section 4 hereof. Said bond shall be approved by the State Engineer, which said approval shall not be unreasonably withheld. Any order of the State Engineer to ETSI issued pursuant to Sections 4 or 5 other than an order under Subparagraph (d), shall be complied with within sixty days after such order becomes final. In the event ETSI does not so comply, the State Engineer may proceed against the surety under said bond. The rights of third parties under said bond shall remain enforceable even though ETSI, under some other legal, administrative, or legislative authority, is authorized to continue its pumping operations.

In the event ETSI for any reason cannot obtain a bond for the purposes herein prescribed, it may establish a line of credit in the amount of One Million Dollars with a bank approved by the State Engineer to guarantee compliance with the provisions of Section 4 hereof. The conditions under which said line of credit will be implemented shall be negotiated and agreed upon between the parties.

7. Appeal.

ETSI may appeal any order of the State Engineer under this Agreement in the manner provided by Section 41-216 of the Laws of Wyoming, and the Wyoming Administrative Procedures Act.

8. Conditions Precedent to Performance.

ETSI's obligation to carry out the directives of any order of the State Engineer providing corrective measures prescribed in Sections 4 and 5 shall be dependent upon complainant's willingness to permit ETSI to enter upon said complainant's premises for the purpose of taking any such corrective measures as may be ordered by the State Engineer.

9. Future Permits.

In acting upon applications submitted by preferred users for permits to appropriate groundwater from the Madison Formation, the State Engineer shall consider whether or not a "water shortage" might occur or the area might be designated a "control area" under Wyoming law, in which event the State Engineer shall include in any new preferred user permits such terms and conditions, including the metering of well discharges and all other reasonable conservation measures, as will minimize the effects of pumping by said preferred users from the Madison Formation.

10. Successors.

This Agreement is binding on the successors and assigns of the parties signatory hereto.

11. Remedy Not Exclusive.

The bond or line of credit and procedure established for corrective measures shall be available only under this Agreement to those persons designated as beneficiaries of this Agreement pursuant to Section 3 hereof, and in no respect shall this Agreement constitute the exclusive remedy for any persons claiming interference as a result of ETSI's pumping.

IN WITNESS WHEREOF, the parties have caused this Agreement to be executed and attested by the proper officers thereunto duly authorized, and their official seals to be hereto affixed as of the day and year first written.

THE OFFICE OF THE STATE ENGINEER
OF THE STATE OF WYOMING

By: ______________________
Floyd A. Bishop,
State Engineer

APPROVED AS TO FORM:

____
Attorney General

ENERGY TRANSPORTATION
SYSTEMS, INC.

By: ______________________
E. J. Wasp,
Vice-President

APPROVED AS TO FORM:

BEST, BEST & KRIEGER

By: ______________________
James H. Krieger

APPENDIX B

Appendix B

GEOLOGY OF THE BLACK HILLS UPLIFT AND PARTS OF THE POWDER RIVER BASIN

INTRODUCTION

Geologic investigations were included in this study in order to understand how stratigraphy and structure control the occurrence and movement of ground water in aquifer systems potentially affected by pumping at the ETSI well fields. These investigations were in two parts: (1) a regional reconnaissance of the geology of the Black Hills uplift and adjacent areas, including the eastern portion of the Powder River Basin and the northern portion of the Hartville uplift (Figure 4-2); and (2) more detailed geologic studies within a 30-mile radius of each of the three proposed ETSI well fields.

Since stratigraphic nomenclature for correlative rock units generally changes from one structural province to the next and from one state to the next, it was important to initially identify stratigraphic units and assign common terms. The formational names most commonly used in the region are shown in Figure 3-2. The terms Madison Group, Formation, Limestone, and aquifer, as used in this report, refer to the entire Mississippian-age carbonate section. The Madison Group has been given two other names in the study area: the Guernsey Formation in the Hartville uplift and the Pahasapa Formation in the Black Hills. For simplicity, the term Madison Group will be used most commonly in this report to describe this rock unit. The Paleozoic stratigraphy and correlations are shown in Figure B-1.

The Madison Group in the Black Hills region and Powder River Basin is the product of a series of depositional, erosional, and tectonic events which occurred from Early Paleozoic through Recent time. Our geologic studies were conducted to define, delineate, and map the physical characteristics resulting from the geologic history of the study area. Specific characteristics studied included:

- The location of known and postulated fault zones and other major structural features

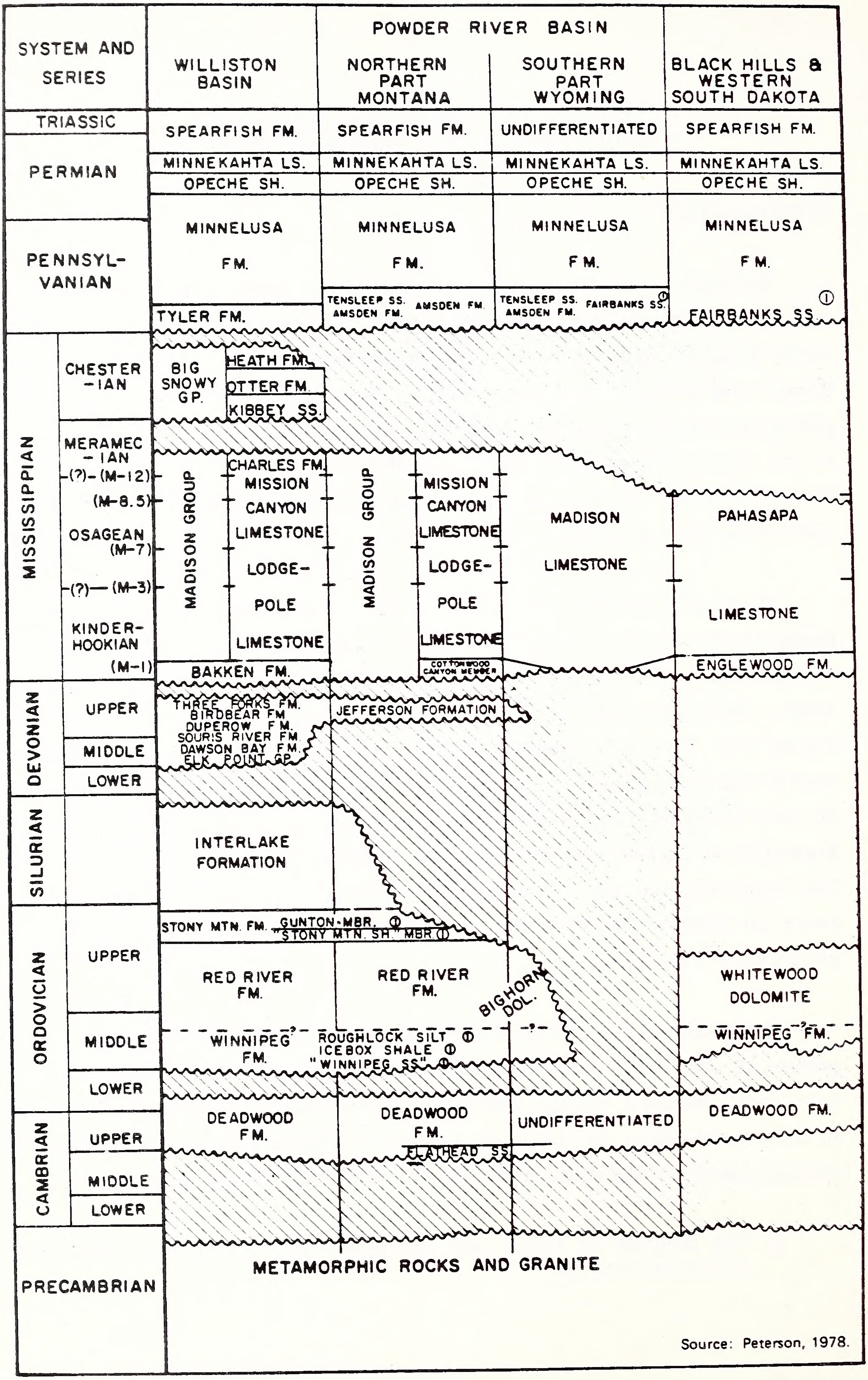


Figure B-1. PALEOZOIC STRATIGRAPHY FOR THE BLACK HILLS AND POWDER RIVER BASIN

- The extent, thickness, outcrop areas, porosity, extent of karst development, and lithologic characteristics of the Madison Group
- The extent, thickness, outcrop area, and lithologic characteristics of stratigraphic units above and below the Madison Group

A series of maps and cross sections were developed from information in the literature plus other sources. These geologic maps and cross sections were developed in order to understand the hydrogeology of the Madison Group; specifically, these items were developed to understand and characterize the lithology, extent, thickness, and porosity of rock units considered to be important in determining the impacts of ground-water withdrawal from ETSI well fields. The final products of the geologic analyses include:

- A contour map of porosity-feet in the Flathead and Winnipeg formations
- Contour maps of thickness and porosity-feet in the Red River Formation
- Isopach map of the Madison Group with lithofacies interpretations
- Isopach map of the Minnelusa Formation
- Isopach map of the upper member of the Minnelusa Formation with lithofacies interpretations
- A series of geologic cross sections
- A generalized geologic map of the region
- A geologic map of the Niobrara County well-field site
- A structural contour map of the top of the Madison Group

Each of the above products proved useful in interpreting hydrogeologic properties of the Madison Group and adjacent strata. The remaining portion of this appendix is a detailed description of the geology of the Black Hills uplift and parts of the Powder River Basin.

REGIONAL STRATIGRAPHY

The sedimentary rocks of the Powder River Basin and the Black Hills uplift are divisible into four sequences on the basis of origin and age (Lisenbee 1979).

Sequences 1 and 3 are marine, and sequences 2 and 4 are predominantly continental. The first three sequences predate Laramide structural activity.

The general lithologic characteristics of the four sequences in the stratigraphic section are summarized below:

- Sequence 1: Lower to middle Paleozoic strata

  The oldest sedimentary rocks are sandstones, shales, and conglomerates of the Flathead, Deadwood, and Winnipeg formations, which together are up to 600 feet thick. Overlying these formations are massive limestones, dolomites, and sandy dolomites of the Red River Formation and the Madison Group, which range in thickness from 1800 feet in southeast Montana to 0 feet in southeastern Wyoming. These units are all marine sedimentary rocks of the shelf facies.

- Sequence 2: Permian- to lower Carboniferous strata

  This sequence is composed predominantly of clastic rocks deposited in a very shallow marine or continental environment. The dominant lithologies are shales and siltstones. Evaporites and sandstones are present in the Permian-age material. Fluvial sandstones are present in the Lower Cretaceous-age Inyan Kara Group. The Triassic and Jurassic-age units, the Sundance and Spearfish formations, are predominantly siltstones and shales and range in thickness from 1200 to 2300 feet.

- Sequence 3: Lower Cretaceous to Paleocene strata

  This sequence consists of a thick (4000 to 5000 feet) series of marine shales (Skull Creek, Mowry, Belle Fourche, and Pierre shales) and an upper nonmarine portion. The marine shales deposited in the Rocky Mountain geosyncline grade upward through regressive sandstone and shale to continental sandstone, shale, and coal. The total thickness of this sequence is about 10,000 feet.

- Sequence 4: Oligocene strata

  This sequence is composed of continental clastics that lie with angular unconformity on the older rocks of the Black Hills uplift and Powder River Basin.

The stratigraphy and geologic history of the Precambrian through Permian periods in the vicinity of the three ETSI well fields are presented in the following sections.

Precambrian Geology

The Precambrian basement rocks exposed in the east-central part of the Black Hills uplift consist largely of metamorphosed sedimentary rocks with lesser amounts of metabasalt and metagabbro (Redden 1975). Schist, granodioritic gneiss, and gabbroic gneiss were found in the upper part of the Precambrian at U.S. Geological Survey (USGS) test well No. 1 near Hulett, Wyoming; and red and black schists were penetrated during the drilling of ETSI test hole O-1 in Niobrara County, Wyoming. Steece (1975) found the gneiss and schist basement rocks beneath Edgemont and Hot Springs, South Dakota, to date from 1410 million to 1460 million years before the present (1410-1460 m.y. B.P.). Except for fracturing and faulting, the porosity and permeability of these rocks are generally very low.

Early Paleozoic Geology

The Cambrian sequence is represented primarily by the Flathead Sandstone and the Deadwood Formation. Resting on the Precambrian basement rocks, the Flathead Sandstone is predominantly a quartzose, slightly feldspathic sandstone, commonly cemented with iron oxide. When deeply buried, it is often silica-cemented (Peterson 1979).

The Deadwood Formation is a white to reddish orange, fine to medium-grained quartz sandstone and dolomite. The Deadwood also contains green shale partings and locally abundant glauconite.

Ordovician strata, which were deposited only in the northern end of the Black Hills region (Figure B-2), consist of a lower clastic sequence and an upper carbonate sequence. The lower clastic unit consists of the Winnipeg Sandstone, Icebox Shale, and Rough Lock Sandstone. The Winnipeg Sandstone is a clean, well-sorted, medium-grained sandstone that is 96 feet thick at USGS test well No. 1. In places, the sandstone contains a silica cement and is quartzitic. This cementation is especially prevalent in the Williston and Powder River basins due to burial by 10,000 to 15,000 feet of sediment and probably precludes any significant porosity (Peterson 1979). Overlying the Winnipeg Sandstone is the Icebox Shale, a unit that is 54 feet thick at USGS test well No. 1, and the thin Rough Lock Sandstone.

The upper carbonate sequence (composed of the Red River Formation in the Powder River Basin, the Big Horn Dolomite in the Williston Basin, and the Whitewood Dolomite in the Black Hills) is composed of fossiliferous fragmental limestone and crystalline dolomite that thins to the south in the Powder River Basin and Black Hills and is absent in Niobrara County (Figure B-2). Beds within these units are tabular in form and contain interbedded porous and nonporous zones. In the central part of the Powder River Basin, these rocks have low porosity (Peterson 1978).

Kohm and Louden (1978) and Asquith and others (1978) reported that the Red River-Big Horn strata were deposited in subtidal to supratidal environments which greatly influenced patterns of porosity development. Supratidal and intertidal limestones were largely replaced by microcrystalline dolomite during early diagenesis and porosity was destroyed. In contrast, subtidal limestone was replaced by sucrosic dolomite, creating important secondary porosity, particularly around animal burrows. Deposition was cyclic, so that porous and nonporous strata are interbedded.

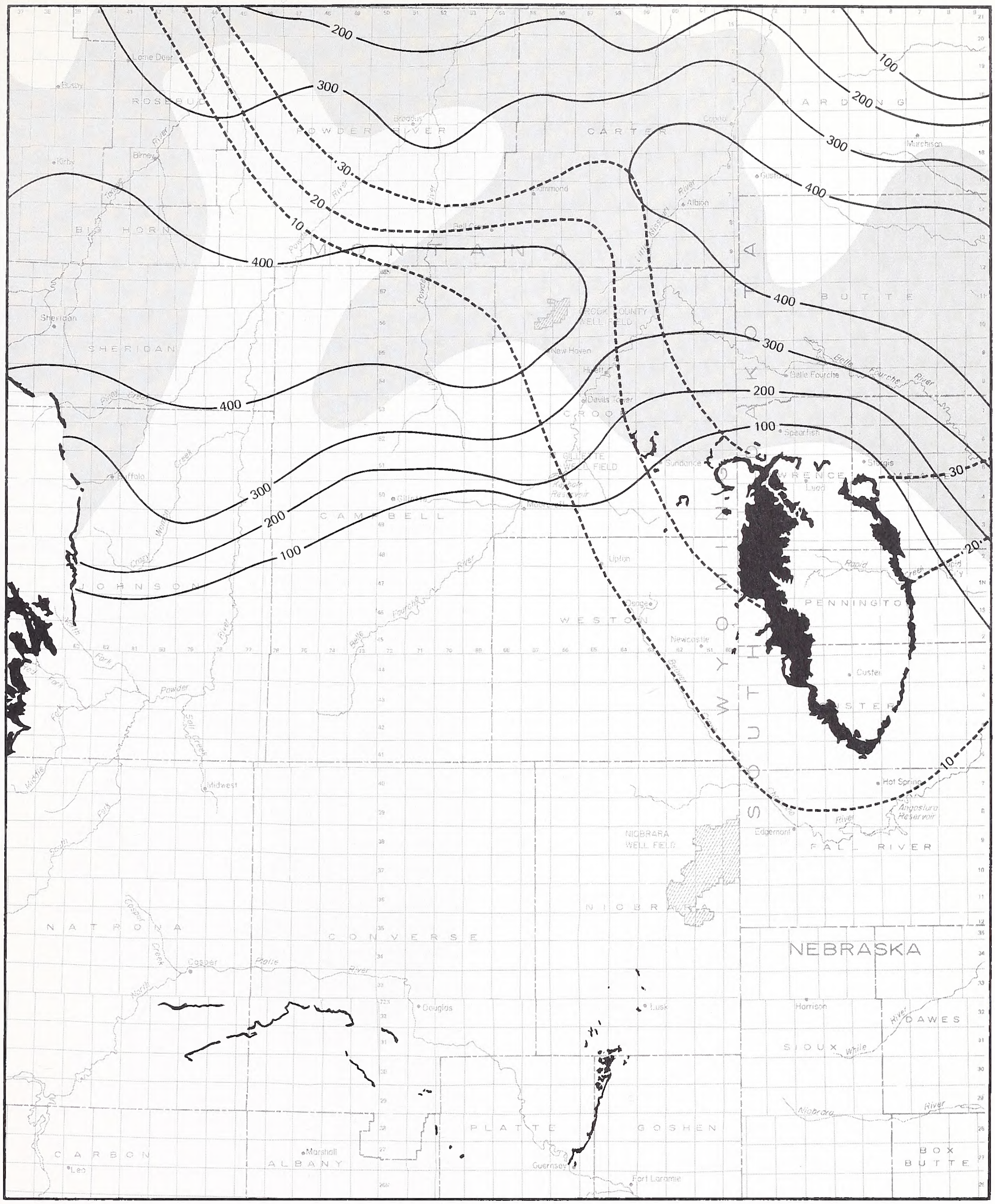
Silurian-age strata are absent throughout most of Montana, Wyoming, and western South Dakota (McMannis 1965; Norwood 1965).

Devonian-age deposits are thin or absent, except in western Montana at the mouth of the Central Montana Trough and in the Williston Basin.

Mississippian Geology

Mississippian-age strata, of which the Madison Group is the largest part (Figure B-3), consist of widespread carbonate beds that locally are excellent aquifers. The thickest Mississippian-age deposits occur along the Cordilleran continental margin west of the Wyoming shelf province. This province was separated from the Montana shelf province by the Central Montana Trough (Rose 1977). On the Wyoming shelf, the thickness decreases southward to about 200 to 300 feet in Niobrara County.

Depending upon geographic location, the Madison Group has been subdivided into as many as 12 units. Where the Madison Group has been treated as a



LEGEND

Source: Adapted from Peterson, 1978

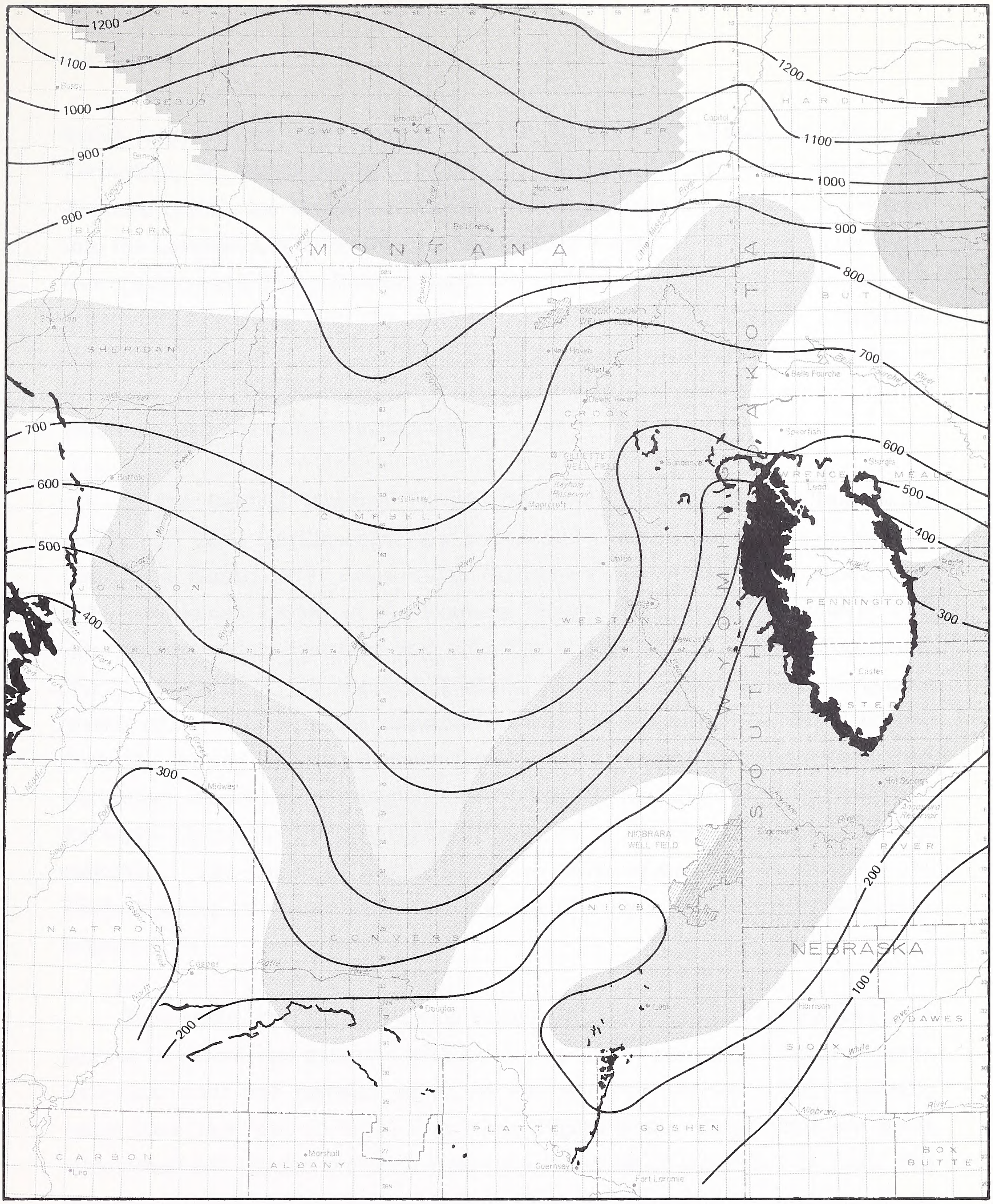
0 5 10 15 20

Isopach of dolomite in the Red River Formation

Isopach of porosity-feet in Winnipeg and Flathead sandstones

Porosity-feet greater than 20 % in the Red River Formation

Figure B-2. ISOPACH AND POROSITY OF THE CAMBRIAN AND ORDOVICIAN WATER-BEARING UNITS



LEGEND

Line of equal thickness 100 ft interval

Greater than 85% Dolomite

Greater than 75% Dolomite

Greater than 50% Limestone

N

0 5 10 15 20
miles

Source: Adapted from Peterson, 1978

Figure B-3. ISOPACH AND PERCENT DOLOMITE OF THE MADISON GROUP

whole unit, it has also been called the Madison Limestone, the Pahasapa Formation, or the Guernsey Formation. Besides the 12 units outlined by Peterson (1978), the Madison Group has been subdivided from oldest to youngest into the Lodgepole, Mission Canyon, and Charles members. In the Williston Basin and northwestern South Dakota, Sandberg (1962) and Kume (1963) included the Englewood Limestone with the argillaceous facies of the Lodgepole Limestone. In the southern portion of the Black Hills, the Englewood Formation is indistinguishable from the Madison Group in the subsurface and is included in the thickness assigned to the Madison Group.

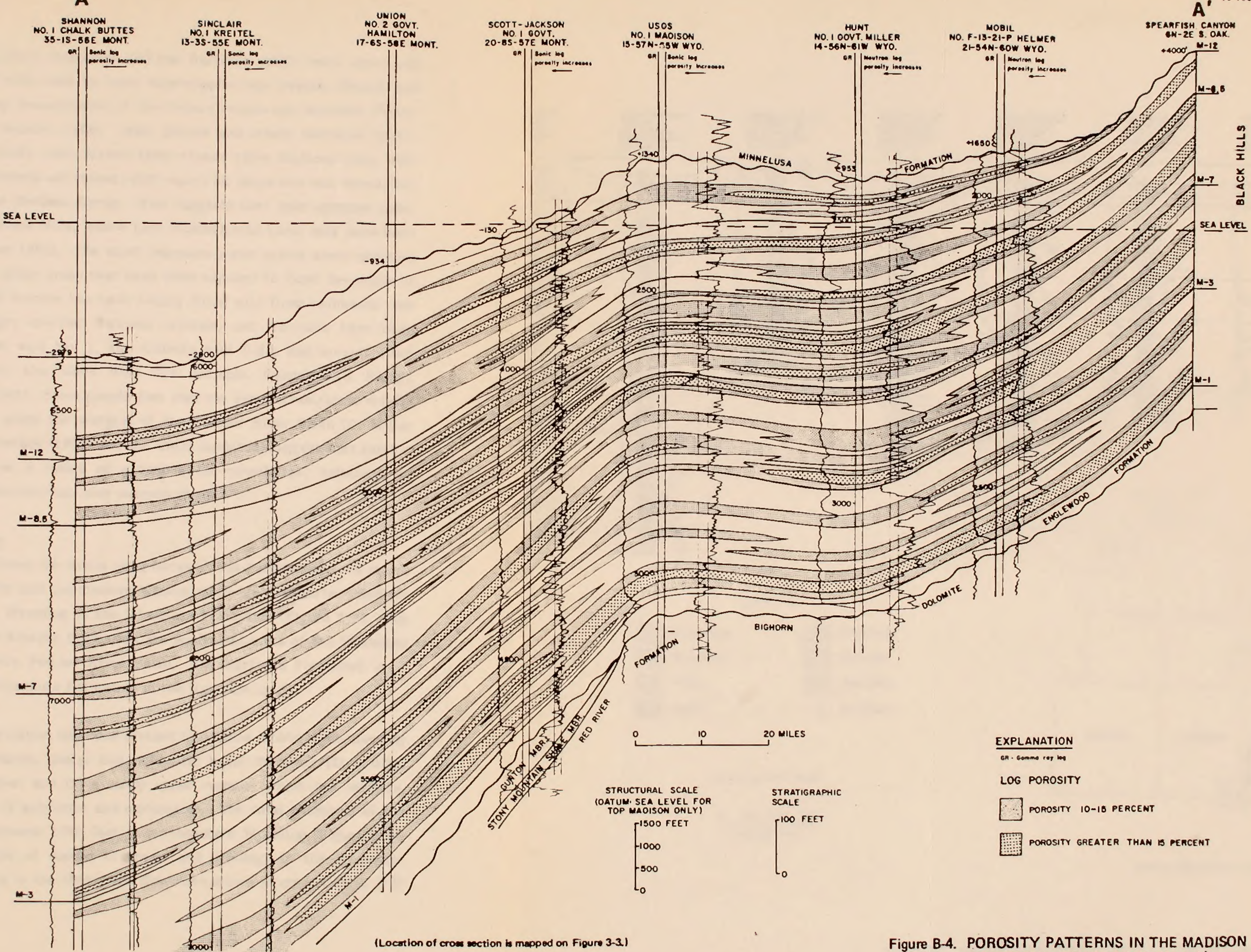
In the Central Montana Trough, the lower parts of the Madison Group consist of dark, argillaceous, low-permeability limestone of the Lodgepole Limestone (Smith 1978; Jenks 1978; Guttschick and others 1976; Sando 1967 1976; Andrichuck 1955). In the Montana Trough, the Lodgepole grades upward into shallow-water limestone and dolomite of the Mission Canyon Formation. North and south of the Central Montana Trough (Figure 4-2), the Lodgepole grades into a shallow-water limestone or dolomite and cannot be differentiated from the Mission Canyon. Because these two units cannot be distinguished from each other in eastern Wyoming or in South Dakota, the names Madison Group and Pahasapa Limestone are used in the literature to describe the entire Madison sequence. The Guernsey Formation is an older name used to describe the Madison Group in southeastern Wyoming, specifically in the Hartville uplift area (Figure B-1).

Regionally, the Madison Group consists of a fine-grained (micritic) fossiliferous limestone and dolomite with small amounts of anhydrite (Peterson 1978). Individual beds and porosity zones, as depicted by Peterson (1978), typically range from less than 10 to 25 feet thick (Figure B-4). These units are often widespread and tabular and seldom attain a thickness of more than 50 feet. The greatest primary porosity in the Madison Group is related to the position of the coarser dolomitic facies. Karst and other well-developed secondary porosity and permeability are relatively prominent and continuous in the upper parts of the section, but the solution openings have been filled with silt and clay in many places, especially away from outcrop areas (Peterson 1978). Deep weathering has been noted on the surface of the Madison Group, even where deeply buried.

This weathering zone of lime, dolomite, and clay is evident in test hole O-1 at the ETSI Niobrara well field site (Stafford 1980).

The porosity and permeability of the shallow-water carbonates deposited on the Wyoming shelf in the middle and upper parts of the Madison Group are significantly greater than those of the deep-water carbonates, because of: (1) the predominance of coarser-grained bioclastic (fossiliferous) and oolitic beds; (2) the development of important secondary porosity due to solution and partial replacement of calcareous grains by medium-grained (sucrosic) dolomite crystals in the shallow, evaporative water on the Wyoming and Montana shelves (Peterson 1978; Rose 1977); and (3) the possible presence of substantial open-fracture porosity even where intergranular porosities are low (less than 15 percent), as indicated at the Bell Creek oil field in Montana. Sando (1974) and Huntoon (1976) reported filled fractures in Madison Group outcrops in the Big Horn Mountains, and Huntoon concluded that the subsurface Madison Group should be less fractured than the uplifted and folded or faulted Madison Group where exposed in these mountains. White and Marchant (1971) reported "very fine" widely developed vertical fractures in Madison Group cores from the northwestern Williston Basin, but they thought that these contributed little to porosity or horizontal permeability. McCaleb and Waylan (1969) reported that fractures in the Madison Group in the Big Horn Basin of western Wyoming have been filled by precipitation of anhydrite cement from circulating ground water. Hence, the effect of fractures on porosity and permeability seems to vary from place to place and is difficult to predict. No one has yet reported on the possibility that fracturing may be more intense and open along structurally controlled lineament zones in the Powder River Basin or that solution enlargement is common along the fractures.

The Antler Orogeny resulted in emergence of most of the Wyoming shelf during the Late Mississippian time, leading to the development of widespread karst and southward truncation of Mississippian rocks (Henbest 1958; Roberts 1966; Sando 1972). Red detritus and karst residium lying on or intermixed with the top of the cavernous Lower Mississippian limestone are widely distributed in the Rocky Mountain region, from northern New Mexico to Montana (Henbest 1958). Karst features include enlarged joints, caves, sink holes, and solution



(Location of cross section is mapped on Figure 3-3.)

Figure B-4. POROSITY PATTERNS IN THE MADISON LIMESTONE, CROSS SECTION A-A'

breccias. In the Big Horn Mountains and the Hartville uplift, most caves and sinkholes were filled with sand by Late Mississippian-age streams (Sando and others 1975) or during transgression of the Pennsylvanian-age shoreline (Sando 1972; Huntoon 1976; Henbest 1958). Well drillers and others (Swenson 1968a, 1968b; Schoon 1979; Kelly 1980; Materi 1980; Steece 1980; Stafford 1980; Wulf 1980; Gries 1968; Whitcomb and others 1958) report bit drops and lost circulation of drilling fluid in the Madison Group. This suggests that open cavities exist, particularly near the Black Hills, where Late Mississippian karst may have been only partly filled (Gries 1980). The karst increases water yields where unfilled, but low well yields in other areas that have been exposed to karst development indicate that the karst terrane has been locally filled with finer sediments such as silt and clay. Vugs, cavities, twinned crystals, and fractures have been reported at USGS test well No. 1, the Gillette well field, and several other Madison wells west of the Black Hills (for example, Osage, LAK Ranch, Newcastle, and Edgemont). Some people feel that the karst is restricted chiefly to the Madison Group along the margins of the Powder River Basin (D. Miller 1979). Huntoon and Womack (1975) and the USGS (undated) suggest that karst is presently developing as a result of ground-water circulation, enhanced by secondary fracturing and solution, near outcrop areas.

Late Paleozoic Geology

Darton (1901) defined the strata lying between the Permian-age red shales of the Opeche Formation and the massive Mississippian-age carbonates (Madison Group) in northeastern Wyoming as the Minnelusa Formation (Figure 3-2). The Tensleep Sandstone and Amsden Formation are equivalent units of the Minnelusa Formation in the western Powder River Basin. The Hartville Formation is an equivalent unit of the Minnelusa Formation in the Hartville uplift.

The Minnelusa Formation has been divided into three informal members by Foster (1958): (1) a sandy, shaly, and dolomitic basal member; (2) a limy, dolomitic middle member; and (3) a sandy upper member which has variable, locally thick sequences of anhydrite and carbonates. The total thickness of the Minnelusa Formation exceeds 1200 feet in northeastern Wyoming (Figure B-5). The general relationships of clastic thickness and lithology in the Minnelusa Formation as they relate to the three well fields are shown in cross section B-B' on Figure B-6.

The transgression of the Late Mississippian-age sea, which began with a southward tilting of the shelf, continued into the Early Pennsylvanian and is represented by shoreline deposits called the Bell Sand or Fairbanks Formation (Sando and others 1975; Foster 1958; Stone 1969). At the Lance Creek oil field in Niobrara County, Wyoming, and in adjacent Sioux County, Nebraska, the Bell Sand is more than 200 feet thick (Bates 1955). Elsewhere, the Bell Sand is only a few feet thick and intertongues laterally with nearshore or tidal-flat dolomite or anhydrite. At USGS Madison test well No. 1 in Crook County, Wyoming, the basal clastic unit is approximately 60 feet thick (Blankennagel and others 1978), and at the Gillette well field the basal clastic unit is only a few feet thick (Arnex 1977, 1979, 1980). The variable thickness is partially the result of infilling of the Mississippian karst topography (Tenney 1966).

The ancestral Rocky Mountains were uplifted during the Middle and Upper Pennsylvanian. Considerable amounts of clastic sediments were deposited during this time in the southwestern part of the present Powder River Basin. In the eastern part of the present Powder River Basin and northeastern Wyoming, a shallow oceanic environment existed in which marine carbonates were deposited with thin evaporite and shale beds. A few tongues of sandstone extend eastward and also interfinger with these carbonates. Brobst and Epstein (1963) described the Middle and Upper Pennsylvanian-age carbonate in the Fanny Peak quadrangle (Wyoming-South Dakota) as consisting of two units: (1) a calcareous unit 200 feet thick, composed primarily of limestone and dolomite, with some calcareous shales, mudstones, and sandstones, and (2) an upper unit as much as 165 feet thick, composed of cherty limestone, dolomite, black chert, sandstone, shale, and siltstone.

The widespread Red Shale Marker in the Minnelusa Formation can be traced over most of the Powder River Basin and southeastern Wyoming and is usually designated as the contact between Permian- and Pennsylvanian-age strata (Tenney 1966). The actual Permian-Pennsylvanian contact is located within 100 feet below the Red Shale Marker (Hoyt 1962). Foster (1958) considers the Red Shale to be a buried laterite, but it is more likely an iron-rich shale (Tenney 1966).

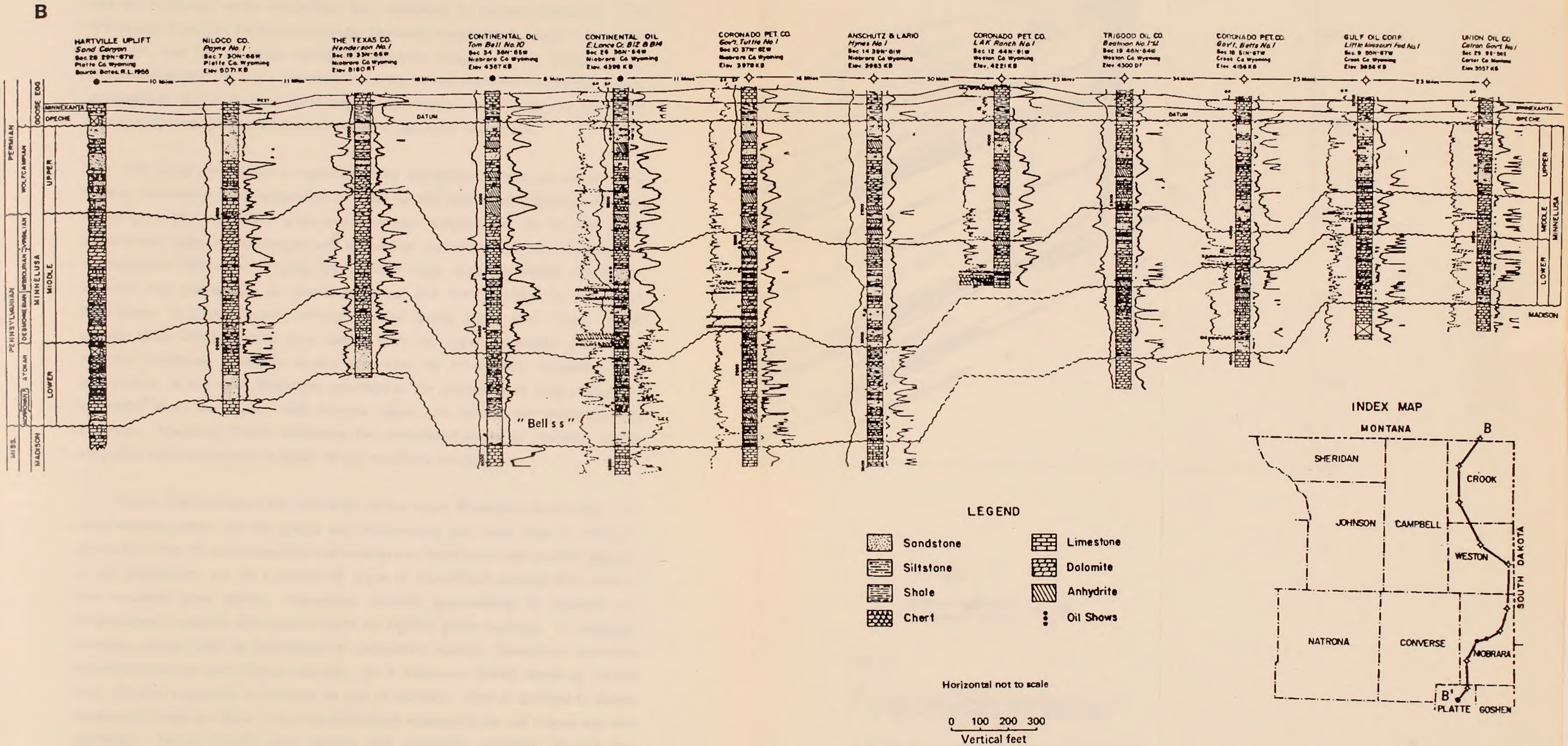
LEGEND

Isopach of the Minnelusa formation; 200-foot contour interval

0 5 10 15 20 miles

Source: Adapted from Taylor, 1966

Figure B-5. ISOPACH OF THE MINNELUSA FORMATION



Source: Adapted from Foster, 1958

Figure B-6. MINNELUSA STRATIGRAPHIC CROSS SECTION B-B' WEST OF THE BLACK HILLS (location of cross section is also mapped on Figure 3-3.)

The early Permian was a time of continued uplift and erosion in south-central Wyoming, while deposition was occurring in eastern Wyoming. The previously deposited Pennsylvanian-age Tensleep Sandstone, located to the south and east, was the principal source of sediment (Agatson 1955; Tenney 1966). Continued deposition and a probable lowering of sea level restricted the marine environment of the Powder River depositional basin, resulting in the deposition of anhydrite sequences prevalent in much of the upper Minnelusa.

The upper Minnelusa is represented by an interbedded sequence of sandstones, carbonates, and evaporites as much as 800 feet thick (Figure B-7). The strata generally vary from clean sands on the periphery of the Powder River depositional basin to carbonates and evaporites basinward and halite deposits in northwestern Nebraska. Facies and isopach maps depict a direct correlation between the percentage of clastic material and the thickness of the upper Minnelusa. In Crook County, several studies (Brady 1958; Arro 1976a, 1976b; Heisey 1963; Trotter 1963) have shown that the upper Minnelusa consists of regional sandstone members locally separated by limestones, dolomites, and anhydrites. In and near Minnelusa outcrops in the southwestern Black Hills, the anhydrite beds are absent and breccia pipes and brecciated materials are common. Braddock (1963) attributes the brecciated zones to leaching of the anhydrite with subsequent collapse of the overlying rocks.

Moore (1975) studied the petrology of the upper Minnelusa sandstones. His work showed that: (1) the grains are well-sorted and very fine to medium-grained in size; (2) geochemically unstable grains constitute less than 25 percent of the population; and (3) a variety of types of interstitial cement fill some of the available pore space. Porosities initially approaching 40 percent are progressively reduced with burial depth by tighter grain packing. In addition, unstable grains such as carbonate or anhydrite undergo dissolution and then reprecipitation as pore-filling cement. At a maximum burial depth of 10,000 feet, effective porosity is between 10 and 15 percent. Even if uplifted to higher structural levels at a later time, the sandstones apparently do not regain any lost porosity. Below 10,000 feet, calcite and anhydrite cements dissolve and apparently leach out. Concurrently, pressure solution of quartz grains occurs and leads to precipitation of silica cement in pore spaces. As Moore (1975) calculated for the eastern flank of the Powder River Basin, porosities should be in the range of 15 to 22 percent at maximum depths of several thousand feet.

Post-Minnelusa folding led to slight erosion of upper Minnelusa strata. Where erosion occurred, the overlying gypsiferous red shale of the Permian-age Opeche Shale is found to thicken from an average of 40 feet to over 100 feet where it filled channels eroded into anticlinal crests. The Opeche Shale is the cap rock that traps much of the upper Minnelusa oil. The Opeche Shale is also the basal portion of a section of several hundred feet of predominantly red gypsiferous shale comprising, in descending order, the Gypsum Springs and Spearfish formations and the upper portion of the Goose Egg Formation. The Opeche is separated from these latter units by the uniformly 30-foot-thick Minnekahta Limestone in eastern Wyoming and adjacent parts of Montana and South Dakota.

REGIONAL STRUCTURE

Black Hills Uplift

The Black Hills uplift is surficially expressed by an elliptically shaped outcrop of Cambrian- through Tertiary-age rocks surrounding a northward-trending core of Precambrian-age granites and metamorphic rocks (Figure 3-1). The uplift has been interpreted to be an isolated dome that rises from the flat Interior Lowland Province. Lisenbee (1978), however, has shown that it is structurally complex and is the easternmost and least of the deformed Laramide uplifts of the Rocky Mountain region.

The Paleozoic-age outcrops around the Precambrian-age core of the uplift are the major surface recharge areas for the Madison aquifer (Konikow 1976). The dip of the beds is much greater on the east side of the core than on the west. As a result, the outcrop area on the west side is much more extensive than on the east.

The uplift is separated from the Powder River Basin by the Black Hills monocline and the Fanny Peak monocline, which have a combined length of 173 miles (Figure B-8). Structural relief on these monoclines is as great as 5500

LEGEND

Isopach of upper Minnelusa; 200 foot contour interval

0 - 20 percent non-clastics in upper Minnelusa

20 - 50 percent non-clastics in upper Minnelusa

50 - 80 percent non-clastics in upper Minnelusa

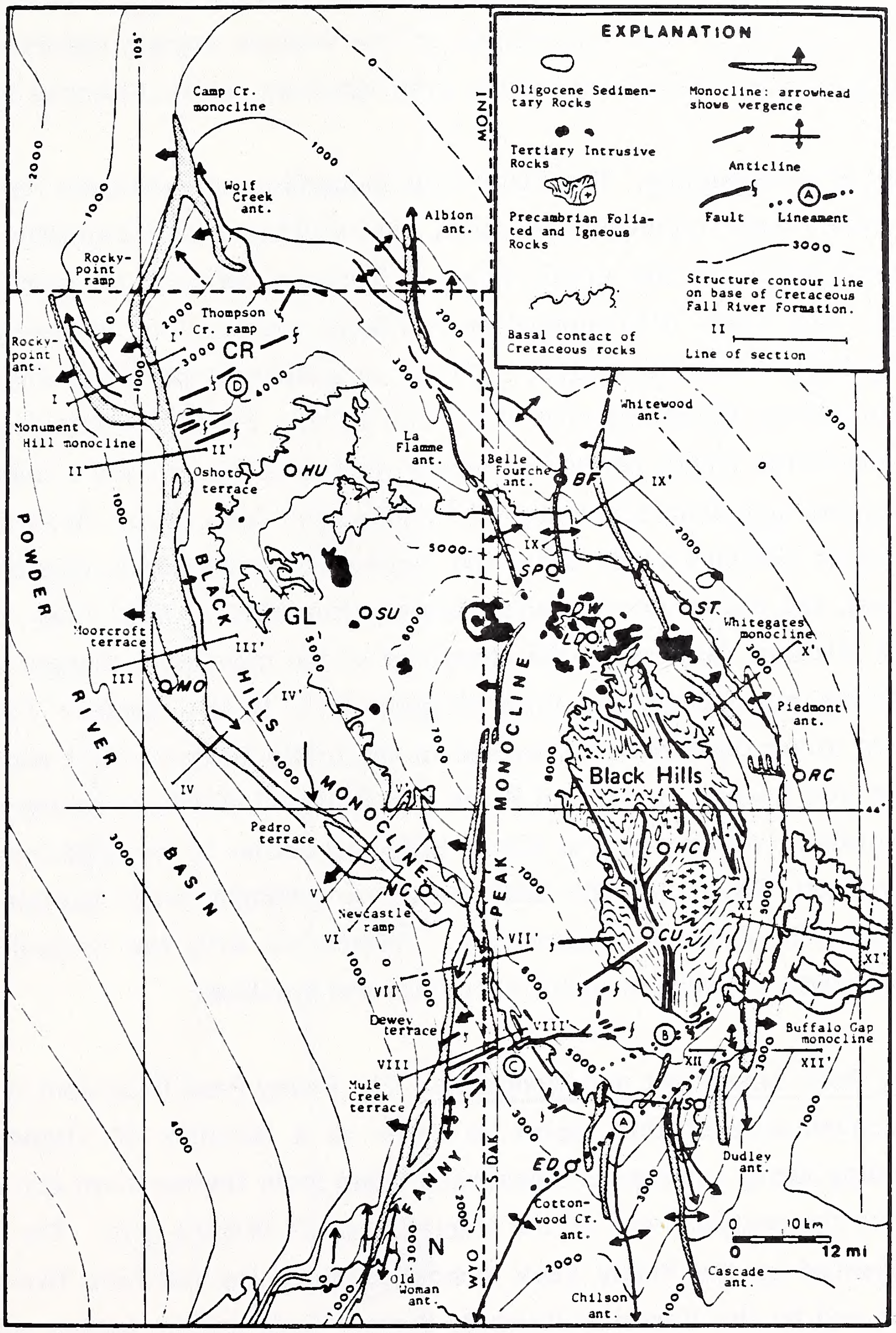
80 - 100 percent non-clastics in upper Minnelusa

N

0 5 10 15 20
miles

Source: Adapted from Tenney, 1966

Figure B-7. ISOPACH AND FACIES OF THE UPPER MINNELUSA FORMATION



Tectonic map of the Black Hills uplift. Lineaments and fault zones are A, Edgemont, B, Long Mountain: C, Dewey, D, Little Missouri. Well field locations are CR, Crook; GI, Gillette; and N, Niobrara. Structure contour interval is 1000 ft (302 m). (Source: Lisenbee, 1978)

Figure B-8. TECTONIC MAP OF THE BLACK HILLS UPLIFT feet, and dips are as great as 90 degrees (Lisenbee 1978). The uplift is separated from the Interior Lowland Province on the east by broad monoclines that dip gently eastward. The monoclines on the western margin apparently represent draping of the sedimentary section over basement faults (Lisenbee 1978).

Black Hills Monocline. The Black Hills monocline extends from its junction with the Fanny Peak monocline, 6 miles east-southeast of Newcastle, to southern Montana north of the Little Missouri River, a distance of approximately 100 miles. The Black Hills monocline continues southeast of its junction with the Fanny Peak monocline (Figure 3-3) for an additional 20 miles, where it dies out at the Dewey structural zone (Lisenbee 1978). From Newcastle to Moorcroft, the monocline trends north 45 degrees west (N45°W) and has a maximum dip of 75 degrees and structural relief of 3200 to 4000 feet. From Moorcroft north to the Little Missouri Fault zone, the monocline trends north, dips as great as 90 degrees, and has structural relief ranging from 3500 to 5500 feet. North of the Little Missouri fault zone, the character of the monocline changes abruptly into branching monoclines and folds (Figures 3-3, B-8). Surface faults are not present along the monocline except in the Little Missouri fault zone. However, Brobst and Epstein (1963) and Black and Roller (1961) have interpreted at least the southern portion of the Black Hills monocline to be underlain by a single major fault offsetting the basement. A geologic cross section across the monocline is shown in Figure B-9. Associated with the monocline along its entire length are several minor anticlines and synclines.

Fanny Peak Lineament and Monocline. The Fanny Peak lineament is a term used for convenience in this report to refer to a complex of aligned structures extending along a north-northeastward trend from the northern end of the Black Hills to the southern end of the Hartville uplift (Figure 3-3). The lineament is represented by the Fanny Peak monocline along the northern two-thirds of its length and by the Hartville-Rawhide-Sunrise fault system (which coincides with the eastern margin of the Hartville uplift) along the southern third of its length. Smaller structures that represent the lineament include the western margins of the Mule Creek, Old Woman, and Hat Creek anticlines, which mark local closure along the crest of the Fanny Peak monocline. The term Fanny Peak lineament was first used by Shapiro (1971) to include only the Fanny Peak monocline and

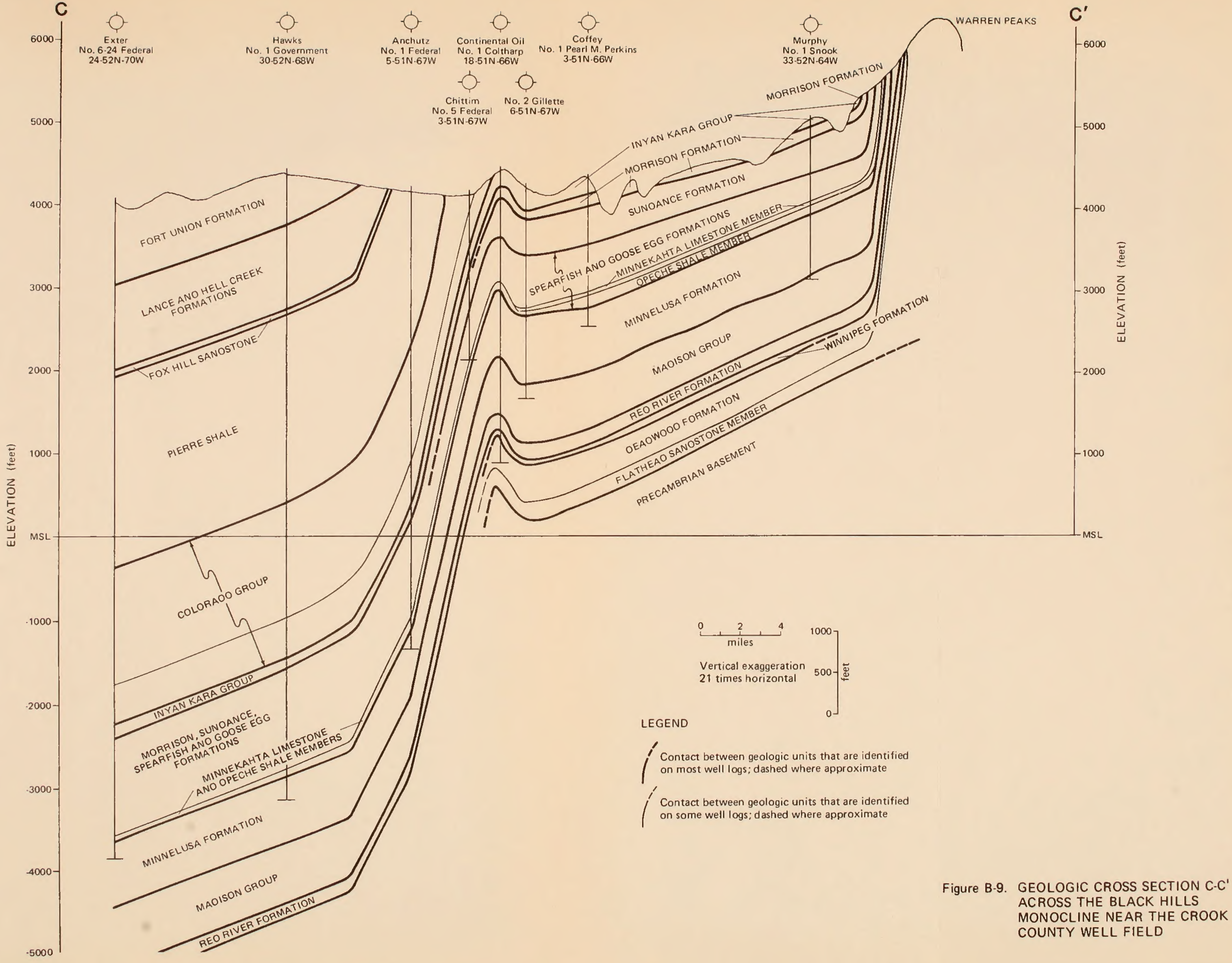


Figure B-9. GEOLOGIC CROSS SECTION C-C′ ACROSS THE BLACK HILLS MONOCLINE NEAR THE CROOK COUNTY WELL FIELD

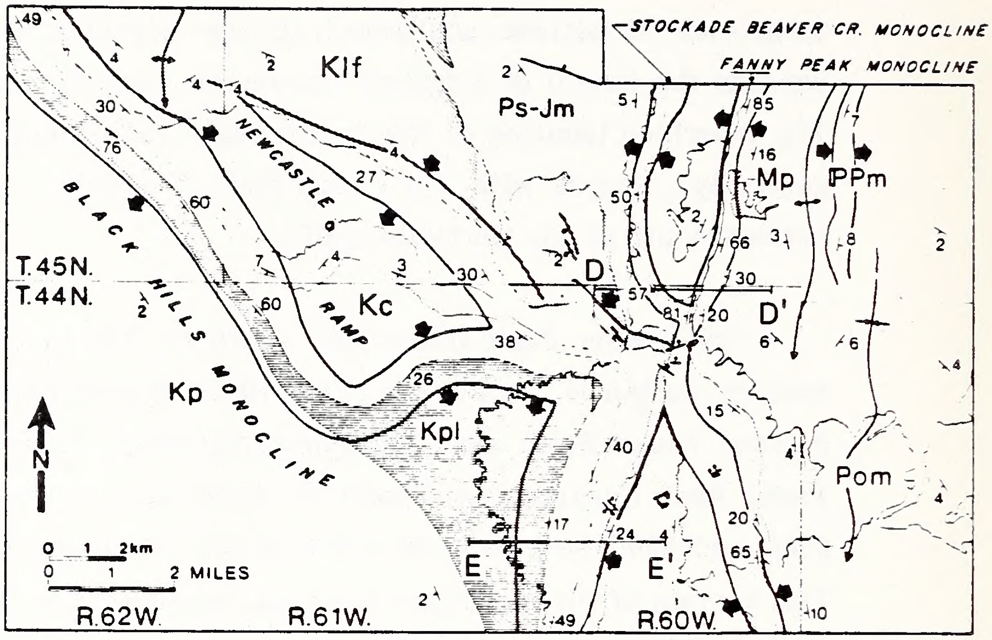
associated structures southward to the Hartville uplift. The present usage extends the length of Shapiro's lineament approximately 40 miles to the south. The described location of the Fanny Peak fault proposed by Wulf (1963) seems to generally coincide with the Fanny Peak lineament. Wulf states that his fault extends south of the Hartville uplift.

The Fanny Peak lineament, south of Newcastle, marks both the southeastern margin of the Powder River Basin and the structural divide between the Powder River Basin and the Denver-Julesberg Basin (Figure 3-3). Along the Fanny Peak lineament just south of Newcastle, the structural relief is between 2000 and 6000 feet and the width of the monocline ranges from 1 to 5 miles. This section of the monocline has been interpreted as drape folding over three or four faults that have displaced the basement rocks (Black and Roller 1961; Lisenbee 1978). North of its junction with the Black Hills monocline, the Fanny Peak monocline is narrower than it is to the south and has less structural relief.

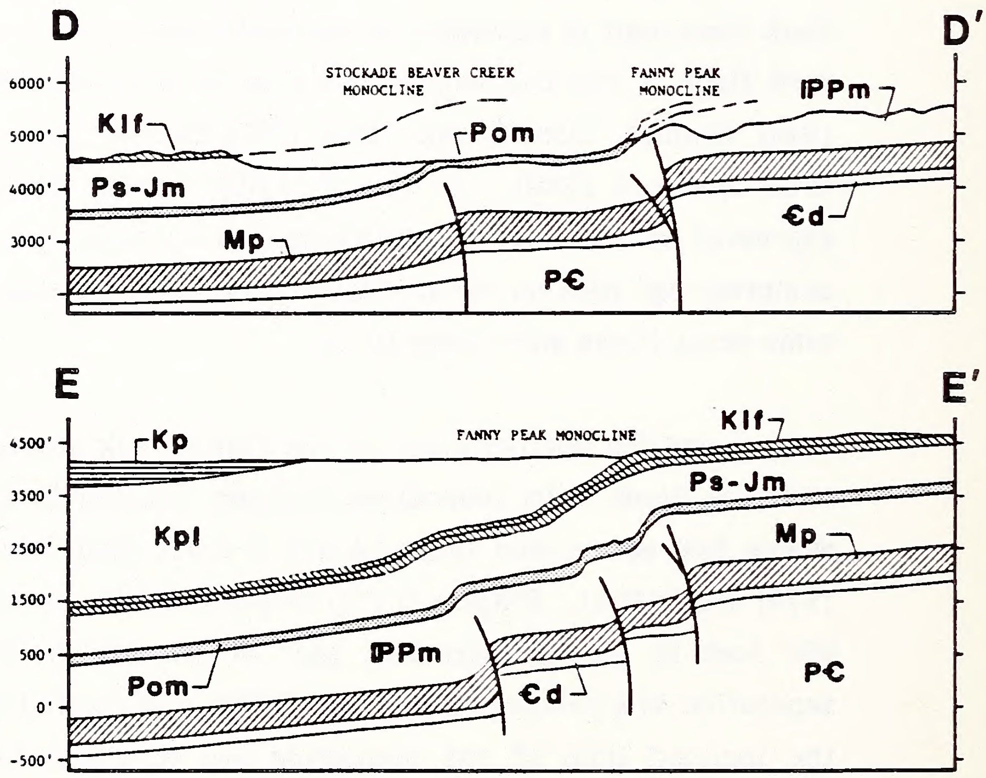
South of the Black Hills uplift, in Niobrara County, Wyoming, the Fanny Peak lineament is expressed as the Old Woman fault, which is exposed along the west flank of the Old Woman anticline in Niobrara County (Kramer and Dobbin 1943; Kramer, Dobbin, and Horn 1957; Horton 1953; Wendell 1974; Whitcomb 1975; Stafford 1980). In the Hartville uplift, the Fanny Peak lineament is expressed as the Hartville-Rawhide-Sunrise fault system, which separates Precambrian-age rock on the southeast from Paleozoic-age rock on the northwest in some areas (Love and others 1955).

Along the northern part of the Fanny Peak monocline, north of its junction with the Black Hills monocline, surface faulting is evident east of Newcastle where two en echelon faults, 4 and 6 miles long, have been mapped (Lisenbee 1978; Wulf 1955). Shapiro (1971) found a maximum stratigraphic separation of 900 feet in the southernmost part of the faults; Wulf (1955) described this separation as a reverse fault. Wulf (1955) also showed that the carbonate beds in the inclined limb of the monocline are intensely fractured. Geologic cross sections across this portion of the monocline are shown in Figure B-10.

Cascade Anticline and Other Folds South of the Black Hills Uplift. Several southward-trending anticlines, the more important of which are the Cascade,



Geologic map of the Newcastle, Wyoming, area (above), location maps for the cross sections (below). The geologic map shows the intersection of the Black Hills and Fanny Peak Monoclines (adapted from Mapel and Fillmore, 1963, and Gott and others, 1974). Monoclinal flexures shown with dark arrowheads. (Adapted from Lisenbee, 1978).



EXPLANATION

Kp, Kpl - Pierre Shale
Kc - Colorado Group
Klf - Inyan Kara Group
Ps-Jm - Spearfish, Gypsum Spring, and Sundance Formations
Pom - Goose Egg Formation
IPPm - Minnelusa Formation
Mp - Madison Group
€d - Deadwood Formation
p€ - Precambrian

Figure B-10. GEOLOGIC CROSS SECTIONS D-D' AND E-E' ACROSS THE FANNY PEAK MONOCLINE

Chilson, Sheep Canyon, Dudley, and Cottonwood Creek anticlines, are located at the southern end of the Black Hills uplift (Figure B-8). With the exception of the Cottonwood Creek anticline, these anticlines have steeply dipping west flanks which form monoclines. The Cascade monocline is the most prominent geologic structure in the area; it extends south from the Edgemont lineament for about 25 miles (Lisenbee 1978), dips westward up to 70 degrees, and has a maximum structural relief of over 1600 feet near Cascade Springs, South Dakota (Post 1967). Lisenbee (1978) suggests, in a geologic section, that the Cascade monocline is formed by drape folding over a basement fault. The Chilson anticline, which is at least 30 miles long, has an amplitude of 800 feet (Gott and others 1974). The Dudley anticline, which can be traced for at least 9 miles, has a maximum amplitude of about 600 feet (Wolcott 1967). The gently dipping Cottonwood Creek anticline has a maximum amplitude of about 500 feet (Gott and others 1974) and underlies the town of Edgemont, South Dakota.

Folds East and North of the Black Hills Uplift. The monoclinal flexures east of the Black Hills uplift are as much as 20 miles wide. Although structural relief is as much as 7000 feet, dips are less than 1 degree. The folds on the north end of the uplift (Figure B-8), called the Whitewood, Belle Fourche, and La Flamme anticlines, have not been well studied. The maximum amplitude of these structures is probably less than 1000 feet, and the average amplitudes are probably less than 500 feet. The structures have steep west limbs with dips that vary from 30 to 70 degrees (Darton and O'Hara 1907).

Lineaments. Based largely upon the works of previous authors, Lisenbee (1979) identified four major northwest-trending zones of "faulting or alignment of structure" in the western part of the Black Hills uplift. These zones are the Edgemont lineament, the Long Mountain fault zone, the Dewey fault zone, and the Little Missouri fault zone (Figure B-8). Descriptions of these zones, which are extracted from Lisenbee (1979), follow:

> The Edgemont lineament trends N60°E for 40 km from Edgemont, South Dakota . . . . It lies along a concealed structure of Precambrian age, which is indicated by the sharp bend in a magnetic anomaly north of Hot Springs (Meuschke and others, 1963; Kleinkopf and Redden, 1975) . . . . The exact nature of this deformation in the basement is unknown.

> The Long Mountain fault zone [B in Figure B-8] is described by Gott and others (1974) . . . . as consisting of small, northeast-trending normal faults exposed in rocks of the Cretaceous Inyan Kara Group and the Jurassic Sundance Formation. The zone begins 10 km north of Edgemont and trends N48°E for a distance of at least 15 km. Individual faults as much as 2 km in length are parallel across an area 7 km wide. Displacement is a maximum of 12 m on individual faults . . . .
>
> The Dewey fault zone [C in Figure B-8] begins on the west at the north end of Mule Creek terrace on the Fanny Peak monocline. It extends N70° to 75°E for approximately 25 km to a point at which it bifurcates into east- and northeast-trending segments. Although the geology is poorly known, the northeast segment appears to be traceable to the Precambrian-Paleozoic contact, and Redden (1975, oral commun.) stated that it can be followed in the Precambrian rocks at least to Custer. The east-trending segment is traceable for about 10 km (Gott and others, 1974, p. 29). In the western part of the zone, Gott and others (Pl. 2) showed several faults in a left en echelon pattern with individual members as much as 13 km in length. Although this pattern suggests possible left slip, direct evidence of such movement is lacking (p. 29). Several smaller faults parallel the longer segments. The north side of the fault zone is uplifted about 500 feet (Gott and others, 1974).
>
> The fourth northeast-trending zone of faulting lies near the Little Missouri River in Wyoming and is here called the Little Missouri fault zone. From the Black Hills monocline on the west [Figure B-8] it extends N55°E for approximately 50 km. Robinson and others (1964, Pl. 1) showed the zone to be approximately 10 km wide along the rim of the monocline and to be represented by only single, discontinuous faults on the east. The faults are normal with maximum displacement of 30 m and are downthrown on the north (Robinson and others, 1964, p. 115). The maximum length of any fault in the group is 5 km . . . .

There are two other prominent lineaments in the western part of the Black Hills uplift. One extends from Sturgis, South Dakota, N75°W to the Wyoming border; and the second lineament extends S25°E from the Little Missouri fault zone to Sundance, Wyoming. Along these lineaments, Eocene intrusive dikes, stocks, and plugs are found, often with annular outcrops of Jurassic- to Cambrian-age rocks. The best known of these features is Devils Tower and the largest is the Warren's Peak complex northwest of Sundance.

Powder River Basin

The Powder River Basin is a deep, asymmetrical basin of Laramide age (Late Cretaceous to late Eocene time, a time equivalent of from 80 m.y. B.P. to

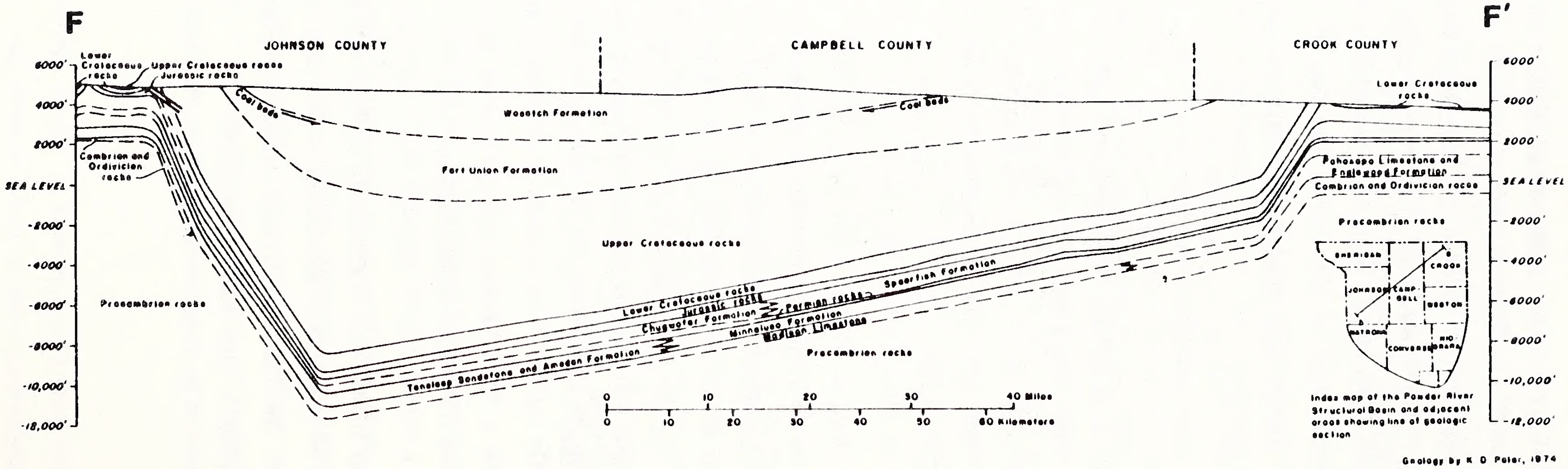
40 m.y. B.P.) (Coney 1971), bounded by the Black Hills uplift on the east, the Big Horn Mountains on the west, the Laramie and Hartville uplifts on the south, and the Miles City arch on the north (Figure 4-2). The deepest part of the basin is on the east side of the Big Horn Mountains, where the surface of the Precambrian basement is about 21,000 feet lower than on the nearby flanks of the Big Horn Mountains. In the deepest part of the basin, the top of the Madison Group is more than 15,000 feet below land surface. A structural cross section of the basin is shown in Figure B-11.

Hartville Uplift

The Hartville uplift is a broad structural platform about 25 miles wide that extends northeastward from the Laramide uplift toward the Black Hills uplift (Figure B-12). The Hartville uplift forms the divide between the Powder River Basin to the northwest and the Denver-Julesberg Basin to the southeast (Old West Regional Commission 1976).

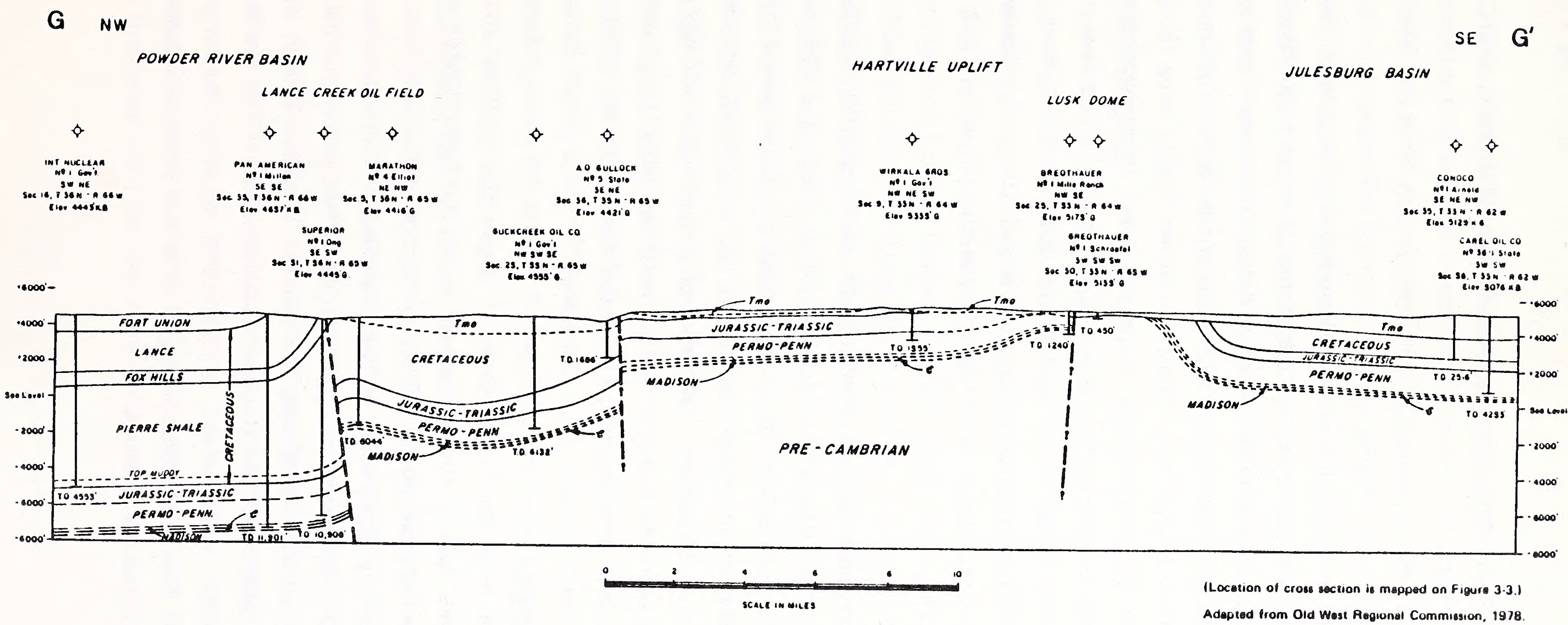
The Shawnee flexure, a sharp monoclinal flexure modified by faulting, separates the Hartville uplift from the Powder River Basin. The geometry of the Shawnee flexure is poorly known. The flexure is only a few miles wide and has a structural relief as great as 10,000 feet (Old West Regional Commission, 1976). The Rawhide-Hartville-Sunrise fault system and associated anticlinal structures, separate the Hartville uplift from the Denver-Julesberg Basin. The faults have displacements of as much as 1200 feet; total structural relief is as great as 5000 feet (Denson and Botinelly 1949). The boundary between the Hartville uplift and the Black Hills uplift is a structurally complex area in east-central Niobrara County, near the proposed ETSI well field (Figure 3-3).

The Madison Group (Guernsey Formation) is exposed in the eroded core of the Hartville uplift and in subsidiary anticlinal structures east of the Hartville fault. These outcrops of the Madison Group (Guernsey Formation) are probably sources of recharge for part of the Madison aquifer.



Source: U.S. Department of the Interior, 1974

Figure B-11. GENERALIZED GEOLOGIC SECTION OF THE POWDER RIVER STRUCTURAL BASIN AND ADJACENT AREAS IN NORTHEASTERN WYOMING



(Location of cross section is mapped on Figure 3-3.)

Adapted from Old West Regional Commission, 1978.

Figure B-12. GEOLOGIC CROSS SECTION G-G' ACROSS THE HARTVILLE UPLIFT

FEATURES INFLUENCING THE DEVELOPMENT OF STRATIGRAPHIC AND STRUCTURAL CONDITIONS

Precambrian Structures

Smith (1965) recognized five west-northwest-trending structural and topographic lineaments that extend from western Montana to near the Black Hills. More recently, Thomas (1974) grouped some of Smith's lineaments into a single lineament zone and recognized three additional lineaments farther north, as well as six northeast-trending lineaments. Zietz and others (1971) have recognized some of these trends on aeromagnetic maps and have interpreted them as lithologic or structural boundaries in the basement rocks. These features are defined mainly by the boundaries of uplifts and basins that formed in the Tertiary. Several of these lineaments—the Lewis and Clark, Nye-Bowler, and the Hope fault—have been active since the Precambrian (Harrison 1972; Rubel 1974; Kleinkopf 1977).

Precambrian structures are also known from the Black Hills, southeast of the area studied by Smith (1965) and Thomas (1974). Gott and others (1974) described some of these structural zones that trend northeast across the west flank of the Black Hills, calling them the Dewey and Long Mountain structural zones and the Edgemont lineament. In terms of ground-water storage, these features are probably not significant. They do, however, have the potential for enhancing the amount and direction of ground-water flow (Peterson 1978).

Cambrian to Devonian Age

Regional isopach maps show no evidence of large-scale thickness control by faults of the Lewis and Clark or other lineament zones, but Smith (1965) presents a sketch map that he interpreted as indicating control of Ordovician sedimentation by vertical faulting along some of the lineaments. More detailed maps, however, show that the eastward-trending Lewis and Clark line in the Belt Basin was also a linear negative area (termed the Central Montana Trough by some workers) during the Cambrian. It extended east-northeastward to the Williston Basin in North Dakota. Harrison and others (1974) reported that high-angle normal faults caused local thickness changes of a few thousand feet in the Flathead Sandstone in western Montana.

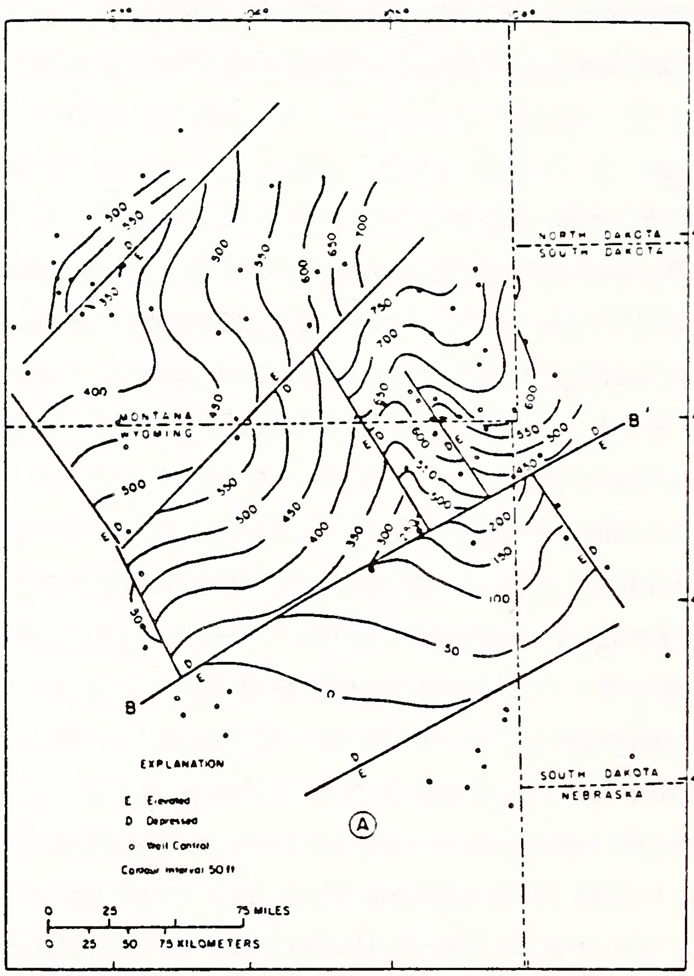
The change from Cambrian-age nearshore sandstone to Ordovician-age carbonates (Flathead or Deadwood Formation of Montana and Wyoming) reflects a global sea level rise at this time. Ordovician-age strata have been eroded in parts of Montana and Wyoming so that isopach maps are deceiving, but Norwood (1965) suggested that slight movement on a basement fault along the Lewis and Clark line (evidenced by en echelon faults of the Lake Basin-Huntley fault zone) may have caused some thinning in central Montana. Brown (1978) makes an argument for structural control of Ordovician sedimentation (Figure B-13).

Mississippian Age

Brown (1978) has argued that vertical movement along lineaments he mapped in the Powder River Basin, Williston Basin, and adjacent areas exerted some control on lithofacies distribution in Madison Group. Linear facies belts for the Madison Group along isopachous lineaments near the Black Hills are shown in Figure B-14. Control for such maps is poor, and the criteria upon which the lithologic interpretations were made are not clear. In addition, confinement of the thickened facies ("thicks," of Brown 1978) directly adjacent to the lineaments is puzzling; one might predict that Brown's depressed block between the two northernmost lineaments should have a high percentage of fragmental limestone throughout. Another problem with the map is that it shows the northernmost lineament to be elevated on the east. In a more comprehensive facies study, Heck (1978) concluded just the opposite: that the Cedar Creek anticline, which is bounded on the northeast by this lineament (fault), was elevated during Lower Mississippian time and received a thin section of shelf limestone, while the area to the northeast received deeper-water limestone.

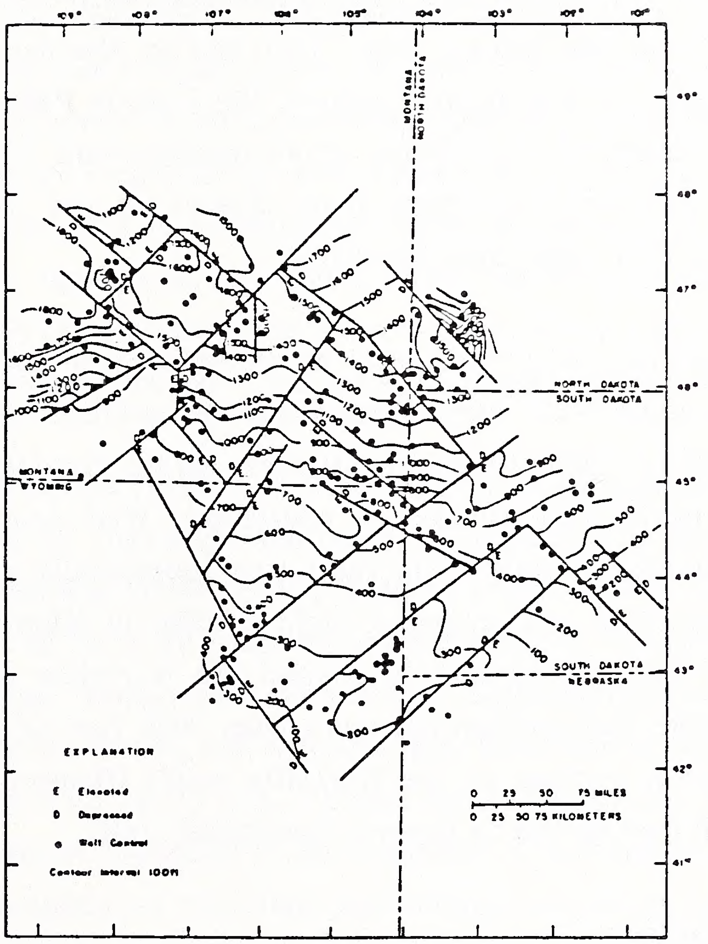
Pennsylvanian Age

Evidences for structural control of Pennsylvanian sedimentation is strong. Norwood (1965) reported that marine offshore bar sandstone was deposited in northeast-trending structural lows within the Central Montana Trough. Farther south, the Owl Canyon Formation, partly equivalent to the upper Minnelusa (Maughan 1963), thins southeastward across the Powder River Basin and grades from red siltstone to the Converse Sands, which pinch out along northeast-trending structures referred to by Maughan (1963) as the Wyoming lineament. This lineament parallels the more southerly Front Range mineral belt, which is



Source: Brown, 1978.

Figure B-13. ISOPACH AND PALEOSTRUCTURE OF ORDOVICIAN ROCKS



Source: Brown, 1978.

Figure B-14. ISOPACH AND PALEOSTRUCTURE OF THE MADISON GROUP part of Warner's (1978) Colorado lineament, mentioned previously as a possible Precambrian fault system. The Wyoming lineament includes a shear zone across which Precambrian rocks of dissimilar age and lithology are juxtaposed in the Laramie, Medicine Bow, and Sierre Madre uplifts (Warner 1978). Warner included it within his postulated Precambrian wrench-fault system, and extended it to the northeast to the Rawhide-Hartville fault and beyond. The Rawhide-Hartville fault may branch into a north-northeastward-trending fault referred to by Wulf (1963) as the Frannie Peak fault and by Shapiro (1971) as the Frannie Peak lineament. At the ground surface, the Frannie Peak lineament consists of an aligned complex of monoclines, small-displacement faults, and the western margins of anticlines that mark local closure on the west of the monocline (Shapiro 1971; Wulf 1963; Lisenbee 1978).

On a smaller scale, northeast- or northwest-trending folds form structural traps for Minnelusa oil in many fields along the northeastern flank of the Powder River Basin (Ware 1963; Trotter 1963; Aaro 1976b; Tranter and Kerns 1972; Berg and Tenney 1967; Wulf 1963). In particular, Wulf proposed that his north-northeast-trending Frannie Peak fault was tectonically active during late- or post-Minnelusa time and produced slight folding in Minnelusa strata. He also extended the fault southward to beyond the Hartville uplift. The Hartville-Rawhide-Sunrise fault system has more than 2000 feet of total structural relief on the basement surface at the Hartville uplift (Denson and Bottenelli 1949), most of which may be due to Eocene (Laramide) uplift.

Laramide Orogeny

The significance of the Lewis and Clark and other lineaments to the Laramide Orogeny and their behavior during this deformational episode have been discussed by several authors. Smith (1965) interpreted the west-northwest-trending lineaments as the surface expression of left-lateral strike-slip faults in the basement. He based his interpretation on the bending of fold axes as they cross the lineaments and on the en echelon fault patterns of the Huntley-Lake Basin fault zone near the eastern end of the Lewis and Clark line. Sales (1968) proposed that the Lewis and Clark and related lineaments separate the Montana-Canada province from the Wyoming-Colorado province. North of the lineaments, the rigid crust of the Canadian Shield resisted the Laramide east-west compression and the overlying sedimentary strata were detached and thrust eastward over the basement. South of the lineaments, the weaker crust was translated eastward, producing a horizontal shear couple and causing the left-lateral displacement. Stone (1969) and Thomas (1974) expanded the shear couple concept to explain the other structural trends associated with the prominent west-northwest and northeast wrench fault. Stone showed that vertical faulting, as well as strike-slip faulting, is important in wrench-fault systems. Thomas emphasized evidence for intensification of Laramide stresses along much older "basement weakness zones" oriented northeast and west-northwest. Evidence for such activity during Precambrian and Paleozoic times has been discussed previously. However, it may be significant that earlier movement was predominantly dip-slip; no significant strike-slip offset has been recognized (Lisenbee 1978; Reynolds 1977a; Harrison and others 1974; Brown 1978). Hence, pre-Laramide structures may not have had the same origin as Laramide structures.

Harrison and others (1974) and Hoppin (1974) have recently questioned the role of lineaments in Laramide tectonics. Harrison and others dispute the hypothesis of left-lateral offset, citing mapping evidence that indicates apparent right-lateral offset of 10 to 20 miles on several faults in the western part of the Lewis and Clark line. Hoppin also showed that contradictions exist between the predicted and observed trends, and amounts and directions of displacement along several supposed wrench faults (e.g., Tongue River, Tensleep). He concluded (p. 2270) that "attempts to reconcile other lineament directions into a single-stress system require complicated rotations and unique sequences of movements to make the aberrant lineaments fit the pattern expected by the theory." On the basis of the contradicting evidence presented by these various workers, it appears that a satisfactory hypothesis relating the lineaments in the northern Rocky Mountains to other Laramide structures and stresses has not been presented.

NIOBRARA COUNTY WELL FIELD

Location

The proposed ETSI Niobrara County well-field site is located northwest of Lusk, Wyoming, and southwest of the Black Hills (Figures 3-3, B-8). The well field site lies on the fringes of the Powder River and Denver-Julesberg basins and along the Fanny Peak lineament. The southern portion of the well field site is underlain by the Old Woman anticline, a topographically subtle feature that has yielded small amounts of petroleum.

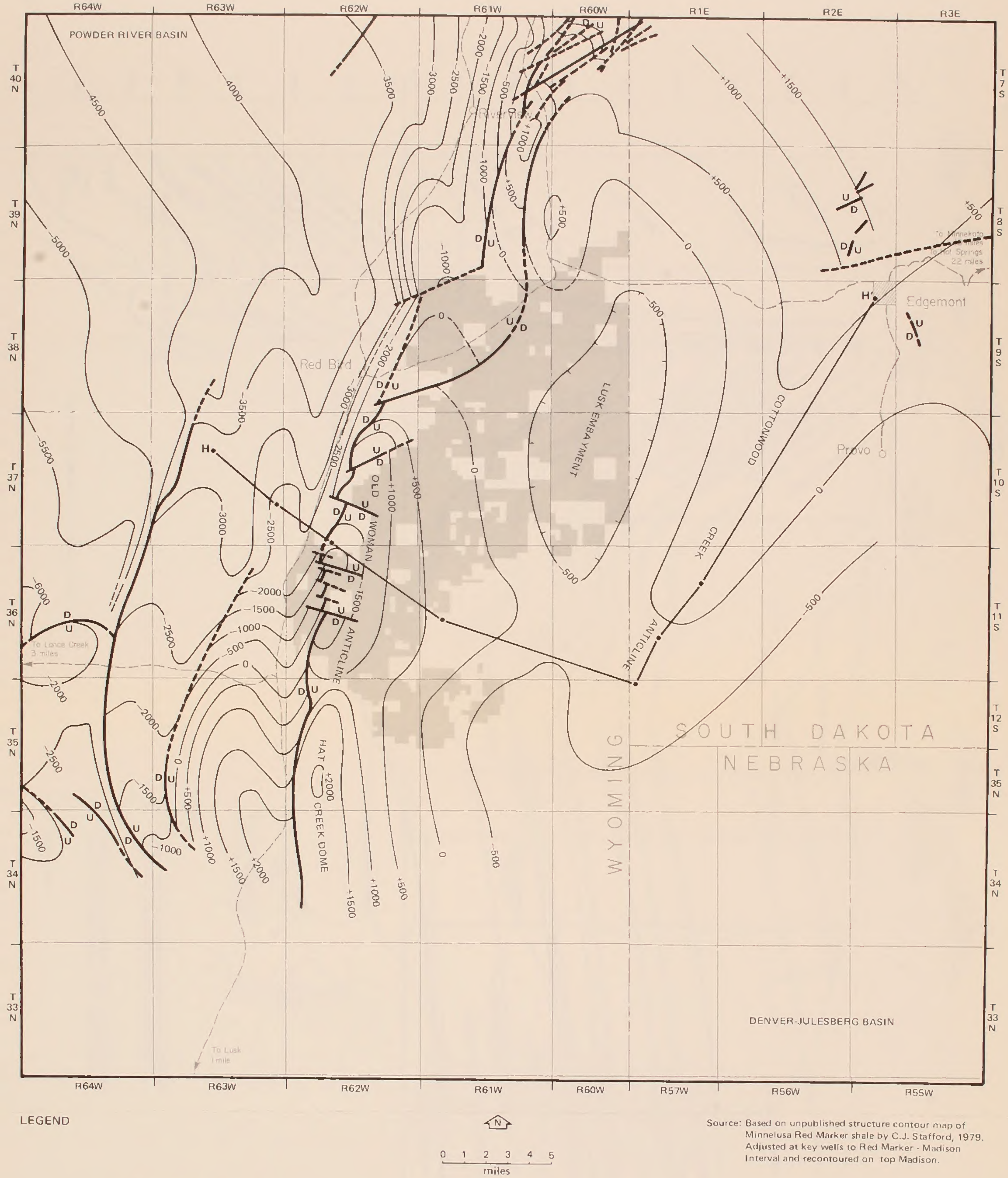
Sources of Data

Studies in connection with oil and gas exploration have yielded most of what is known about the subsurface geology of the region surrounding the ETSI Niobrara County well field site. Northrop (1939) mapped the geologic structure on the Fall River Formation. Kramer and Dobbin (1943) defined the subsurface structure of much of the region for their investigation of the Lance Creek, Buck Creek, Little Buck Creek, and Old Woman (Cow Gulch) oil fields. In the 1950s and 1960s, many articles appeared in oil and gas symposia on the Powder River Basin.

Data used for constructing isopach and structure contour maps were Petroleum Information (P.I.) scout cards, unpublished structure and isopach maps by C.J. Stafford and George Wulf, and USGS Water Supply Paper 1788 by Whitcomb (1965). The unpublished masters' theses of Wulf (1955) and Horton (1953) provided interpretation of the structure across the Fanny Peak lineament.

Structural Geology

The Niobrara County well field site is in a structurally complex area located near the boundaries of four structural provinces: the Black Hills uplift, the Hartville uplift, the Powder River Basin, and the Denver-Julesberg Basin (Figures 3-1, B-15). The well field is located on a structural high east of the Fanny Peak lineament and is bordered on the east by the Lusk embayment, an extension of the Denver-Julesberg Basin, and on the west by the Powder River Basin. The major structural features are described in detail below and are shown on a structural cross section of the region (Figure B-15), and on Figure B-16, where a detailed structural contour map of the top of the Madison Group in the vicinity of the Niobrara well field site is shown. Other structural information has been previously discussed on a regional basis.



LEGEND

Structure contours on top of Madison Group Elevation in feet (MSL)

Fault or steep monoclinal fold Dashed where approximately located
U - Upthrown side
D - Downthrown side

Location of geologic cross section and well logs used for section control

Source: Based on unpublished structure contour map of Minnelusa Red Marker shale by C.J. Stafford, 1979. Adjusted at key wells to Red Marker - Madison Interval and recontoured on top Madison.

Figure B-15. STRUCTURAL GEOLOGY OF THE NIOBRARA COUNTY WELL FIELD

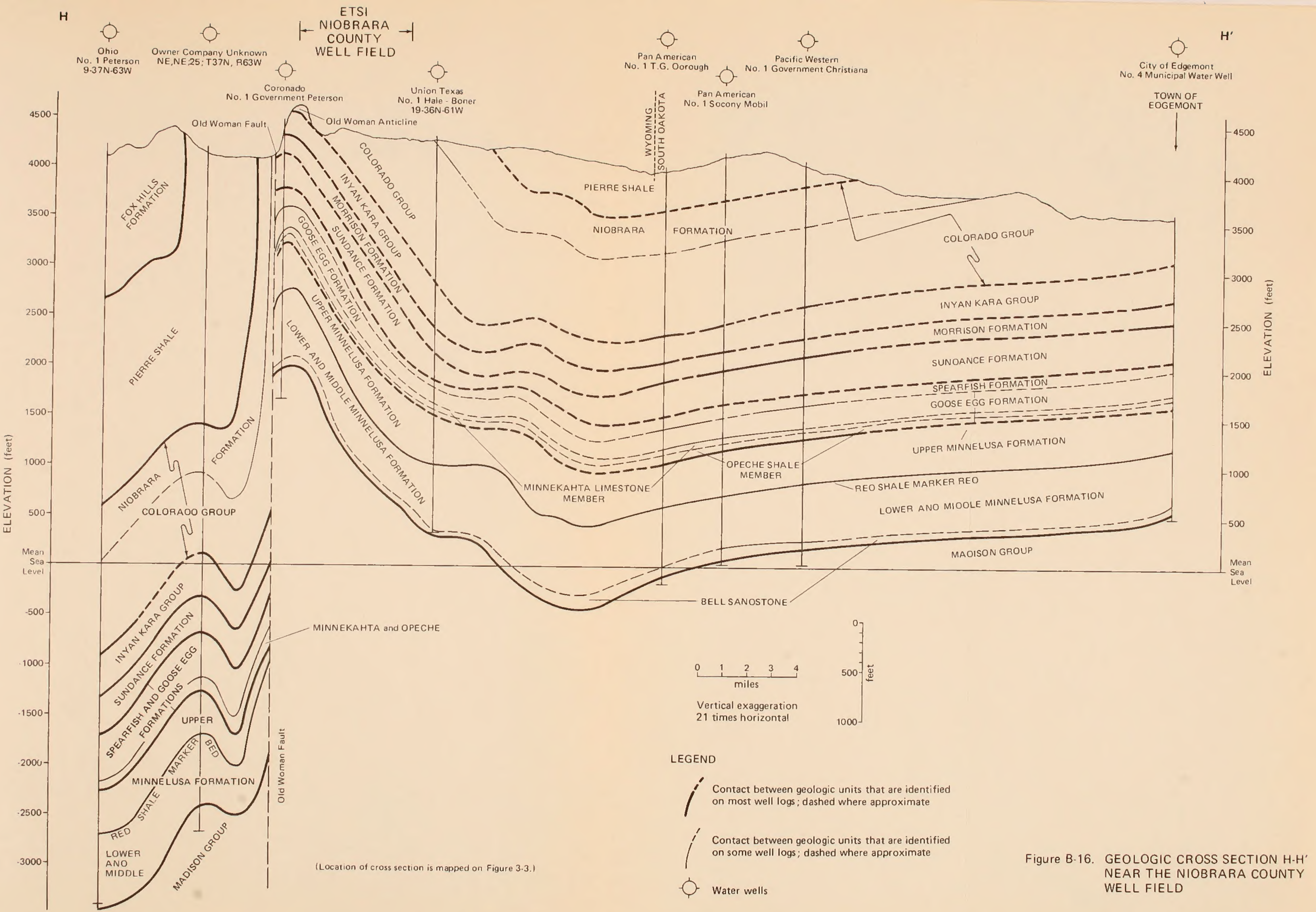


Figure B-16. GEOLOGIC CROSS SECTION H-H' NEAR THE NIOBRARA COUNTY WELL FIELD

Fanny Peak Lineament, Fanny Peak Monocline, and Old Woman Anticline. The Fanny Peak lineament is represented by structures extending south from the northern Black Hills through the Hartville uplift. The structures representing the Fanny Peak lineament near the Niobrara County well field include the Fanny Peak monocline, the Old Woman anticline, and the Old Woman fault.

The Old Woman anticline is one of several analogous structures along the eastern (high) side of the Fanny Peak monocline (Kramer and Dobbin 1942; Horton 1953; Wulf 1955, 1963). The Old Woman anticline is an asymmetrical anticline trending north to south, with the east flank dipping 5 to 20 degrees and the west flank dipping vertically (Kramer and Dobbin 1943). The west flank of the anticline is offset downward 2000 to 4000 vertical feet from the anticlinal crest in less than 4000 horizontal feet (Stafford 1980) (Figure B-15). The Old Woman anticline is expressed topographically as a low bluff east of Old Woman Creek and is expressed structurally by the outcrop pattern of the exposed formations. The Pierre Shale surrounds the anticline with the Niobrara Formation, Carlile Shale, Graneros Shale, and Inyan Kara group exposed progressively upward toward the center of the anticline (Figure B-17). The Morrison and Sundance formations are exposed in a small outcrop near the top of the Old Woman anticline. The axis of the Old Woman anticline extends to the south with less structural relief, where it is called the Hat Creek anticline (Figure B-16).

Along the Fanny Peak monocline, on the west side of the Old Woman anticline, apparent thinning of some beds occurs and other beds are faulted along a 24-mile-long northward-trending vertical normal fault called the Old Woman fault. The Old Woman fault and the Fanny Peak monocline to the north are intersected at high angles by several nearly vertical normal faults of small offset. These faults are visible in aerial photographs of the Old Woman anticline and were mapped by Horton (1953) and Stafford (1980). These faults parallel the trace of major normal faults between the Old Woman and Redbird oil fields and are parallel to faults mapped in surface outcrop north of the Mule Creek oil field by Northrop (1939).

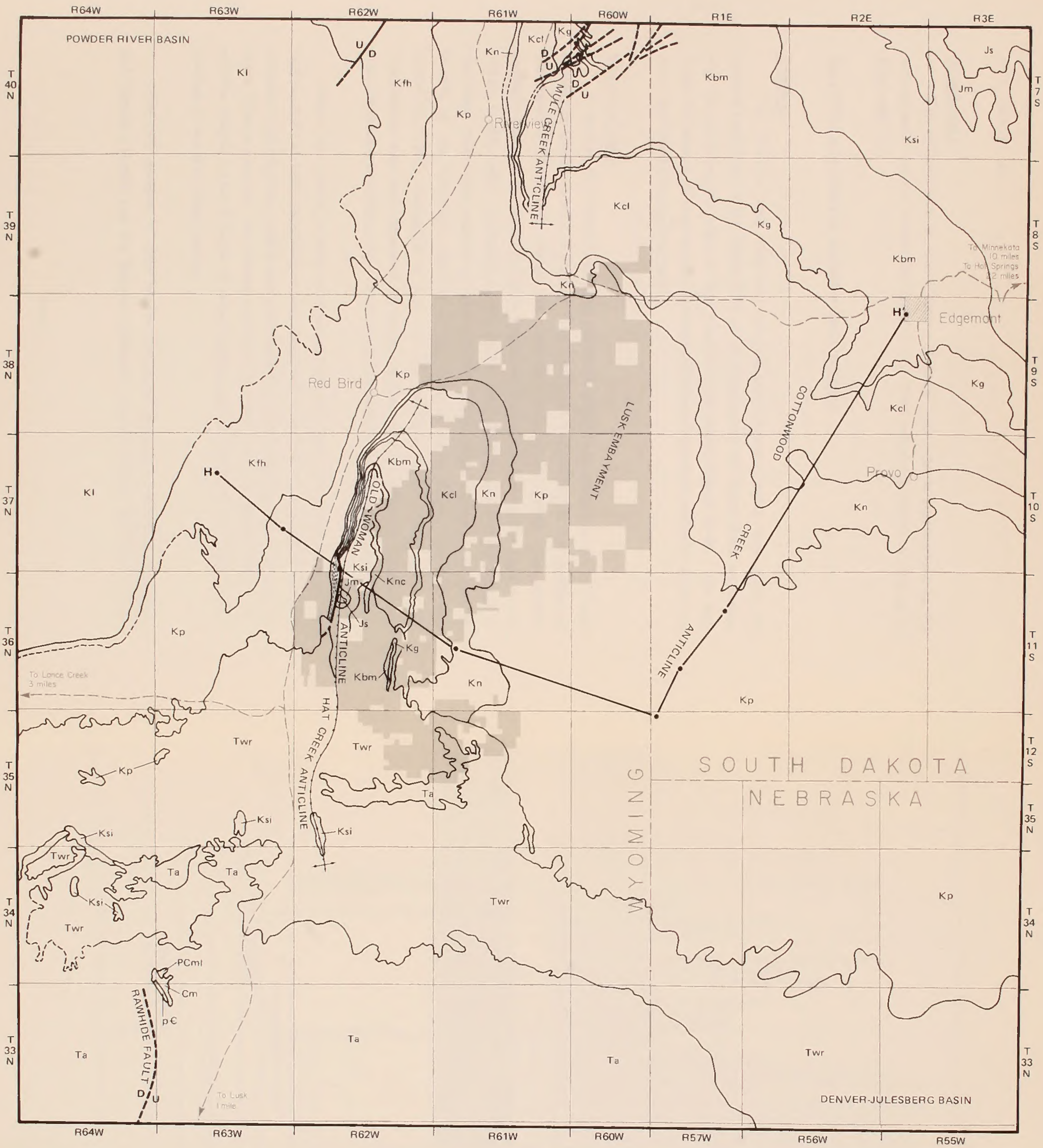
Lusk Embayment. The Lusk embayment, a northern extension of the Denver-Julesberg Basin (Wulf 1974), is the deep structural basin located east of the

Niobrara County well field. The eastern flank of the Lusk embayment is formed by the Cottonwood Creek anticline, which extends south and west from beneath the city of Edgemont.

Structures That Are Important Oil Traps. West of the Old Woman anticline are several anticlinal structures from which oil is being produced. The Lance Creek field is situated on an anticline faulted along its western edge. The anticline is formed by an extension of the Shawnee flexure. This fault is shown by Albanese (Old West Regional Commission 1978) to be a reverse fault at depth and to have a down-to-the-west throw ranging from 2000 to 4000 feet (Figure B-12). Albanese shows that displacement of this magnitude has positioned the Madison Group on the east side of the fault against the Pierre Shale on the west side. Oil and gas are produced at the Lance Creek field from the Muddy Sand, Dakota (Fall River) Sandstone, Morrison Formation, Sundance Formation, and the Leo Sands of the Minnelusa Formation. There has been limited production from the Bell Sand in the Lance Creek field (Stafford 1980).

Along an east-northeast trend east of the Lance Creek field are several other oil fields, called East Lance Creek and Little Buck Creek. Northwest of the Old Woman anticline, oil is being produced from the Anthills fields (Glass 1975). All of these fields produce primarily from the Cretaceous-age Dakota (Fall River) Sandstone. The Little Buck Creek field has also produced from the Converse Sand and the Leo Sands of the Minnelusa Formation (Biggs and Espach 1960). Of these fields, only Lance Creek has any faults known to be connected with these anticlinal structures.

East of the Old Woman fault are several other oil fields situated on anticlines, including the Cow Gulch (Old Woman anticline) oil field and the Pine Lodge to the south, and the Redbird field to the north of the Old Woman anticline (Glass 1975). Production in these anticlinal structures, which are situated on the structurally high side of the Fanny Peak lineament, is from the Pennsylvanian Leo Sands of the Minnelusa Formation (Thomas 1957; Petroleum Information 1977). Oil shows are reported in the Cow Gulch (Old Woman anticline) oil field from the Bell Sand and Deadwood Formation (Stafford 1980).



LEGEND

MIOCENE	Ta	Arikaree formation
OLIOCENE	Twr	White River group
UPPER CRETACEOUS	Kl	Lance formation
	Kfh	Fox Hills sandstone
	Kp	Pierre shale
	Kn	Niobrara formation (COLORADO GROUP)
	Kcl	Carlile shale (COLORADO GROUP)
	Kg	Greenhorn limestone (COLORADO GROUP)
	Kbm	Belle Fourche and Mowry shales undifferentiated (COLORADO GROUP)
LOWER CRETACEOUS	Knc	Newcastle sandstone (COLORADO GROUP)
	Ksi	Skull Creek Shale and Ihyan Kara group undifferentiated
UPPER JURASSIC	Jm	Morrison formation
	Js	Sundance formation
PERMIAN-PENNSYLVANIAN	PCml	Minnelusa formation
MISSISSIPPIAN	Cm	Madison Group
PRE-CAMBRIAN	p€	Pre-Cambrian rocks

N

0 1 2 3 4 5
miles

Source: Modified from Whitcomb, 1965, Plate 1; Love, et al, 1955, Geologic Map of Wyoming; Darton, 1951, Geologic Map of South Dakota.

Axis of Anticline

Fault, dashed where approximately located.
U - Upthrown side
D - Downthrown side

Location of geologic cross section and well logs used for section control

Figure B-17. SURFICIAL GEOLOGY OF THE NIOBRARA COUNTY WELL FIELD

Stratigraphy

The stratigraphy of the Niobrara County well field is summarized in the stratigraphic column shown in Figure B-18. This column is based on the log of ETSI well O-1.

GILLETTE AND CROOK COUNTY WELL FIELDS

Location

The Gillette well field and the proposed Crook County well field are located northwest of the Black Hills uplift adjacent to the Black Hills monocline and the northeastern edge of the Powder River Basin (Figure B-8). The well fields are separated from each other by a distance of approximately 27 miles and hence are discussed together here.

Sources of Data

A number of reports have been published which have described the surficial geology of Crook County, Wyoming. The first systematic study of the geology of the northern Black Hills region was made by Darton (1905, 1909). The general geologic features of the Black Hills region were again described by Darton and O'Hara (1905, 1907). During the early 1920s, the northern and western flanks of the Black Hills were mapped by Rubey (1929, 1931). More recently, as part of studies of the bentonite deposits of the Missouri River Basin, Knechtel and Patterson (1955) remapped a part of the northern Black Hills area. A compilation map was expanded by Mapel, Robinson, and Theobald (1959), who also prepared a structure map of the top of the Dakota (Fall River) Formation.

Since the 1950s, a large number of articles have been published on the region, most of them reporting on mapping studies carried out as part of uranium resource investigation studies and data collected while drilling for oil along the Black Hills monocline. No attempt is made to reference all these articles. The articles judged to be of value in understanding the structure and stratigraphy of the region are mentioned below.

The best sources of data on the structural geology are Mapel, Robinson, and Theobald (1959) and the Dakota structure map by Barlow and Haun (1977).

Other data available for constructing structure contour maps were P.I. (Petroleum Information) scout cards for all wells penetrating the Madison Group within 30 miles of the well-field sites, scout cards for many Minnelusa wells in the area, well logs from the Madison wells at the Bell Creek oil field (Montana Oil and Gas Commission 1980), a well log for Madison test well No. 1 (Blankennagel and others 1977), well logs from Gillette city wells at the new well field near Moorcroft, Wyoming (Arnex 1977, 1979, 1980), and a well log from the Madison water well at Devils Tower, Wyoming (Whitcomb and Gordon 1964).

Lithologic and electric logs were available only for Madison test well No. 1 (Blankennagel and others, 1977) and for the Gillette Madison wells (Arnex 1977, 1979, 1980). Lithologic well logs were also available for the Devils Tower Madison well (Whitcomb and Gordon 1964) and for the Bell Creek field wells. General lithologic descriptions of water-bearing units in Crook County are given in Whitcomb and Morris (1964).

Structural Geology

A structure map of the top of the Madison Group (Figure 3-3), showing mapped faults and major anticlines and synclines and two geologic cross sections (Figures B-9, B-19), summarizes the structural geology of the region. Except for the mapped faults that were taken from Mapel and others (1959), the structural map and cross sections were derived from primary data sources.

The structure map and cross sections show the major structural features in the area, including the steep Black Hills monocline, the Tertiary intrusives ringed by annular outcrops of pre-Permian rocks, and the surface of the Madison Group. The cross sections show the continuity of the formations in the region, the general thickening of the Madison Group and Red River Formation to the north, the thinning of the Minnelusa Formation to the north, and the relative constancy of the thickness of the Opeche and Minnekahta formations.

The Gillette well field is situated just east of the Black Hills monocline on a small structure called the Eggie Creek syncline (Figure 3-1). The maximum structural relief on the Pine Ridge and Oil Butte anticlines southwest and northwest of the well field is approximately 500 feet where the syncline lies

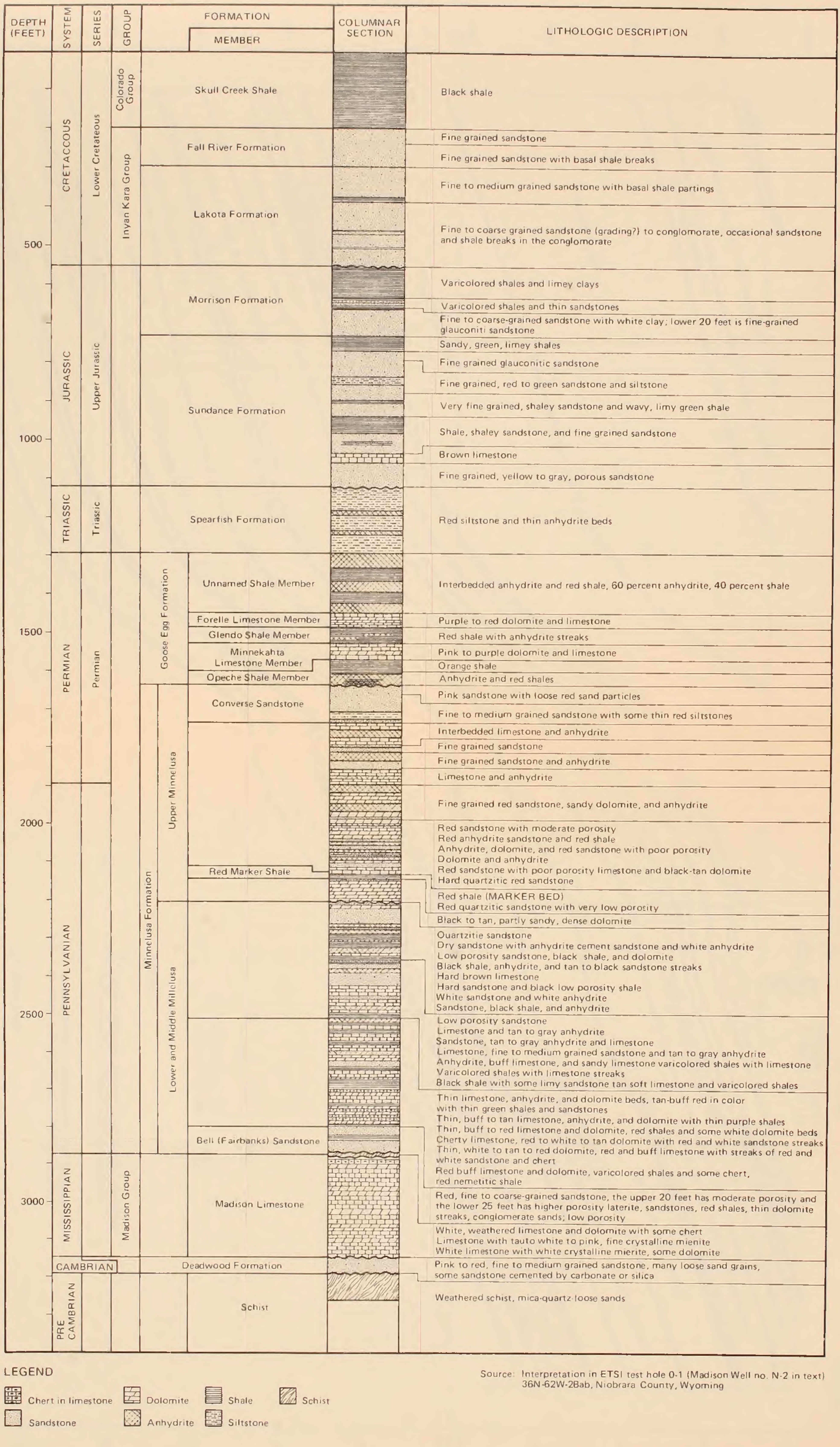


Figure B-18. STRATIGRAPHIC COLUMN FOR THE NIOBRARA WELL FIELD SITE

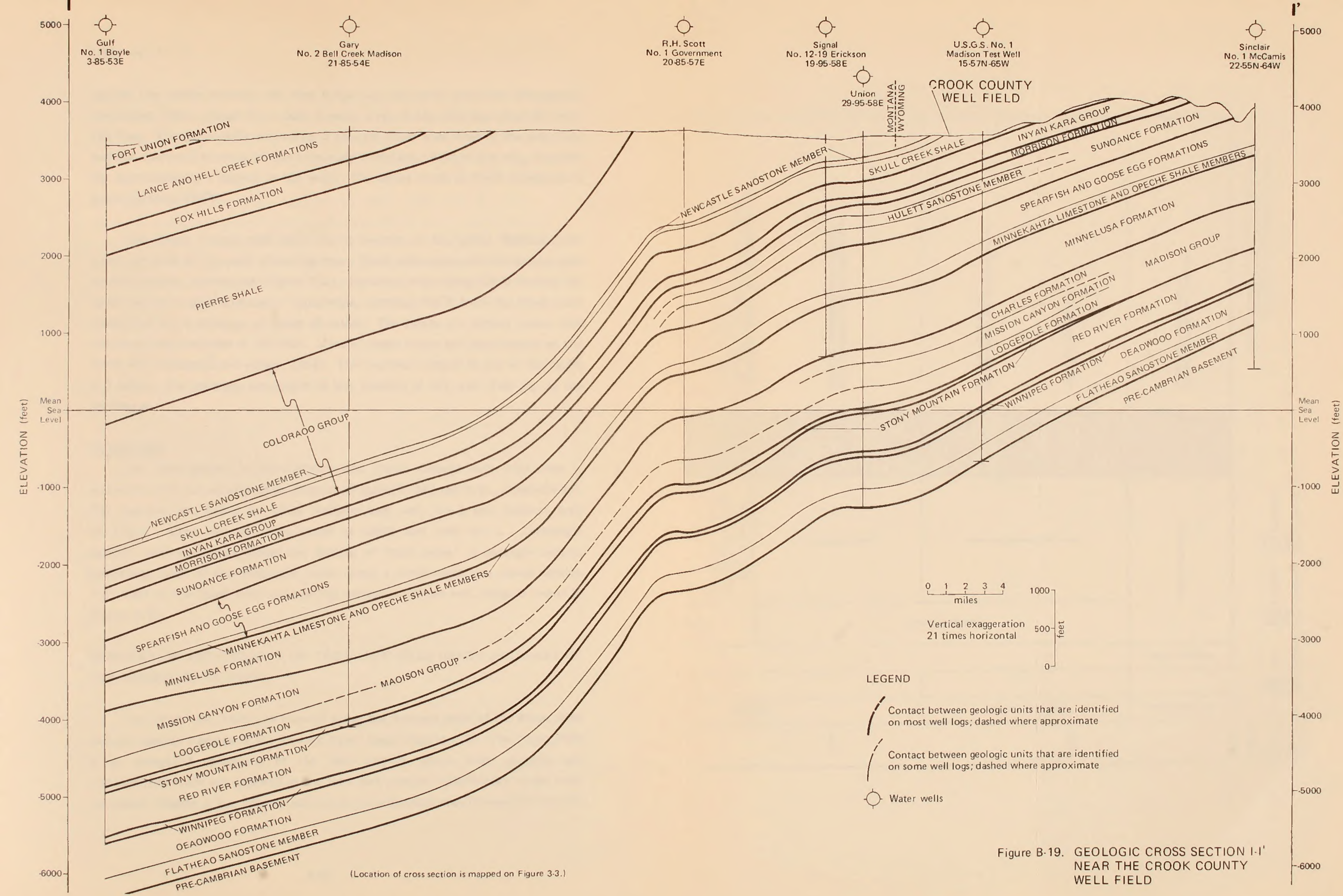


Figure B-19. GEOLOGIC CROSS SECTION I-I' NEAR THE CROOK COUNTY WELL FIELD

against the saddle between the Pine Ridge and Oil Butte anticlines (Bergendahl and others 1961), though the saddle directly west of the site has relief of about 180 feet. The Black Hills monocline is about 6 miles wide west of the well field and has a structural relief of approximately 5000 feet. East of the site, the beds dip approximately 1 degree to the west. The strike of all of these structures is approximately N20°W.

The Crook County well field site is located on the Little Missouri fault zone northeast of the point where the steep Black Hills monocline bifurcates into several smaller monoclines (Figure 3-3). Robinson and others (1964) showed the fault zone to be approximately 7 miles wide, trending N55°E from the Black Hills monocline for a distance of about 30 miles. The faults are normal faults with maximum displacement of 100 feet. Most of these faults are downthrown on the north side (Robinson and others, 1964). The maximum length of any of the faults is 3 miles. The geologic structures in the vicinity of the well field dip to the northwest.

Stratigraphy

The stratigraphy at the Gillette and Crook County well-field sites is summarized in two stratigraphic columns (Figures B-20 and B-21, respectively). The columns are based on USGS Madison test well No. 1 and Gillette well No. CR-2. Core samples were taken at USGS test well No. 1. Lithologic samples were collected during the drilling of these holes. A geologic section portraying much of the Paleozoic rocks along a north-south line (cross section J-J') west of the Black Hills and passing through all three well fields is shown in Figure B-22.

SUMMARY OF THE GEOLOGY OF THE BLACK HILLS UPLIFT AND PART OF THE POWDER RIVER BASIN

The three well fields are located along the western parts of the Black Hills and the eastern margins of the Powder River Basin (Figure 4-2). The Black Hills is an elongated upwarping of the land surface where older granitic and metamorphic rocks are exposed in the core and younger sedimentary rocks form the flanks (Figure 3-1). These rocks range from Precambrian through Tertiary in age. The rocks dip most steeply along the eastern side of the uplift and less steeply along the western and northern sides. In a number of places, especially in the northern part of the area, the uplift is pierced by Tertiary-age intrusions, the best known of which is Devils Tower.

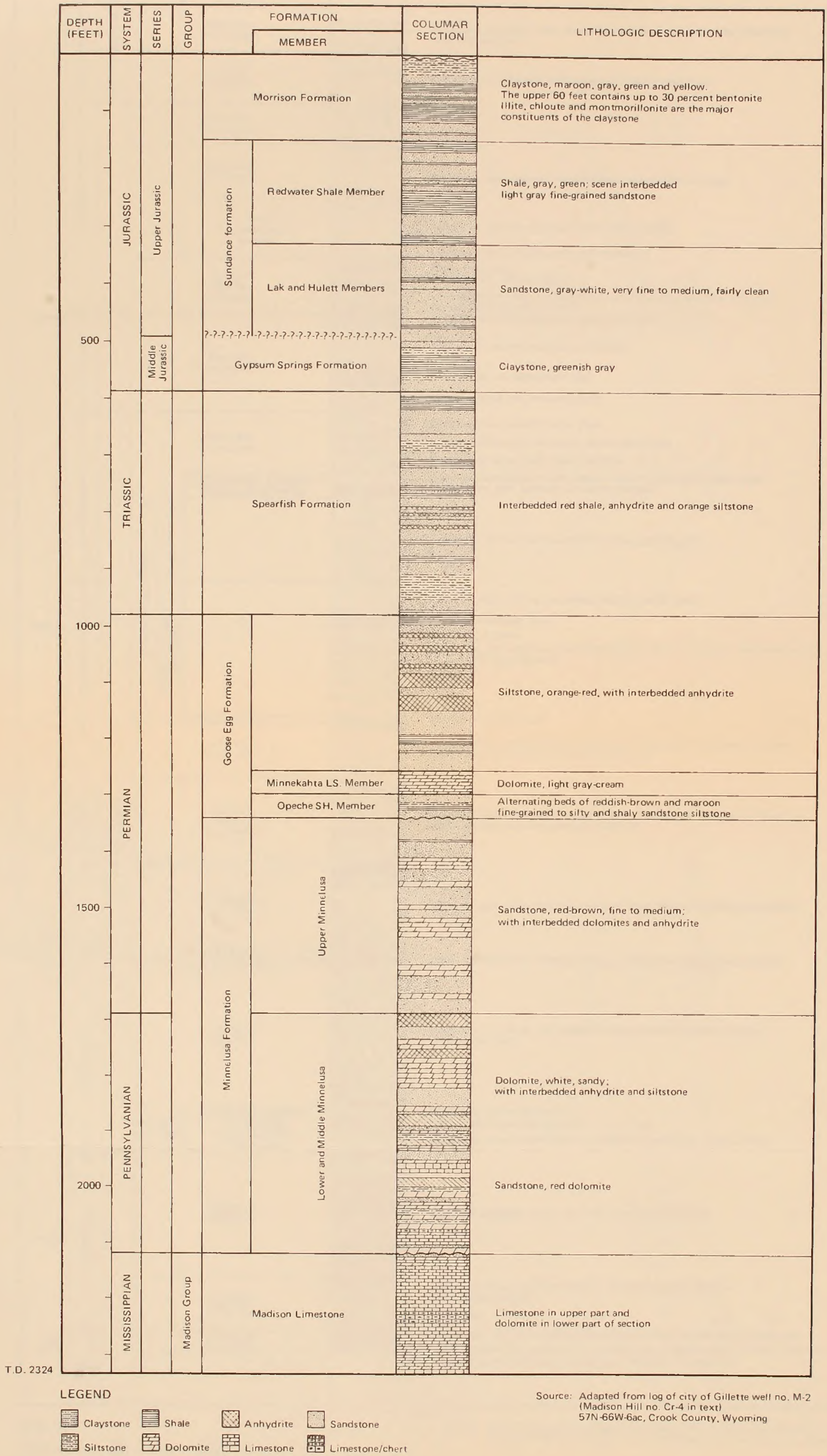
West of the Black Hills, the Powder River Basin surficially forms a relatively large, flat plain surrounded by the Big Horn Mountains on the west, the Laramide Range and Hartville uplift on the south, and the similarly flat plain overlying the Williston Basin and Central Montana Trough on the north. In the subsurface, the Powder River Basin forms an asymmetrical depression which is deepest along its western side near the Big Horn Mountains (Figure 3-3). The basin is filled with varying thicknesses of sedimentary deposits ranging from Cambrian through Tertiary in age.

The basal Cambrian-age sediments are composed primarily of sandstones, siltstones, and finer-grained claystones. Little economic use is made of these units.

Above the Cambrian are Ordovician, Mississippian, and Pennsylvanian carbonates, with lesser amounts of shale, sandstone, and anhydrite. Of particular interest to the study are the Madison Group (Pahasapa Limestone) and the Minnelusa Formation. The Madison Group is composed chiefly of limestone and dolomite. Karst development and solution activity have affected the upper part of the Madison Group and along certain fractures and joints.

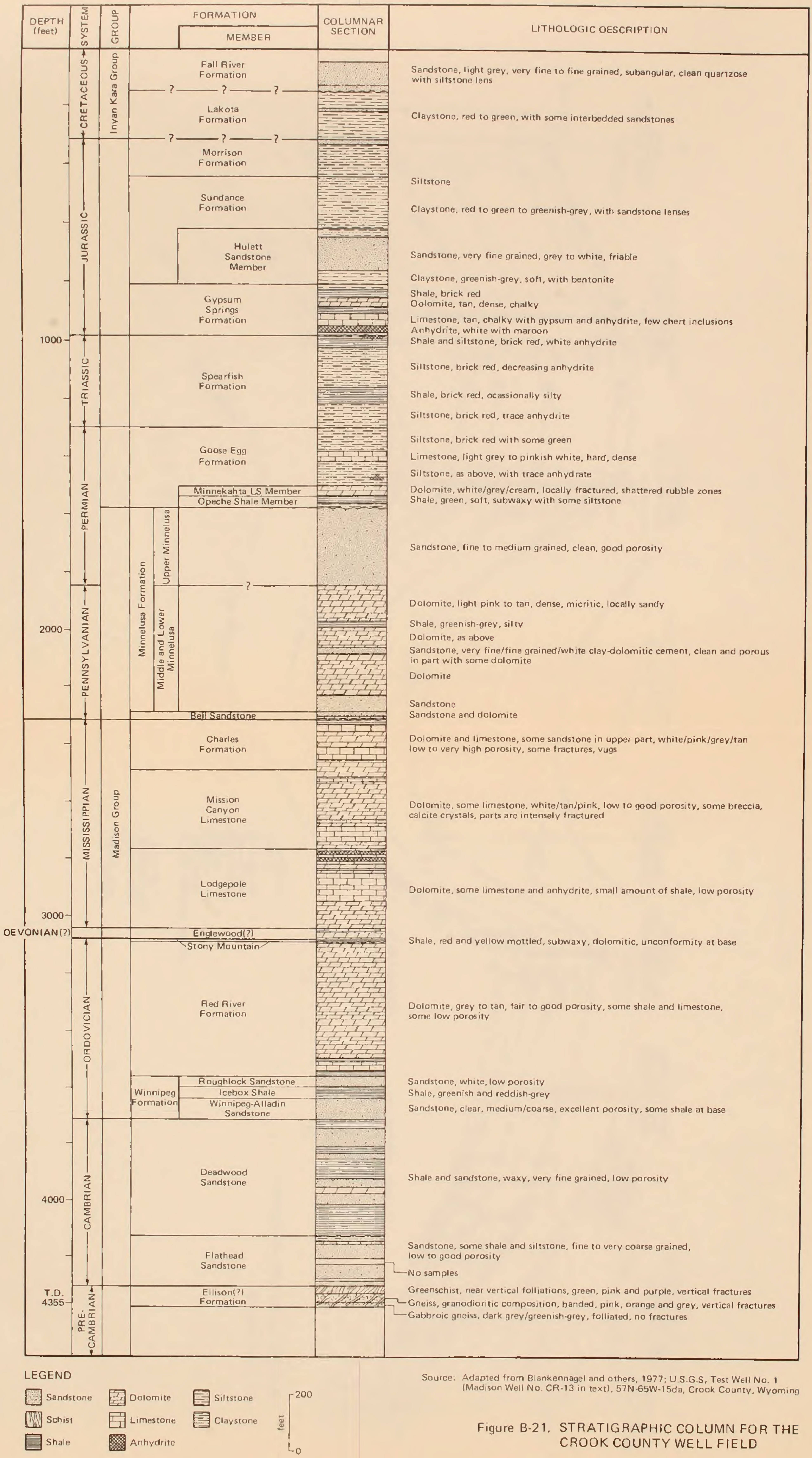
Overlying the Madison Group is the Minnelusa Formation. The Minnelusa Formation is composed predominantly of sandstone, with smaller amounts of dolomite, shale, and anhydrite. The Bell Sand forms a discontinuous part at the base of the Minnelusa Formation. Some oil is produced from several of the sandstone beds in the Minnelusa Formation (Converse and Leo Sands); much of this activity occurs in the northeastern part of the Powder River Basin. The upper part of the Minnelusa Formation is an aquifer for a number of wells around the perimeter of the Black Hills.

Above the Minnelusa Formation are Permian, Triassic, Jurassic, and Cretaceous sediments composed largely of shales, siltstones, and claystones,



Source: Adapted from log of city of Gillette well no. M-2 (Madison Hill no. Cr-4 in text) 57N-66W-6ac, Crook County, Wyoming

Figure B-20. STRATIGRAPHIC COLUMN FOR THE GILLETTE WELL FIELD SITE



Source: Adapted from Blankennagel and others, 1977; U.S.G.S. Test Well No. 1 (Madison Well No. CR-13 in text), 57N-65W-15da, Crook County, Wyoming

Figure B-21. STRATIGRAPHIC COLUMN FOR THE CROOK COUNTY WELL FIELD

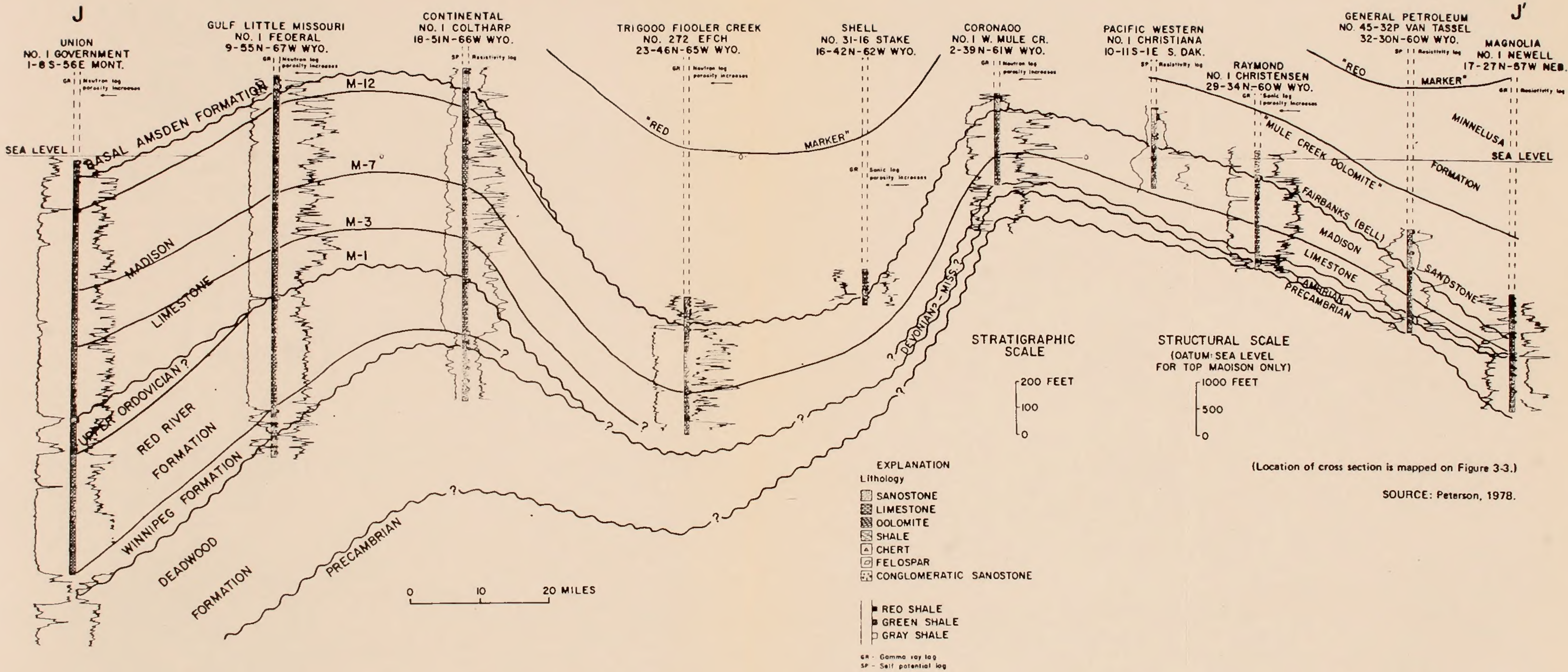


Figure B-22. GEOLOGIC CROSS-SECTION J-J'
WEST OF THE BLACK HILLS

with small amounts of limestone and sandstone. The Pierre Shale forms the thickest part of this sequence and hydraulically separates geologic units above and below the shale. The components of the Inyan Kara Group (Dakota-Lakota Sandstones) are important aquifers in the area. These aquifers are separated from the Minnelusa Formation by a relatively large amount of claystone, siltstone, and gypsum, with small amounts of limestone and sandstone.

Above the Cretaceous-age sediments are Tertiary-age siltstones, sandstones, and coal. Ground-water supplies are derived from isolated lenses within these sediments.

The Black Hills-Powder River Basin region has been subjected to relatively large amounts of tectonic activity, some of which dates to the Precambrian. Faulting and folding have displaced sediment, causing depositional patterns to change and lithologies to vary. The Black Hills monocline, the Fanny Peak lineament, and the Cascade monocline, along with the largest structural elements in the area, are some of the more important features that have been the result of or have influenced the development of the structural and stratigraphic conditions in the area.

The Madison Group in the Black Hills and Powder River Basin is the product of a series of depositional, erosional, and tectonic events that occurred from early Paleozoic through Recent time. Mississippian-age bioclastic carbonates were deposited over a wide, shallow shelf covering the present states of Wyoming, South Dakota, Montana, and parts of Nebraska and Colorado. Post-depositional dolomitization enhanced the moderate primary porosity of these limestones. Secondary porosity enhanced the primary porosity of the carbonates, with the subsequent formation of karst and zones of well-developed secondary porosity and permeability in the upper part of the Madison Group during Late Mississippian time. The Madison Group carbonate complex was buried by the Pennsylvanian influx of clastic sediments and shaly limestones of the Minnelusa Formation. These Pennsylvanian and Permian sediments were deposited in an ever-increasing shallow basin and culminated in an evaporitic sequence. These sediments were, in turn, overlain by a moderately thick siltstone sequence. Throughout the Mesozoic, deposition of several tens of thousands of feet of limestone, terrigenous sands, shales, and coal beds took place over the region. The Laramide Orogeny uplifted and exposed to erosion the entire Mesozoic and Paleozoic sections. Subsequent deposition of terrigenous clastics occurred sporadically in restricted basins during Tertiary time.

Tectonic forces and subsequent erosion are responsible for shaping the Madison aquifer. The Laramide-age Black Hills and Hartville uplift exposed the Madison Group at the surface, providing large recharge areas and permitting development of post-Mesozoic porosity formation which, in places, continues to the present day.

APPENDIX C

SPRINGS OF THE BLACK HILLS

TABLE C-1

SPRINGS OF THE BLACK HILLS
(Tabulation is restricted to known springs with a discharge greater than 0.2 cfs)

Spring Location Number	Location of Spring	Name of Spring	Source of Water and Type of Spring	Average Flow (cfs)	Temp. (°C)	Dates of Measurements	Comments
Custer County, South Dakota							
CU-1	2S-7E-27b	Deadman Gulch Springs	A series of springs that have discharge from the Spearfish Formation.	0.8	10	1968-1970	
CU-2	2S-7E-34b	Battle Creek Springs, 5 miles west of Hermosa	A series of springs that occur either at the Madison-Minnelusa contact or in the Minnelusa Formation. They are probably resurgent springs.	1	4-16	1967-1970	Battle Creek loses 4 cfs a few miles upstream where the creek crosses the Madison Limestone.
CU-3	3S-7E01cc	Grace Coolidge Springs, west of Hermosa	A series of springs that probably issue from the Sundance Formation.	1	-	1967-1970	
CU-4	6S-6E-14cd	Beaver Creek Spring	This spring issues from the contact of the Minnekahta and Spearfish formations along a small anticline in Beaver Creek valley.	9	-	1967-1970	
Fall River County, South Dakota							
F-1	7S-5E-11ad	Cold Brook Spring at Cold Brook Reservoir	The spring discharges from the Minnekahta Group above Cold Spring Reservoir. All the water seeps back into the limestone in the reservoir area.	0.7	-	1968-1970	
F-2	7S-5E-14a	Hot Brook Springs	The probable source of the spring flow is the Madison Group. The springs are located near the axis of the Cascade anticline where the Madison Group is exposed in the canyon of Hot Brook.	2	24	1968-1970	
F-3	7S-5E-24	Hot Springs	The several large springs in the town of Hot Springs, occur at the Minnekahta-Spearfish contact.	23	31	1968-1970	The largest of the Hot Springs is known as Evans' Plunge.
F-4	8S-5E-18(?)	Cold Spring	The spring occurs at the Minnekahta-Spearfish contact.	1	18	1968-1970	
F-5	8S-5E-19ddd	Cascade Spring	The spring occurs at the Minnekahta-Spearfish contact.	23	19	1968-1970	The largest spring in the Black Hills of South Dakota.

TABLE C-1 Continued

Spring Location Number	Location of Spring	Name of Spring	Source of Water and Type of Spring	Average Flow (cfs)	Temp. (^{o}C)	Dates of Measurements	Comments
Lawrence County, South Dakota							
L-1	2N-2E-10(?)	Headwater Spring on South Fork of Rapid Creek	This spring occurs on the central limestone plateau at the contact between the Madison Group and the Deadwood Formation.	3	5	1968-1970	
L-2	3N-2E-26	Tilson Creek Springs	A series of springs where Tilson Creek crosses the Madison Group and Deadwood Formation.	2	-	1969	
L-3	4N-1E 4N-2E 5N-1E 5N-2E	Spearfish Creek Springs	These springs mainly occur as water table springs and seeps on the central limestone plateau along the channels of Spearfish Creek and its tributaries.	40	-	1968-1969	Rahn and Gries (1973) stated that 12 cfs of the total discharge comes from Little Spearfish Creek, 10 cfs comes from the East Fork, 9 cfs from upper Spearfish Creek, and 10 cfs from springs in Spearfish Canyon below Cheyenne Crossing.
L-4	7N-1E-21	Crow Creek Springs	A series of springs that discharge from the Spearfish Formation.	17	10		The flow capital is the combined discharge of many springs along Crow Creek at Cox Lake and at Mirror Lake.
Meade County, South Dakota							
M-1	3N-6E-11bac	Elk Creek at Piedmont Spring	The spring discharges from alluvium overlying the Spearfish Formation.	2	10	1968-1970	
M-2	4N-6E-20c	Morris Creek Spring	This spring occurs at the Minnekahta-Spearfish contact.	0.4	-	1969	
M-3	5N-5E-11b	Bear Butte Springs	A series of small springs that discharge from the alluvium along Bear Butte Creek. The Sundance Formation underlies the alluvium in this area.	0.6	-	1968-1970	
M-4	5N-5E-24c	Alkali Creek near Black Hills Cemetery Springs	A series of small springs that discharge from the alluvium which overlies the Sundance Formation.	0.6	-	1969	
M-5	5N-5E-33caa	Alkali Creek above Sturgis Reservoir Springs	A series of small water table springs in the Madison Group.	0.2	-	1969	

TABLE C-1 Continued

Spring Location Number	Location of Spring	Name of Spring	Source of Water and Type of Spring	Average Flow (cfs)	Temp. (°C)	Dates of Measurements	Comments
Pennington County, South Dakota							
P-3	2N-6E-16dbd 2N-6E-16ddc 2N-6E-22bcd 2N-7E-18ca	Gravel Spring Doty Spring Dome Spring Lang Spring	A series of resurgent springs along Box Elder Creek where it crosses the Madison Group and the Minnelusa Formation.	13	-	1966-1970	
P-5	1N-1E-5cda	Beaver Creek Spring	This spring occurs near the Madison-Minnelusa contact.	2	6	1969	
P-6	1N-2E	Castle Creek Springs	A series of small springs that occur as water-table springs on the central limestone plateau and that occur at the Madison Group-Deadwood Formation contact.	4		1968	The flow was measured 1 mile northwest of Deerfield.
P-2	2N-2E-15(?)	Rhoads' Fork Spring	This spring occurs at the Madison Group-Deadwood Formation contact.	4	6	1969	
P-7	1N-7E-8dbc	Cleghorn Spring	This spring discharges from the outcrop of the Minnelusa or the Minnekahta Formation.	10	12	1968-1970	Rapid Creek loses 3 cfs crossing the Madison Group outcrop a few miles upstream of Cleghorn Spring.
P-8	1S-2E-10	South Fork of Castle Creek and Pole Creek Springs	A series of small springs that occur at the Madison Group-Deadwood Formation contact.	1	7	1968-1970	
P-9	1S-2E-11bbd	Ditch Creek Springs	A series of small springs that occur at the Madison Group-Deadwood Formation contact.	3	5	1970	
P-10	2S-3E-2ccc	Spring Creek Springs	A series of small springs that occur at the Madison Group-Deadwood Formation contact.	0.2	5	1969	
P-1	2N-1E-19(?)	Soldier Creek Springs	A series of small water table springs in the channel of Soldier Creek on the central limestone plateau.	0.4	-	1969	Flow measured at 48N-61W-20, Wyoming.
P-4	2N-7E-32add	City Spring	This spring occurs at the Spearfish-Minnekahta Formation contact.	1	12	1968-1970	

TABLE C-1 Concluded

Spring Location Number	Location of Spring	Name of Spring	Source of Water and Type of Spring	Average Flow (cfs)	Temp. (°C)	Dates of Measurements	Comments
Crook County, Wyoming							
CR-1	52N-60W-18 52N-61W-13	Sand Creek Springs	A series of small springs that issue from Madison Group which is exposed for several miles in the bed of Sand Creek.	24	12	1968-1970	
CR-2	53N-60W-28	Montana Lake	Springs that issue from the Spearfish Formation feed Montana Lake.	?	-	-	
Weston County, Wyoming							
W-1	45N-60E 46N-60E	Stockdale Beaver Creek Springs	A series of springs that occur at the Minnekahta-Spearfish contact exposed along the stream for several miles.	13		1968-1970	
W-2	48N-60W	Cold Springs Creek Springs	A series of springs that occur when the creek channel crosses the Madison Group and Minnelusa Formation outcrops.	2	-	-	

Data sources: Cox 1962; Rahn and Gries 1973; Stockdale 1974.

APPENDIX D

CHEMICAL ANALYSES OF MADISON FORMATION WATER

Data sources for Table D-1:

1. U.S. Geological Survey data base.
2. Wyoming Water Resources Research Institute.
3. Hodson, 1974.
4. Wyoming State Engineer's Office, Wyoming Water Planning Program.
5. City of Sundance, Wyoming.
6. U.S. Geological Survey, 1977.
7. Chemical and Geological Laboratories, 1979 and 1980.
8. U.S. Geological Survey, 1977.
9. Gries, 1977.
10. Bechtel Laboratory, 1974.
11. Chemical and Geological Laboratories, 1974.
12. Chemical and Geological Laboratories, 1979.

Abbreviations used in Table D-1:

T = time of day
F = field measurement
ND = not detected at level given in parentheses
K = casing record unknown or dubious
M = completed in Bell Sand Member of Minnelusa as well as in Madison
C = sodium combined with potassium

Note: Temperature readings listed in Table D-1 may be spurious.

TABLE D-1

CHEMICAL ANALYSES OF MADISON GROUP WATERS
(Values in milligrams per liter unless otherwise noted)

Well No. (Township-Range Section)	Well Depth (ft)	Date of Sample	Temp. (°C)	Silica (SiO_2)	Total Iron (µg/l)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	F	NO_3	B (µg/l)	P (µg/l)	Dissolved Solids: Residue at 180°C	Dissolved Solids: Sum of Constituents	Hardness: Total $CaCO_3$	Hardness: Non carbonate	Specific Conductance (µmhos/cm^2)	pH (units)	Data Source
NIOBRARA COUNTY, WYOMING																								
36N-62W-28 aba	3274	15 Apr 74	—	23.5	0.5	114	30.9	36.4	5.9	256	0	122	110.0	1.56	1.20	15.0	—	744	704	412	—	805	7.80	10
		26 Apr 74	46.0	20.0	—	110	35.0	36.0	6.1	242	0	120	130.0	3.60	0.98	70.0	—	--	584	420	220	1030	7.00	1,2
36N-62W-28 baa	3118	22 May 74	—	23.0	0.5	88	51.0	29.2	4.2	232	0	98	125.0	2.20	5.30	1.0	—	720	661	430	—	950	7.50	10
		24 May 74	54.0	23.0	—	98	35.0	28.0	6.1	219	—	110	110.0	3.00	1.10	60.0	—	--	526	390	210	930	7.00	1,2
		2 Jun 74	—	22.0	0.5	84	29.0	30.3	5.8	207	0	120	72.5	1.44	2.20	1.0	—	600	579	330	—	750	7.65	10
		8 Jun 74	—	27.0	0.5	78	25.5	29.8	4.8	207	0	104	70.0	1.28	6.40	1.7	—	560	556	305	—	670	7.65	10
		12 Jun 74	—	22.0	3.9	80	23.0	29.6	8.3	201	—	109	57.5	1.20	1.0	1.0	—	510	536	295	—	690	7.65	10
		13 Jun 74	—	20.0	4.0	90	24.0	27.8	4.2	207	—	108	62.5	1.20	5.30	4.0	—	600	554	325	—	740	7.50	10
		20 Jun 74	—	--	13.0	85	24.0	42.0	6.0	232	0	110	74.0	—	--	—	—	455	—	--	--	--	7.30	11
38N-61W 35d	—	30 Sep 78	—	26.5	140.0	80	17.0	44.0	7.0	256	0	115	32.0	0.57	—	ND(1.0)	--	418	414	270	--	625	8.10	12
WESTON COUNTY, WYOMING																								
44-60-05 bb2	1300M	10 Dec 47	14.0	7.8	—	55	13.0	37.0	7.8	300	0	27	2.8	0.7	1.8	140	--	298	300	191	0	504	7.2	1,3
44-63-26 cac	8381	13 May 75	35.0	4.5	—	73	22.0	11.0	4.8	101	0	200	7.6	1.4	0	40	20	398	374	270	190	550	7.5	1,2
		15 Dec 79	31.0	—	9.1	133	37.0	12.0	4.0	210	0	295	10	1.64	—	ND(1.0)	--	570	584	484	—	950F	6.8F	7
		15 Feb 80	19.0	—	24.1	118	32.0	6.0	4.0	176	0	270	8	1.43	—	—	--	568	521	421	—	700F	7.1F	7
		13 Mar 80	—	—	10.2	100	41.0	12.0	5.0	207	0	252	10	1.45	—	—	--	534	520	418	—	770	6.9	7
		12 Apr 80	—	—	11.8	122	31.0	11.0	5.0	195	0	274	8	1.46	—	—	--	590	544	432	—	775	7.2	7
		13 May 80	—	—	4.1	127	31.0	10.0	3.0	173	0	295	11	1.55	—	—	--	640	599	445	—	800	7.2	7
45-61-20 dca	2638	7 Jan 50*	--	9.0	—	54	33.0	6.9C	C	—	--	34	5.0	—	--	—	—	290	—	335	--	--	--	1,3
		1 Apr 57	24.0	14.0	10.0	84	28.0	2.8	2.2	290	0	38	2.0	0.2	1.9	—	--	297	296	274	37	504	7.4	1,3
		15 Mar 62	28.0	13.0	30.0	63	28.0	2.5	1.8	291	0	38	1.2	0.3	0.9	30	--	291	292	274	35	507	7.7	1,3
		28 Jan 69*	—	--	--	68	25.0	6.9	9.1	287	0	45	1.1	—	0.3	0	—	315	300	270	37	519	7.3	1,3
		13 May 75	25.0	12.0	—	63	29.0	2.6	2.1	326	0	51	1.5	2	0.89	9	10	296	323	280	10	460	7.5	1,2
45-61-21 cbd	2872	28 Jan 69	—	—	—	76	29.0	3.2	2.2	276	0	87	1.4	—	0.2	30	—	385	—	310	83	578	7.4	1,3
45-61-28 ab	2738K	15 Mar 62	26.0	13.0	70.0	62	29.0	2.9	1.8	289	0	37	1.4	0.3	0.9	10	—	288	290	273	36	504	7.4	1,3
		12 May 75	25.0	12.0	—	83	29.0	2.6	2.2	312	0	43	1.7	0.3	0.84	9	10	291	309	280	21	550	7.3	1
		15 Dec 79	24.0	—	ND(.03)	65	34.0	5.0	1.0	305	0	46	3	0.26	--	ND(1.0)	--	306	298	302	--	490F	7.4F	7
		15 Feb 80	23.0	—	—	62	30.0	1.0	1.0	278	0	44	6	—	--	--	--	278	281	278	--	490F	7.4F	7
		13 Mar 80	—	--	—	85	32.0	3.0	1.0	305	0	44	4	—	--	--	--	382	299	294	--	475	7.1	7
		12 Apr 80	—	--	—	87	30.0	2.0	2.0	305	0	48	5	—	--	--	--	312	308	291	--	500	7.3	7
		13 May 80	—	—	—	70	27.0	3.0	1.0	293	0	45	5	—	--	--	--	296	295	286	--	490	7.6	7

TABLE D-1 Continued

Well No. (Township-Range Section)	Well Depth (ft)	Date of Sample	Temp (°C)	Silica (SiO_2)	Total Iron (µg/l)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	F	NO_3	B (µg/l)	P (µg/l)	Dissolved Solids: Residue at 180°C	Dissolved Solids: Sum of Constituents	Hardness: Total $CaCO_3$	Hardness: Non carbonate	Specific Conductance (µmhos/cm²)	pH (units)	Data Source
WESTON COUNTY, WYOMING (cont.)																								
45-61-28 Newcastle No. 4	—	15 Dec 79	24.0	—	0.04	80	30.0	6.0	2.0	130	0	108	0	0.40	—	ND(1.0)	--	370	352	323	--	580F	7.4F	7
		15 Feb 80	22.0	—	—	62	30.0	2.0	2.0	200	0	109	4	0.39	--	--	--	374	306	278	—	550F	7.2F	7
		13 Mar 80	—	—	—	77	34.0	6.0	2.0	281	0	110	4	--	--	--	--	382	372	332	—	590	7.3	7
		12 Apr 80	—	—	—	73	38.0	4.0	2.0	293	0	100	6	--	--	--	--	376	369	338	--	575	7.5	7
		13 May 80	—	—	—	73	36.0	5.0	3.0	283	0	104	4	--	--	--	--	388	364	330	--	560	7.6	7
45-61-29 cbb1	3073	15 Mar 62	27.0	14.0	60	76	33.0	6.1	2.6	257	0	117	2.5	0.4	1.0	20	—	405	379	327	116	642	7.4	1,3
		13 May 75	30.0	13.0	—	78	35.0	4.7	3.3	283	0	130	1.9	—	0.93	10	—	412	407	340	110	610	7.6	1
45-61-30 ad1	3028	15 Mar 62	30.0	14.0	40	76	32.0	4.4	2.8	268	0	105	1.8	0.4	0.9	10	—	386	369	322	102	601	7.4	3
		18 Jun 68	31.0	13.0	10	75	33.0	5.2	2.3	266	2	108	1.6	0.5	0.8	10	—	382	372	324	--	603	8.3	3
		28 Jan 69	--	--	—	77	31.0	3.6	2.5	268	0	114	1.1	--	0.3	0	—	490	—	--	--	602	7.3	3
		29 Aug 75	32.0	13.0	10	74	34.0	4.6	2.3	—	—	100	1.5	0.5	--	2	--	--	--	320	—	560	7.9	2
45-61-30 ac	—	15 Dec 79	28.0	—	ND(.03)	76	33.0	8.0	2.0	254	0	104	6	0.45	--	--	--	380	345	325	--	600F	7.1F	7
		15 Feb 80	28.0	—	—	75	34.0	2.0	2.0	264	0	102	6	0.44	—	--	--	352	350	327	—	600F	7.2F	7
		13 Mar 80	—	—	—	75	35.0	6.0	1.0	281	0	108	4	—	--	--	--	356	368	331	—	570	7.5	7
		12 Apr 80	--	—	--	75	34.0	2.0	2.0	268	0	100	6	—	--	--	--	380	351	327	--	575	8.1	7
		13 May 80	—	—	—	71	35.0	3.0	2.0	271	0	102	5	--	--	--	—	364	353	321	--	575	7.7	7
45-61-33 ab1	3596	4 Jun 69	22.0	13.0	30	76	26.0	2.9	2.3	276	0	74	1.2	0.6	0.2	0	—	336	332	298	72	534	7.9	1,2,3
		29 Aug 75	28.0	12.0	170	64	28.0	2.9	1.9	288	0	48	1.4	0.5	0.19N	0	0	—	301	280	39	520	7.7	1,2
		13 Jul 76	—	13.0	20D	73	31.0	2.5	2.1	284	—	86	2.1	0.6	0.05N	10	—	308	351	310	78	—	--	1
46-60-17 cb1	—	6 Sep 74	12.5	12.0	—	430	50.0	3.6	1.9	233	—	1000	1.6	—	0.38N	50	—	--	1620	1300	1100	1940	—	1
46-60-31 ba1	1170K	9 Dec 47	16.0	11.0	50	58	9.8	36.0	6.8	306	0	16	1.8	0.5	1.5	100	--	290	292	185	0	492	7.1	1,3
		24 Oct 68	16.0	13.0	40	65	24.0	2.8	1.5	318	0	12	0.4	0.3	0.7	0	--	270	276	260	0	473	8.2	1,2,3
		15 Aug 74	15.5	13.0	20D	59	28.0	3.1	1.8	306	0	13(8)	1.4	0.3	0.4	20	—	--	272	260	9	472	7.6	1,2
		15 Dec 79	14.0	—	ND(.03)	59	32.0	5.0	1.0	323	0	8	5	0.28	—	ND(1.0)	--	268	268	279	—	359F	7.3F	7
		15 Feb 80	13.5	—	—	63	23.0	1.0	1.0	305	0	10	4	—	--	--	—	257	257	252	—	354F	7.1F	7
		13 Mar 80	--	—	—	60	28.0	3.0	1.0	305	0	14	4	—	--	--	—	255	259	265	—	450	7.7	7
		12 Apr 80	—	—	—	59	27.0	2.0	2.0	305	0	11	4	—	—	--	—	256	256	258	—	450	7.3	7
		13 May 80	—	—	—	62	25.0	3.0	1.0	303	0	10	4	—	--	--	--	274	253	258	—	255	7.6	7
46-62-18 bdc1	2677K	5 Jun 69	16.0	12.0	30	62	28	1.9	1.4	296	0	27	0.8	0.3	0	0	—	268	279	270	27	480	7.8	1,2,3
		14 Jun 72	14.5	11.0	—	61	28	1.1	1.9	296	0	21	1.3	0.3	0.7	20	—	--	271	270	--	488	7.9	2
		15 Aug 74	14.0	12.0	90D	60	28	1.1	1.1	299	—	23	1.5	0.3	0.24	20	—	--	276	270	20	488	7.5	1,2
		13 Jul 76	—	12.0	20D	66	27	1.3	1.2	299	—	17	0.8	0.3	—	6	--	259	273	280	31	—	--	1

TABLE D-1 Continued

Well No. (Township-Range Section)	Well Depth (ft)	Date of Sample	Temp (°C)	Silica (SiO_2)	Total Iron (µg/l)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	F	NO_3	B (µg/l)	P (µg/l)	Dissolved Solids: Residue at 180°C	Dissolved Solids: Sum of Constituents	Hardness: Total $CaCO_3$	Hardness: Non carbonate	Specific Conductance (µmhos/cm^2)	pH (units)	Data Source
WESTON COUNTY, WYOMING (cont.)																								
46-62-18 bdcl (cont.)		13 Dec 79	10.5	—	ND(.03)	62	32	3.0	1.0	315	0	25	4	0.34	—	ND(1.0)	—	292	280	286	—	333F	7.2F	7
		15 Feb 80	9.5	—	—	60	25	1.0	1.0	283	0	17	4	—	—	—	—	246	245	253	—	342F	7.2F	7
		13 Mar 80	—	—	—	65	28	3.0	1.0	329	0	21	4	—	—	—	—	264	290	277	—	450	7.5	7
		12 Apr 80	—	—	—	60	25	1.0	1.0	283	0	22	3	—	—	—	—	272	258	265	—	450	7.5	7
		13 May 80	—	—	—	68	24	2.0	1.0	303	0	20	4	—	—	—	—	274	268	268	—	460	7.7	7
46-63-10 dcal	2592M	2 May 41	—	—	—	76	23	7.0C	C	307	0	43	5.0	—	—	—	—	348	307	290	33	—	—	1,3
		9 Dec 47	24.0	5.6	50	70	19	18.0	2.4	296	0	47	1.2	0.6	1.0	70	—	346	311	252	9	529	7.1	1,3
		8 Apr 58	23.0	15.0	0	80	26	2.6	0.6	298	0	69	1.0	0.2	0.6	—	—	311	342	306	62	563	7.5	1,3
		11 Jul 72	23.5	13.0	—	74	26	1.5	1.4	295	0	51	1.3	0.4	0.9	20	—	—	315	290	—	538	1.8	2
46-63-15 bd	2991	11 Jul 72	—	13.0	—	64	27	2.2	1.4	293	0	24	1.7	0.5	1.0	10	—	—	279	270	—	496	7.7	2
		14 Dec 79	22.0	—	ND(.03)	62	33	3.0	1.0	316	0	29	3	0.32	—	ND(1.0)	—	290	285	290	—	420F	7.6F	7
		15 Feb 80	20.0	—	—	60	27	1.0	1.0	293	0	22	4	—	—	—	—	290	261	261	—	438F	7.5F	7
		13 Mar 80	—	—	—	63	28	2.0	1.0	292	0	28	4	—	—	—	—	246	268	272	—	470	7.5	7
		12 Apr 80	—	—	—	60	28	1.0	1.0	288	0	26	2	—	—	—	—	274	259	265	—	465	6.3	7
		13 May 80	—	—	—	63	27	1.0	1.0	293	0	26	4	—	—	—	—	258	266	268	—	460	7.7	7
46-63-17 cbcl	3605	15 Jun 72	26.5	14.0	—	61	28	1.5	1.4	299	0	20	1.3	0.3	0.9	30	—	—	275	260	—	478	7.8	2
		13 May 75	26.5	11.0	—	62	27	1.6	1.6	329	0	27	1.6	0.3	0.84	10	10	262	295	270	0	480	7.6	1,2
	—	14 Dec 79	23.5	—	ND(.03)	63	32	4.0	1.0	323	0	21	4	0.31	—	ND(1.0)	—	270	281	289	—	459F	6.8F	7
		15 Feb 80	22.0	—	—	52	22	1.0	1.0	244	0	19	2	—	—	—	—	230	217	220	—	442F	7.5F	7
		13 Mar 80	—	—	—	63	28	3.0	1.0	305	0	18	4	—	—	—	—	240	264	272	—	455	7.4	7
		12 Apr 80	—	—	—	63	27	1.0	1.0	305	0	20	2	—	—	—	—	280	265	268	—	450	7.1	7
		13 May 80	—	—	—	63	25	2.0	1.0	298	0	20	2	—	—	—	—	300	261	260	—	425	7.7	7
46-64-13 cca	4522	22 May 69	37.0	14	310.00	61	26	1.8	1.4	273	0	29	0.7	0.4	0.5	10	—	266	269	258	34	484	7.8	1,2,3
46-64-23 ccb	5121M	15 Jun 72*	19.0	56	—	28	28	2.9	1.9	275	0	33	1.7	0.4	0.7	20	—	—	279	250	—	465	7.8	2
	—	14 Dec 79	41.0	—	ND(.03)	59	32	3.0	1.0	298	0	35	2	0.39	—	ND(1.0)	—	266	276	270	—	620F	6.7F	7
		15 Feb 80	20.0	—	—	59	28	1.0	1.0	273	0	27	8	—	—	—	—	258	258	262	—	600F	7.2F	7
		13 Mar 80	—	—	—	58	29	5.0	1.0	293	0	28	4	—	—	—	—	258	268	264	—	435	7.4	7
		13 May 80	—	—	—	64	24	3.0	1.0	276	0	33	4	—	—	—	—	256	265	258	—	430	7.5	7
46-65-20 ccd	—	14 Dec 79	45.0	—	1.30	108	32	27.0	2.0	220	0	263	14	3.60	—	ND(1.0)	—	602	559	401	—	1112F	6.8F	7
		15 Feb 80	40.0	—	4.28	115	25	18.0	2.0	190	0	230	26	3.30	—	—	—	546	510	390	—	1112F	7.3F	7
		13 Mar 80	—	—	1.52	100	39	39.0	3.0	268	0	240	22	3.3	—	—	—	580	576	410	—	825	6.9	7
		12 Apr 80	—	—	1.50	101	30	33.0	3.0	220	0	230	22	3.09	—	—	—	512	526	376	—	800	6.7	7
		13 May 80	—	—	0.15	104	28	34.0	3.0	210	0	230	24	3.48	—	—	—	530	523	375	—	775	6.9	7
46-65-23 bad	7737	14 May 75	47.0	23	—	71	32	2.7	2.3	232	0	120	1.3	1.0	0.84	9	20	389	369	310	120	670	7.5	1,2
		14 Dec 79	58.0	—	ND(.03)	74	37	5.0	1.0	235	0	133	4	1.18	—	ND(1.0)	—	394	365	337	—	970F	7.6F	7
		15 Feb 80	63.0	—	—	67	30	2.0	1.0	205	0	110	7	1.23	—	—	—	356	316	291	—	950F	7.9F	7

TABLE D-1 Continued

Well No. (Township-Range Section)	Well Depth (ft)	Date of Sample	Temp (°C)	Silica (SiO_2)	Total Iron (µg/l)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	F	NO_3	B (µg/l)	P (µg/l)	Dissolved Solids: Residue at 180°C	Dissolved Solids: Sum of Constituents	Hardness: Total $CaCO_3$	Hardness: Non carbonate	Specific Conductance (µmhos/cm²)	pH (units)	Data Source
WESTON COUNTY, WYOMING (cont.)																								
46-65-23 bad (cont.)		13 Mar 80	—	—	—	74	34	6.0	2.0	244	0	126	4	—	—	—	—	370	365	324	—	560	7.6	7
		13 May 80	—	—	—	71	36	4.0	2.0	229	0	132	6	—	—	—	—	412	363	325	—	525	7.7	7
46-66-25 cbb	8780	15 Jun 72	79.0	46	—	180	46	9.0	4.2	177	0	460	4.3	3.1	0.5	20	—	—	834	630	—	1060	7.6	2
47-60-4 adal	360	3 Jun 69	10.0	12	40.00	62	23	1.0	0.8	291	0	5.2	1.0	0.5	0.1	0	—	248	249	250	11	435	7.9	1,2,3
		12 Jul 72	7.5	12	—	58	24	2.2	1.4	298	0	2.5	1.7	0.2	0.80	10	—	—	249	240	0	444	8.0	1,2
		14 Aug 74	8.0	12	20D	59	24	0.4	0.7	297	—	3.5	1.7	0.1	0.25	20	—	—	249	250	3	446	7.8	1,2
		30 Aug 75	8.0	12	420.00	57	24	1.3	0.7	299	0	1.8	1.0	0.1	0.19N	0	0	—	245	240	0	420	8.1	1,2
48-65-25 cc	3162	11 Jul 72	—	13	—	92	40	2.9	2.1	275	0	170	1.7	3.6	0.7	20	—	—	457	390	—	713	7.7	2
		13 Dec 79	27.0	—	ND(.03)	90	44	4.0	2.0	259	0	190	6	3.46	—	ND(1.0)	—	462	464	408	—	700F	7.4F	7
		15 Feb 80	22.0	—	—	89	39	1.0	2.0	303	0	180	5	3.20	—	—	—	486	416	383	—	650F	7.6F	7
		13 Mar 80	—	—	—	92	42	6.0	1.0	281	0	166	6	—	—	—	—	452	448	402	—	685	7.2	7
		12 Apr 80	—	—	—	91	41	2.0	2.0	278	0	160	6	—	—	—	—	476	439	396	—	685	7.1	7
		13 May 80	—	—	—	89	43	3.0	2.0	273	0	169	6	—	—	—	—	452	447	399	—	650	7.6	7
48-65-35 ccb1	3193	11 Jul 69	28.0	12	40.00	93	34	20.0	1.5	267	0	174	1.5	1.2	0.5	20	—	482	469	374	160	724	7.7	1,2,3
CROOK COUNTY, WYOMING																								
51-66-6 cad	—	12 Dec 79	22.0	—	3.50	148	56	11.0	2.0	272		335	28	2.65	—	ND(1.0)	—	756	707	600	—	920F	7.5F	7
		20 Feb 80	23.0	—	—	104	40	4.0	ND(1.0)	281		195	4	0.66	—	—	—	506	488	424	—	800	6.8	7
52-61-24 aac	0	21 Dec 63	—	13	—	140	29	2.0	1.9	274		228	3.1	0	1.9	0	—	—	588	468	243	911	7.7	1,1
52-62-18 c	—K	27 Jul 78	12.0	13	10D	120	30	2.6	1.4	270		200	1.4	—	—	30	—	517	503	420	200	760	7.3	1
52-63-25 dc	1123M	16 Mar 73	—	11	40.00	65	16	2.1	1.2	268		7.4	1.7	0.6	0.9	10	—	(236)	—	226	—	421	8.3	5
		13 Dec 79	9.0	—	0.07	52	17	3.0	1.0	250		4	2	0.36	—	ND(1.0)	—	210	204	200	—	230F	7.6F	7
		15 Feb 80	10.0	—	—	50	16	1.0	1.0	229		0	3	—	—	—	—	190	182	191	—	240F	7.6F	7
		13 Mar 80	—	—	—	57	16	3.0	1.0	244		6	4	—	—	—	—	202	205	208	—	335	7.8	7
		12 Apr 80	—	—	—	55	16	2.0	1.0	244		8	2	—	—	—	—	212	205	203	—	320	7.1	7
		13 May 80	—	—	—	63	14	3.0	1.0	254		10	4	—	—	—	—	216	221	215	—	350	7.8	7
53-65-18 bbd	1315	11 Jul 62	—	12	260.00	112	43	4.0	1.0	264		275	1.5	0.5	0	—	—	600	579	460	244	—	7.2	1,3
		28 Apr 70	15.0	9.7	100.00	112	35	3.3	1.5	261		210	3.4	1.2	0.2	20	—	526	504	424	210	788	7.9	1,2,3

TABLE D-1 Continued

Well No. (Township-Range Section)	Well Depth (ft)	Date of Sample	Temp (°C)	Silica (SiO_2)	Total Iron (μg/l)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	F	NO_3	B (μg/l)	P (μg/l)	Dissolved Solids: Residue at 180°C	Dissolved Solids: Sum of Constituents	Hardness: Total $CaCO_3$	Hardness: Non carbonate	Specific Conductance (μmhos/cm²)	pH (units)	Data Source
CROOK COUNTY, WYOMING (cont.)																								
53-65-18 bbd (cont.)		27 Sep 73	—	10.5	20.00	112	36	3.0	2.0	194		185	1.5	0.3	1.5	—		--	500	429	—	650	7.5	2
		30 Aug 75	17.0	11	150.00	110	38	3.7	1.5	273		210	2.6	0.5	0.18N	2.0		—	512	430	210	850	7.6	1,2
		30 Aug 75	10.0	11	50.00	66	24	1.9	1.2	307		15	1.7	0.2	0.72N	0		—	273	260	12	460	7.6	1,2
		12 Dec 79	15.0	—	1.30	115	42	4.0	1.0	264		240	5	0.52	--	ND(1.0)		558	539	460	--	600F	7.8F	7
		15 Feb 80	13.0	—	1.76	98	35	2.0	1.0	220		194	6	0.56	—	—		494	442	245	—	510F	7.9F	7
		13 Mar 80	—	--	2.17	101	34	4.0	1.0	244		182	4	0.54	—	—		474	443	392	—	675	7.5	7
		12 Apr 80	—	--	1.15	110	39	3.0	2.0	278		200	4	0.58	—	—		534	494	435	—	725	7.1	7
		13 May 80	--	--	ND(.03)	115	36	2.0	1.0	273		200	5	0.58	—	—		522	493	435	--	700	7.9	7
57-65-15 da	4355	21 Oct 76	35.5	25	310D	180	40	9.2	7.0	214		470	6.6	1.9	3.2N	210		1060	--	620	440	1380	7.1	6
		14 Feb 80	35.0	—	38.00	51	28	5.0	3.0	49		177	18	1.33	—	ND(1.0)		320	303	242	—	580F	8.1F	7
CUSTER COUNTY, SOUTH DAKOTA																								
6S-5E-24 baaa	780	11 Jul 78	15.1	15.0	80D	47.0	18	9.7	2.9	228	0	14	3.7	0.5	0.09N	30	0	211	224	190	5	410	7.4	1
6S-6E-15 abdd	939	1 Nov 77	—	17.0	20D	40.0	15	9.2	2.3	200	—	9.4	2.5	0.4	0.00N	30	0	183	195	160	0	—	--	1
BUTTE COUNTY, SOUTH DAKOTA																								
12N-3E-28	4858		56.7	35.5	1.00	571.7	120	36.0	13.0	121	—	1622	61	--	--	--	--	2710	—	--	--	--	6.5	9
9N-3E-27	4016		51.7	19.2	0.20	381.0	91	26.0	13.0	129	—	1175	51	--	--	--	--	1894	—	—	--	--	6.7	9
9N-3E-28	3510		42.2	3.3	0.58	167.0	67	12.9	5.9	154	—	489	18	--	—	--	--	896	—	--	--	--	7.7	9
LAWRENCE COUNTY, SOUTH DAKOTA																								
7N-1E-21	1306	ND	11.1	12.0	0.01	87.0	24	2.1	1.4	264	—	103	0.6	0.3	1.0	—	--	362	—	--	--	580	7.7	9
6N-2E-15	860	ND	13.3	10.0	0.01	52.0	23	2.1	1.1	274	—	8.2	0.6	0.2	0.5	—	--	233	—	--	--	405	7.8	9
MEADE COUNTY, SOUTH DAKOTA																								
6N-6E-19	1350		12.8	11.0	0.02	462.0	96.0	3.9	2.5	198	—	1400	0.9	1.2	0.5	—	--	2080	—	--	--	2250	7.5	9
5N-5E-26	1100		27.8	11.0	0.06	51.5	27.6	2.0	2.0	224	—	12	2	—	—	--	--	230	—	--	--	--	8.13	9

TABLE D-1 Concluded

Well No. (Township-Range Section)	Well Depth (ft)	Date of Sample	Temp (°C)	Silica (SiO_2)	Total Iron (µg/l)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	F	NO_3	B (µg/l)	P (µg/l)	Dissolved Solids: Residue at 180°C	Dissolved Solids: Sum of Constituents	Hardness: Total $CaCO_3$	Hardness: Non carbonate	Specific Conductance (µmhos/cm²)	pH (units)	Data Source
PENNINGTON COUNTY, SOUTH DAKOTA																								
2N-7E-34	1275		13.9	—	--	--	--	—	--	--	--	—	--	--	--	--	--	189	--	--	--	--	--	9
2N-7E-34	1930		13.9	—	--	31.0	22	8.0	—	—	--	263	0.7	—	—	--	--	223	—	--	--	--	--	9
2N-9E-18	4645		12.2	21.0	—	73.0	29	8.0	3.0	204	—	214	3	0.6	—	--	--	1210	—	--	--	--	--	9
2N-8E-13	4436		9.7	21.0	0.01	91.0	33	4.9	3.7	204	--	204	1.0	0.6	0.4	—	--	461	--	—	--	678	7.7	9
POWDER RIVER COUNTY, MONTANA																								
08S-54E-21 adad	7100	7 Jul 77	56.2	32.0	50.00	200.0	48	38.0	8.0	205	0	520	57	3.6	--	90	0	1080	1200	—	--	1460F	7.0F	8
09S-53E-22 abac	7100	7 Jul 77	52.7	33.0	20.00	190.0	46	38.0	7.9	212	0	480	56	3.3	--	90	0.03	1010	1100	—	--	1380F	6.9F	8
FALL RIVER COUNTY, SOUTH DAKOTA																								
9S-2E-1 acdb	3455	17 Jun 74	—	33	0.50	130	40	176	13.9	220	--	310	263	0.84	3.1	1	--	1120	1196	490	--	1700	7.4	10
			12.4	33	0.50	130	33	180	14.3	232		285	257	0.92	2.2			1140				1630	7.6	9
9S-2E-1 aa	3060	17 Jun 74	—	35	33.40	114	26	107	5.8	238	—	215	140	0.74	5.3	26	--	806	893	390	--	1260	7.60	10
9S-2E-1 aaac	2955	17 Jun 74	—	37	0.50	108	26	92.9	7.9	238	—	180	125	0.61	2.2	3	--	880	824	375	—	1080	7.70	10
10S-2E-3 acda	3855	17 Jun 74	—	32	22.4	118	28	191	16.5	201	—	285	252	1.02	2.2	19	—	1070	1130	410	—	1620	7.55	10
			45.0	30	.05	110	30	203	18.0	180	—	319	269	1.3	1.6			1070				1730	7.5	9
10S-2E-3 ddaa	4000	17 Jun 74	—	34	5.20	118	29	197	14.8	189	--	300	265	1.06	2.2	17	--	1090	1150	415	—	1650	7.65	10
Cascade Spring	--	17 Jun 74	—	--	7.00	573	82	56	7.0	256	0	1525	72	—	--	--	--	2441	--	--	--	--	7.4	11

APPENDIX E

MADISON GROUP WELLS

Data sources for Tables E-1 through E-10 are as follows: Belden, 1980; M. Brown, 1979; Cox, 1962; Gries, 1977; Hodson, 1971; Howells, 1980; Keene, 1973; Kelly, 1980b; Stockdale, 1974.

Key to abbreviations used in Tables E-1 through E-10:

A = abandoned
D = domestic water supply
I = irrigation and/or industrial use
M = municipal water supply
N = none; no flow
O = observation well
S = stock (livestock) water supply
T = test well
U = unknown
W = water flooding
Y = yes
bls = below land surface
e = estimated

TABLE E-1

MADISON GROUP WELLS: BUTTE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
B-1	8N-2E-222bdb	Country Club	I	—	1968	3175	—	—	—	—	15	—	—	U	
B-2	9N-3E-20cddd	—	I	—	1977	3099	—	—	3702	—	1400	—	—	U	Lodgepole (Madison) well. Irrigation well. Flow measured by Bradford to be 832 gpm.
B-3	9N-3E-27	Harmon-Olson	—	—	1952	3000	110	685	—	3000 + (U)	—	—	52	U	
B-4	9N-3E-27	Harmon-Olson	—	—	—	—	—	—	—	—	—	—	—	U	
B-5	9N-3E-27a	—	—	—	—	—	—	—	—	—	—	—	—	U	
B-6	9N-3E-28	Ken Bean	—	—	1976	—	100	—	—	—	—	—	42	U	Could be well 9N-3E-27a.
B-7	11N-3E-17cd	—	—	—	1962	3002	—	—	3695	—	4325	—	—	U	Mission Canyon (Madison) well. Oil test well completed as water well.
B-8	12N-3E-28acb	Delzer	—	—	1977	3205	—	—	—	3210 + (U)	4	—	56	U	Charles (Madison) well.
B-9	12N-3E-32acbc	—	S	—	1977	3148	—	—	—	—	202	—	57	U	Irrigation well. May be open to some Devonian-age rock.

TABLE E-2

MADISON GROUP WELLS: CUSTER COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (^{o}C)	Karstic Zone at Top	Remarks
CU-1	3S-6E-13d	Test well	T	—	1956	3930	—	--	--	--	--	--	--	U	Madison and Deadwood well.
CU-2	6S-5E-24baaa	L. Kaiser	D	—	1977	4110	—	--	3635	3629 (1978)	—	—	15	U	Well produces 50 gpm with 225 feet of drawdown when pumped.
CU-3	6S-4E-1db	—	S&D	—	1977	4330	—	—	4315	—	--	—	—	U	Reported to produce 2 gpm when pumped.
CU-4	6S-6E-15abdd	Streeter Ranch	S	—	--	3420	—	--	--	--	--	--	42	U	Oil test well converted water well.
CU-5	6S-6E-15b	Palensky, Streeter	S	—	1949	3508	—	--	--	--	--	--	42	U	

TABLE E-3

MADISON GROUP WELLS: FALL RIVER COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
F-1	9S-2E-1aaac	CB&Q Railroad Well No. 1	A	—	1907	3448	TD 2980	—	3621	—	300	102 (1975)	50(1908) 54(1975)	U	Well recased in 1974, resulting in 40 psi increase in uranium mill well 100 yards or less to the southeast.
F-2	9S-2E-1acdb	City of Edgemont No. 2 (City Park)	Waste	160	1911	3455	2921	62	3672	3843 (1962)	575	100 (1979)	52(1913) 54(1975)	Y	Well reported to flow to waste beginning in 1975.
F-3	9S-2E-1bcdc	City of Edgemont Well No. 3	M	200	1936	3571	3165	18	3660	3656 (1975)	700	150 (1979)	52(1936) 53(1956, 1975)	Y	Flow in 1946 was 250 gpm; flow in 1955 was 175 gpm; flow in 1958 was 100 gpm; flow in 1975 was 220 gpm.
F-4	9S-2E-1aaac	CB & Q Railroad Well No. 2 (Uranium Mill Well)	M&I	250	1946	3449	TD 2955	—	3703	3650 (1979)	1000 (reported)	200 (1979)	52	Y	Shut-in pressure increased from 55 to 951 psi when RR well No. 1 (above) was recased in 1974. Still, this is not true shut-in pressure since valve was not completely closed when pressure measured. Lost circulation while drilling well.
F-5	9S-2E-1aa	Mines Development	M&I	400	1962	3445	TD 3060	--	3644	3646 (1979)	450	270 (1979)	60	U	Well reported to flow to waste in 1974. Well elevation may be incorrect.

TABLE E-3 Concluded

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
F-6	9S-2E-1da	City of Edgemont	M	200	1962	3575	2970	60	3651	—	275	150 (1979)	—	U	
F-7	10S-2E-3ddaa	Provo Well No. 1/ Cheyenne Feeders	S	200	1942	3655	TD 4000	270	—	--	165	85 (1979)	60(1942) 57(1975)	Y	
F-8	10S-2E-3acda	Provo Well No. 2	S	200	1943	3655	TD 3855	105	—	--	506	125 (1979)	58(1943) 57(1955)	U	Well reported to initially flow at 800 gpm; measured flow was 485 gpm by Gries (no date).
F-9	10S-4E-4ba	Woodward-Morton No. 1 (gov't.)	—	--	--	3484	2880	—	--	--	--	--	--	--	Original flow has stopped.
F-10	10S-4E-4da	M. Kerns	—	--	--	3050	3172	—	--	--	--	--	--	--	Oil test well, reported to 30 to 40 gpm.
F-11	10S-4E-20da	Kerns (Lakota-Shiloh)	--	--	--	3560	2785	Total Section	—	--	Flowed	--	--	--	Taps Minnelusa and Madison. An oil test well now used for stock watering. Reported flow was 35 gpm.

TABLE E-4

MADISON GROUP WELLS: LAWRENCE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
L-1	3N-1E-19d	—	S	—	1947	—	—	—	—	—	—	—	—	U	Questionable Madison well.
L-2	4N-2E-29	—	D	—	1977	—	—	—	—	—	—	—	—	U	
L-3	5N-4E-13/14	—	—	—	—	—	—	—	—	—	—	—	—	U	Reported production was 85 gpm. May be Minnelusa well.
L-4	5N-4E-15dbcb	Potter	D	—	1977	4210	—	—	—	—	—	—	—	U	Well goes "dry" in dry years.
L-5	5N-4E-19	—	D	—	1975	—	—	—	—	—	—	—	—	U	Questionable Madison well.
L-6	5N-4E-23aaad	V. Simon	D	—	—	3890	—	—	3852	—	—	—	—	U	Reported to pump at 20 gpm.
L-7	6N-2E-10d	City of Spearfish	M	—	1962	3673	—	11	—	—	600	—	13	U	Most, if not all, of well is a Minnelusa well.
L-8	6N-2E-15	City of Spearfish	M	—	1975	3689	—	—	—	—	1000	—	—	U	
L-9	6N-4E-21ac	—	Oil Test	—	1924	3590	—	—	—	—	—	—	—	U	Reported production was 140 gpm.

TABLE E-4 Concluded

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
L-10	6N-4E-21	Town of Whitewood	M	--	--	--	--	--	--	--	200	--	--	U	
L-11	7N-1E-16acdc	So. Dakota Dept. Game, Fish and Parks	I&S	--	1973	3420	--	--	--	--	300	--	--	U	Madison and Minnelusa well. Stockdale (1974) reports 2 wells at the McNenny Fish Hatchery, each 350 feet deep and flowing 1000 to 1100 gpm.
L-12	7N-1E-21	So. Dakota Dept. Game, Fish and Parks, No. 19	I&S	--	--	--	--	--	--	--	1100	--	13	U	
L-13	7N-2E-23cd	Johnson, Warren	--	--	1971	--	--	--	--	--	--	--	--	U	May be Minnelusa well.

TABLE E-5

MADISON GROUP WELLS: PENNINGTON COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
	1S-7E-7d	—	D&S	—	—	—	—	—	—	—	—	—	—	U	
	1N-7E-12d	—	D	—	—	—	—	—	—	—	—	—	—	U	
	1N-7E-15	Arrowhead Country Club	—	—	—	—	—	—	—	—	—	—	—	U	
	1S-7E-19c	—	D	—	—	—	—	—	—	—	—	—	—	U	
	1S-7E-20c	—	D	—	—	—	—	—	—	—	—	—	—	U	
	1N-7E-27d	—	D	—	—	—	—	—	—	—	—	—	—	U	
	1S-7E-28b	—	D	—	—	—	—	—	—	—	—	—	—	U	
	1N-8E-9b	Rapid Valley Water Co.	—	—	—	—	—	—	—	—	—	—	—	U	
	1N-8E-9b	Rapid Valley Water Co.	—	—	—	—	—	—	—	—	—	—	—	U	
	1N-8E-10d	Rapid Valley Water Co.	—	—	—	—	—	—	—	—	—	—	—	U	
	2N-6E-26aad	—	D&S	—	1954	3940	—	—	3633	—	—	—	—	U	Pumped well.
	2N-6E-31a	—	D&S	—	—	—	—	—	—	—	—	—	—	U	
	2N-6E-35a	Test well	D&S	—	1955	3980	—	—	—	—	—	—	—	U	
	2N-7E-1b	C. Lien	—	—	1976	—	—	—	—	—	—	—	—	U	
	2N-7E-34bdcc	Black Hills Power and Light	—	—	1930	—	—	—	—	—	—	—	14	U	Drilled to Precambrian.

TABLE E-5 Continued

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (^oC)	Karstic Zone at Top	Remarks
	2N-7E-34c	Black Hills Power and Light	—	—	1959	—	—	—	—	—	—	—	14	U	
	2N-8E-13bdc	Rapid City Airport Well No. 2	—	—	1942	3210	—	—	2702	—	—	—	37.8	U	2 wells located here. Howells (1980) says this is Ellsworth AFB.
	2N-8E-18	Rapid City Airport Well No. 1	—	—	—	—	—	—	—	—	—	—	—	U	
	2N-9E-7	Ellsworth AFB	—	—	1942	--	—	—	—	—	—	—	49	U	
	1S-7E-32bcb	—	D&S	—	1978	4290	—	—	—	—	—	—	—	U	Pumped well.
	1S-7E-32bcb	—	D	—	1978	—	—	—	—	—	—	—	—	U	Pumped well.
	1S-7E-33ab	—	D	—	1977	—	—	—	—	—	—	—	—	U	Pumped well.
	2N-6E-35cac	—	D	—	1972	4130	—	—	3730	—	—	—	—	U	Reported to produce 15 gpm when pumping.
	2N-6E-35daa	Housing development	D	—	1977	4105	—	—	3805	—	—	—	—	U	Madison and Deadwood well. Pumped well.
	2N-7-18bca	—	D	—	1976	3920	—	—	3520	—	—	—	—	U	Reported to produce 25 gpm when pumping.
	2N-7-31bb	—	D or S	—	1955	3830	—	—	3595	—	—	—	—	U	Pumped well.
	3N-16-28ca	Old oil test report	—	—	1931	2957	—	—	—	—	—	—	—	U	
	1N-7-16	Carriage Hills housing development	D	—	1977	—	—	—	—	—	—	—	—	U	

TABLE E-5 Concluded

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (^{o}C)	Karstic Zone at Top	Remarks
	1N-7-16	2 mi west of Carriage Hills housing development	D	—	1976	—	—	—	—	—	—	—	—	U	45 gpm pumped.
	1N-7-16	2 mi west of Carriage Hills housing development	D	—	1974	—	—	—	—	—	—	—	—	U	35 gpm pumped.
	1N-6E-2	—	D	—	1977	—	—	—	—	—	—	—	—	U	Pumped well.
	1N-7E-9b	Rapid City Well No. 3	M	—	1938	3376	—	—	3376	—	—	—	—	U	Flows when not pumped. Pumped at 670 gpm.
	1N-7E-9bcd	Rapid City Well No. 1	M	—	1935	3359	—	—	3359	—	—	—	—	U	Madison to Deadwood well. Still in use. Flows when not pumped.
	1N-7E-18	—	D	—	1977	—	—	—	—	—	—	—	—	U	Minnelusa or Madison pumped well.
	1N-7E-32dbab	Housing development	D	—	1973	3970	—	—	—	—	—	—	—	U	Madison and Deadwood pumped at 25 gpm.
	2N-6E-14	—	D	—	1977	—	—	—	—	—	—	—	—	U	Pumped 13 gpm.
	2N-6E-15	—	D&S	—	—	—	—	—	—	—	—	—	—	U	Pumped 13 gpm.
	2N-6E-15	—	D&S	—	—	—	—	—	—	—	—	—	—	U	Pumped.
	2N-6E-35	—	D	—	1972	—	—	—	—	—	—	—	—	U	Pumped 15 gpm.
	2N-6E-36	Housing development	D	—	1977	—	—	—	—	—	—	—	—	U	Madison and Deadwood Pumped.
	2N-7E-10	—	D	—	1947	—	—	—	—	—	—	—	—	U	Pumped.

TABLE E-6

MADISON GROUP WELLS: MEADE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
ME-1	2N-6E-1ccd	—	D	—	—	4115	—	—	3615	3533 (1973)	—	—	—	U	Reported to produce 19.7 gpm with 7.7 ft of drawdown.
ME-2	4N-5E-19	—	D	—	1961	—	—	—	—	—	—	—	—	U	Madison, Red River, or Deadwood well.
ME-3	5N-5E-9	Town of Sturgis	M	—	—	—	—	—	—	—	500	—	—	U	Madison and Minnelusa well.
ME-4	5N-5E-16cad	—	D&S	—	1972	3630	—	—	3055	—	—	—	—	U	Questionable Madison well. Well reported to produce 10 gpm pumping.
ME-5	5N-5E-21	Town of Sturgis	M	—	—	—	—	—	—	—	290	—	—	U	Questionable Madison well.
ME-6	5N-5E-26ab (No. 5 well)	Black Hills National Cemetery	D & S	—	1954	3625	—	—	—	—	—	—	28	U	Mission Canyon (Madison) well. Pumped well. Wells No. 1, 2, 3, and 4 tap the Minnekahta and Madison-Deadwood interval. Two are Madison wells; all are pumped. No other data are available.
ME-7	5N-5E-36dbcb	Housing development	D	—	1928	3720	—	—	3276	—	—	—	—	U	
ME-8	6N-6E-19bcaa	Bear Butte State Park	D & S	—	1956	3190	—	—	—	—	225	—	13	U	Supplies campground, park, picnic ground, ranch, and buffalo herd.

TABLE E-7

MADISON GROUP WELLS: CROOK COUNTY, WYOMING

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
CR-1	51N-63W-10	City of Sundance	A	A	1950	—	592	175	490 bls	—	—	—	—	U	Abandoned when it was found that well would yield only 12 gpm.
CR-2	51N-63W-14c	City of Sundance	A	A	—	—	—	—	—	—	—	—	—	U	
CR-3	51N-66W-6bcb	City of Gillette M1	M	N	1979	4303.5	2370	397	3861	—	N	—	—	Y	
CR-4	51N-66W-6bc	City of Gillette M2	M	N	1977	4280	2325	300	3863	—	N	—	—	Y	
CR-5	51N-66W-6cab	City of Gillette M3	M	N	1980	—	—	—	—	—	N	—	—	U	
CR-6	51N-66W-6cad	City of Gillette M4	M	N	1980	4254	2370	155	3859	—	N	—	—	U	
CR-7	51N-66W-6cdb	City of Gillette M5	M	N	1980	—	—	—	—	—	N	—	—	U	
CR-8	51N-66W-6cdc	City of Gillette M6	M	N	1980	—	—	—	—	—	N	—	—	U	
CR-9	51N-66W-6cdd	City of Gillette M7	M	N	1980	—	—	—	—	—	N	—	—	U	
CR-10	51N-66W-6dcd	City of Gillette M8	M	N	1980	—	—	—	—	—	N	—	—	U	
CR-11	52-63-25dc	City of Sundance	M	200(e)	1971	4745	1100	23	—	4313	N	—	—	U	Maximum potential yield is about 400 gpm. Maximum pump capacity is 200 gpm.
CR-12	53N-65W-18bbd	Devils Tower	D	5	1962	3865	1299	42	—	3860	—	—	40	U	
CR-13	57N-65W-15da	USGS Madison test well No. 1	T	N	1977	3604	2292	750	3700	—	650	—	—	U	Hole open to both Madison and Red River.

TABLE E-8

MADISON GROUP WELLS: NIOBRARA COUNTY, WYOMING

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet)		Flow Rate		Temp. (°C)	Karstic Zone at Top	Remarks
									Initial	Later (year)	Initial	Later (year)			
N-1	36N-62W-21cca	ETSI-05	T	—	1974	4241	2776	276	—	—	N	--	—	U	
N-2	36N-62W-28ab	ETSI-01	T	—	1974	4248	2870	270	3700	—	N	—	—	U	
N-3	36N-62W-28ba	ETSI-T2	T	—	1974	4244	2800	280	—	—	N	—	—	U	
N-4	37N-61W-5b	ETSI-T3	T	—	1974	—	—	—	—	—	N	—	—	U	
N-5	38N-61W-35d	ETSI-M1	T	—	1978	—	—	—	—	—	N	—	—	U	
N-6	39N-61W-2a	Coronado Oil Co.	W	A	1962	3784	2818	81	—	3655	N	—	—	U	Well abandoned 1968.

TABLE E-9

MADISON GROUP WELLS: WESTON COUNTY, WYOMING

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
W-1	44-60-5bb	LAK Ranch	D&S	—	1945	4400	1152	148	—	—	—	20(H)	—	U	
W-2	44-62-2dca	Les Aimonetto	A	A	1955	4089	5406	814	—	—	—	—	—	U	Abandoned.
W-3	44-63-26cac	W. Townsend (No. WSW-1)	W	1.5	1967	3979	—	—	—	3879	N	—	—	U	
W-4	45-61-20dca	City of Newcastle No. 1	M	1650	1949	4360	2612	26	4822	4737 (1978)	1600	1500 (1974)	—	Y	
W-5	45-61-20d	City of Newcastle No. 4	M	360	1978	4340	—	—	4720	—	650(e)	—	—	U	
W-6	45-61-21cbd	City of Newcastle No. 3	M	400	1965	4625	2211	661	4690 4718	4685	75	50	—	U	
W-7	45-61-28ab	Fountain Motel (Voss-Carlson No. 1)	D	800(e)	1962	4440	2695	43	—	4710	1000 1500(e)	1200(e)	—	Y	
W-8	45-61-29cbb	Tesoro Petroleum (Wyo. refinery)	W I	200(e)	1960	4240	2965	108	4702	4586	115	120	—	U	
W-9	45-61-30adb	City of Newcastle No. 2	M	1500	1961	4280	2810	218	—	4580	650	—	—	U	
W-10	45-61-33ab	Coronado Oil Co.	I	A	1964	4378	3185	411	—	4800	—	290	—	U	Use discontinued in 1966.
W-11	46-60-31ba	Fred Martens, Shadder No. 1	S	100	1942	4760	1097	81	—	—	150	59 (1980)	—	U	
W-12	46-61-29bac	Cambria Well	A	A	1900	5120	1947	398	—	—	—	—	—	U	Abandoned in 1928.
W-13	46-63-18bdc	D. Seely	S	2.5	1957	4505	2350	327	—	—	2.4	1.6 (1980)	—	U	
W-14	46-63-10dca	Black Hills Power & Light No. 1	I	840	1941	4372	2580	18	—	4767 (1978)	800	520 (1980)	—	U	
W-15	46-63-10ca	Black Hills Power & Light No. 3		N	1979	4385	—	—	—	4674 (1980)	320	—	—	U	

TABLE E-9 Concluded

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Karstic Zone at Top	Remarks
W-16	46-6315bd	Black Hills Power & Light No. 2	M	320	1951	4320	2685	387	—	4713 4733	500	200 (1980)	—	U	
W-17	46-63-14/15	Black Hills Power & Light No. 4		N	1979	4384	—	—	—	4379 (1980)	83	—	—	U	
W-18	46-63-17cbc	Buttes Gas & Oil (Osage No. 2)	W	115	1969	4172	3181	424	4820	4600 (1973)		800	—	U	
W-19	46-64-13cca	Coronado Oil Co. No. W-2	W	120	1960	4068	4084	438	4260	—	—	30	—	U	
W-20	46-64-19bdc	Terra Resources No. 122	A	A(1963)	1956	4290	7114	428	4070	—	N	—	—	U	Plugged in 1963.
W-21	46-64-23ccb	Buttes Gas & Oil (Osage West No.1)	W	350	1965	4130	4410	715	3907	3760 (1973)	N	—	—	U	
W-22	46-65-20cdd	Terra Resources No. W-122WS	W	140	1960	4445	7740	369	3915	3795	N	—	—	U	
W-23	46-65-23bad	Terra Resources well 272	W	190	1959	4291	7337	400	3895	3870	N	—	—	U	Fiddler Creek East.
W-24	46-66-25dbb	Terra Resources	W	N	1962	4870	8396	390	4070	3990	N	—	—	U	Fiddler Creek West.
W-25	47-60-4ada	Western County Mallow Camp No. 4	—	N	1965	6030	230	150	—	5836	N	—	—	U	
W-26	48-65-25cc	City of Upton well No. 1 (old No. 4)		U	1949	4332	2900	261	4200(G)	4172	N	—	—	U	Combined water use, with well No. 2 estimated to be 200 ac-ft/yr.
W-27	48-65-35ccb	City of Upton well No. 2		U	1961	4150	2729	464	4192(G)	4138	—	—	—	U	

TABLE E-10

MADISON GROUP WELLS: POWDER RIVER COUNTY, MONTANA

Well No.	Location	Well Name or Owner	Use	1979 Water Production (acre-feet)	Year Drilled	Elevation (feet)	Depth to Top of Madison (feet)	Feet of Madison Penetrated	Potentiometric Surface Elevation (feet)		Flow Rate		Temp. (^{o}C)	Karstic Zone at Top	Remarks
									Initial	Later (year)	Initial	Later (year)			
P-1	85-54E-21ad	Bell Creek Madison No. 2	W	745	1970	3632	6870	760	—	3700 (1980)	Flowed	—	—	U	
P-2	85-54E-27cb	Bell Creek Madison No. 1	W	745	1969	3684	6627	981	3712	3725 (1980)	Flowed	—	—	U	Well open to Red River.
P-3	85-54E-29cd	Bell Creek Madison No.3	W	450	1972	3623	6830	520	3752	3711 (1980)	Flowed	—	—	U	
P-4	95-53E-22ab	Ranch Creek Well No. 1	W	200	—	3478	6840	206	3686	3694 (1980)	Flowed	—	—	U	

APPENDIX F

MINNELUSA FORMATION WELLS

Data sources for Tables F-1 are as follows: Busby and others, 1979; Darton, 1909; Eisen and others, 1980; Howells, 1980; Whitcomb and Gordon, 1964; Whitcomb and Morris, 1964; Williams, 1948.

Key to abbreviations used in Tables F-1 through F-10:

A = abandoned or not in use
D = domestic water supply
I = irrigation and/or industrial use
M = municipal water supply
O = observation well
S = stock (livestock) water supply
T = test well

TABLE F-1

MINNELUSA WELLS: CROOK COUNTY, WYOMING

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet)		Flow Rate		Temp. (°C)	Remarks
						Initial	Later (year)	Initial	Later (year)		
CR-2	53N-65W-18bac	Devils Tower	-	1934	-	-	-	N	-	-	USGS water-level monitoring well.
CR-1	53N-65W-17ba	Porter Long	-	-	-	-	-	-	-		
CR-3	54N-64W-7c	Hulett	M	1934	-	-	21 ft above land surface	375	96(1962)		
CR-4	54N-64W-7c	Hulett	M	1934	-	-	(1962)	350	85(1962)	-	
CR-5	54N-65W-13bd	JH Ranch	D&I	1943	-	-	-	280	180(1956)	-	
CR-6	54N-65W-22	McAmis	-	1959	-	-	-	flowed	-	-	Drilled as an oil well, but later recompleted as a water well.
CR-7	54N-65W-29dd	77 Ranch	D&S	1944	-	-	-	225	-	-	

TABLE F-2

MINNELUSA WELLS: WESTON COUNTY, WYOMING

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
W-1	44N-60W-5bb	LAK Ranch	S&D	1945	4440	-	-	50	41(1960)	-	Flow uncontrolled in 1960.
W-3	45N-61W-2ba	Martens	-	1933	4700	-	-	-	20(1948) 8(1960)	-	
W-4	45N-61W-28	-	-	-	-	-	-	-	-	-	Wells, Busby, and Glover (1979) report as a water well.
W-5	46N-60W-31	Martens	-	1941	4760	-	-	-	-	-	
W-2	44N-60W-6	-	S&D	-	-	-	-	-	-	-	
W-9	47N-60W-31	-	S	-	-	-	-	-	-	-	
W-5	46-60W-32	-	S&D	-	-	-	-	-	-	-	
W-7	46N-62W-18	-	S	-	-	-	-	-	-	-	
W-8	46N-63W-1	-	S	-	-	-	-	-	-	-	
W-10	47N-61W-14	-	S&D	-	-	-	-	-	-	-	
W-11	48N-60W-9	-	S	-	-	-	-	-	-	-	
W-12	48N-60W-17	-	S	-	-	-	-	-	-	-	
W-13	48N-60W-19	-	D&S	-	-	-	-	-	-	-	
W-14	48N-60W-20	-	S	-	-	-	-	-	-	-	
W-15	48N-60W-21	-	S	-	-	-	-	-	-	-	
W-16	48N-60W-28	-	S	-	-	-	-	-	-	-	
W-17	48N-61W-6	-	S	-	-	-	-	-	-	-	
W-18	48N-61W-7	-	S	-	-	-	-	-	-	-	
W-19	48N-61W-7	-	S	-	-	-	-	-	-	-	
W-20	48N-61N-29	-	D&S	-	-	-	-	-	-	-	
W-21	48N-61W-30	-	D&S	-	-	-	-	-	-	-	
W-22	48N-62W-1	-	S	-	-	-	-	-	-	-	
W-23	48N-62W-1	-	S	-	-	-	-	-	-	-	
W-24	48N-62W-1	-	D&S	-	-	-	-	-	-	-	

TABLE F-3

MINNELUSA WELLS: BUTTE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
B-1	7N-1E-11abd	-	S	1966	3400	3573	3488(1971) 3502(1976)	1300	800(1971)	17	Irrigation well. USGS observation well.
B-3	7N-1E-12aa	-	S	1962	3340	3470	3474(1965) 3479(1969) 3456(1971)	700	500 (1970)	20	Irrigation well. USGS observation well.
B-8	8N-1E-19cba	Oil test	T	1954	3406	above 3406	-	-	-	-	Flowing.
B-14	8N-1E-33acd	-	D	1953	3493	3505	-	25	-	-	
B-15	8N-3E-2bdbc	-	S&I	1961	2990	3190	3056(1965) 3035(1970)	75 75	7.1(1965) 0.9(1970)	38(1961) 20(1970)	USGS observation well.
B-18	8N-3E-31aca	-	S&I	1960	3190	3371	-	800	-	-	
B-19	8N-3E-33ccd	-	S&I	1961	3275	3423	3409(1965) 3420(1970) 3485(1975)	47	50(1965) 70(1970)	22	Casing repaired prior to 1965.
B-20	9N-3E-27adbd	-	-	1951	3050	3641	-	1600 to 2000	-	-	Oil test well converted to water well.
B-23	9N-8E-14bb	-	S	1964	2862	3028	3019(1969)	60	50 (1969)	61(1964) 59(1969)	Discontinued USGS observation well.
B-9	8N-1E-20caa	-	S	1953	3362	-	-	-	-	-	Flowing.
B-16	8N-3E-2db	-	S	1960	2990	-	-	-			
B-21	9N-5E-24aca	-	S&D	1935	-	-	-	50	-	-	
B-2	7N-1E-11ac	-	-	-	-	-	-	-	-	-	
B-4	7N-2E-2	-	-	-	-	-	-	-	-	-	
B-5	7N-2E-3bdd	-	-	-	-	-	-	-	-	-	
B-6	7N-2E-6/7	-	-	-	-	-	-	-	-	-	
B-7	8N-1E-8bc	Newell Exp. Stn.	-	-	-	-	-	-	-	-	

TABLE F-3 Concluded

Well No.	Location	Well Name Owner	Use	Year Drilled	Elevation (feet)	Potentionmetric Surface Elevation (feet) Initial	Potentionmetric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
B-10	8N-1E-22	-	-	-	-	-	-	-	-	-	
B-11	8N-1E-28 dc	-	-	-	-	-	-	-	-	-	
B-12	8N-2E-22	-	-	-	-	-	-	-	-	-	
B-13	8N-2E-30	-	-	-	-	-	-	-	-	-	
B-17	8N-3E-13/14	-	-	-	-	-	-	-	-	-	
B-22	9N-8E-	Swanson	-	-	-	-	-	-	-	-	Irrigation well.
B-24	1ON-4E-4	-	D&S	-	1972	-	-	-	-	-	

TABLE F-4

MINNELUSA WELLS: CUSTER COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
CU-1	2S-7E-34bdbc	-	D	1978	3947	3518	-	12	-	13	
CU-2	3S-7E-10ba	-	D or S	1954	3505	> 3505	-	25	-	-	
CU-3	3S-7E-17dcdc	-	S	1954	3648	3639	-	-	-	-	
CU-4	3S-7E-33aacb	Cobb Sisters	S	1964	3655	> 3655	-	8	11(1977, 1978)	15	
CU-5	4S-2E-24eaad	-	D or S	1951	5010	4890	-	-	-	-	
CU-10	5S-6E-2baa	-	D or S	1968	3900	3770	-	-	-	-	Reported to produce 15 gpm with 140 feet of drawdown.
CU-12	6S-3E-25dac	-	D or S	1976	4350	4344	-	-	-	-	Reported to produce 2 gpm when pumped.
CU-13	6S-4E-4cc	-	D or S	1977	4665	4621	-	-	-	-	Reported to produce 1 gpm when pumped.
CU-17	6S-5E-25add	-	D&S	1951	3935	3585	-	-	-	-	
CU-18	6S-5E-30ac	-	D&S	1958	4510	> 4510	-	2	-	-	
CU-6	4S-3E-30bcbb	-	S	1961	5120	-	-	-	-	-	Pumped well.
CU-8	5S-2E-14cabd	-	D	1958	-	-	-	-	-	-	Pumped well.
CU-9	5S-2E-14ddcb	-	D	1946	4685	-	-	-	-	-	Reported to produce 4 gpm when pumped.
CU-14	6S-4E-24da	-	S	1975	4365	-	-	-	-	-	
CU-16	6S-5E-24	Pump D	S	1952	-	-	-	-	-	-	
CU-7	4S-7E-25dddd	-	-	-	-	-	-	-	-	-	
CU-11	5S-7E-6cc	-	-	-	-	-	-	-	-	-	
CU-15	6S-4E-29da	Rock quarry	-	-	-	-	-	-	-	-	
	4S-2E-2adb	Jewel Cave	-	-	-	-	-	-	-	-	Pumps 10 gpm.

TABLE F-5

MINNELUSA WELLS: FALL RIVER COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Ele-vation (feet)	Potentiometric Surface Elevation (feet) Initial	Later (year)	Flow Rate Initial	Later (year)	Temp. (°C)	Remarks
F-2	7S-5E-14d	Housing development	D	1954	3500	3465	-	-	-	-	Reported production was 100 gpm by bailing method.
F-1	7S-5E-7c	G. Smith	D	1977	3900	3540	-	-	-	-	Reported production was 10 gpm by pumping.
F-3	7S-5E-17c	-	D	1977	3900	3560	-	-	-	-	Reported production was 10 gpm by pumping.
F-4	7S-5E-17ddaa	D. Elkjer	D	1977	3900	3555	-	-	-	-	Reported production was 8 gpm by pumping.
F-5	7S-5E-22bccd	W. Kilbreath	D	1977	4070	3670	-	-	-	-	Reported production was 6 gpm with 100 feet of drawdown by driller, but measurement "not very good."
F-6	7S-5E-22cdc	County Club Estates	D	1977	-	230 ft below lsd.	-	-	-	-	Reported production was 134 gpm with 150 ft of drawdown.
F-7	7S-5E-26cbcc	-	D	1977	-	3340	-	-	-	-	Reported production was 50 gpm pumped.
F-8	8S-5E-8dacd	-	D or S	1977	3875	3515	-	-	-	-	Reported production was 16 gpm pumped.

TABLE F-6

MINNELUSA WELLS: LAWRENCE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet)		Flow Rate		Temp. (°C)	Remarks
						Initial	Later (year)	Initial	Later (year)		
L-1	5N-3E-1ad	-	D&S	1973	4330	4217	-	-	-	-	
L-2	5N-4E-14da	-	D&S	1957	3840	3650	-	-	-	-	
L-3	5N-4E-4E-15ad	Housing development	D	1973	4185	3765	-	-	-	-	Reported to produce 75 gpm by pumping.
L-4	5N-4E-15dd	-	D	1964	4260	3714	-	-	-	-	Reported to produce 5 gpm by pumping.
L-5	5N-4E-15dd	-	D	1977	4260	4225	-	-	-	-	Reported to produce 6 gpm with 45 ft of drawdown while pumping.
L-6	5N-4E-23aaad	-	-	1978	3890	3850	-	-	-	-	Reported to produce 20 gpm while pumping. Driller reported static water level at 3660 ft on 9/7/77.
L-7	5N-4E-23aabc	-	D	1974	3910	3727	-	-	-	-	Reported to produce 7 gpm with 67 ft of drawdown while pumping.
L-8	5N-4E-23adca	-	D	1974	3910	3853	-	-	-	-	Reported to produce 7 gpm while pumping.
L-9	6N-2E-4d	-	D	1977	3580	3568	-	-	-	-	Reported to produce 100 gpm with 158 ft of drawdown while pumping.
L-10	6N-2E-9d	-	D or S	Before 1918	3660	3695	-	-	-	-	
L-11	6N-2E-14c	Country Club	D	1965	3760	3670	-	-	-	-	Reported to produce 175 gpm while pumping.
L-14	6N-2E-23bbba	-	A	1904	3770	above 3770	3694(1956) 3718(1970) 3717(1975) 3732(1978)		-	-	Darton (1909) reported that this well originally flowed.
L-16	6N-2E-25bb	-	D	1974	4150	3890	-	-	-	-	
L-17	6N-3E-17aa	-	D&S	1976	3830	3551	-	-	-	-	
L-18	6N-3E-23	-	D&S	1960	3795	"above 3545"	-	-	-	-	
L-23	6N-4E-16cad	-	D&S	1973	3600	3490	-	-	-	-	Questionable Minnelusa well. Reported production was 150 gpm pumping.

TABLE F-6 Concluded

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
L-24	6N-4E-21dcbc	-	S	1977	3650	3510	-	-	-	-	Reported production was 60 gpm while pumping.
L-26	6N-4E-28ab	-	D	1979	3720 ±80	3585	-	-	-	-	Reported production was 15 gpm while pumping.
L-27	6N-4E-36caca	-	D	1973	3590	3490	-	-	-	-	
L-30	7N-1E-14ccdd	-	I,O	1975	3464	3487	-	512	-	12	USGS observation well.
L-31	7N-1E-14ccdd	-	I,O	1978	3464	3496	-	520	-	12	
L-39	7N-1E-25db	-	D&S	1959	3540	3530	-	-	-	-	Reported production was 20 gpm while pumping.
L-40	7N-1E-26acb	-	O	1960	3524	3496	3500(1965) 3486(1970) 3497(1975) 3505(1978)	-	-	-	USGS observation well.
L-41	7N-1E-26ddd	-	D	1978	3640	3563	-	-	-	-	
L-42	7N-1E-29bba	-	O	1976	3470	3516	-	-	-	-	USGS observation well.
L-43	7N-1E-30cda	-	O,S	1960	3570	3571	3569(1961) 3574(1964)	None (1964)	6.7	18	Discontinued USGS observation well.
L-47	7N-2E-19acc	Sugar Mill Ranch well	I,O	1960	3405	-	3490 (1965)	-	-	13	Discontinued USGS observation well.
L-52	7N-2E-22bca	-	I	1960	3437	-	3483 (1961)	630	522(1961) 485(1966) 325(1970)	15	Discontinued USGS observation well.
L-55	7N-2E-32bb	-	D&S	1960	3545	3485	-	-	-	-	
L-56	7N-3E-7aaba	-	I,O	1962	3320	3432	3459(1963) 3516(1964) 3449(1970) 3519(1975) 3518(1978)	333(1962)	462(1963) 500(1964) 333(1970) 420(1975)	-	USGS observation well. Potentiometric head varies significantly by season.

TABLE F-7

OTHER WELLS: LAWRENCE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
L-12	6N-2E-15	-	D	1978	-	-	-	-	-	-	
L-13	6N-2E-22bb	-	D	1977	-	-	-	-	-	-	Questionable Minnelusa well.
L-14	6N-2E-24cb	-	D	1974	-	-	-	-	-	-	
L-15	6N-2E-25ad	-	D	1978	4210	-	-	-	-	-	State Game and Fish project.
L-19	6N-3E-5	-	D	-	-	-	-	-	-	-	
L-20	6N-3E-14ba	-	D	-	-	-	-	-	-	-	
L-25	6N-4E-22cbcb	-	Oil test	1924	3595	-	-	-	-	-	
L-21	6N-3E-22dc	-	D&S	1960	-	-	-	-	-	-	
L-22	6N-3E-23cc	-	D	1960	-	-	-	-	-	-	
L-28	6N-4E-36bc	-	D	1974	-	-	-	-	-	-	
L-29	6N-4E-36da	-	D	1973	-	-	-	-	-	-	Questionable Minnelusa well.
L-32	7N-1E-19bccc	-	-	1961	3440	-	-	-	-	12	
L-33	7N-1E-20cc	-	-	1962	3530	-	-	-	-	-	
L-34	7N-1E-21cc	-	D	1956	3480	-	-	43	40(1960) 25(1970) 18(1971) 60(1972)	-	South Dakota Dept. Game, Fish and Parks. Well repaired between 1971 and 1972. Two Minnelusa wells and one Minnelusa spring reported here flowing at 100p, 800, and 1000 gpm, respectively.
L-35	7N-1E-23bc	-	S	1956	3520	-	-	-	-	11	
L-36	7N-1E-23cb	-	I&S	1960	-	-	-	1100	-	-	
L-37	7N-1E-23cb	-	I	1955	-	-	-	1100	-	11	
L-38	7N-1E-24bc	-	I&S	1960	-	-	-	300	-	16	
L-44	7N-1E-32bbb	-	D&S	1960	3560	-	-	90	-	14	
L-45	7N-2E-8bc	-	D&S	1962	3285	-	-	-	-	-	
L-46	7N-2E-18ca	-	-	1961	3450	-	-	600	-	12	
L-48	7N-2E-19cca	-	I&S	1962	-	-	-	1200	-	-	
L-49	7N-2E-19cd	-	I&S	1964	3437	-	-	600	-	-	Possible Madison well or Minnelusa-Madison well.
L-50	7N-2E-20da	-	D&S	1964	3390	-	-	38	-	-	

TABLE F-7 Concluded

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
L-51	7N-2E-21ac	-	-	1965	3440	-	-	725	-	-	
L-53	7N-2E-23cdba	-	I	1960	3880	138	173(1965) 242(1970)	-	-	13	Well repaired in 1970.
L-54	7N-2E-29aaa	-	I&S	1960	3415	-	-	90	-	-	
L-57	7N-3E-12bb	-	D,I&S	1961	3210	-	-	130	-	16	
L-58	7N-4E-19badc	Railroad well at Minnekahta depot	-	1894	4167	-	-	-	-	-	

TABLE F-8

MINNELUSA WELLS: MEADE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
ME-1	2N-6E-1aabb	-	D&S	1977	3725	3432	-	-	-	-	
ME-2	2N-7E-4cdd	-	D&S	1959	3405	3416	-	35	-	-	
ME-3	2N-7E-4d	-	D	1973	3430	3390	-	-	-	-	Pumped well.
ME-4	2N-7E-6dccd	-	D	1959	3520	3425	-	-	-	-	Reported to produce 15 gpm (when pumped).
ME-5	2N-7E-7bb	Borden Dairy	I	1972	3730	3660	-	-	-	-	Reported to produce 45 gpm when pumped.
ME-10	2N-7E-8bba	-	D	1959	3500	3425	-	-	-	-	Reported to produce 60 gpm with 625 ft of drawdown when pumped.
ME-14	3N-6E-9bbd	-	D	1973	3750	3506	-	-	-	-	Pumped well.
ME-15	3N-6E-10 bc	-	D	1978	3475	3425	-	-	-	-	Pumped well.
ME-20	3N-6E-14 bc	Housing development	D	1975	3460	3280	-	-	-	-	Use discontinued in 1977. Reported to produce 36 gpm when pumped.
ME-21	3N-6E-14cba	-	D	1973	3485	-	-	-	-	-	Reported to produce 50 gpm with 500 ft of drawdown when pumped.
ME-25	3N-6E-16aaab	-	D	1973	3570	3530	-	-	-	-	Reported to produce 40 gpm when pumped.
ME-26	3N-6E 16 aaba	-	D	1973	3590	3545	-	-	-	-	Reported to produce 40 gpm when pumped.
ME-28	3N-6E-23db	-	D or S	1973	3560	3520	-	-	-	-	Questionable Minnelusa well. Reported to produce 26 gpm with 220 ft of drawdown when pumped.
ME-29	3N-6E-23dccb	-	D	1972	3605	3485	-	-	-	-	Reported to produce 10 gpm when pumped.
ME-30	3N-6E-25addc	-	D	1976	3615	3435	-	-	-	-	Reported to produce 5 gpm with 40 ft of drawdown when pumped.
ME-31	3N-6E-26abab	-	D	1972	3630	3494	-	-	-	-	Reported to produce 30 gpm with 104 ft of drawdown when pumped.
ME-32	3N-6E-26adb	-	D	1950	3640	3555	-	-	-	-	Pumped well.
ME-33	3N-6E-36badd	-	D	1977	3725	3445	-	-	-	-	Reported to produce 24 gpm when pumped.
ME-34	3N-6E-36cadd	-	D	1977	3880	3520	-	-	-	-	Reported to produce 18 gpm when pumped.

TABLE F-8 Continued

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
ME-35	3N-6E-36bdaa	-	D	1977	3720	3440	-	-	-	-	Pumped well.
ME-36	3N-6E-36bdbcc	-	D	1977	3810	3460	-	-	-	-	Reported to produce 18 gpm when pumped.
ME-37	3N-6E-36dbbd	-	D	1975	3740	3440	-	-	-	-	Pumped well.
ME-38	3N-6E-36dd	-	D	1961	3700	3635	-	-	-	-	Pumped well.
ME-43	3N-7E-31caa	-	D	1975	3630	3480	-	-	-	-	Reported to produce 15 gpm when pumped.
ME-47	4N-6E-29abc	Rest stop on highway I-90	D	1967	3542	3515	-	-	-	-	Reported to produce 5 gpm when pumped.
ME-53	5N-5E-4d	-	D, S	1973	3550	3320	-	-	-	-	Questionable Minnalusa well. Reported to produce 30 gpm with 430 ft of drawdown when pumped.
ME-56	5N-5E-5bcb	-	D	1958	3555	3444	-	-	-	-	
ME-57	5N-5E-5ccc	-	D	-	3515	3365	-	-	-	-	Pumped well.
ME-58	5N-5E-5ccc	-	D	-	3530	3454	-	-	-	-	Pumped well.
ME-59	5N-5E-5d	-	D or S	1965	3480	3300	-	-	-	-	Pumped well.
ME-60	5N-5E-5dcac	Outlaw Inn	D	1977	3495	3400	-	-	-	-	Reported to pump 30 gpm with 126 ft of drawdown.
ME-61	5N-5E-5dcc	-	D or S	1965	3505	3300	-	-	-	-	Pumped well.
ME-62	5N-5E-6aca	-	D	1972	3610	3458	-	-	-	-	Reported to produce 85 gpm when pumped.
ME-63	5N-5E-6ada	-	D	1974	3640	3489	-	-	-	-	Reported to produce 80 gpm when pumped.
ME-64	5N-5E-6dbbd	Sturgis Industrial Park	I	1965	3665	3465	-	-	-	-	Pumped well.
ME-65	5N-5E-7aab	Community well	D	1971	3550	3362	-	-	-	-	Pumped well.
ME-72	5N-5E-7acb	-	D	-	3605	3467	-	-	-	-	Pumped well.
ME-73	5N-5E-7abc	-	D	1962	3605	3461	-	-	-	-	Pumped well.
ME-74	5N-5E-7abbb	-	D	1959	3580	3540	-	-	-	-	Pumped well.
ME-75	5N-5E-7acb	-	D	1972	3600	3528	-	-	-	-	Pumped well.
ME-76	5N-5E-7cbd	-	D	1973	3660	3629	-	-	-	-	Pumped well.
ME-77	5N-5E-7ca	-	D	1973	3610	3420	-	-	-	-	Reported to produce 10 gpm when pumped.

TABLE F-8 Concluded

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
ME-78	5N-5E-7cbd	-	D	1973	3670	3470	-	-	-	-	Reported to produce 12 gpm with 60 ft of drawdown when pumped.
ME-82	5N-5E-8ddbd	-	D	1972	3660	3295	-	-	-	-	Reported to produce 28 gpm when pumped.
ME-83	5N-5E-9abca	St. Martin's Academy	D	1955	3440	3104	-	-	-	-	Reported to produce 11 gpm when pumped.
ME-84	5N-5E-9adbc	City of Sturgis	D	1960	3570	3210	-	-	-	-	Reported to produce 272 gpm when pumped.
ME-85	5N-5E-9dcb	Racetrack at fairgrounds	D	1958	3505	3109	-	-	-	-	Pumped well.
ME-87	5N-5E-11bdc	Ft. Meade V.A. Hospital	D	1958	3330	3108	-	-	-	-	Pumped well.
ME-91	5N-5E-16daba	State highway shop buildings, Sturgis	D	1964	3530	3150	-	-	-	-	Pumped well.
ME-92	5N-5E-16daa	City of Sturgis	D	1948	3550	3132	-	-	-	-	Pumped well.
ME-94	5N-5E-21aaa	Test hole	T	1931	3600	3225	-	-	-	-	
ME-95	5N-5E-22cb	Test hole	T	1931	3710	-	-	-	-	-	
ME-96	5N-5E-25cad	Sturgis dairy cow supply	S	1973	3700	3130	-	-	-	-	Reported to produce 15 gpm with 20 ft of drawdown when pumped.
ME-98	5N-5E-36add	-	D&S	1976	3690	3180	-	-	-	-	Pumped well.
ME-99	5N-7E-19ac	Missile site supply	D	1959	2955	3202	-	2400	-	-	

TABLE F-9

OTHER WELLS: MEADE COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
ME-6	2N-7E-7adab	Town of Blackhawk	D	-	3580	-	-	-	-	-	Reported to produce 225 gpm when pumped
ME-7	2N-7E-8bbcd	Town of Blackhawk	D	-	3510	-	-	-	-	-	Reported to produce 225 gpm when pumped
ME-8	2N-7E-8bab	-	D	1960	3525	-	-	-	-	-	Reported to produce 4 gpm when pumping.
ME-9	2N-7E-8cdbc	-	D&S	1960	3577	-	-	-	-	-	Reported to produce 50 gpm when pumping.
ME-11	2N-7E-10ccbb	-	D&S	1956	3395	-	-	60	35 (1961)		
ME-12	3N-6E-9	-	D	1972	-	-	-	-	-	-	Reported to produce 35 gpm when pumping.
ME-13	3N-6E-9dd	-	D	1960	-	-	-	-	-	-	Pumped well.
ME-16	3N-6E-10aba	-	D	-	3410	-	-	-	-	-	
ME-17	3N-6E-10aba	-	D	-	-	-	-	-	-	-	
ME-18	3N-6E-10ca	-	D	1962	-	-	-	-	-	-	Reported to flow in 1962.
ME-19	3N-6E-10cd	-	D	1956	-	-	-	-	-	-	Reported to flow in 1962.
ME-22	3N-6E-14bc	-	D	1970	-	-	-	-	-	-	
ME-24	3N-6E-15bc	-	D	1977	-	-	-	-	-	-	Reported to produce 15 gpm when pumped.
ME-27	3N-6E-23	-	D	1969	-	-	-	-	-	-	
ME-22	3N-6E-14bc	-	D	1975	-	-	-	-	-	-	Reported to produce 36 gpm when pumped.
ME-23	3N-6E-26aab	-	D or S	1975	3590	-	-	-	-	-	Reported to produce 30 gpm with 340 ft of drawdown and 50 gpm with 500 ft of drawdown when pumped.
ME-39	3N-6E-36ba	-	D	-	-	-	-	-	-	-	Questionable Minnelusa well. Reported to produce 35 gpm when pumped.
ME-40	3N-6E-36bbd	Housing development	D	1976	3750	-	-	-	-	-	Reported to produce 60 gpm when pumped.
ME-41	3N-6E-36d	-	D	1961	-	-	-	-	-	-	Pumped well.
ME-42	3N-6E-36dbc	-	D	1973	-	-	-	-	-	-	Reported to produce 4 gpm when pumped.
ME-44	4N-6E-16dcba	-	D&S	1961	3460	-	-	10	-	-	
ME-45	4N-6E-29	-	D	1972	-	-	-	-	-	-	Reported to produce 130 gpm when pumped
ME-46	4N-6E-29baa	Rest stop on highway I-90	D	1962	-	-	-	-	-	-	Reported to produce 350 gpm when pumped

TABLE F-9 Concluded

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
ME-48	4N-6E-32	-	D or S	1972	-	-	-	-	-	-	Reported to produce 50 gpm when pumped.
ME-49	4N-6E-32bdd	-	D or S	1970	-	-	-	-	-	-	Reported to produce 50 gpm when pumped.
ME-50	4N-6E-32bda	-	D or S	1970	-	-	-	-	-	-	Reported to produce 40 gpm when pumped.
ME-51	4N-6E-32b	-	D	1972	-	-	-	-	-	-	Pumped well.
ME-52	4N-6E-32c	-	D	1973	-	-	-	-	-	-	Pumped well.
ME-54	5N-5E-5cc	-	I	-	3505	-	-	-	-	-	Reported to produce 500 gpm when pumped
ME-55	5N-5E-5dcd	Conoco Oil Co. restaurant	D	1966	3490	-	-	-	-	-	Pumped well.
ME-66	5N-5E-7	-	D	1974	-	-	-	-	-	-	Reported to produce 7 gpm when pumped.
ME-67	5N-5E-7	-	D	1973	-	-	-	-	-	-	Pumped well.
ME-68	5N-5E-7	-	D	1965	-	-	-	-	-	-	Pumped well.
ME-69	5N-5E-7	-	D	1968	-	-	-	-	-	-	Reported to produce 6 gpm when pumped.
ME-70	5N-5E-7a	-	D	1968	-	-	-	-	-	-	Reported to produce 14 gpm when pumped.
ME-71	5N-5E-7acc	-	D	-	3605	-	-	-	-	-	Pumped well.
ME-79	5N-5E-7bddb	-	-	-	-	-	-	-	-	-	
ME-80	5N-5E-7cbc	-	D	1952	3660	-	-	-	-	-	Reported to produce 25 gpm when pumped.
ME-81	5N-5E-8aa	-	D	1971	3560	-	-	-	-	-	Pumped well.
ME-86	5N-5E-9dca	Sturgis swimming pool	D	-	3505	-	-	-	-	-	Pumped well.
ME-88	5N-5E-15dcaa	Concrete tile company	I	1961	3571	-	-	-	-	-	Pumped well.
ME-89	5N-5E-16a	-	D	1960	-	-	-	-	-	-	Reported to produce 7 gpm when pumped.
ME-90	5N-5E-16abc	-	D	1963	3643	-	-	-	-	-	Pumped well.
ME-93	5N-5E-18ba	-	D	1948	-	-	-	-	-	-	Questionable Minnelusa well. Reported to produce 15 gpm when pumped.
ME-97	5N-5E-31	-	S	1973	-	-	-	-	-	-	Pumped well.
ME-100	6N-6E-19bbca	Bear Butte State Park	A	1950	3187	-	-	32.4	-	-	Use discontinued in 1956.
ME-101	7N-5E-11dd	-	-	1957	-	-	-	-	-	-	
ME-102	7N-5E-29ac	-	-	1959	-	-	-	-	-	-	

TABLE F-10

MINNELUSA WELLS: PENNINGTON COUNTY, SOUTH DAKOTA

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (°C)	Remarks
P-1	1N-6E-12da	-	D	1959	4620	3720	-	-	-	-	Reported to produce 2.5 gpm when pumped.
P-2	1N-7E-3bcdd	Sioux Park No. 1	-	1964	3300	3374	3397 (1978)	-	-	11	Reported to produce 27 gpm when pumped.
P-3	1N-7E-3bcdd	Sioux Park No. 2	-	1965	3300	3422	3429 (1979)	-	-	-	
P-6	1N-7E-7ac	-	D	1932	3506	3491	3441 (1933) 3423 (1939) 3456 (1939)	-	-	-	20 ft deep in 1932, deepened to 95 ft in 1933, 152 ft in 1939. Pumped well.
P-7	1N-7E-7aca	-	D	1941	3494	3432	-	-	-	-	Pumped well.
P-8	1N-7E-10cadd	-	D	1958	3415	3395	-	-	-	-	Pumped well.
P-10	1N-7E-23bdab	Housing development	D	1973	3840	-	-	-	-	-	Pumped well.
P-12	1N-7E-32dca	Housing development	D	1967	3660	3587	-	-	-	-	Reported to produce 20 gpm when pumped.
P-13	1N-7E-33ba	-	D or S	1954	3820	3430	-	-	-	-	Pumped well.
P-18	2N-7E-10bcda	-	D	1926	3730	3066	-	-	-	-	Pumped well. Meade County.
P-19	2N-7E-17dddc	-	D	1955	3460	3440	-	-	-	-	Pumped well.
P-21	2N-7E-20aa	Drive-in theater	D	1954	3470	3460	-	-	-	-	Reported to produce 28 gpm when pumped.
P-22	2N-7E-27bbb	-	D or S	1961	3431	3416	-	-	-	-	Pumped well.
P-24	2N-7E-28dd	Brick plant	D	1959	3360	-	-	5	-	-	
P-25	2N-7E-31bc	-	D or S	1955	3750	3420	-	-	-	-	
P-26	2N-7E-32bca	-	D or S	1959	3510	3460	-	-	-	-	Pumped well.
P-27	2N-7E-32bccc	-	D or S	1951	3565	3448	-	-	-	-	Reported to produce 6 gpm when pumped.
P-28	2N-7E-32caa	-	D or S	1959	3525	3450	-	-	-	-	Reported to produce 28 gpm with 5 ft of drawdown when pumped.
P-35	2N-7E-34bcca	Cement plant	D	1964	3320	3408	3425 (1979)	300	-	10	
P-36	3N-7E-34bdc	Test well	T	1958	3360	3325	3434 (1978)	150	-	-	Minnelusa-Minnakahta well.

TABLE F-10 Concluded

Well No.	Location	Well Name or Owner	Use	Year Drilled	Elevation (feet)	Potentiometric Surface Elevation (feet) Initial	Potentiometric Surface Elevation (feet) Later (year)	Flow Rate Initial	Flow Rate Later (year)	Temp. (^oC)	Remarks
P-37	2N-7E-34abca	Test well	T	1959	3325	-	-	-	-	-	Flowing well.
P-38	1S-1E-28	-	S	1977	6420	6411	-	-	-	-	Reported to produce 10 gpm when pumped.
P-39	2S-1E-10bada	-	D	1926	3730	3540	-	-	-	-	Pumped well.
P-9	1N-7E-16	Carriage Hills	-	1977	-	-	-	-	-	-	Reported to produce 150 gpm when pumped
P-4	1N-7E-4dcb	Rapid City No. 4	M	1939	3346	-	-	-	-	-	Flows and is pumped.
P-5	1N-7E-5ab	-	D	1958	3530	-	-	-	-	-	Pumped well.
P-12	1N-7E-29ddc	Housing development	D	1948	3920	-	-	-	-	-	Pumped well.
P-11	1N-7E-27ab	-	D	1960	3540	-	-	-	-	-	Pumped well.
P-14	1N-7E-33	-	D	1977	-	-	-	-	-	-	Pumped well.
P-15	2N-6E-35	-	D	1977	-	-	-	-	-	-	Reported to produce 25 gpm when pumped.
P-16	2N-6E-35	-	D	-	-	-	-	-	-	-	Pumped well.
P-17	2N-6E-35	-	D	-	-	-	-	-	-	-	Pumped well. 2 wells located here.
P-20	2N-7E-17dd	Ponderosa Trailer Court	D	1957	3460	-	-	-	-	-	Pumped well.
P-23	2N-7E-27aab	-	D	1957	3435	-	-	-	-	-	Pumped well.
P-29	2N-7E-32a	-	D	1977	-	-	-	-	-	-	Pumped well.
P-30	2N-7E-32cabb	-	D	-	3520	-	-	-	-	-	Reported to produce 2 gpm when pumped.
P-31	2N-7E-32cddd	-	D	1960	3490	-	-	-	-	-	Pumped well.
P-32	2N-7E-33dab	Cement plant	-	-	3400	-	-	-	-	-	Well flows when not pumped. Reported to pump 250 gpm.
P-33	2N-7E-33dab	Cement plant	-	-	3400	-	-	-	-	-	Well flows when not pumped. Reported to pump 80 gpm.
P-34	2N-7E-33dab	Cement plant	-	-	3400	-	-	-	-	-	Well flows when not pumped. Reported to pump 600 gpm.
P-40	2S-7E-9	-	D	1977	-	-	-	-	-	-	Pumped well.

APPENDIX G

OIL AND GAS FIELDS NEAR PROPOSED ETSI WELL FIELDS

TABLE G-1

OIL AND GAS FIELDS PRODUCING FROM PERMIAN AND PENNSYLVANIAN FORMATIONS NEAR THE PROPOSED NIOBRARA COUNTY WELL FIELD

Name of Oil or Gas Field	Location (Township - Range)	Number of Producing Wells in 1978	Production Type/Status
Wyoming			
Mail Creek	39N-60,61W	29	Water flood
Red Bird NE	38N-61W	0	Abandoned
Red Bird	38N-62W	3	
Cow Gulch	36N-62W	0	Abandoned
Buck Creek	36N-63W	5	
Little Buck Creek	36N-64W	Unknown	
Lance Creek E.	36N-64W	6	
Pine Lodge	35N-63W	2	
Lance Creek	35,36N-65W	61	Water flood
South Dakota			
Unknown	65-2E	5	
Unknown	9S-2E	1	
Indian Creek	12S-1E	4	

Sources: Wyoming Oil and Gas Conservation Commission, 1978 (for producing data); Glass et al., 1975 (for field names).

TABLE G-2

OIL AND GAS FIELDS PRODUCING FROM PERMIAN AND PENNSYLVANIAN FORMATIONS NEAR THE PROPOSED CROOK COUNTY WELL FIELD

Name of Oil or Gas Field	Location (Township - Range)	Number of Producing Wells in 1978	Production Type/Status
Adon	52N-72N	0	Abandoned
Adon Road	52N-72W	3	
Adon Road N.	52N-72W	1	
AM - Kirk	46N-70W	5	
Arrow	53N-69W	0	
Basin	47N-70W	2	Water flood
Basin NW	47N-70W	5	Water flood
Bishop Ranch	48N-70W	1	
Bishop Ranch S	48N-70W	7	Water flood
Booten (Booton)	54N-70W	1	
Breen	47N-72W	7	
Bullmarch	53N-69W	2	
Camp Creek	54N-70,71W	10	
Cardinal	51N-69W	2	
C - H	52N-70W	6	Water flood
Calbaugh	47N-71W	2	
Corral Creek	55N-68W	1	
County Line	52N-68W	1	
Deadman Creek	53N-67W	4	
Double Shield	51N-70W	1	
Driscoll Creek	56N-68,69W	1	
Duvall Ranch	49N-69W	12	Water flood
Garner Lake	51N-69W	0	Abandoned
Gibbs	52N-69W	5	
Grasshopper Butte	50N-66,67W	0	Abandoned

TABLE G-2 Continued

Name of Oil or Gas Field	Location (Township - Range)	Number of Producing Wells in 1978	Production Type/Status
Grassland	53N-70W	1	Water flood
Gray	50N-69W	0	
Guthery	51N-68W	5	Water flood
Halverson	49N-69W	17	Water flood
Hoover Gulch	52N-69W	2	
Jewell (Jewel)	54N-67W	2	
Kane	51N-70W	3	
Kiehl	53N-67W	2	
Kuehne Ranch	51N-69,70W	12	Water flood
Kuehne Ranch, E	51N-69W	1	
Kuehne Ranch, SE	51N-69W	1	
Kummer Field	51N-68W	16	Water flood
Lad	54N-68W	1	
Little	55N-70W	0	Abandoned
Little Mitchell Creek	52N-69W	5	Water flood
Little Mo	53N-68W	2	
MAC	52N-69W	1	
M - D	53N-69W	4	
Mellot Ranch	52N-68W	4	Water flood
Minturn	50N-71W	1	
Mitchell Creek	53N-70W	0	Abandoned
NW (not listed)			
OK	51N-70W	5	
Olson (Olsen)	49N-71W	2	
Pickrell Ranch	49N-69W	2	Water flood
Pleasant Valley	51N-69W	1	
Pownall Ranch	53N-70W	8	
Prong Creek	50,51N-67,68W	5	

TABLE G-2 Continued

Name of Oil or Gas Field	Location (Township - Range)	Number of Producing Wells in 1978	Production Type/Status
Rainbow Ranch	48N-71W	3	
Rainbow Ranch, N	49N-71W	5	
Raven Creek	48,49N-69W	24	Water flood
Reel	49N-68,69W	8	Water flood
Reynolds Ranch	52N-68W	2	
Robinson Ranch	50N-67W	5	Water flood
Robinson Ranch, E	50N-67W	3	
Robinson Ranch, S	49N-67W	7	
Rocky Point	56,57N-69W	26	
Roers	53N-70W	2	
Rourke Gap	48N-71W	5	
Rozet	50N-69,70W	39	
Rozet, E	50N-69W	10	
Rozet, S	50N-69,70W	9	
Rozet, W	50N-70W	11	
RT	50N-68W	0	Abandoned
Semlek	52N-68W	4	Water flood
Semlek, SW	52N-68W	1	
Semlek, W	52N-68W	7	
Sharp	49N-71W	1	
Simpson Ranch	51N-69W	0	Abandoned
Slattery	48,49N-68,69W	15	
Soda Well	54N-70W	2	
Soda Well E	54N-70W	4	
Texas Trail	53N-68W	2	
Tholson	49N-70W	6	Water flood
Timber Creek	49N-70W	17	
Timber Creek, NW		0	
Toland	50N-70W	0	

TABLE G-2 Concluded

Name of Oil or Gas Field	Location (Township - Range)	Number of Producing Wells in 1978	Production Type/Status
Wagon Spoke	52N-69W	3	
Wallace	52N-70W	10	Water flood
Wallace S	51N-70W	1	
Well Creek	50N-69W	1	
Whistler	51N-70W	3	Water flood
Windmill	51N-69W	7	
Wolff	49N-72W	2	
Yellow Hammer	47N-70W	2	
York	53,54N-69W	0	Abandoned

Sources: Wyoming Oil and Gas Conservation Commission, 1978 (for production data); Glass et al., 1975 (for field names).

APPENDIX H

MADISON AQUIFER TESTS

APPENDIX H
MADISON AQUIFER TESTS

The results of aquifer tests performed on the Madison aquifer along the western flanks of the Black Hills are presented and reviewed in this appendix. A summary of these tests is presented in Table H-1. Previous attempts at interpreting the aquifer test data are shown here to have produced estimates of aquifer parameters that are not useful for assessing aquifer behavior on a regional scale. A new model of the hydraulic behavior of the Madison is developed that explains the behavior of the Madison aquifer observed during testing.

H.1 NIOBRARA COUNTY MADISON AQUIFER TESTS

The Niobrara County aquifer tests consisted of two sets of pump tests: (1) a series of five tests conducted in 1974 in the southeast portion of the ETSI well field, and (2) a series of three tests conducted in 1978, 13 miles northeast of the 1974 tests (Table H-1).

H.1.A 1974 AQUIFER TESTS

The 1974 aquifer tests utilized five wells completed in one or more geologic units: (a) three wells in the Madison Group and in the Bell Sand; (b) one well in the upper portion of the Minnelusa Formation; and (c) one well in the shallower Lakota Sandstone. All five wells are approximately one mile east of the Fanny Peak lineament and are adjacent the Old Woman anticline. A summary of well construction data is tabulated in Table H-2.

Five aquifer tests were conducted from April through September 1974 for durations of 2 to 24.5 days, at pumping rates ranging from 0.13 to 0.40 cfs (60 to 180 gpm). The basic data from the five pump tests are summarized in Table H-3. The response of the Madison aquifer to pumping stress during all five aquifer tests was identical. Within 24 hours of the start of pumping, the drawdown in the observation wells stabilized and remained stable for the duration of the test. There was no water-level response in the observation wells completed in the upper Minnelusa Formation or the Lakota Sandstone. Time-drawdown data from

TABLE H-1

SUMMARY OF MADISON AQUIFER TESTS,
EASTERN POWDER RIVER BASIN, WYOMING

Pumping Well and Location	Date	Type Of Test	Duration (days)	Observation Wells	Pumping Rate(s) (cfs)	Remarks
ETSI O-1	4/24/74	Constant Discharge	4.5	3	0.13	First of five tests at proposed Niobrara County well field.
ETSI T-2	5/3/74	Constant Discharge	5	3	0.28	
ETSI T-2	5/19/74	Constant Discharge	24.5	3	0.33-0.40	Discharge reduced from 0.40 cfs to 0.33 cfs after 20,000 minutes.
ETSI T-2	8/28/74	Constant Discharge	4	4	0.38	Additional observation well O-5.
ETSI T-2	9/7/74	Constant Discharge	2	4	0.38	
City of Newcastle No. 1	9/1/77	Step Discharge	1.5	1	0.68, 1.67	Pumping rates are changes in flow at pumping well.
USGS MTW No. 1	8/16/77	Step Discharge	1	None	0.40, 0.59, 1.17	Hole was open to all units, Red River and above.
USGS MTW No. 1	8/17/77	Constant Head Variable Discharge	0.25	None	Various from 0.29 to 1.11 gpm	Same as above.
City of Gillette M-2	9/20/77	Step Discharge	0.5	None	Various from 0.04 to 1.45	
City of Gillette M-2	9/21/77	Constant Discharge	1	None	1.11	Sudden reduction in specific capacity part way through test.

TABLE H-1 Continued

Pumping Well and Location	Date	Type Of Test	Duration (days)	Obervation Wells	Pumping Rate(s) (cfs)	Remarks
ETSI M-1	9/12/78	Step Discharge	1	None	Various from 0.27 to 0.40	Stabilized drawdown; temperature effects during recovery.
ETSI M-1	9/13/78	Constant Discharge	1	None	0.26	Stabilized drawdown; no recovery data.
ETSI M-1	9/19/78	Constant Discharge	0.2	None	0.26	Stabilized drawdown; temperature effects during recovery.
ETSI M-1	9/19/78	Step Discharge	0.7	None	Various from 0.26 to 0.45	Temperature effects during recovery.
ETSI M-1	9/20/78	Constant Discharge	12.5	None	0.26	Stabilized drawdown; temperature effects during recovery.
City of Newcastle No. 4	10/13/78	Step Discharge	1	None	Various from 0.06 to 1.34	Problems with accurate flow measurement.
City of Newcastle No. 4	10/14/78	Constant Discharge	1	None	0.45	Some problems with flow measurement, possible change in flow rate in nearby city Well No. 1.
City of Gillette M-1	5/3/79	Step Discharge	1	None	Various from 0.18 to 0.37	First 2.5 hours were step-discharge test, next 20+ hours constant rate of 0.37 cfs.
City of Gillette M-1	6/28/79	Step Discharge	1	None	Various from 0.18 to 1.41	Well was acid-fractured after 5/3/79 test.
City of Gillette M-1	6/29/79	Constant Discharge	5+	1	1.41	
City of Gillette M-4	2/5/80	Step Discharge	0.2	None	Various from 0.37 to 1.52	

TABLE H-1 Concluded

Pumping Well and Location	Date	Type Of Test	Duration (days)	Observation Wells	Pumping Rate(s) (cfs)	Remarks
City of Gillette M-4	2/5/80	Constant Discharge	1	None	1.46	Drawdown stabilized within 10 minutes.
City of Gillette M-3	3/17/80	Step Discharge	2	3	Various from 0.18 to 1.38	Step-discharge portion for first few hours, constant 1.38 ± cfs thereafter.
City of Gillette M-3	4/22/80	Step Discharge	1	2	Various from 1.8 to 0.55	
City of Gillette M-3	4/23/80	Constant Discharge	4	2	0.67	Flow during first 24 hours was approximately 0.55 cfs.

TABLE H-2

CONSTRUCTION DATA FOR 1974 NIOBRARA COUNTY TEST WELLS

Well No.	Location (feet)[a]	Total Depth (feet)	Formation in Which Well Is Completed	Elevation (feet)[b]
T-1	1900' W	1523	Upper Minnelusa	4250.38
T-2	——	3116	Madison	4244.42
O-1	750' E	3274	Madison	4247.57
O-2	250' E	505	Lakota	4247.79
O-5	1500' N	3130	Madison	4241.29

Source: Anderson and Kelly, 1974.

[a]With respect to well T-2.

[b]Measuring point of elevation from assumed bench mark of 4244 feet.

TABLE H-3

DESCRIPTION OF 1974 NIOBRARA COUNTY AQUIFER TEST

Test No.	Date (1974)	Duration	Pumped Well	Discharge (cfs)	Pumped Well Drawdown (feet)	Observation Well and Maximum Drawdown
1	Apr. 24-29	4.5 days	O-1	0.13	88	T-2; 5.5 feet
2	May 3-8	5 days	T-2	0.28	266	O-1; 7.5 feet
3	May 19-June 12	24.5 days	T-2	0.33-0.40	330-390	O-1; 11 feet
4	Aug. 28-Sept. 1	4 days	T-2	0.38	370	O-1; 11.5 feet O-5; 0.3 feet
5	Sept. 7-9	2 days	T-2	0.38	370	O-1; 11.7 feet O-5; 0.3 feet

Source: Anderson and Kelly, 1974

pumping well T-2 and observation well O-1 during aquifer test No. 3, a 24.5-day test that is representative of all the tests, are shown in Figures H-1 and H-2.

Rahn (1975), Anderson and Kelly (1974), Stockdale (1974), and Halepaska (1975) have analyzed the results from one or more of these tests. The analytical methods used in the pump test analyses and the aquifer parameter estimates derived in each study are listed in Table H-4.

Two approaches were used in this study to analyze the aquifer test data. The first approach was the application of the Theis (1935) nonequilibrium type-curve method to the analysis of early time test data. This approach assumes that: (1) the stabilization of drawdown was related to a transient phenomenon (such as a nearby high-transmissivity zone), and (2) that prior to stabilization, the aquifer behaves as an infinite nonleaky aquifer. The second approach used both the semilog method of Hantush (1955) and the type-curve method of Walton (1962) to analyze the data. This approach assumes that stabilization in drawdowns is due to leakage from overlying formations and that the drawdowns conform with the Hantush and Jacob (1955) prototype for leaky aquifers. The parameter estimates calculated using these two approaches are summarized in Tables H-5 and H-6.

Interpretations of the aquifer behavior assume that either the Niobrara well field is very near a high-transmissivity zone or that very high rates of leakage occur. Image well theory can be used to locate the high-transmissivity zones that might explain aquifer behavior. A high-transmissivity zone northeast of the site could explain observation well data, but there is no geologic evidence that a high-transmissivity area lies northeast of the test site. Furthermore, a high-transmissivity zone probably would not act as a perfect recharge boundary, as image well theory assumes. The calculated leakage coefficient, 4×10^{-9} sec^{-1}, is much too large for the Minnelusa Formation. The most likely interpretation of aquifer behavior based on this analysis is that the aquifer at the test site is both leaky and/or close to a high-transmissivity area. However, neither of these explanations, or even a combination of these explanations, completely explains the aquifer behavior.

TABLE H-4

SUMMARY OF ANALYSES OF 1974 NIOBRARA COUNTY AQUIFER TESTS

Source	Methods Used	Estimates of Parameters	Remarks
Anderson and Kelly, 1974	Hantush (1956) "leaky-aquifer"	Transmissivity = 0.0023 to 0.0046 ft^2/sec Storage coefficient = 5×10^{-5} Leakage coefficient = 4.28×10^{-9} to 5.21×10^{-9} sec^{-1}	Report shows only analyses of second and third tests.
Stockdale, 1974	Hantush (1956) "leaky-aquifer"	(same as above)	Verification of analyses by Anderson and Kelly, 1974.
Rahn, 1975, 1979	Theis (1935) nonequilibrium type-curve (nonleaky) Jacob (1956) modified nonequilibrium (nonleaky)	Theis method: Transmissivity = 0.0044 ft^2/sec Storage coefficient = 9.54×10^{-5} Jacob method: Transmissivity = 0.01 ft^2/sec Storage coefficient = 6.5×10^{-5}	No "leaky-aquifer" methods used. Rahn's 1979 analysis used "delayed-yield" concept (see Bouwer, 1978; Neuman, 1980). Only first three tests were analyzed. See Section 2 for further analysis.
Halepaska, 1975	Finite-difference computes model	General aquifer properties: Transmissivity = 0.0077 ft^2/sec Storage coefficient = 10^{-5} Fault zone properties: Transmissivity = 0.77 ft^2/sec Storage coefficient = 10^{-1}	Analysis was designed only to show that certain geologic conditions (and not necessarily leakage) could cause stabilization of drawdown. See Section 2 for further discussion.
Office of Technology Assessment, 1978	(same as Anderson and Kelly, 1974, and Stockdale, 1974, above)		Verification of correct application of Hantush (1956) "leaky-aquifer" method by Anderson and Kelly, 1974, and Stockdale, 1974.

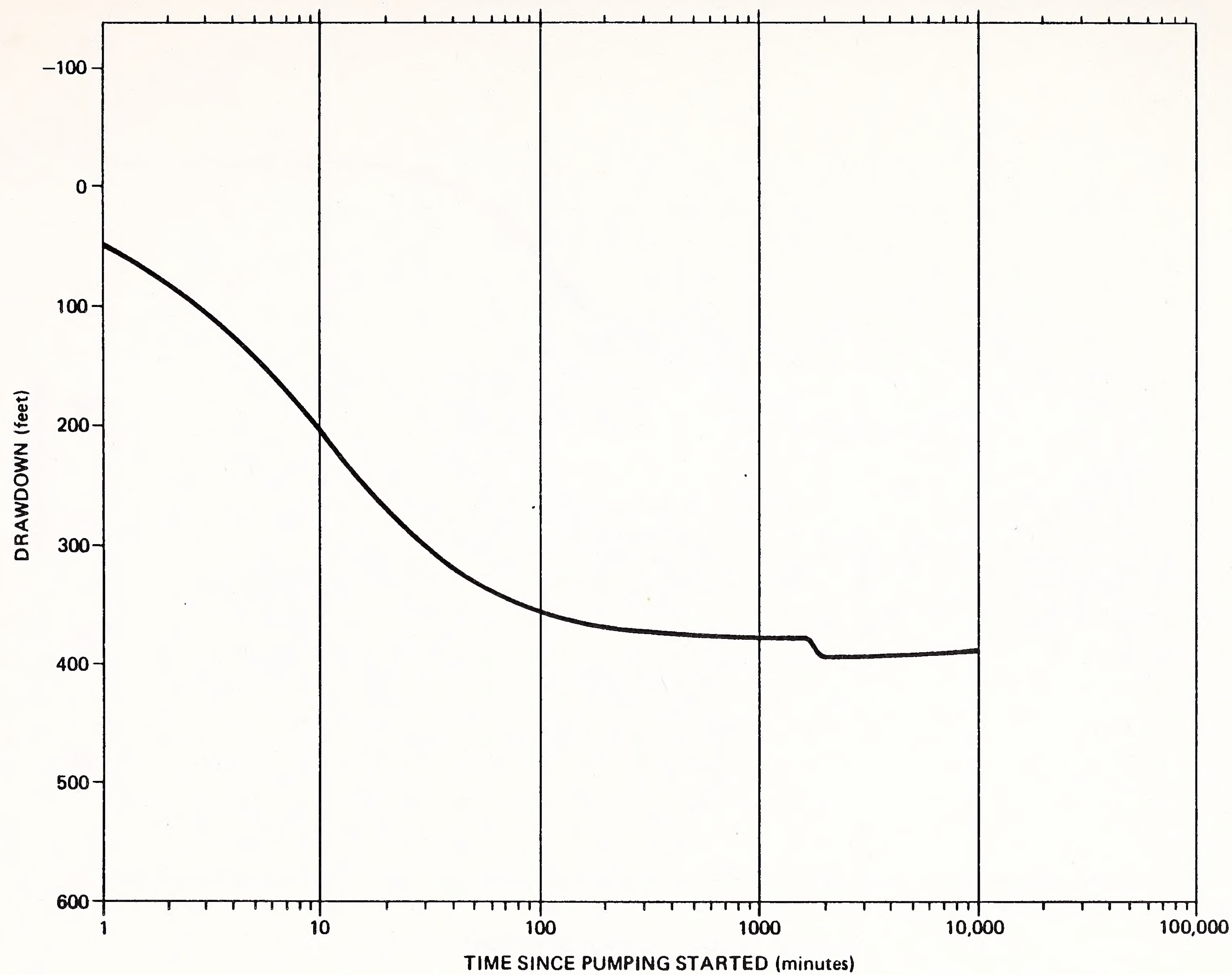


Figure H-1. TIME-DRAWDOWN DATA DURING PUMPING OF WELL T-2, 1974 NIOBRARA COUNTY AQUIFER TEST NO. 3

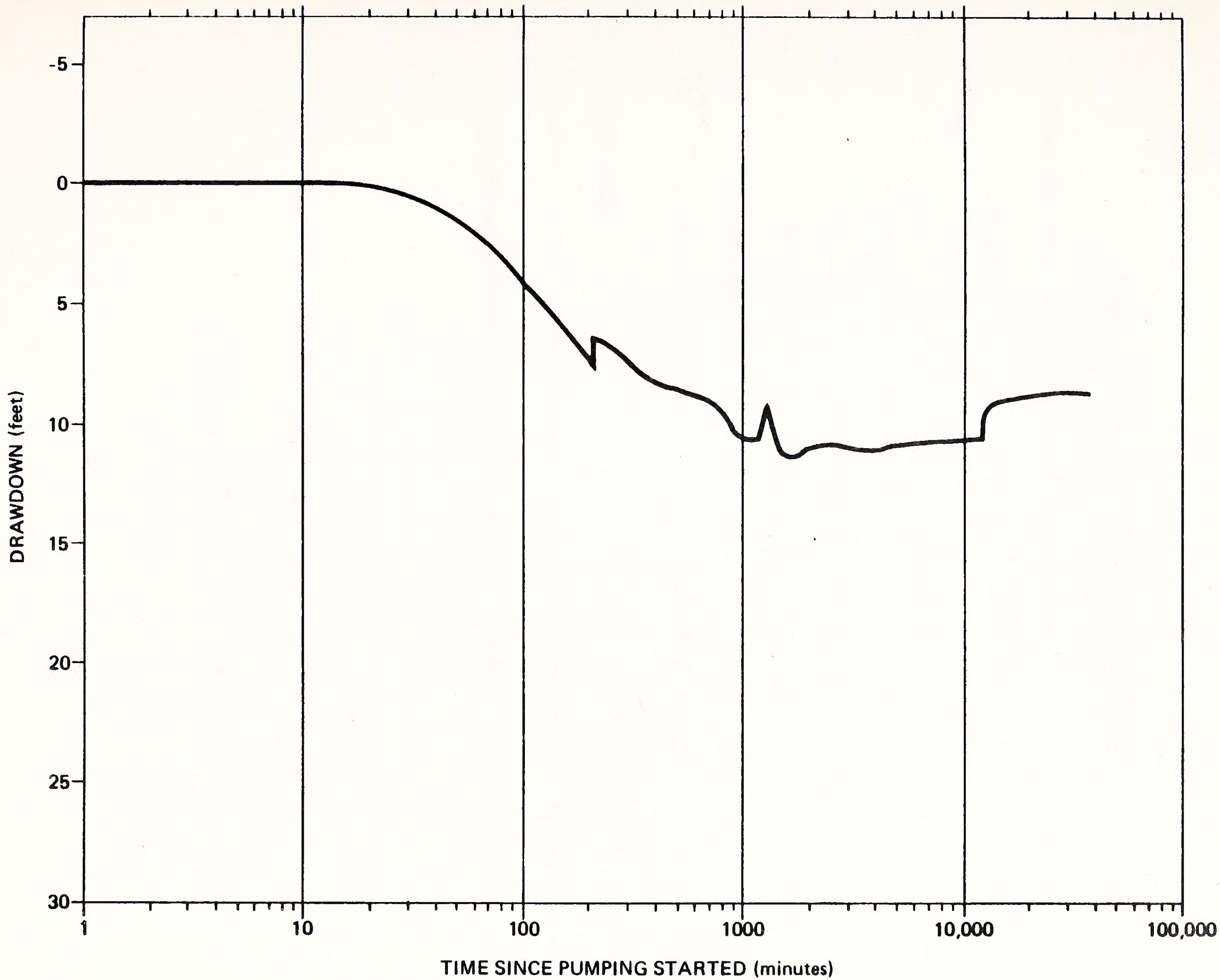


Figure H-2. TIME-DRAWDOWN DATA DURING PUMPING FOR OBSERVATION WELL O-1, 1974, NIOBRARA COUNTY AQUIFER TEST NO. 3 (5/19/74–6/12/74)

TABLE H-5

SUMMARY OF ANALYSES OF PUMP TESTS
USING THEIS NONLEAKY AQUIFER EQUATION*

Test No.	Type of Data	Method of Analysis	Transmissivity T (ft^2/sec)	Storage Coefficient S
3	Pumping	Type-Curve	0.0043	8.9×10^{-5}
4	Pumping	Type-Curve	0.0042	8.4×10^{-5}
4	Recovery	Type-Curve	0.0025	7.6×10^{-5}
5	Pumping	Type-Curve	0.0043	7.9×10^{-5}
5	Recovery	Type-Curve	0.0034	8.0×10^{-5}
Average Values			0.0037	8.0×10^{-5}

* Pump tests using ETSI well O-1, Niobrara County well field.

TABLE H-6

SUMMARY OF ANALYSES OF PUMP TEST DATA
USING HANTUSH-JACOB LEAKY AQUIFER EQUATION*

Test No.	Type of Data	Method of Analyses	Transmissivity T (ft^2/sec)	Storage Coefficient S	Leakage Factor, B (ft)	Leakage Coefficient K'/b' (sec^{-1})
3	Pumping	Type-Curve	0.0017	5.7×10^{-5}	580	4.95×10^{-9}
3	Pumping	Semi-Log	0.0014	5.4×10^{-5}	540	4.80×10^{-9}
4	Pumping	Type-Curve	0.0013	4.8×10^{-5}	540	4.33×10^{-9}
4	Pumping	Semi-Log	0.0013	5.2×10^{-5}	540	4.33×10^{-9}
4	Recovery	Type-Curve	0.0013	4.7×10^{-5}	540	4.49×10^{-9}
4	Recovery	Semi-Log	0.0013	4.7×10^{-5}	540	4.33×10^{-9}
5	Pumping	Type-Curve	0.0017	5.3×10^{-5}	630	4.18×10^{-9}
5	Pumping	Semi-Log	0.0017	5.5×10^{-5}	630	4.18×10^{-9}
5	Recovery	Type-Curve	0.0015	5.0×10^{-5}	570	4.49×10^{-9}
5	Recovery	Semi-Log	0.0015	5.1×10^{-5}	590	4.33×10^{-9}
Average Values:			0.0015	5.0×10^{-5}	570	1.55×10^{-9}

* Pump tests using ETSI well O-1.

H.1.B 1978 AQUIFER TESTS

The 1978 Niobrara County aquifer tests were conducted using an abandoned oil well that was drilled through the Madison Group to the Precambrian basement. This well is located approximately 13 miles northeast of the site of the 1974 Niobrara County aquifer tests. Five tests were conducted (both constant-discharge and step-discharge) from September 12 to 20, 1978. Three conditions of these tests make analysis of the results difficult. First, during the pump tests, the discharge water temperature increased from an ambient temperature of 16°C at the start of the pumping to 48°C near the end of pumping. This resulted in the expansion of the water column in the borehole and caused water levels to rise significantly above the original static water level after pumping had stopped. Second, and most important, the drawdown during all of these tests stabilized within 24 hours after pumping started, and remained stable for the duration of the test. Third, no observation wells were available, so that test results reflect only conditions at and near the well bore. An analysis of the data (both pumping and recovery) indicated a transmissivity in the range of 0.0023 to 0.023 ft^2/sec. The storage coefficient is estimated as 10^{-4} to 10^{-5}.

H.2 GILLETTE WELL-FIELD AQUIFER TESTS

Eight Madison water wells were drilled between 1977 and 1980 north of Moorcroft in Crook County, Wyoming. These wells are to be used by the city of Gillette as a source of municipal water. All of the wells are located within Section 6 of T53N R66W. This well field has provided a unique opportunity for observing the response of the Madison aquifer to pumping. Six aquifer tests, using one or more observation wells, have been conducted to date. Similar aquifer responses have been observed during all six aquifer tests. The results of the June 1980 test, in which well CR-8 was pumped at a rate of 1.3 cfs for 6 days, is described below:

- Drawdowns in all of the wells stabilized after only a short period of pumping.

- Drawdown in proportion to discharge in the pumped well is relatively small.

- In several wells, drawdowns are greater in wells farther from the pumped well than they are in wells closer to the pumped well.

The depth of each of the five wells used in the aquifer tests and the feet of Madison penetrated in each well vary markedly. During the drilling of two of the wells, a bit drop and lost circulation of drilling fluid was reported in the top of the Madison Group. The other three wells penetrate a much thicker section of the Madison Group; in none of these wells was a bit drop or lost circulation zone encountered in the top of the Madison Group.

H.3 NEWCASTLE TESTS

Aquifer tests were conducted at Newcastle from September 1 to 2, 1977, (using city wells No. 1 and No. 3) and from October 13 and 16, 1978 (using city well No. 4). The September 1977 tests consisted of:

1. A step-discharge test using city well No. 1 as the pumping (flowing) well and city well No. 3 (2760 feet away) as the observation well

2. A constant-discharge test, again using city well No. 1 as the pumping (flowing) well, and city well No. 3 as the observation well

Analysis of the time-pressure decline and recovery data from well No. 3 indicated an aquifer transmissivity of approximately 0.09 ft^2/sec and a storage coefficient of 9×10^{-5}.

The October 1978 Newcastle aquifer tests consisted of both a step-discharge test and a constant-discharge test performed using city well No. 4 as the pumping (flowing) well. Results from the step-discharge test indicated a declining specific capacity with increasing flow (from 0.011 cfs/ft at 0.11 cfs to 0.004 cfs/ft at 1.34 cfs), while results from the constant-discharge test indicated a transmissivity of approximately 0.017 ft^2/sec. No storage coefficient was calculated because no observation well data were available.

H.4 AQUIFER TESTS AT U.S. GEOLOGICAL SURVEY TEST WELL NO. 1

Hydrologic tests at USGS test well No. 1 in Crook County, Wyoming, included a series of drill-stem tests, two open-hole flow tests, and a spinner survey.

Drill-stem test data indicated transmissivities for the Mission Canyon Member and for the combined Mission Canyon-Charles section of the Madison Group approximately 0.037 ft^2/sec and 0.005 ft^2/sec, respectively (Blankennagel 1977). Red River Formation transmissivity was estimated at approximately 0.011 ft^2/sec over a 180-foot interval on the basis of drill stem data. The spinner survey indicated that approximately 60 percent of the water discharged came from the Red River Formation.

H.5 AQUIFER PROPERTIES DETERMINED FROM MADISON PUMP TESTS

Most Madison water wells have been tested for short periods of time to observe water-level response to pumping or flow. The results of short-term pumping tests were compiled by Eisen and others (1980) and are presented as Table H-7. The specific capacity of a well being pumped is a function of both the aquifer and the construction of the well. Kelly and others (1980) have shown that Madison wells often exhibit decreasing specific capacity with increasing discharge. They conclude that at low yields the specific capacity is predominantly a function of aquifer properties and that these data can be used to estimate aquifer transmissivity. At higher yields, they conclude that well properties cause nonlinear head losses; as a result of these losses, use of the calculated specific capacity values will result in an underestimation of the true transmissivity near the well bore. Transmissivities calculated by Kelly from the specific capacity data range from less than 0.0015 ft^2/sec to over 0.3 ft^2/sec (1000 to 200,000 gpd/ft).

H.6 MODEL OF MADISON AQUIFER TEST BEHAVIOR

The most important observations related to the hydraulics of the Madison aquifer are a consistent stabilization of water levels during pumping tests and the wide range in reported transmissivities for the aquifer. The time-drawdown behavior during tests is typical of leaky aquifers that conform with the Hantush-Jacob (1955) prototype. Therefore, the most direct explanation of this behavior

TABLE H-7

CALCULATED SPECIFIC CAPACITIES
(YIELD PER UNIT DRAWDOWN AT THE INDICATED PRODUCTION RATE)
OF MADISON GROUP WELLS, EASTERN POWDER RIVER BASIN, WYOMING

Township/Range -Section (1/2, 1/4)	Date	Test Duration (hr)	Drawdown (ft)	Yield (cfs x 10^3)	Specific Capacity (cfs/ft x 10^3)	Data Source	Remarks
CROOK COUNTY							
+52/63-25 dc	—/—/71?	1	58	0.39	6.7	1	"Held for 24 hours"
		1	14	0.42	30.3	1	"Held for 30 days"
	—/—/72	24	74	0.45	6.0	2	
53/65-18 bbd	09/26/62	140 min	1	0.03	33.4	2	Step discharge and
		80 min	4	0.06	13.8	2	recovery tests
		120 min	6	0.07	11.1	2	
		110 min	9	0.08	9.1	2	
		95 min	10	0.09	8.9	2	
		12	13	0.10	7.8	2	
		16	19	0.12	6.5	2	
57/65-15 dac	10/20/76	--	--	--	4.7	4	From dst (#15)
		--	--	--	2.5	4	From dst (#16)
NIOBRARA COUNTY							
WESTON COUNTY							
44/63-26 cac	06/06/67	5	23	0.56	24.3	1	
	06/—/67	5	175	0.56	3.1	3	
45/61-20 dca	—/—/49	?	462*	3.6	7.8	1	
	unknown	?	173	1.3	7.8	3	-Static water level
		?	277	2.2	8.0	3	presumed equal to
		?	462	3.3	7.1	3	original SIP (+462 ft)
	unknown	?	127	1.3	10.5	2	-Static water level
		?	231	2.2	9.6	2	presumed equal to
		?	416	3.3	8.0	2	1962 SIP (+416 ft)

TABLE H-7 Continued

(T/R-Sec., 1/2, 1/4)		Date	Test Duration (hr)	Drawdown (ft)	Yield (cfs)	Specific Capacity (cfs/ft x 10^3)	Data Source	Remarks
45/61-21	cbd	04/--/66	72	200	1.0	5.1	3	
		09/01/66	72	141?	1.0	7.4	1	-Reported drawdown may not include SIP component
		unknown	?	60*	0.11	1.8	2	
+45/61-28	ab-	—/--/62?	3 weeks	270*	2.7	9.8	1,2	
		07/--/65	?	18	0.61	34.1	3	
45/61-29	cbb	05/20/60	8 min	462*	0.26	0.6	1	
		unknown	?	346*	0.27	0.8	2	
45/61-30	adb	07/--/60?	?	300*	1.5	4.9	2	
45/61-33	ab	04/--/64?	?	323*	0.65	2.0	1,2	"Restricted surface flow"
46/63-10	cda	08/28/79	739 min	638?	1.3	2.0	1	
46/63-15	bdc	—/--/51	?	393*	1.11	2.9	2	
		unknown	?	393*	0.42	1.1	2	
46/63-17	cbc	—/--/69	?	531*	1.8	3.3	1	"Flow through 2 inch hose"
		—/--/69?	?	647*	1.8	2.7	1,2	Different reported SIP
		08/--/73	?	427*	1.8	4.2	2	Flow may not be 1973 data
46/64-13	cca	—/--/60?	?	92*	0.07	0.7	2	Yield may not be 1960 data
+46/64-19	bdc	—/--/56?	?	80	0.62	7.8	3	Plugged, 1965
46/64-23	ccb	03/05/65	6	65	0.16	2.5	1	Swab test
		06/--/72	several weeks	293	0.69	2.5	3	
46/65-20	cdd	09/19/60	6	295?	0.95	3.1	1	
46/65-23	bad	06/--/72	2 mos	76	0.50	6.7	3	
		unknown	?	400	1.3	3.3	2	

TABLE H-7 Concluded

(T/R-Sec., 1/2, 1/4)	Date	Test Duration (hr)	Drawdown (ft)	Yield (cfs)	Specific Capacity (cfs/ft x 10^3)	Data Source	Remarks
46/66-25 dbb	04/16/62	1	30	0.79	26.3	1	
	06/--/72	4 mos	211	0.80	3.8	3	
47/60-4 aa	08/09/65	36	5?	0.02	3.6	1	
48/65-25 cbb	--/--/49	55 min	517	0.03	0.1	1	
	06/--/72	6	110	0.47	4.2	3	
48/65-35 cc-	06/--/72	5	101	0.35	3.3	3	6 hr (source 2)

Source: Eisen and others, 1980.

Data sources:

1. State Engineer's Office Permit Files.
2. USGS (Swenson et al., 1976).
3. USGS (Hodson, 1974).
4. USGS (Blankennagel et al., 1977).
5. Anderson and Kelly, 1976.

Notes:

\+ Well also completed in overlying formation.
* Flow test drawdown presumed equal to SIP.

is that it is caused by leakage into the Madison aquifer from overlying and/or underlying strata. However, analyses of test data by leaky-aquifer theory result in relatively high leakage properties that are not consistent with the geologic character of the adjacent strata. Alternative explanations generally involve a region of high transmissivity, presumably caused by geologic structures (faults) located near the well site. However, the observed stabilization cannot be reproduced without having this region acting as a perfect recharge boundary or, in other words, a source of water at a constant head. In the Gillette well field tests, where data from several observation wells are available, analysis of even the early part of the data results in effective transmissivities that increase with distance from the pumped well. This is inconsistent with results that would be expected from a nearby high-transmissivity region that acts as a perfect recharge boundary. Thus, this concept is very difficult to justify from a physical standpoint. Also, even if a fault or other structure (considered as a region of high transmissivity) were present, it must be capable of transmitting the effect of the stress to a large surface area in order to produce the observed type of stabilization. This large area of influence increases the potential for leakage to have a significant effect. Therefore, it is apparent that leakage cannot be completely ruled out as a potentially important factor.

The nature of areas of high transmissivity has been clarified somewhat by the recent drilling at the Gillette well field. At this site, two of the eight wells drilled to date are completed in a zone within the upper part of the Madison Group where bit drops and circulation losses have occurred. The most reasonable explanation of this is that well-developed zones of secondary porosity and permeability that occur in Madison outcrop areas persist in the subsurface. Other wells in this field that did not encounter well-developed zones of secondary porosity and permeability exhibit behavior during pump tests that is distinctly different from the wells completed in this high-transmissivity zone. Anomalous behavior observed during pumping tests at other sites on the western flanks of the Black Hills can be explained using these zones of high transmissivity. Evidence of well-developed zones of secondary porosity and permeability in the Madison Group have also been reported at Newcastle, Osage, and Edgemont.

Based on these observations, the hydrogeologic structure of the Madison aquifer along the western flanks of the Black Hills is described as follows. The rock comprising the bulk of the Madison Group has a moderate transmissivity on the order of about 0.004 ft^2/sec. Well-developed zones of secondary porosity and permeability within the upper part of the Madison Group creates local zones of high transmissivity ranging up to 1.5 ft^2/sec or more. These zones are randomly distributed areally, that is, they are not present everywhere; however, they are assumed to be areally continuous from the hydraulic viewpoint. The high leakage properties obtained from the analyses of pumping test data are a relative measure of the hydraulic connection between the high-transmissivity zone and the main bulk of the Madison aquifer.

H.5.A COMPUTER SIMULATION

The six-day pumping test conducted at the Gillette well field during June 1980 was numerically simulated to test the conceptual model, and to investigate the effect of changes in system parameters on aquifer response.

The numerical model was constructed to simulate (in a radial coordinate system) withdrawal from a well in an aquifer system composed of several layers of differing properties. Each layer represented all or part of a hydrogeologic unit in the conceptual model. The Madison Group was divided into two zones. Zone 1, simulated as a single layer, represented the zone of high transmissivity, and Zone 2, simulated as four layers, represented the main bulk of the Madison aquifer. The overlying Minnelusa Formation was considered as a single-layer unit, and the remaining strata above the Minnelusa Formation were also grouped together into a single layer.

Estimates of the hydrologic properties of these units were developed by examining selected parts of several aquifer tests within the Gillette well field. After some minor adjustments, the values presented in Table H-2 gave a simulated response that was reasonably similar to that observed during the recent test. These results are compared with observed drawdowns at three of the observation wells in Figure H-3. The observation wells, labeled CR-5, CR-3, and CR-1, are located 760 feet, 1560 feet, and 3640 feet, respectively, from the pumping well. A fourth well, CR-4, located at a radius of 1235 feet, is

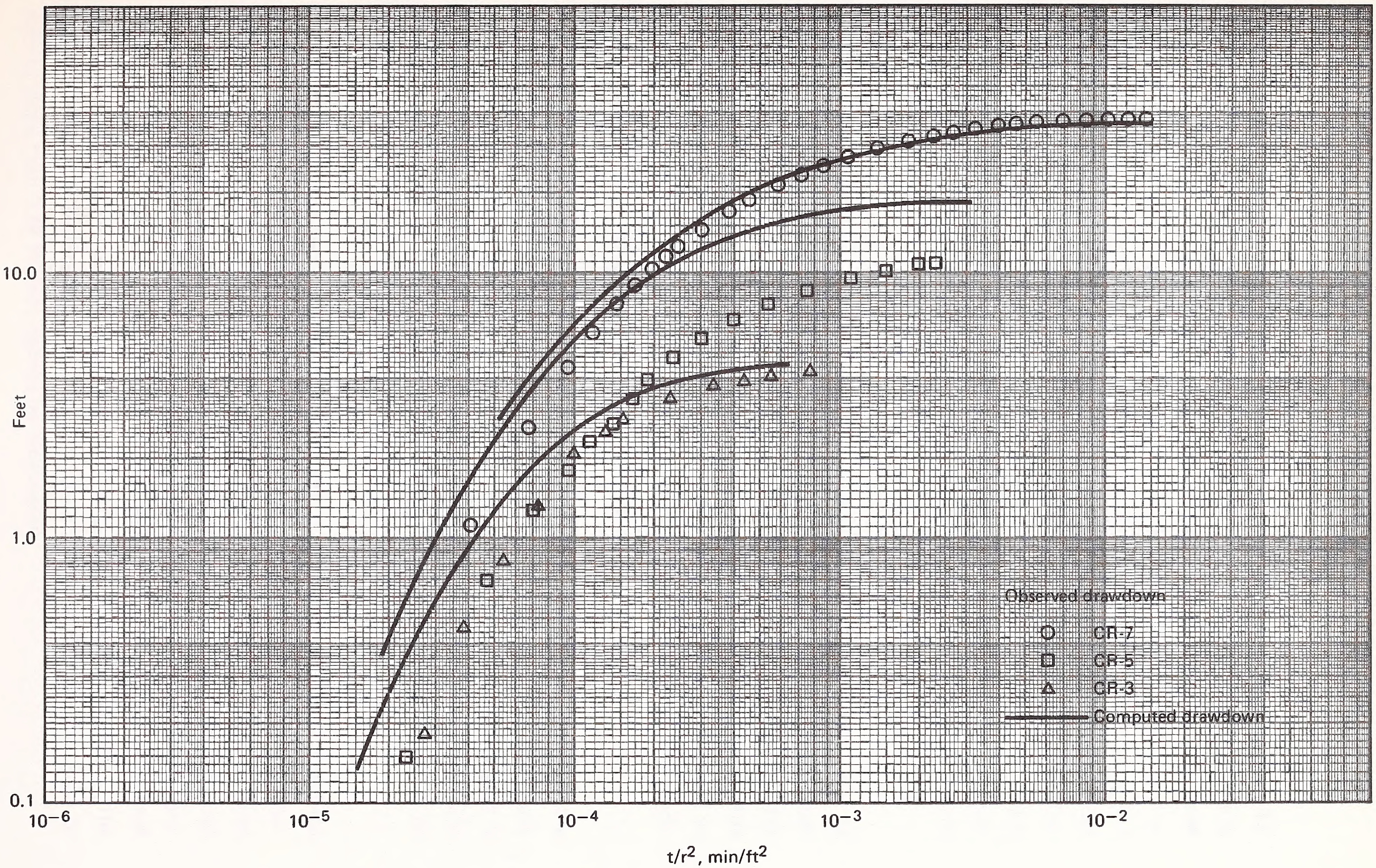


Figure H-3. COMPARISON OF COMPUTED AND OBSERVED DRAWDOWNS FOR THE GILLETTE WELL-FIELD PUMPING TEST

completed in the high-transmissivity zone and had a total drawdown of about 0.6 foot during the 6-day test. The simulated drawdown at the CR-4 location was also 0.6 foot. The simulated drawdowns at equivalent CR-5 and CR-1 locations are reasonably close to the observed values. The drawdown computed at the equivalent CR-3 location is about 8 feet more than the observed value at the end of the test. However, experiments with the numerical model have demonstrated that alternative areal distributions of the high-transmissivity zone can significantly affect computed drawdowns. Also, it is clear that the exact areal distribution cannot be determined. Thus, the relative proximity of an observation well to the actual high-transmissivity zone can easily produce the amount of deviation that exists for CR-3.

In any case, the first purpose of the simulation analysis was not to reproduce the observations exactly, but rather to test whether the conceptual model can produce the essence of the observed behavior with reasonable estimates of aquifer properties. The numerical model can reproduce the observed aquifer behavior using the values of aquifer properties presented in Table H-8. In light of the uncertainty in the areal distribution of the high-transmissivity zone, the model may not be unique.

The second purpose of the simulation analysis was to investigate the significance of several factors that are critical in terms of forecasting long-term regional aquifer response. First, tests were conducted to examine whether a high-transmissivity zone of limited areal extent could produce reasonable results. Second, tests were conducted to determine which properties could be estimated reliably from the data collected during the 6-day test.

Simulations in which the radial extent of the high-transmissivity zone was varied from about 5000 feet to over 100,000 feet concluded that this zone must extend at least 25,000 feet radially from the pumped well (that is, over an area of about 70 square miles) in order to produce reasonable results. This indicates that the randomly distributed actual high-transmissivity zone must be hydraulically continuous and extend to an even larger radial distance in order to collect the required amount of water. Hence, in forecasting the regional response of the system, effective transmissivity values for the Madison aquifer on the order of 0.03 to more than 0.08 ft^2/sec cannot be discounted.

TABLE H-8

SUMMARY OF BASIC HYDROLOGIC PROPERTIES
USED IN THE GILLETTE WELL FIELD SIMULATION

Hydrogeologic Unit	Transmissivity (ft^2/sec)	Storage Coefficient	Leakage* (sec^{-1})
Lower Cretaceous	1.5×10^{-6}	10^{-4}	
Minnelusa	0.0062	10^{-4}	10^{-11}
Madison, Zone 1	1	3×10^{-5}	10^{-9}
Madison, Zone 2	0.0078	10^{-4}	2.5×10^{-9}

*The value of leakage expresses the degree of potential vertical conduction of water between adjacent units.

In terms of estimating reliable values of the aquifer properties, the simulation analysis of the 6-day test is only partially successful. Results show that if water is produced from a well completed in the low-transmissivity zone, as was the case in this test, the high-transmissivity zone merely collects water from a number of sources and transmits it to the vicinity of the withdrawal. This is accomplished with a small hydraulic gradient because of the high-transmissivity zone. In the vicinity of the withdrawal, flow between the high-transmissivity zone and the producing well in the low-transmissivity zone occurs with a larger gradient associated with the lower-transmissivity zone. These larger drawdowns are very local, extending only a few thousand feet from the producing well. Much smaller drawdowns in the high-transmissivity zone extend over large areas, however, in order to collect the required amount of water. Thus, the observation well records in this test do not contain any information that can be used to estimate physical properties associated with the collection process of the high-transmissivity zone. The collected water will be derived from a combination of several sources. These are (1) leakage from adjacent low-transmissivity zones within the Madison Group, (2) storage within the high-transmissivity zone, (3) leakage of overlying formations such as the Minnelusa Formation, and (4) lowering of the water table in outcrop areas of the Madison Group. However, since data from this pumping test do not reveal information on how the pumped water is distributed among these possible sources, estimates of related physical properties cannot be made.

Also, estimation of the properties in the low-transmissivity zone is hindered because aquifer response characteristics deviate from the prototype behavior used to analyze them, especially at larger radial distances from the production well. This can be clearly demonstrated by analyzing the response characteristics of the simulation model, in which the properties are known a priori. Analyses based on a leaky-aquifer prototype (Hantush and Jacob 1955) indicate transmissivities for the Madison aquifer of about 0.0093, 0.012, and 0.026 ft^2/sec at the equivalent locations of CR-5, CR-3, and CR-1, respectively. However, the transmissivity of the interval open to these wells is uniformly 0.0077 ft^2/sec. Thus, at larger radii the prototype is invalid and, if used, will produce erroneous estimates of system properties.

H.5.B APPLICATION OF THE CONCEPTUAL MODEL TO OTHER MADISON AQUIFER TESTS

The two-layer system proposed in this section for Madison aquifer response to short-term pumping tests can be used to explain the pumping test at the city of Gillette well field, the results from the 1974 and 1978 Niobrara County pumping tests, and the general results from the 1976 and 1977 Newcastle pump tests. The 1974 and 1978 Niobrara County pumping tests have been described previously in this section, but a review of certain parameter estimates is instructive. When the time-drawdown curves from observation well O-1 during the 1974 Niobrara well-field tests are analyzed for leakage (using the Hantush-Jacob leaky-aquifer equation), a leakage coefficient value of 4.6×10^{-9} sec^{-1} is obtained. For a confining bed only 100 feet thick, this value would translate to a vertical hydraulic conductivity of 4.6×10^{-7} ft/sec. This latter value is large for a confining bed in general but is similar to the estimated horizontal hydraulic conductivity of 4.6×10^{-6} ft/sec of the Madison aquifer, also estimated using the Hantush-Jacob equations.

Because ETSI Niobrara County observation well O-1 is only 750 feet from the pumping well, the low transmissivity of 0.0015 ft^2/sec estimated from its time-drawdown data represents that of the massive "lower zone" of the Madison. The general drawdown at the more distant Niobrara County observation well O-5 does not support this low transmissivity for regional aquifer behavior.

The leakage coefficient of 4.6×10^{-9} sec^{-1} represents instead the effective vertical permeability of the Madison aquifer, and in particular the leakage coefficient from the upper high-transmissivity zone to the lower, massive carbonate unit.

A second major aspect was the significantly lower drawdown in the Niobrara County observation wells when compared with that predicted using parameter estimates from time-drawdown data at or near the pumping well. In particular, the drawdown in well O-5 (1500 feet north of the pumping well) was approximately 0.3 foot; this is substantially less than the 2 feet that would have been expected using parameters derived from observation well O-1 (750 feet from pumping well) time-drawdown data.

An analysis made by comparing drawdown in Niobrara County observation well T-2 using O-1 as the pumping well against that using O-1 as the observation well and T-2 as the pumping well indicates that a recharge boundary could be expected 2000 feet to the northeast of T-2 (in the direction of and 800 feet northeast of O-5). At present, no geologic evidence exists for such a recharge boundary, especially one with the required transmissivity that is several orders of magnitude larger.

The 1978 Niobrara County pump tests used only a pumping well with no observation wells and therefore could not be interpreted using the two-layer system. However, the early stabilization of drawdown that was observed tended to confirm the behavior seen at the 1974 tests 13 miles to the southeast.

Results from Newcastle pump tests were not amenable to detailed interpretation with respect to the conceptual model. However, both the performance of each well and the variation in estimated aquifer parameters at each of the closely spaced wells support certain aspects of the "dual-unit" Madison model. For example, while Newcastle wells No. 3 and No. 4 are approximately 2760 feet and 650 feet, respectively, from well No. 1, the transmissivities calculated at each varied by a factor of 5. In addition, the free flow of each well differs dramatically-from 50 gpm at well No. 3, to 500 gpm at well No. 4, to 1200 gpm at well No. 1.

The results of the Niobrara County and Newcastle tests, therefore, support the contentions that:

1. Pumping test results can be best explained with a model of the Madison aquifer with high- and low-transmissivity zones.

2. Well-developed zones of secondary porosity and permeability developed in the upper portion of the Madison Group are randomly distributed, and well yields will vary widely depending on the proximity of a Madison well to high-transmissivity zones.

H.6 CONCLUSIONS

The computer simulation of the 6-day test at the new Gillette well field and other analyses conducted on the basis of the proposed conceptual model, led to the following conclusions about the Madison aquifer on the western flanks of the Black Hills:

1. The hydraulic behavior of the Madison aquifer can be best described with a conceptual model similar to that proposed. However, because the exact areal distribution of the high-transmissivity zones is not known, regional assessments of the aquifer have to be based on models that use an effective average of the properties of the high- and low-transmissivity zones.

2. Estimates of some Madison aquifer system properties that may be important factors in a long-term regional assessment cannot be obtained from the analysis of short-term pumping tests.

3. Analysis of short-term Madison aquifer tests may produce misleading results unless it is clear that the physical system is reasonably described by the prototype model.

4. Conclusive documentation of aquifer system properties that may lead to regional assessments based on the proposed conceptual model will be available only when the effects of large-scale, long-term water production are carefuly observed.

APPENDIX I

STREAM FLOW DURATION DATA

APPENDIX I

This appendix contains flow-duration data for the following USGS stream gaging stations:

Figure No.	USGS Stream Gaging Station No.	Gaging Station Name	State	Monitoring Location No. (Figure 6-1)
I-1	06428500	Belle Fourche River at WY-SD state line	SD	SG-1
I-2	06430000	Murray Ditch at WY-SD state line	SD	SG-2
I-3	06430500	Redwater Creek at WY-SD state line	SD	SG-3
I-4	06429905	Sand Creek near Ranch A, near Beulah, WY	WY	SG-4
I-5	06431500	Spearfish Creek at Spearfish, SD	SD	SG-5
I-6	06427500	Belle Fourche River below Keyhole Reservoir	WY	SG-6
I-7	06426500	Belle Fourche River below Moorcroft, WY	WY	SG-7
I-8	06429500	Cold Springs Creek at Buckhorn, WY	WY	SG-8
I-9	06392900	Beaver Creek at Mallo Camp, near Four Corners, WY	WY	SG-9
I-10	06392950	Stockade-Beaver Creek near Newcastle, WY	WY	SG-10
I-11	06394000	Beaver Creek near Newcastle, WY	WY	SG-11
I-12	06402000	Fall River at Hot Springs, SD	SD	SG-12
I-13	06395000	Cheyenne River at Edgemont, SD	SD	SG-13

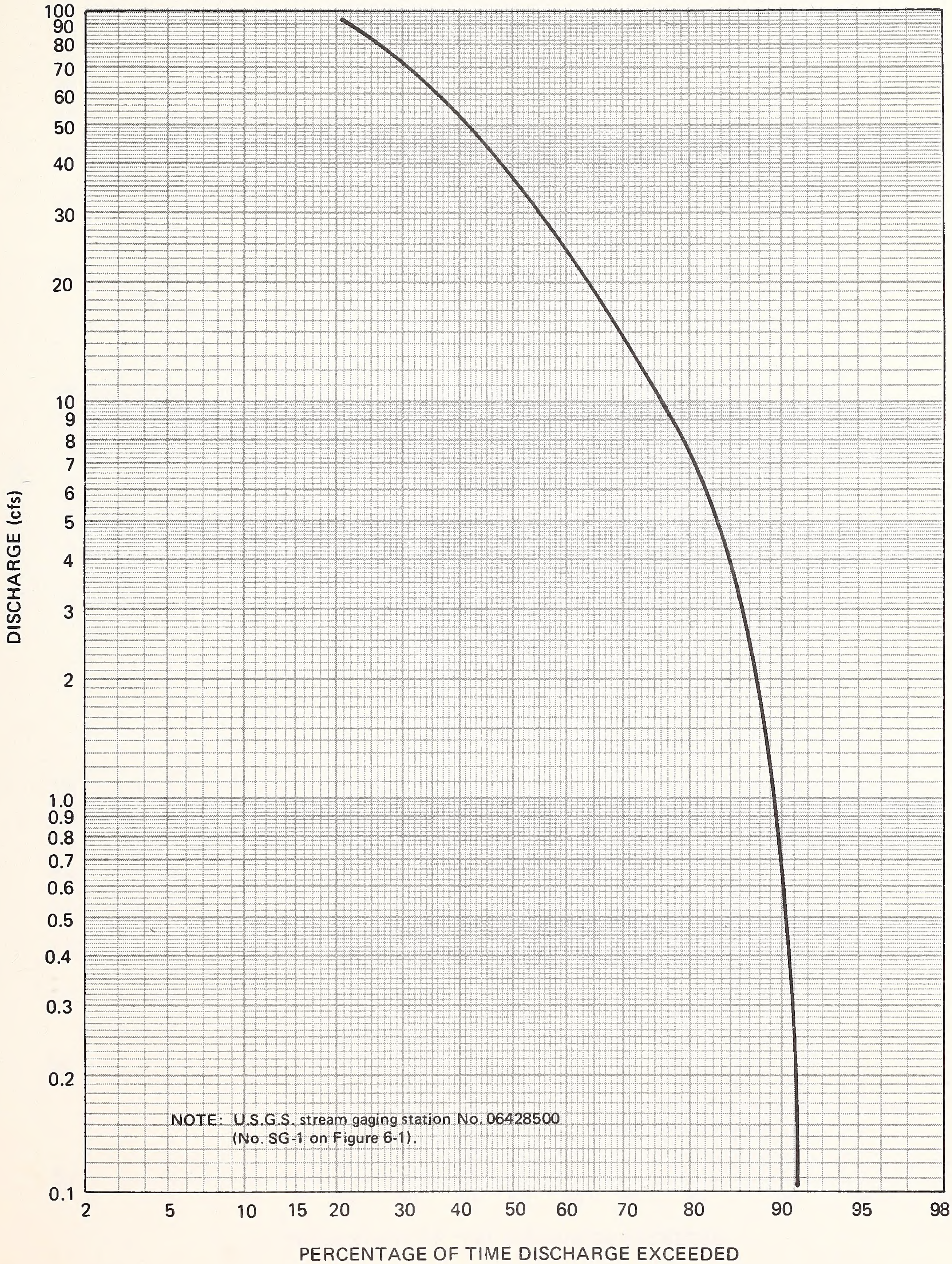


Figure I-1. BELLE FOURCHE RIVER AT WYOMING-SOUTH DAKOTA STATE LINE

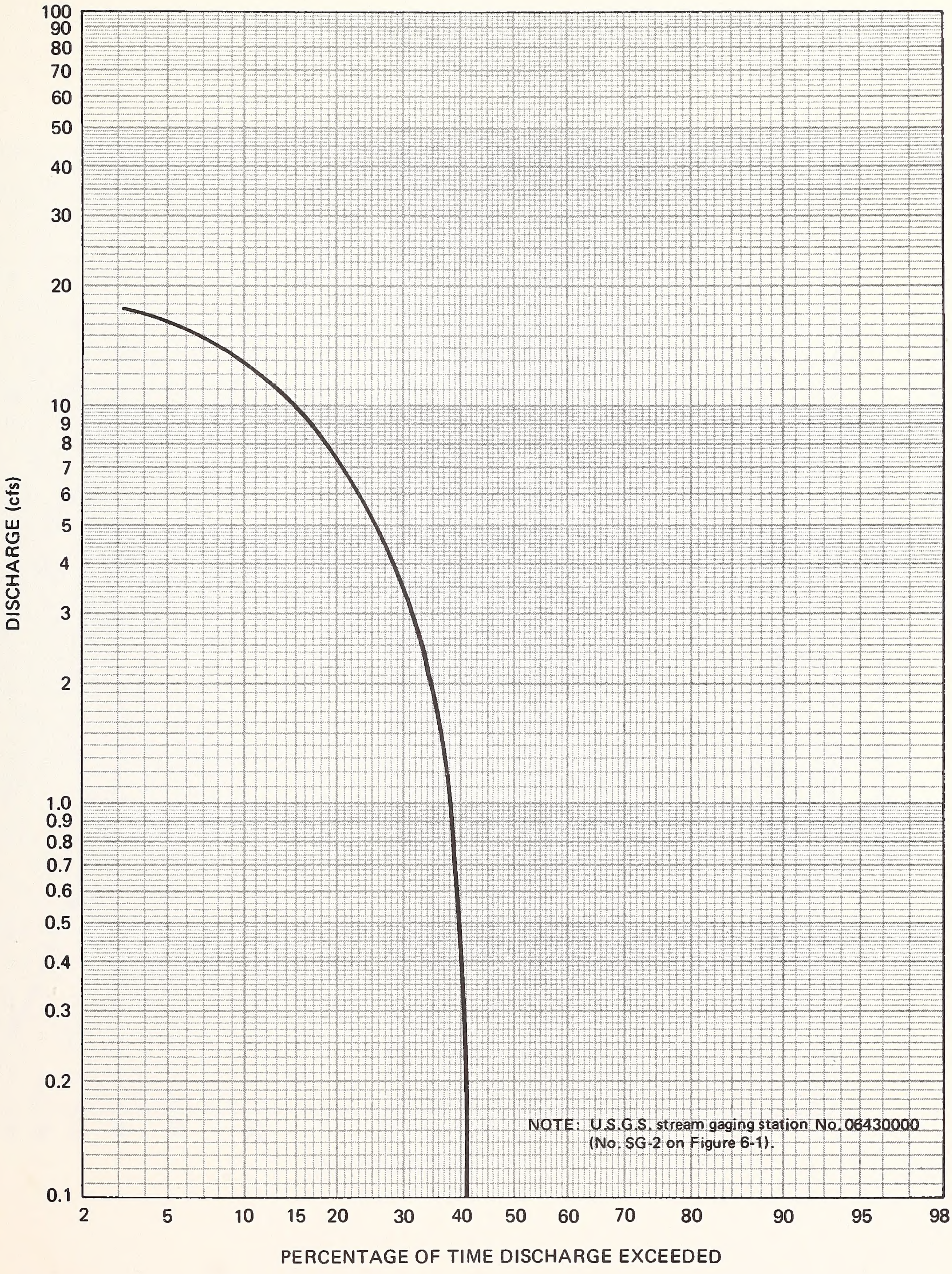


Figure I-2. MURRAY DITCH AT WYOMING-SOUTH DAKOTA STATE LINE

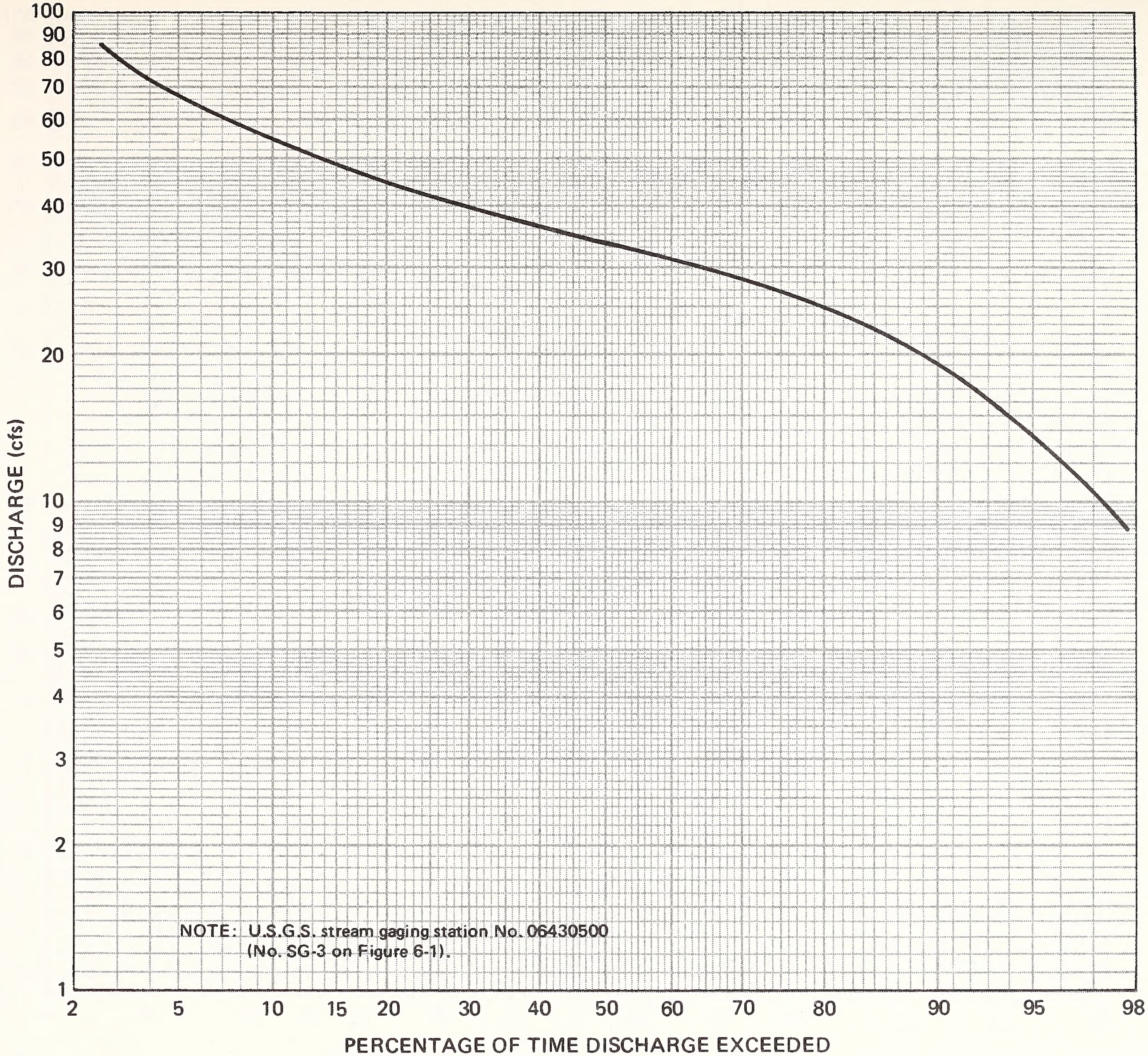


Figure I-3. REDWATER CREEK AT WYOMING-SOUTH DAKOTA STATE LINE

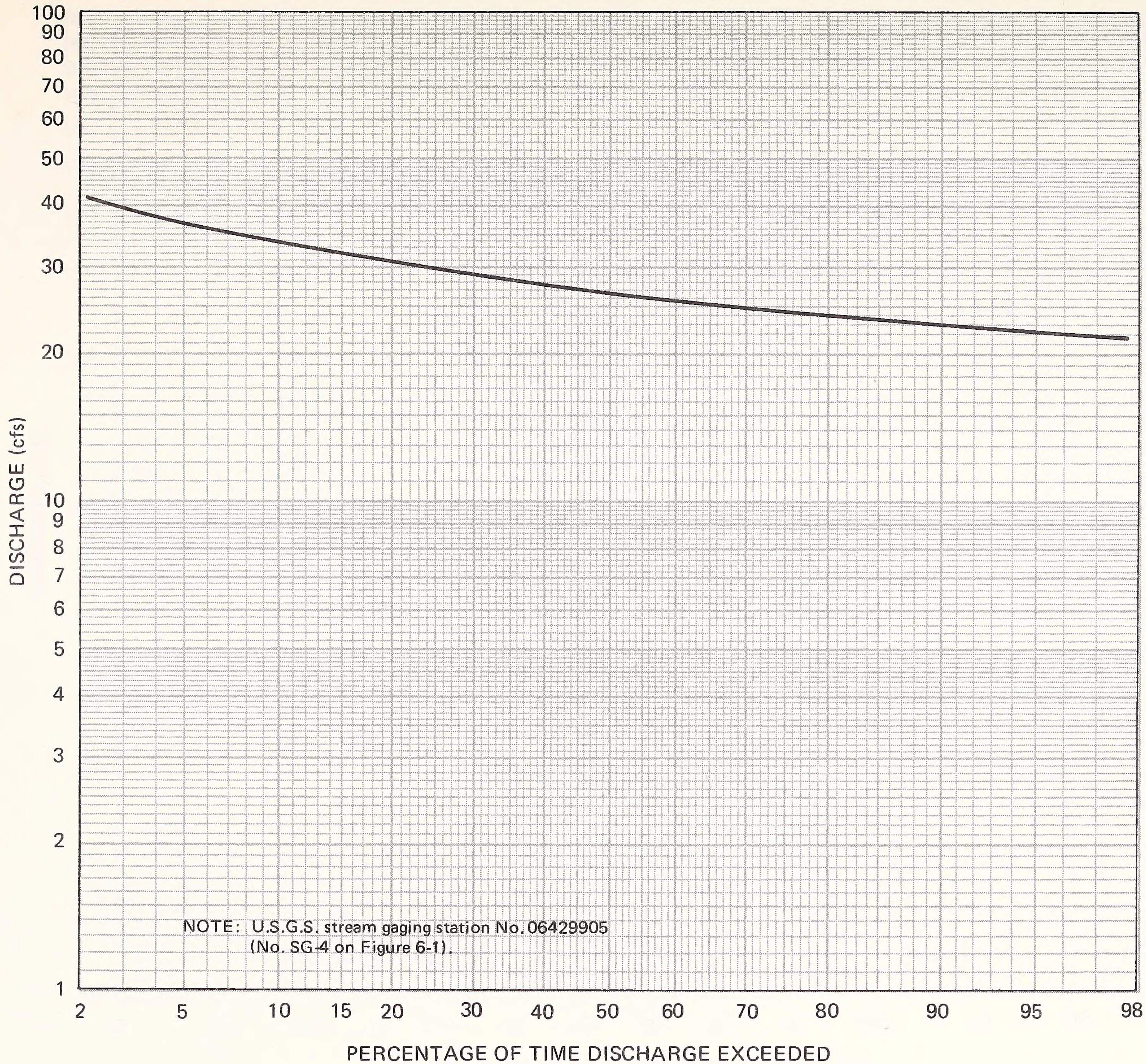


Figure I-4. SAND CREEK NEAR RANCH A, NEAR BEULAH, WYOMING

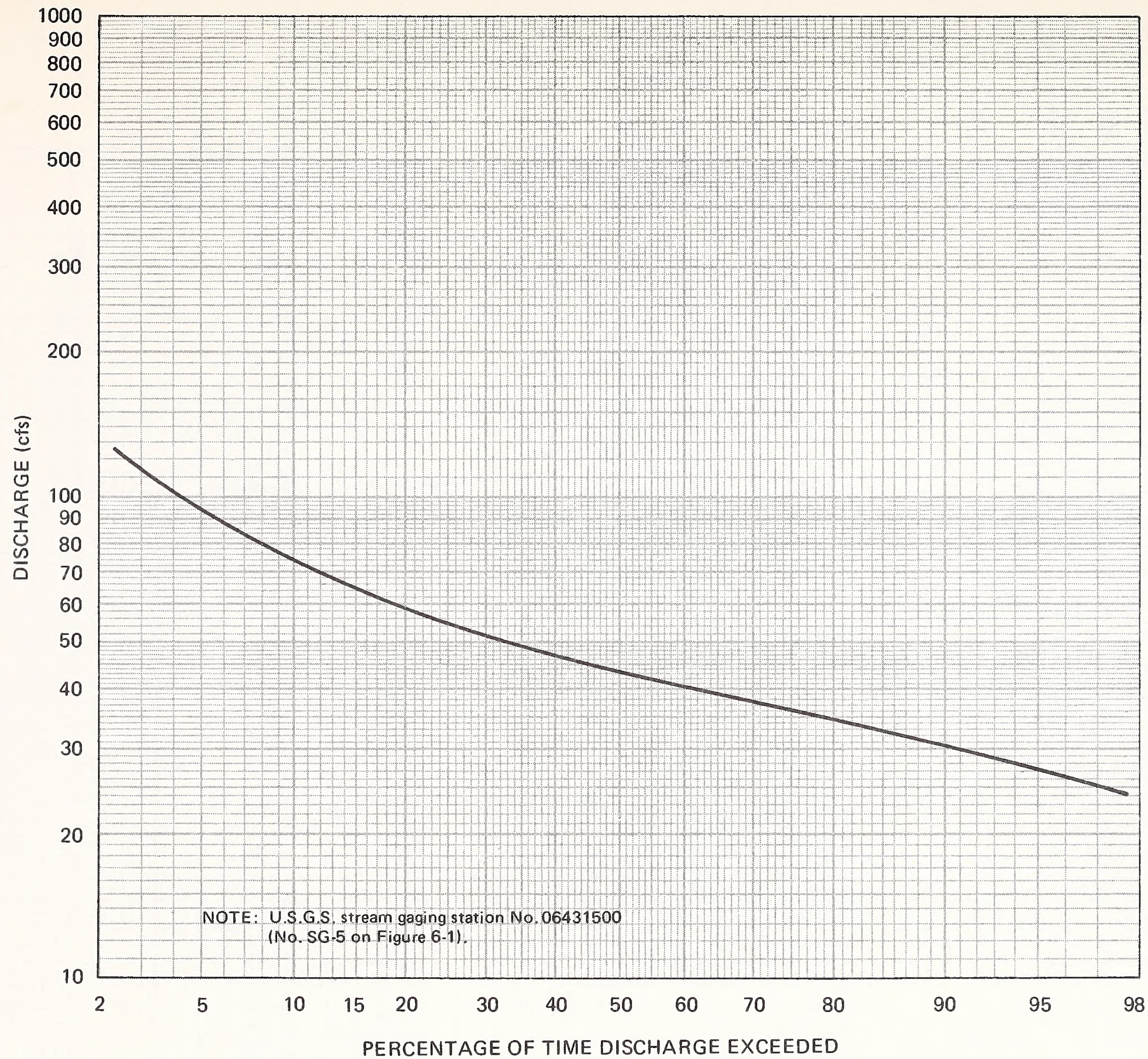


Figure I-5. SPEARFISH CREEK AT SPEARFISH, SOUTH DAKOTA

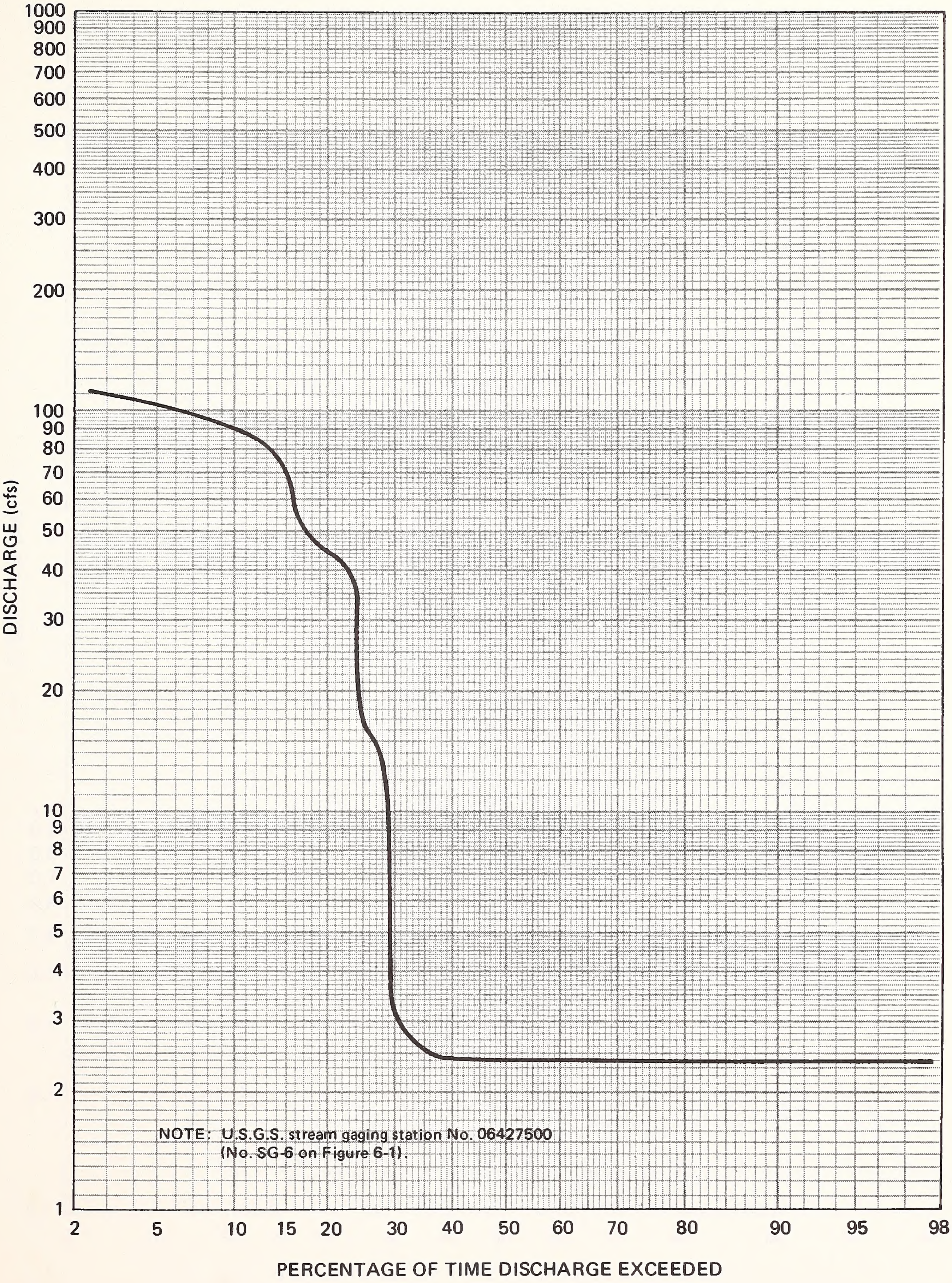


Figure I-6. BELLE FOURCHE RIVER BELOW KEYHOLE RESERVOIR, WYOMING

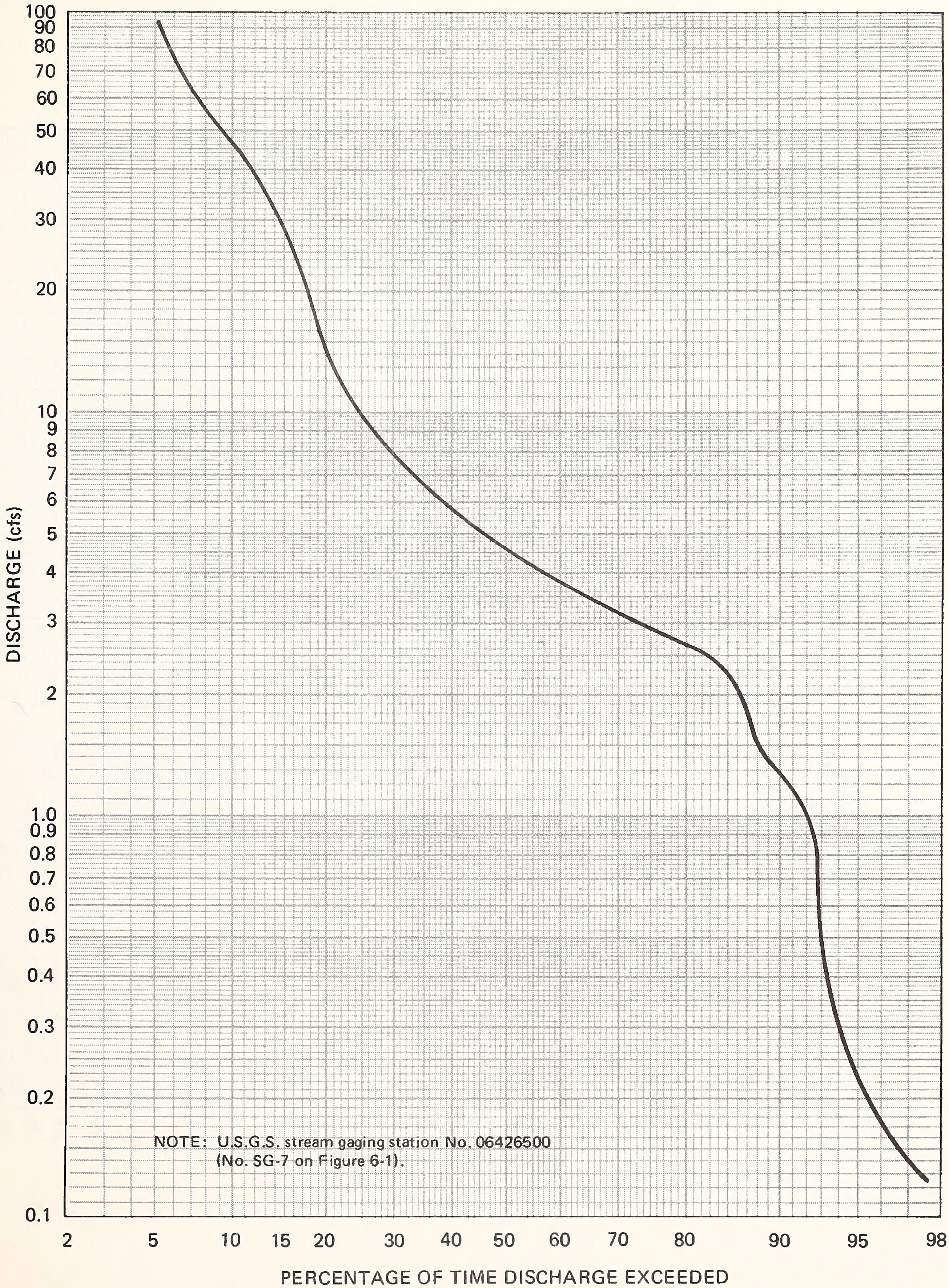


Figure I-7. BELLE FOURCHE RIVER BELOW MOORCROFT, WYOMING

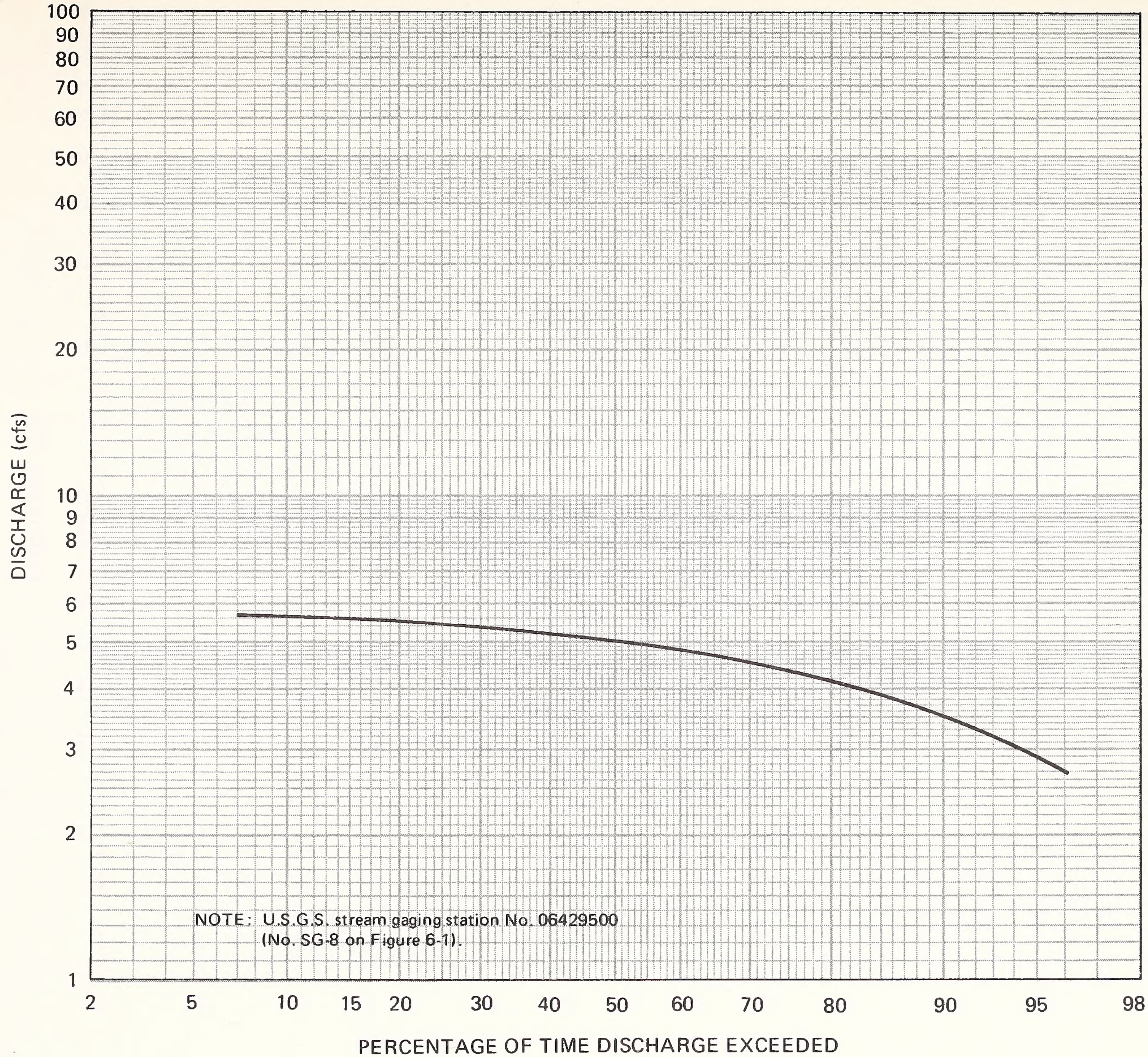


Figure I-8. COLD SPRING CREEK AT BUCKHORN, WYOMING

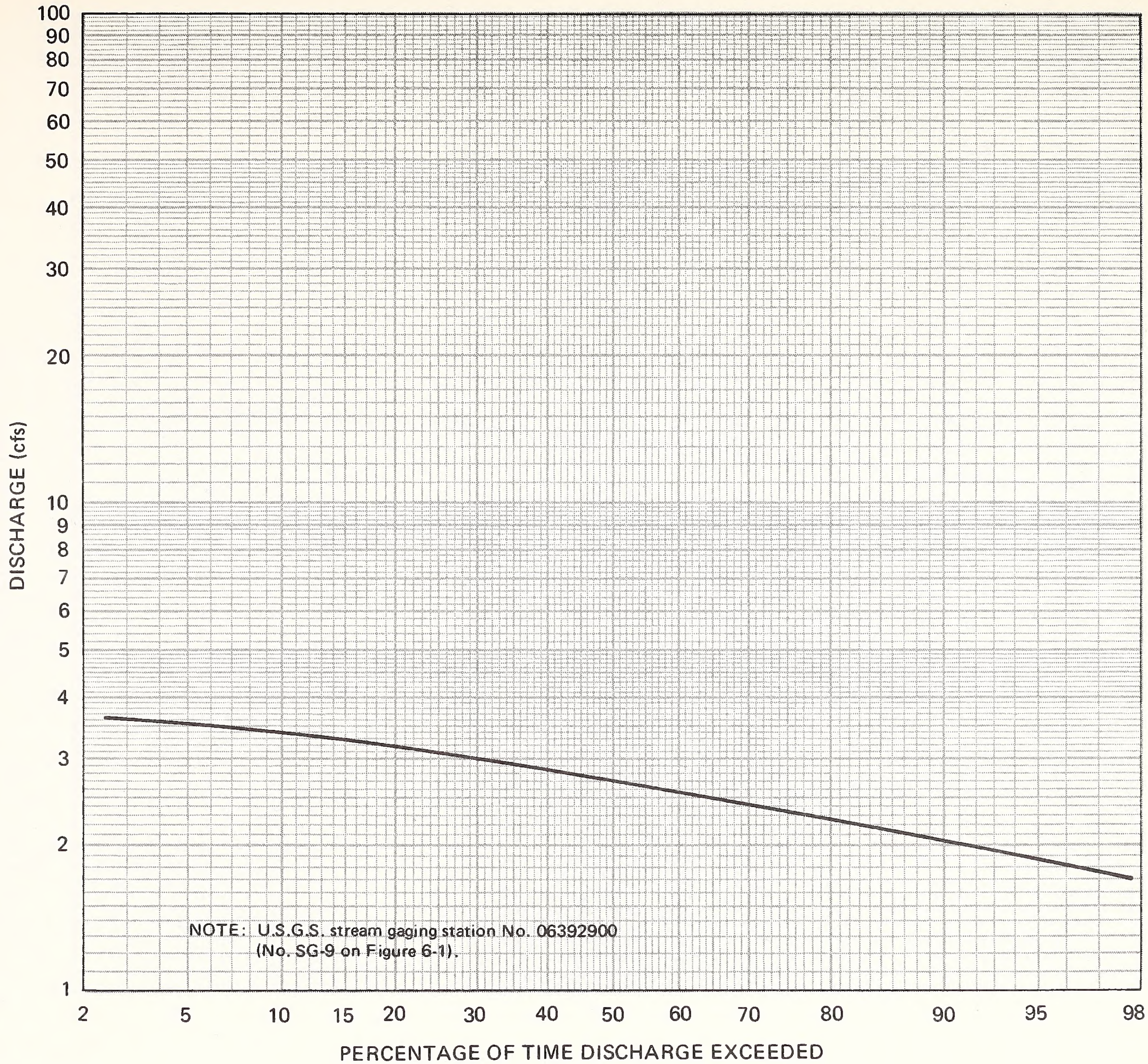


Figure I-9. BEAVER CREEK AT MALLO CAMP, NEAR FOUR CORNERS, WYOMING

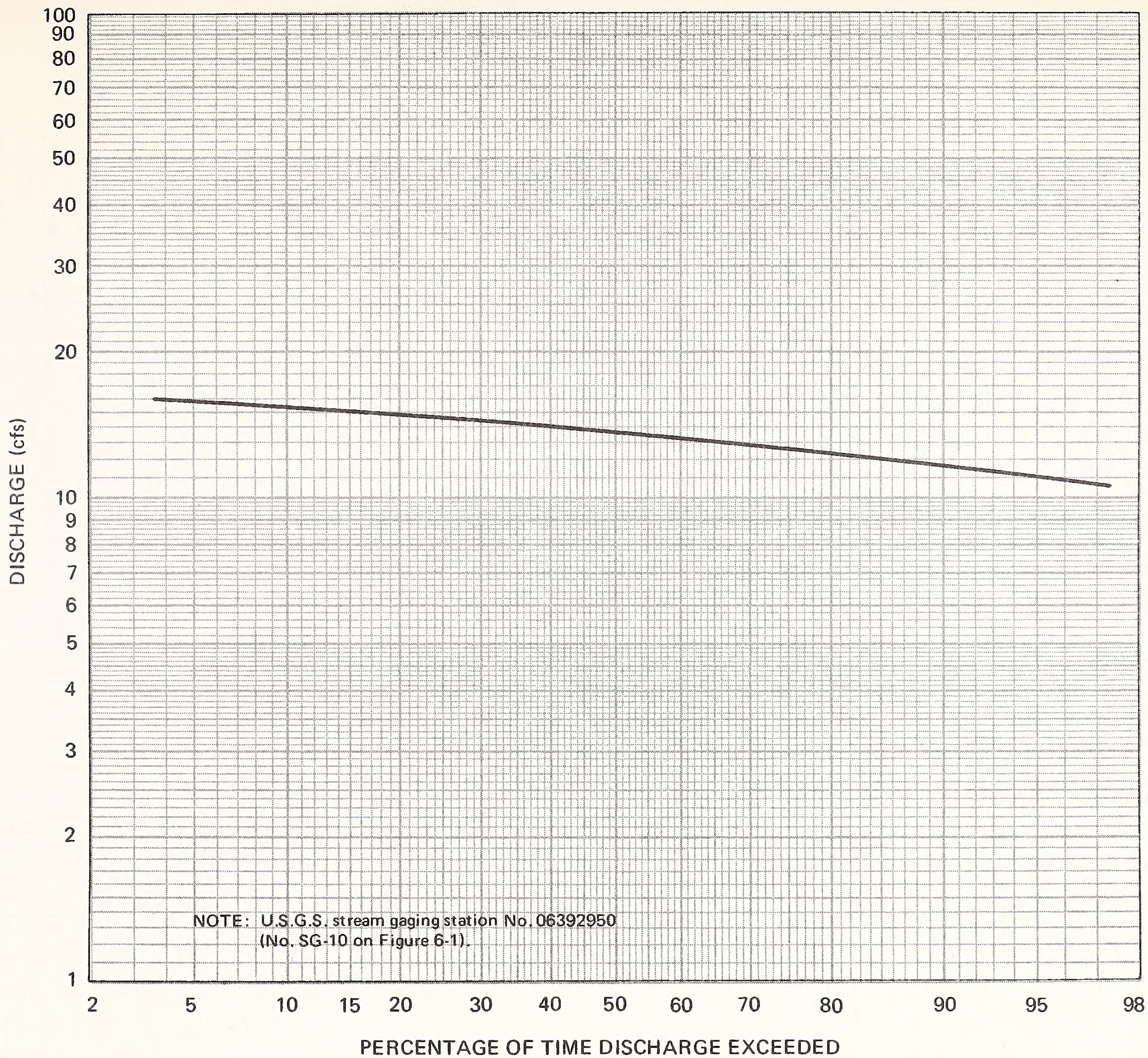


Figure I-10. STOCKADE-BEAVER CREEK NEAR NEWCASTLE, WYOMING

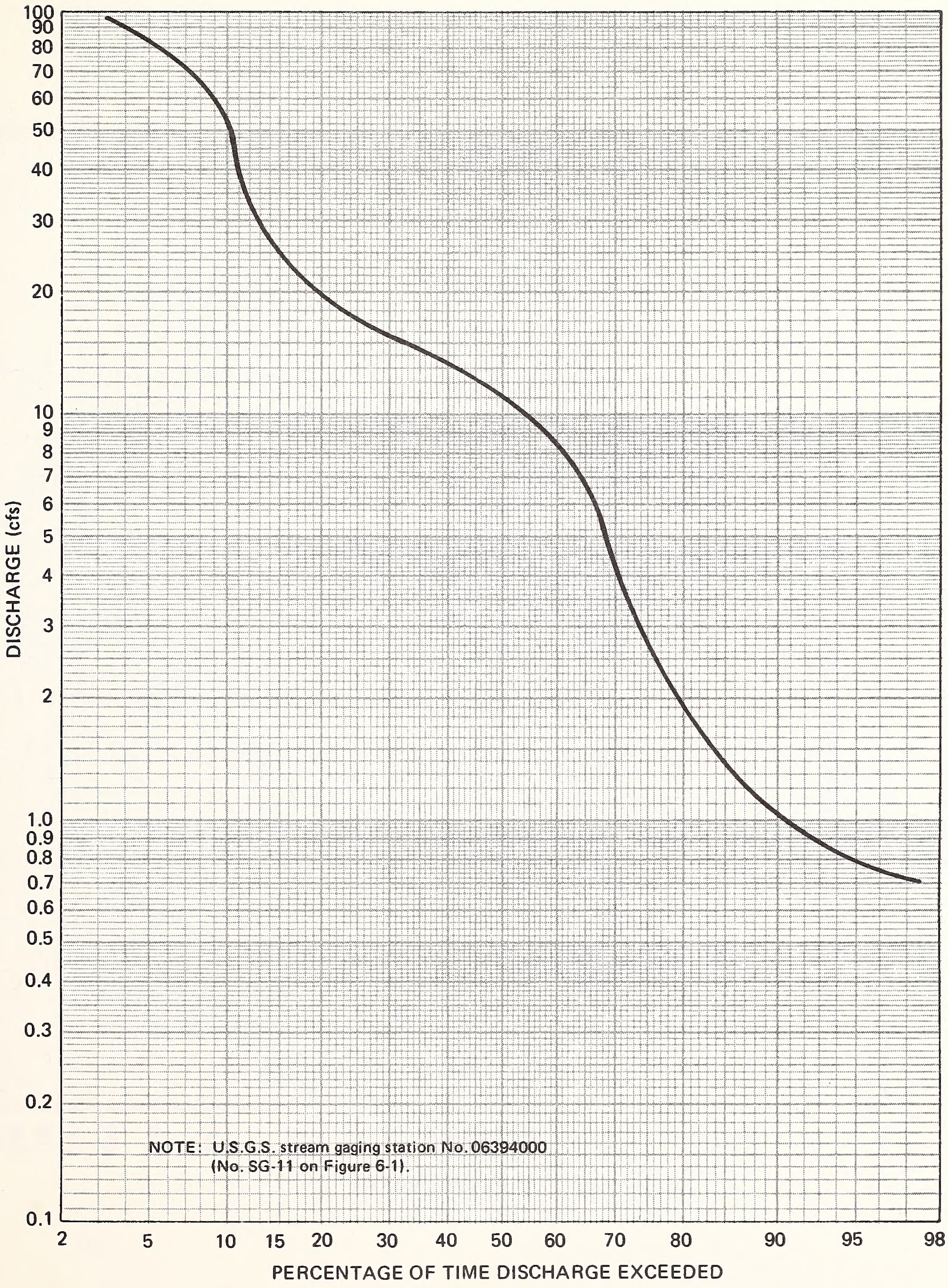


Figure I-11. BEAVER CREEK NEAR NEWCASTLE, WYOMING

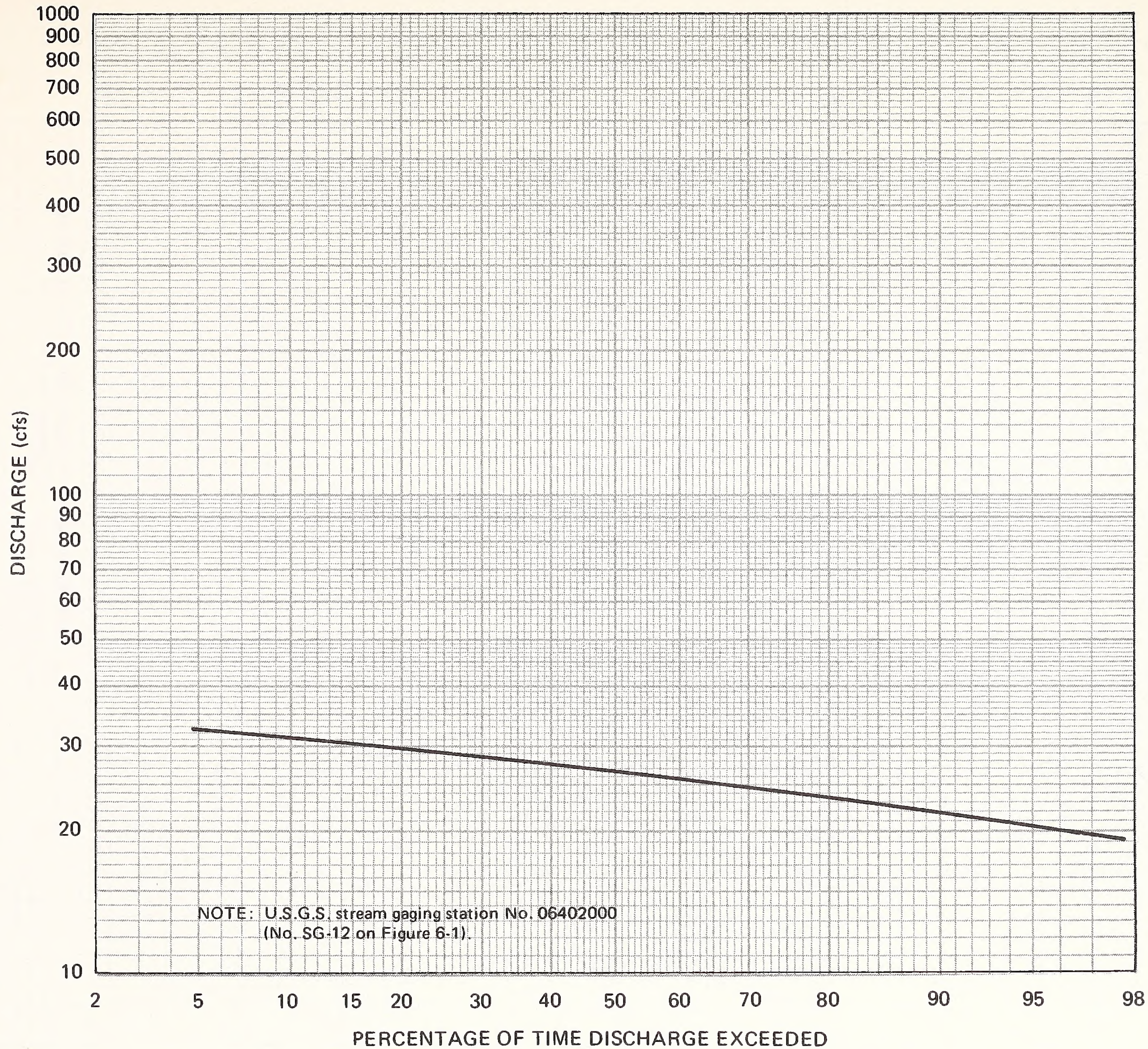


Figure I-12. FALL RIVER AT HOT SPRINGS, SOUTH DAKOTA

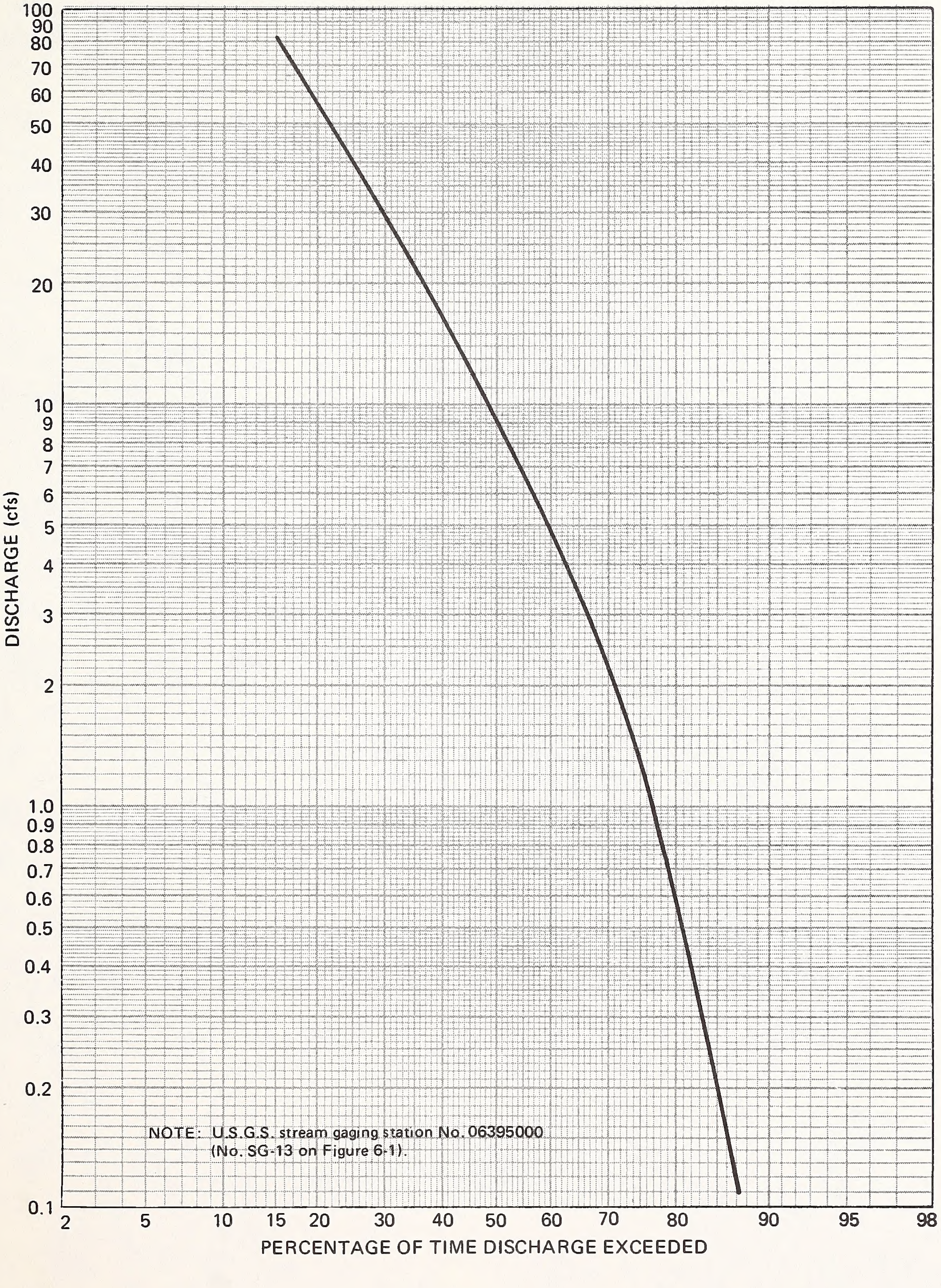


Figure I-13. CHEYENNE RIVER AT EDGEMONT, SOUTH DAKOTA