Water in Carbonate Rocks of the Madison Group in Southeastern Montana— A Preliminary Evaluation

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TABLES

FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

Multiply English units	*By*	*To obtain SI units*
	Length	
Inches (in.)	25.4	Millimetres(mm).
Feet (ft)	.3048	Metres (m).
Miles (mi)	1.609	Kilometres (km).
	Area	
Acres	4,047	Square metres (m^2).
Square miles (mi^2)	2.590	Square kilometres (km^2).
	Volume	
Gallons (gal)	3.785	Litres (1).
Cubic feet (ft^3)	.02832	Cubic metres (m^3).
Acre-feet (acre-ft)	1,233	Cubic metres (m^3).
	Velocity	
Feet per second (ft/s)	0.3048	Metres per second (m/s).
	Flow	
Gallons per minute (gal/min)	0.06309	Litres per second (l/s).
	6.309×10^{-5}	Cubic metres per second (m^3/s).
Cubic feet per second (ft^3/s).	28.32	Litres per second (1/s).
Cubic feet per minute (ft^3/min).	.4720	Litres per second (1/s).
	4.720×10^{-4}	Cubic metres per second (m^3/s).
Barrels per hour (bbl/hr)	.00416	Litres per second (l/s).
Barrels (42 gal) per day (bbl/d)	.1590	Cubic metres per day (m^3/d).
	Mass	
Ton (short)	0.9072	Tonne (t).

	Pressure	
Pounds per square inch (lb/in^2).	70.31	Grams per square centimetre (g/cm^2).
	7.569	Metres of water (m).
	.07031	Kilograms per square centimetre (kg/cm^2).
	Transmissivity	
Feet squared per day (ft^2/d).	0.0929	Metres squared per day (m^2/d).
Cubic feet per day per foot [$(ft^3/d)/ft$].	.0929	Cubic metres per day per metre [$(m^3/d)/m$].
	Hydraulic conductivity	
Feet per day (ft/d)	0.3048	Metres per day (m/d).

WATER IN CARBONATE ROCKS OF THE MADISON GROUP IN SOUTHEASTERN MONTANA—A PRELIMINARY EVALUATION

By W. R. MILLER

ABSTRACT

The Madison Group of Mississippian age comprises, from oldest to youngest, the Lodgepole and Mission Canyon Limestones and the Charles Formation. The Madison crops out in the Bighorn and Pryor Mountains and in the mountains west of the study area. These rocks consist of cyclically deposited normal-marine carbonates and restricted-marine carbonates and evaporites. The Madison ranges in thickness from about 700 feet (210 metres) in the Bighorn Mountains to about 2,000 feet (610 metres) in the Williston basin. The top of the Madison ranges in depth from land surface in the mountains to about 10,000 feet (3,000 metres) below land surface along the Montana-Wyoming border.

The potentiometric surface of water in the Madison Group slopes northeastward from the outcrops. Potentiometric lows occur in the Cat Creek anticline–Porcupine dome area along the Bighorn River and at the north end of Powder River basin. Potentiometric highs occur in outcrop areas, on the interstream divide between the Bighorn, Tongue, and Yellowstone Rivers, and along the Cedar Creek anticline. The potentiometric surface ranges from 1,200 feet (370 metres) below land surface in the topographically high areas in the southern part of the area to 1,000 feet (300 metres) above land surface along the Yellowstone River.

Yields from wells range from about 50 gallons per minute (3 litres per second) at several places to a reported 1,400 gallons per minute (88 litres per second) from a flowing well on the north side of the Porcupine dome. Yields estimated or reported from drill-stem tests range from about 1 to 157 gallons per minute (0.1 to 9.9 litres per second).

Water from the Madison generally contains less than 3,000 milligrams per litre dissolved solids south of T. 1 N., and from 3,000 to 10,000 milligrams per litre in most of the remaining area; in the Williston basin the concentration increases to more than 100,000 milligrams per litre. In the southeastern and southwestern parts of the area, calcium, magnesium, and sulfate ions constitute more than 75 percent of the dissolved constituents, in milliequivalents per litre. North of about T. 8 N., sodium, potassium, and chloride ions constitute more than 50 percent of the dissolved constituents; in the Williston basin, sodium, potassium, and chloride ions constitute more than 75 percent of the total.

INTRODUCTION

Coal development in the Powder River basin of southeastern Montana and northeastern Wyoming will place a heavy demand on the area's limited surface-water and shallow ground-water resources. Few streams in the area are perennial. Because streamflow is small during much of the year, surface water commonly is insufficient to meet present demands. Therefore, use of surface water in the area for the orderly development of coal would require surface storage during periods of high flow and accompanying distribution systems or a reduction in the present usage. Ground water has been developed for domestic and stock use from shallow coal and sandstone aquifers in the basin, but the generally low yields of these aquifers preclude use of the water for coal development.

The ability of deep aquifers to supply water for industrial use is poorly known. However, preliminary analyses of oil-test data (G. M. Murray and J. W. Nordquist, written commun., 1968) indicate that Madison Group carbonate rocks of Mississippian age, which are largely undeveloped, may be a supplemental source of industrial water for coal development.

PURPOSE AND SCOPE

This investigation of water in the Madison Group was started in 1972 by the U.S. Geological Survey in cooperation with the Montana Bureau of Mines and Geology. The purposes of the study were (1) to catalog the types and sources of readily available data, (2) to assess the availability and chemical quality of water from these data, and (3) to evaluate drill-stem tests and geophysical logs and related interpretive techniques to determine their suitability for use in a detailed geohydrologic study of the Madison Group.

Basically, this report identifies the sources and types of available data, summarizes selected geohydrological data, and briefly describes the methods and results of interpreting drill-stem tests and geophysical logs. The sources and types of available data are listed in table 1.

TABLE 1.—*Sources and types of available data*

Source	Location	Data type[1]
Federal Government		
U.S. Geological Survey:		
Conservation Division[2]	Billings, Mont.	GDI, GPI, QWI.
Geologic Division	Denver, Colo.	GM.
Water Resources Division[3]	Billings, Mont.; Denver, Colo.	GDS, GPS, GM, GW, DSTS, QWS.
U.S. Bureau of Reclamation	Billings, Mont.	GDI.

TABLE 1.—*Sources and types of available data*—Continued

Source	Location	Data type[1]
State government		
Montana Department of Natural Resources and Conservation:		
Oil and Gas Division	Billings, Mont.	GP, GD, DSTI, QWI
Water Resources Division	Helena, Mont.	GW.
Montana Bureau of Mines and Geology.	Butte, Mont.	GW, DSTI, QWI.
Private		
Oil companies and independent oilmen. [4]	Nationwide.	
Mining companies[5]	do.	
Service companies:		
American Stratigraphic Co.	Billings, Mont.	GD.
Calgon Laboratories	Casper, Wyo.	QW.
Chemical and Geological Labortories.	do.	GD, QW.
Continental Laboratories	Billings, Mont.	GD.
Core Laboratories, Inc.	Casper, Wyo.	GD.
Dowell, Inc.	do.	QW.
Dresser Atlas	do.	GP.
Halliburton, Inc.	do.	QW, DST.
Johnston Testers, Inc.	do.	DST.
Lane Wells, Inc.	do.	GD, GP.
Petroleum Information, Inc.	Billings, Mont.; Casper, Wyo.; Denver, Colo.	GD, QW, DST.[6]
Petro-Well Libraries	Billings, Mont.	GD, GP.
Rocky Mountain Well Log Service.	Casper, Wyo.	GP.
Schlumberger	Billings, Mont.	GP.
Virgs Testers	Sterling, Colo.	DST.
Yapuncich, Sanderson and Brown Laboratories.	Billings, Mont.	QW, GD.
Consulting geologists	([7])	QW, GD, GP, DST.

[1]Data types: GD, Geological data; includes all types of sample and lithologic description and logs, well histories, completion data, and laboratory analyses of cores and cuttings. GP, Geophysical logs; includes all types of borehole geophysical logs. GM, Geologic maps. GW, Groundwater data. DST, Drill-stem test data available. QW, Quality of water data; includes partial and complete chemical analyses and analyses from other data sources. I, As a suffix to any of the above symbols, indicates only incomplete data available. S, As a suffix to any of the above symbols, indicates only selected data available.
[2]Includes only data pertaining to Federal leases and Indian lands.
[3]Includes only data pertaining to completed or ongoing projects.
[4]Includes only data pertaining to prospects or fields in which company has a vested interest.
[5]Mainly coal companies who have drilled test holes in the Madison Group.
[6]Many data in form suitable for computer manipulation.
[7]Consulting geologists who have contributed data to this project are widely distributed.

Geohydrologic data and interpretations include structure, thickness, potentiometric-surface and water-quality maps; analysis of selected geophysical logs to estimate and delineate zones of porosity and permeability; analysis of drill-stem-test data for yield and transmissivity; and analysis of water-quality data.

The concepts developed during this study are useful in describing how water moves through the aquifer and suggest where and what types of additional data are needed to better understand hydrologic conditions in the aquifer.

LOCATION AND EXTENT OF AREA

The study area (fig. 1) comprises about 30,000 square miles (80,000 km^2) in southeastern Montana. It includes most of the area in Montana underlain by strippable coal deposits of the Paleocene Fort Union Formation. The main streams are the Yellowstone River and its major tributaries, the Bighorn, Tongue, and Powder Rivers.

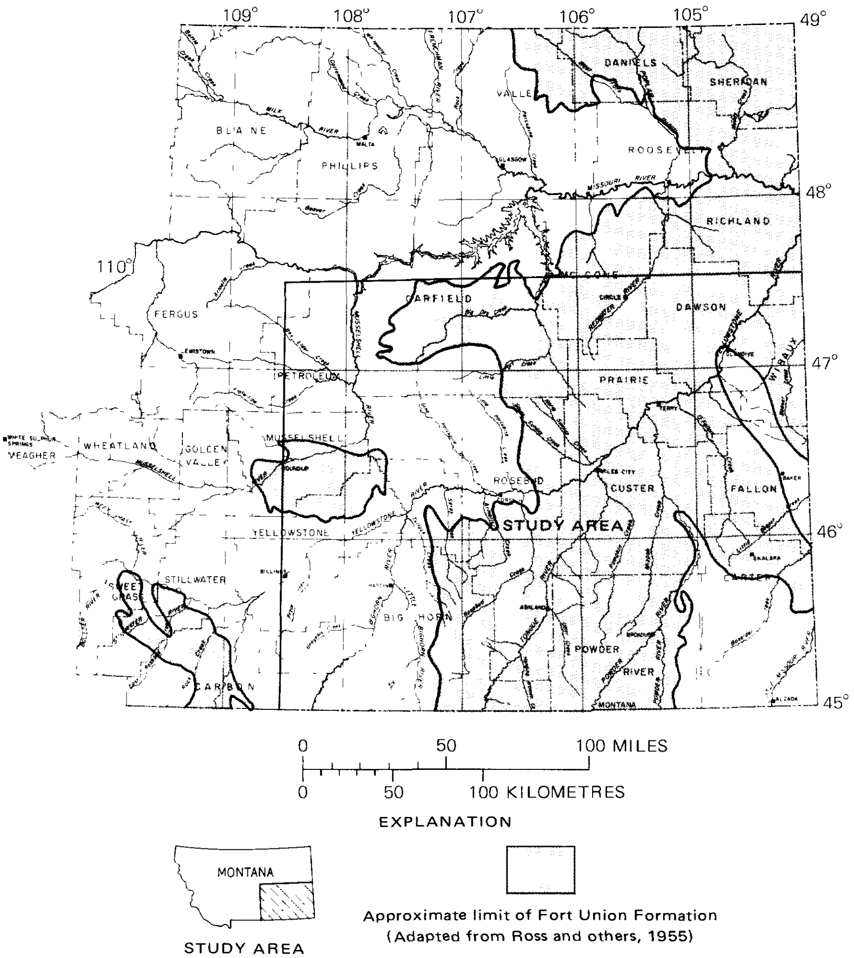


FIGURE 1.—Index map of study area.

PREVIOUS INVESTIGATIONS

Many geologic studies of the Madison Group or equivalent rocks have been made in eastern Montana and adjacent States. The major regional studies were by Sloss (1950), Nordquist (1953), Andrichuk (1955), Mickelson (1956), Beikman (1962), Sandberg (1962), Gries and Mickelson (1964), and, more recently, by Sando (1972). The reports by Nordquist (1953), Andrichuk (1955), and Gries and Mickelson (1964) are the most comprehensive and describe the lithology, stratigraphy, and depositional history of the Madison. The only hydrologic studies that discuss the Madison Group are Hodson, Pearl, and Druse (1973), Gries and Crooks (1968), Whitcomb, Morris, Gordon, and Robinove (1958), Miller (1969), and Swenson, Miller, Hodson, and Visher (1976); these were brief discussions or pertained to areas outside the study area. Crawford (1942) briefly discussed the water quality in the Madison.

LOCATION-NUMBERING SYSTEM

In this report, locations are numbered according to their geographic position within the rectangular grid system used by the Bureau of Land Management. The location number may consist of as many as 11 characters. The first three characters specify the township and its position north, N, or south, S, of the Montana base line; the next three specify the range and its position east, E, of the Montana principal meridian; the next two are the section number. The next characters identify the location within the section: the first denotes the quarter section (160-acre tract); the second, the quarter-quarter section (40-acre tract); the third, the quarter-quarter-quarter section (10-acre tract). The subdivisions of the section are designated A, B, C, and D in a counterclockwise direction beginning in the northeast quadrant. For example, well 14N55E21DBA is in the NE¼NW¼SE¼ sec. 21, T. 14 N., R. 55 E. The location-numbering system is shown in figure 2.

GEOLOGIC SETTING

EXTENT AND STRUCTURE

Carbonate rocks of the Madison Group of Mississippian age are the most widespread and thickest Paleozoic rocks in eastern Montana. Surface exposures of the Madison Group within the study area are limited to two structural features—the Bighorn and Pryor Mountain uplifts (fig. 3). However, Madison rocks are exposed in the Little Rocky Mountains northwest of the study area; in the Judith uplift, Big Snowy uplift, and Beartooth Mountains west and southwest of the study area; and in the Black Hills uplift southeast of the study area.

The structural configuration of the top of the Madison in the study area (pl. 1*D*) indicates that the Porcupine dome, Black Hills uplift, and Cedar Creek anticline are major structural highs, and that the Bull Mountains, Powder River, and Williston basins, where the Madison is

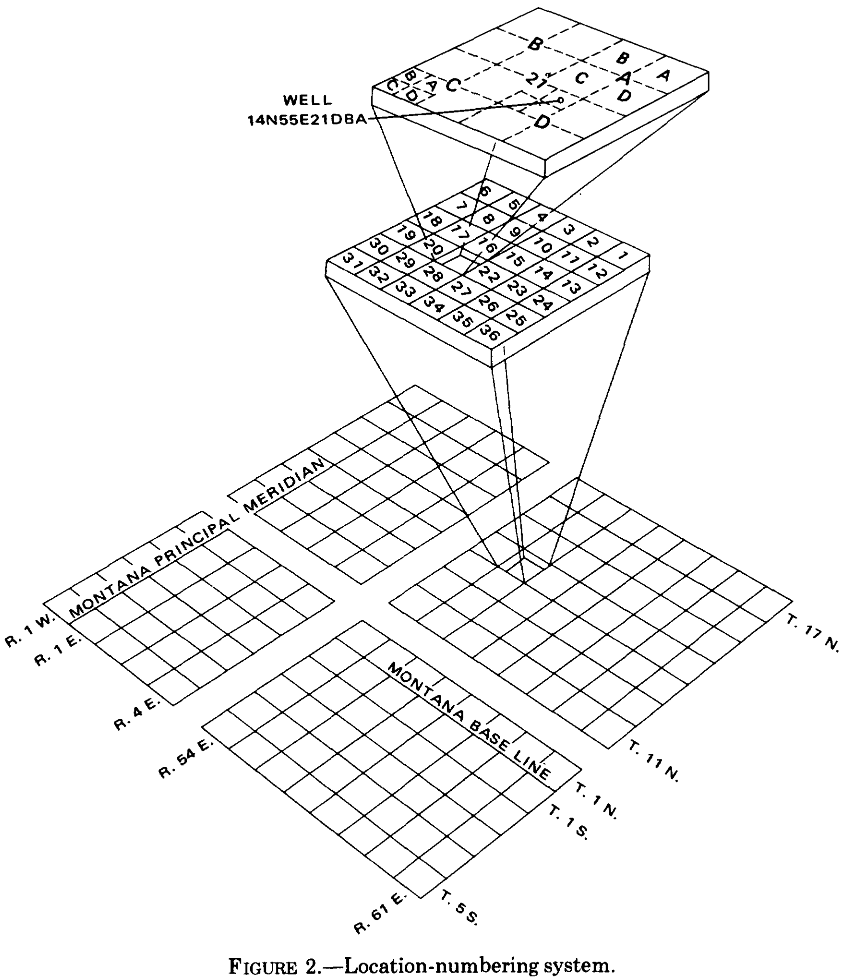


FIGURE 2.—Location-numbering system.

deeply buried, are the major lows. A series of tightly folded, locally faulted northwest-trending anticlines and synclines occur northwest of the Bull Mountains basin and Porcupine dome. The Lake Basin fault zone, a northwest-trending lineament, lies south of the Bull Mountains basin. These areas are shown diagramatically (pl. 1*D*), and the structure contours are omitted. Values of some of the data points are not shown, but the points are retained to indicate relative data density. The top of the Madison ranges in depth from land surface in outcrop areas to about 10,000 feet (3,000 m) below land surface along the Montana-Wyoming border.

STRATIGRAPHY

Devonian rocks unconformably underlie the Madison in most of the area (fig. 4), except in the southeast, where Ordovician and Silurian rocks underlie the Madison, and in the Porcupine dome area, where Cambrian and Ordovician rocks underlie the Madison. Mississippian rocks of the Big Snowy Group overlie the Madison comformably to disconformably in most of the northern part of the area, Jurassic rocks overlie the Madison unconformably in the northwestern part, and Pennsylvanian rocks overlie the Madison unconformably in the rest of the area.

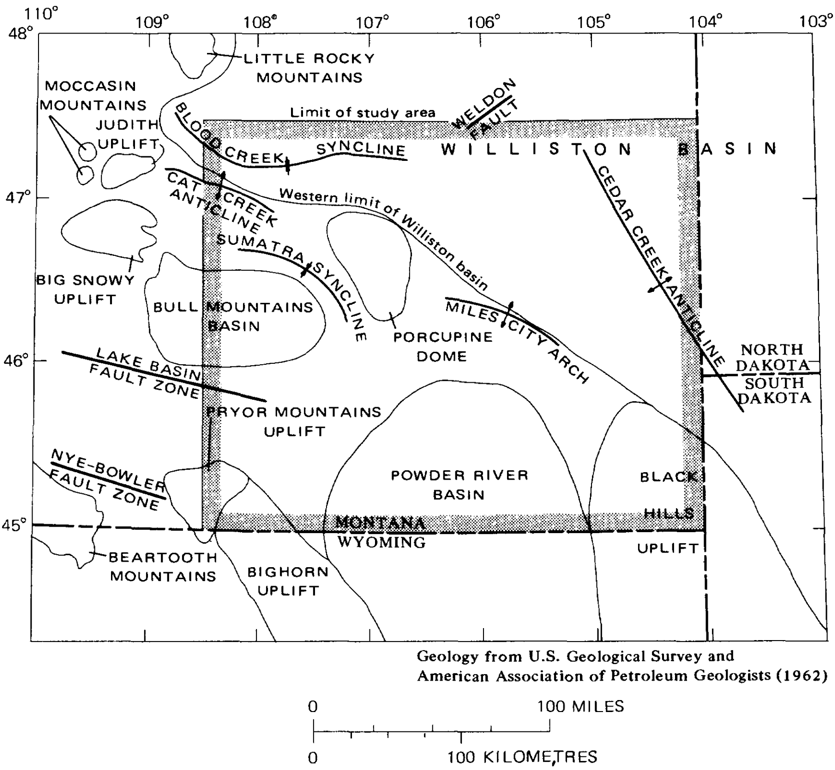


FIGURE 3.—Tectonic features of study and adjacent areas.

The Madison is about 2,000 feet (610 m) thick (pl. 2, map) in the northeast corner of the study area in the Williston basin. In central Montana the Madison is about 1,600 feet (490 m) thick. From central Montana the Madison appears to thin northward and northwestward; it also thins southward, to about 800 feet (240 m) on the Montana-Wyoming border and about 700 feet (210 m) in the Bighorn Mountains. Correlation sections (pl. 2, sections) show the thickness of the Madison and the relation of the Madison to the overlying and underlying rocks.

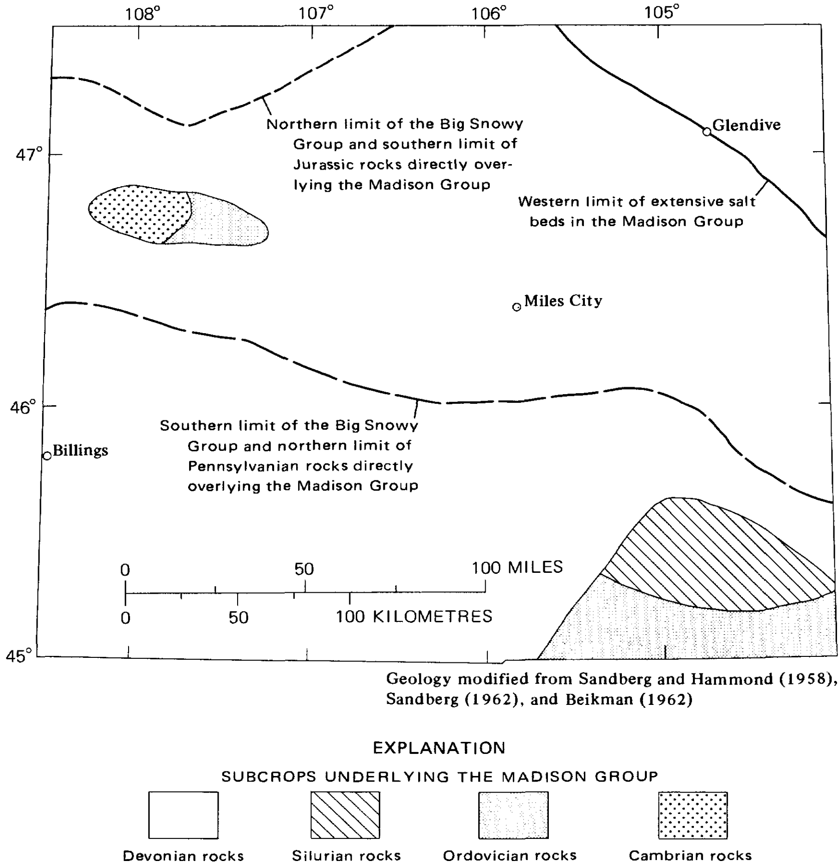


FIGURE 4.—Areal distribution of rocks that underlie and overlie the Madison Group.

Plate 2 is generalized because control is insufficient to reflect all thickness changes caused by erosion since deposition of the Madison.

The Madison Group is divided into the Lodgepole Limestone at the base, the Mission Canyon Limestone, and the Charles Formation at the top. Deposition of the Madison carbonates was mostly continuous and, according to Nordquist (1953) and Andrichuk (1955), was also cyclic, with deposition of both normal-marine (formed in open water) carbonates and restricted-marine (formed in restricted water) carbonates and evaporites. Local penecontemporaneous and later widespread postdepositional areal and subareal erosion and karstification have created solution breccias that can be mapped in the surface exposure. Although these solution breccias probably extend into the subsurface over much of the area, as evidenced by lost-circulation zones, they are difficult to detect without cores. These breccias may also contain some of the zones of higher porosity and permeability that occur today.

The description of the stratigraphy and lithology of the Madison Group in this report is condensed from Nordquist (1953) and Andrichuk (1955). The reader is referred to these reports for detailed discussions of the Madison.

The Lodgepole Limestone is mainly a thin-bedded argillaceous dense to crystalline limestone or dolomitic limestone or dolomite. Locally, it is massive and contains large reef complexes. The lodgepole is dark colored and interbedded with organic shales in the Williston basin. In central Montana the lower part is argillaceous and contains variegated shale partings, whereas the upper part is coarsely crystalline and commonly oolitic or fragmental limestone and crystalline dolomite. Southward, the Lodgepole grades to predominantly crystalline dolomite with interbedded dense to crystalline limestone. An abrupt facies change from limestone to dolomite exists in extreme southeastern Montana. Evaporites occur in the upper part but are confined to an area in Big Horn County.

Porosity and permeability in the Lodgepole Limestone are mainly associated with oolitic to fragmental limestone in the upper part and with coarsely crystalline dolomite where they occur in the lower part. Locally, fine vuggy to pinpoint porosity occurs in the rest of the Lodgepole.

The contact of the Lodgepole Limestone and the overlying Mission Canyon Limestone is gradational and arbitrarily picked as the change from thin- to thick-bedded limestone. In the subsurface the contact is difficult to correlate regionally, but locally it can be distinguished by its character on geophysical logs.

Regionally, the Mission Canyon exhibits two depositional cycles of normal-marine and restricted-marine sediments. The first, or lower, cycle is poorly developed, whereas the upper cycle is more easily recognized. The Mission Canyon Limestone is mainly a dense to crystalline thick-bedded to massive limestone or dolomitic limestone. In the Williston basin, the basal Mission Canyon consists of dark-colored partly argillaceous limestone similar to the Lodgepole in that area. Thick, widespread evaporites, including halite, overlie the basal Mission Canyon and grade upward to another section of dark dense partly argillaceous limestone overlain by evaporites. Andrichuk (1955) and Nordquist (1953) considered the upper evaporite to be the basal Charles Formation.

In central Montana, the basal Mission Canyon consists of dense to crystalline marine limestone that contains beds of coarsely crystalline, or oolitic and pisolitic, or fragmental bioclastic limestones. These grade upward to a massive evaporite section containing fine to coarsely crystalline porous dolomite and interbedded anhydrite and dolomitic limestone. A widespread anhydrite facies at the top is considered to be the basal part of the Charles Formation.

From the Big Snowy uplift south through Yellowstone County to Big Horn County, the evaporite facies, mainly anhydrite, thickens. There, the lower cycle carbonates are oolitic limestone, whereas the upper cycle carbonates are finely crystalline dolomite. From south-central to southeastern Montana, the upper cycle is a thick sequence of finely crystalline porous dolomite, and the anhydrite facies is absent.

Porosity and permeability in the Mission Canyon are highest in oolitic, pisolitic, and fragmental limestones and in coarsely crystalline dolomite. Porosity in the Mission Canyon is both primary and secondary. Locally, solution and collapse breccia occur in the outcrop of the Mission Canyon. The extent of these collapse features in the subsurface is unknown, but several drillers' logs of oil tests in the southern and western parts of the area indicate lost-circulation zones in the Mission Canyon. Irregular pinpoint or vuggy porosity occurs in the rest of the carbonate section of the Mission Canyon. Solution of anhydrite and halite has resulted in the development of porous zones in the evaporites.

The contact of the Mission Canyon Limestone and the overlying Charles Formation is arbitrarily placed at the base of a thick evaporite unit (Mickelson, 1956, p. 70). In the northern part of the area the top of the Mission Canyon is the base of a bed of dark-gray shale, informally called the Richey shale. It can be readily distinguished on geophysical logs.

The Charles Formation consists mainly of restricted-marine sediments. In the Williston basin the Charles is mainly thick anhydrite and halite beds, containing interbedded dense dolomite and limestone. In central Montana the Charles consists of evaporites at the base, grading upward to normal-marine carbonates and then to dolomite and anhydrite, interbedded with dense limestone. The normal-marine carbonates in central Montana are dense to coarsely crystalline, contain oolitic and fragmental zones, and thin eastward toward the Williston basin.

The Charles Formation thins southward into Wyoming, and is mainly dense limestone having interbeds of fine fragmental limestone and crystalline dolomite. The basal evaporite of the Charles thickens from central Montana through Yellowstone and Big Horn Counties; locally anhydrite occurs. In extreme southern and southeastern Montana the Charles is fine to coarsely crystalline dolomite containing thin beds of limestone; anhydrite and halite beds are absent.

Porosity and permeability in the Charles are highest in coarsely crystalline dolomite and in fragmental limestone. Irregular pinpoint and vuggy porosity occurs in other carbonate-rock beds in the Charles. Solution of anhydrite has created some porosity. Solution breccias with high porosity occur in the upper part.

HYDROLOGY

Water is under artesian pressure in most of the Madison aquifer. Only in the outcrops is the water under water-table, or unconfined, conditions. The beds above and below the aquifer are not perfect confining beds because water moves through them; relative to the aquifer, however, these beds have low permeability. Artesian pressure in the aquifer is great enough to cause wells to flow in most of eastern Montana, except in the topographically high areas south of the Yellowstone River.

Water occurs in several types of voids or pores in the rock. When the rock was being deposited, space was left between individual grains, resulting in voids that remain even after the formation has been deeply buried. Also, during or after deposition limestone may be changed to dolomite, a process that decreases the volume of rock and results in more void spaces. Void spaces in the aquifer may be increased by secondary processes, such as fracturing induced by folding or faulting, or by water that percolates through the formation, dissolving part of the rock. All three types of voids occur in the Madison aquifer; however, few quantitative measurements have been made of the percentage of voids, or porosity. Measurements indicating the amount of interconnection and ease with which water moves through the voids (permeability) are even more sparse.

Water enters the Madison aquifer where it crops out in the mountains (pl. 1*D*). In general, the water moves northeastward and is discharged by upward leakage in the east-central part of the study area. Through the years, recharge and discharge have equalized; withdrawals from wells are relatively small and probably have not significantly disturbed this equilibrium. Upward leakage through the confining beds must be slow because these beds have low permeability, although in some places their permeability has probably been increased by fracturing. Upward leakage may be one of the important controls on the amount of water moving through the aquifer because no more water can be transmitted through the aquifer than can leak upward through the confining beds. If upward leakage is a major control, then increased artificial discharge, such as from wells, would result in more water moving through the aquifer and would eventually increase the amount of recharge.

Most of the information describing the Madison aquifer is from test holes drilled to find oil. In most of eastern Montana, the aquifer is too deep to have been considered an economical source of water for irrigation, domestic, or stock supplies. Hydrologic information from oil-test holes consists mainly of data obtained during drill-stem tests and from geophysical logs. Both sources of data are described in the following sections and are the basis for most of the conclusions in this report.

TRANSMISSIVITY FROM DRILL-STEM TESTS

Drill-stem tests can be used to evaluate an uncased hole for potential yield, to collect samples of the fluid in the rock, and to estimate transmissivity. Examples of drill-stem-test charts are shown in figure 5. The theory and methods of analysis of drill-stem tests have been described by Griffin (no date), Murphy (1965), and Bredehoeft (1965), and the tools and procedures used in conducting drill-stem tests have been described by Lynch (1962, p. 284–325).

In drill-stem tests, packers, valves, pressure-recording devices, and a section of perforated pipe attached to the drill string are used to isolate selected stratigraphic intervals. Fluid from the formation flows into the drill stem through a tester valve, which generally is located between the packers, thereby permitting the type, amount, and pressure of the contained fluid to be determined.

The result of a typical drill-stem test is shown in figure 5*A* for the Mission Canyon Limestone. The drill-stem test can be divided into several parts:

1. Segment *AB* represents lowering the drill string into the hole. The irregular stepwise appearance of the curve is caused by the addition of joints of pipe to the drill string. The pressure measured is the pressure of the column of drilling fluid in the drill hole.
2. When the perforated pipe section is in place, the packers are expanded to isolate the selected interval and the pressure-recording devices from the column of drilling fluid in the hole. The pressure-recording device is inside the pipe and can be below, between, or above the packers, sometimes at all three places. The tester valve is opened (point *B*) and the pressure on the fluid in the formation and on the pressure-recording device is reduced essentially to atmospheric conditions (point *C*). The tester valve is left open for a few minutes, thus allowing fluid from the formation to flow into the drill string (segment *CD*).
3. The shut-in valve is closed and theoretically the formation pressure increases (segment *DE*) asymptotically to the undisturbed formation pressure. The initial shut-in period (segment *DE*) normally ranges from 15 to 60 minutes.
4. The shut-in valve is reopened, and if the packers completely isolated the interval, the pressure returns to the same value (point *F*) as recorded at the end of the initial-flow period. Fluid from the formation flows into the drill string for a period of time, normally 30 to 120 minutes, and the pressure on the pressure-recording device increases (segment *FG*) as the drill string fills.
5. The shut-in valve is closed for a final shut-in period (segment *GH*) and the pressure again recovers toward the undisturbed formation pressure. The final shut-in period usually ranges from "equal to" to "twice as long as" the final production period.

6. After recovery is complete, the packers are retracted, and the drill pipe is removed from the hole (segment *HJ*). As the drill pipe is removed the types and amounts of fluids recovered are recorded; a sample of the fluid can be collected for chemical analysis.

Curves recorded during drill-stem tests are of different shapes, depending on the permeability and yield of the tested zones. For example, the pressure-buildup segments of figures 5*A* and 5*B* (segments corresponding to *DE* and *GH* of fig. 5*A*) are L-shaped, which indicates high permeability. The pressure buildup segments of figure 5*A* are slightly more L-shaped than those of figure 5*B*, but the higher pressure reached at the end of the flow periods (segments corresponding to *KL* and *MN* of fig. 5*B*) indicates that the zone tested in figure 5*B* produced more fluid than that in figure 5*A*. The pressure buildup segment of figure 5*C* (segment *PQ*) exhibits a larger radius of curvature and is indicative of moderate permeability. The flow-period curve (segment *OP*), however, indicates that much fluid was recovered. Zones having low or poor permeability exhibit pressure-buildup curves having a large radius of curvature (segments *ST* and *VW*) as shown by figure 5*D*. The flow-period curves in figure 5*D* (segments *RS* and *UV*) indicate that a small amount of fluid was produced during the test.

Drill-stem test data are analyzed according to the basic equation by Horner (1951):

$$p_w = p_0 - \frac{2.30 q \mu}{4 \pi k h} \log \frac{t_0 + \Delta t}{\Delta t}, \tag{1}$$

where

p_w = pressure at the well bore at any time,
p_0 = undisturbed formation pressure,
q = production rate or recovery during the test,
μ = dynamic viscosity of the fluid,
k = intrinsic permeability of the producing formation,
h = thickness of tested interval,
t_0 = time of production, and
Δt = elapsed time since end of production period or flow period.

According to Bredehoeft (1965) equation 1 can be simplified as

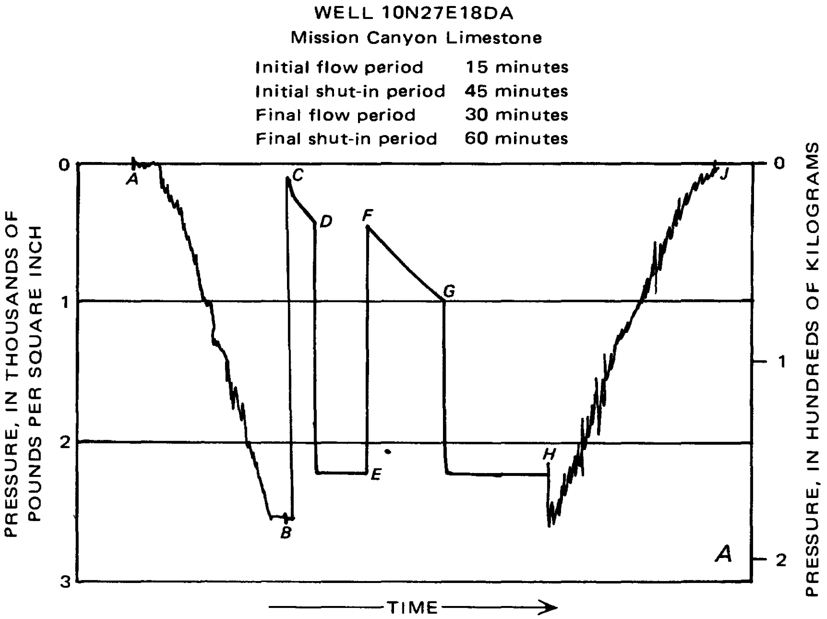
$$\frac{kh}{\mu} = \frac{2.30 q_a}{4 \pi \Delta p}, \tag{2}$$

where

q_a = average production rate during the drill-stem test, and
Δp = pressure change per one log cycle of time.

But, from Todd (1959, p. 52),

$$k = \frac{\mu K}{\gamma},$$



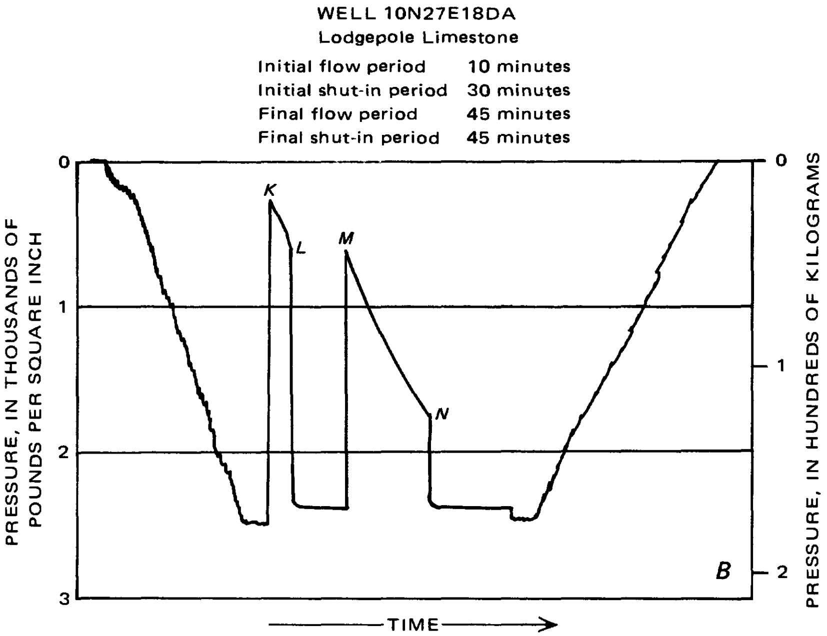
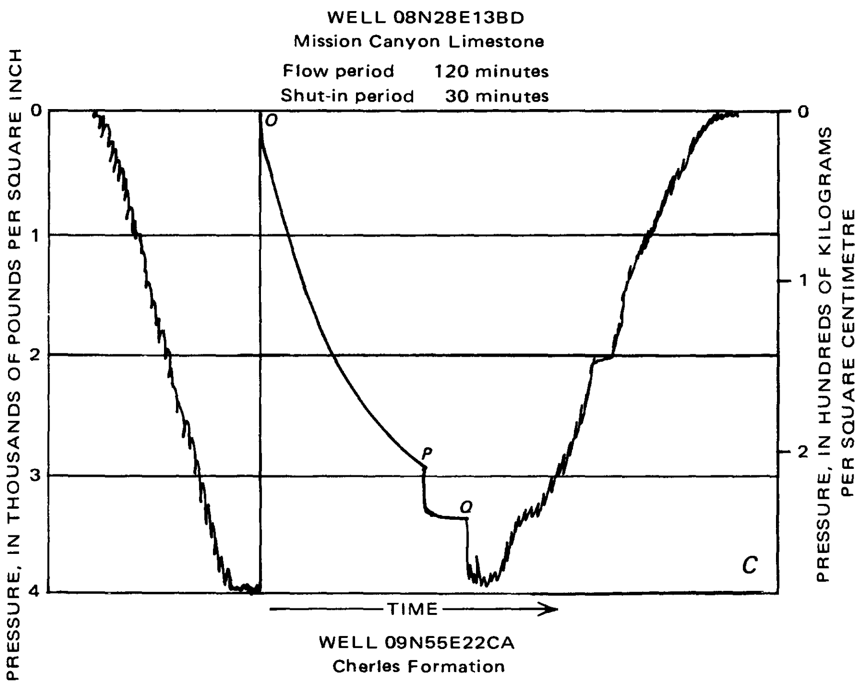
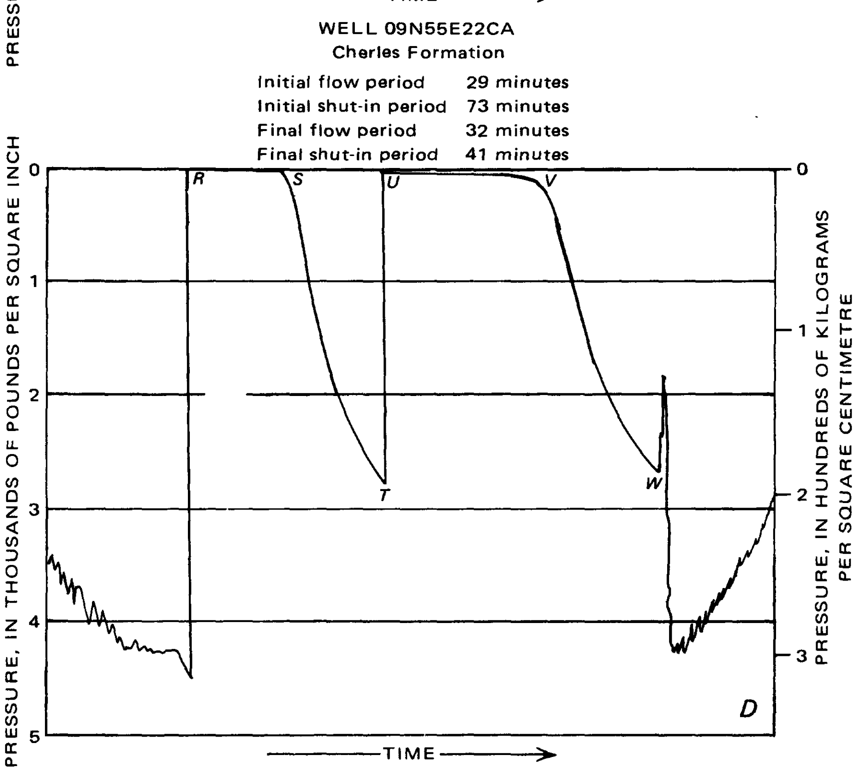


FIGURE 5 (above and right).—Selected drill-stem-test curves of the Madison Group.


WELL 08N28E13BD
Mission Canyon Limestone
Flow period 120 minutes
Shut-in period 30 minutes
PRESSURE, IN THOUSANDS OF POUNDS PER SQUARE INCH
0
1
2
3
4
PRESSURE, IN HUNDREDS OF KILOGRAMS PER SQUARE CENTIMETRE
0
1
2
O
P
Q
C
TIME


WELL 09N55E22CA
Cherles Formation
Initial flow period 29 minutes
Initial shut-in period 73 minutes
Final flow period 32 minutes
Final shut-in period 41 minutes
PRESSURE, IN THOUSANDS OF POUNDS PER SQUARE INCH
0
1
2
3
4
5
PRESSURE, IN HUNDREDS OF KILOGRAMS PER SQUARE CENTIMETRE
0
1
2
3
R
S
U
V
T
W
D
TIME

where

K = hydraulic conductivity, and

γ = specific weight of water per unit area.

Therefore, equation 2 reduces to:

$$\frac{Kh}{\gamma}=\frac{0.183q_a}{\Delta p}, \qquad (3)$$

Because the specific weight of pure water is unity at 4°C, and because errors in calculating Kh for water temperature less than 45°C, and dissolved-solids concentrations less than 10,000 mg/l (milligrams per litre) will be less than 1 percent, the left side of equation 3 is approximately equal to the transmissivity. Therefore, equation 3 can be rewritten as

$$T \doteq 114\frac{q_a}{\Delta p}, \qquad (4)$$

where

T = transmissivity, in cubic feet per day per foot,

q_a = average production rate, in cubic feet per minute, and

Δp = pressure change, in pounds per square inch per log cycle of time.

Equation 4 can also be written in metric units as

$$T=0.00183\frac{q_a}{\Delta p}, \qquad (5)$$

where

T = transmissivity, in cubic metres per day per metre,

q_a = average production rate, in cubic metres per second, and

Δp = pressure change, in kilograms per square centimetre per log cycle of time.

Transmissivity of the Madison Group was estimated from drill-stem-test data and equation 4. Most of the drill-stem tests of exploratory test holes in the study area are listed in table 2. Selected yield and recovery data from drill-stem tests are listed in table 3. Transmissivities estimated from drill-stem tests are summarized in table 4.

The transmissivities of the Madison, estimated from drill-stem tests (table 4), are apparently low for an aquifer that yields more than 1,000 gal/min (63 l/s) to at least a few wells. (See section entitled, "Availability of Water.") Several conditions may cause this. For example, the Madison is not an isotropic homogeneous aquifer, and drill-stem tests are made on relatively thin zones believed to contain oil. The production period of the test is generally of short duration, and the drilling fluid might inhibit recovery of fluid from the tested interval by partly plugging the aquifer. Also, the estimated transmissivities might represent a thinner zone of the aquifer than is indicated by the tested interval because (1) the length of the perforated part of the drill-stem-test tool is generally small compared to the tested thickness; (2) perforations are of small diameter and are limited in number; and (3) fluid might be produced only from the parts of the aquifer adjacent to the perforations, owing to physical characteristics of the drilling fluid. The drilling fluid might impede vertical movement of fluid in the annular space within the tested interval. Even though the preceding factors could have an adverse effect on the validity of transmissivities estimated from drill-stem tests, the tests cannot be ignored as sources of permeability data, especially where other data are not available.

POTENTIOMETRIC SURFACE AND MOVEMENT OF WATER

Contours on the potentiometric surface for the Madison Group (pl. 1*A*) are based on data from drill-stem tests and from production and observation wells. The contours near the Bighorn Mountains, a major recharge area, have been extrapolated from altitudes of streams where they cross the outcrops. The data range in age from 1946 to 1974. The early drill-stem-test data are of dubious quality because shut-in pressures were reported without reference to depth of the pressure-recording device, length of shut-in time, or whether recovery had reached equilibrium. Later data are of better quality and reflect undisturbed formation pressures. Some pressures have been computed directly from the drill-stem-test charts.

Plate 1*A* is a pressure-head map of the aquifer, assuming that it contains a single homogeneous fluid. The altitude of the pressure head is determined from the shut-in pressures from the following equation modified from Murphy (1965, p. 15):

$$h = (FSIP \times C) - PRD + LSD, \qquad (6)$$

where h is the altitude of the water surface, in feet above mean sea level; $FSIP$ is the final bottom-hole shut-in pressure in pounds per square inch, measured by the pressure-recording device; C is a factor to convert $FSIP$ to equivalent feet of water; PRD is the depth of the pressure-recording device, in feet below the measuring point; and LSD is altitude of the measuring point, in feet above mean sea level. The factor C used in this report equals 2.307 feet of water per pressure increment of 1 lb/in^2. It assumes pure water at a temperature of 39.2°F (4°C) having a density of 1.00 g/cm^3. Equation 6 can be expressed in the metric system if h, PRD, and LSD are in metres, $FSIP$ is in kilograms per square centimetre, and C is a factor to convert $FSIP$ to equivalent metres of water. The factor C in the metric system equals 10.00 metres of water per pressure increment of 1 kg/cm^2. The resultant map (pl. 1*A*) reflects the surface of water in the Madison Group if it contained a homogeneous fluid having a density of 1.00 g/cm^3. It defines the hydraulic gradient and the general direction of movement of water.

TABLE 3.—*Selected yield and recovery data from drill-stem tests*

[Other data in tables 2, 4, and 5. Well: See text for explanattion of well number. Formation tested: CRLS, Charles Formation; MSNC, Mission Canyon Limestone; LDGP, Lodgepole Limestone; MDSN, Madison Group undivided. DST: Drill-stem test number. Interval tested: In feet below surface reference. PRD: Depth of pressure-recording device, in feet below surface reference; e, estimated. Altitude: Altitude of surface reference, in feet above mean sea level; G is ground, KB is kelly bushing, DF is drilling floor. Recovery period: Duration of recovery period analyzed, in minutes; I or F, initial or final. Flow period: Duration of flow period preceding analyzed recovery period, in minutes. Flow rate: Flow rate, in gallons per minute (gal/min) and cubic feet per minute (ft^3/min). Initial flow pressure: Flow pressure at start of flow period, in pounds per square inch (lb/in^2). Final flow pressure: Flow pressure at start of recovery period, in pounds per square inch. Hydraulic pressure: Pressure of mud column in annular space, in pounds per square inch; first number is at start of test, second number is at end of test. Total time of test: Time from start of initial flow period to end of final recovery period, in minutes. To convert pounds per square inch to pressure head, in feet, multiply by 2.307 feet per pounds per square inch. Recovery times and pressures computed from charts in 1973 by W. R. Miller unless otherwise indicated]

Well: 01S60E20DB.
Date: 8-5-54.
PRD: 6,300 feet, e. Altitude: 3,153 feet, KB.
Flow period: 104 minutes.
Initial flow pressure: 0 lb/in^2.
Hydraulic pressure: 3,448 lb/in^2.
Recovery data:

Formation tested: LDGP. DST: 1.
Interval tested: 6,293 to 6,340 feet.
Recovery period: 31 minutes, F.
Flow rate: 52 gal/min, 0.69 ft^3/min.
Final flow pressure: 375 lb/in^2.
Total time of test: 153 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0.00	375	0.54	1,161	3.81	2,443
.01	392	.73	1,315	5.24	2,495
.04	418	.74	1,520	6.26	2,520
.05	443	.78	1,674	8.5	2,572
.10	494	.88	1,879	10.1	2,597
.17	546	1.09	1,982	12.5	2,623
.20	648	1.21	2,084	15.3	2,649
.22	751	1.46	2,187	19.2	2,674
.25	853	2.03	2,290	31	2,716
.35	1,161	2.87	2,367		

Well: 07S59E03AB.
Date: 9-13-61.
PRD: 4,384 feet. Altitude: 3,502 feet, KB.
Flow period: 5 minutes.
Initial flow pressure: 595 lb/in^2.
Hydraulic pressure: 2,355 lb/in^2.
Recovery data: ([1]).

Formation tested: MSNC. DST: 1.
Interval tested: 4,496 to 4,650 feet.
Recovery period: 30 minutes, I.
Flow rate: 39 gal/min, 5.2 ft^3/min.
Final flow pressure: 870 lb/in^2.
Total time of test: 125 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0	870	9	1,974	18	1,981
3	1,939	12	1,978	27	1,981
6	1,965	15	1,980	30	1,983

[1]Compiled by Halliburton, Inc.

TABLE 3.—*Selected yield and recovery data from drill-stem tests*—Continued

Well: 08S46E11AA.
Date: 7-24-64.
PRD: 9,748 feet. Altitude: 3,931 feet, KB.
Flow period: 5 minutes.
Initial flow pressure: 3,535 lb/in².
Hydraulic pressure: 5,383 lb/in².
Recovery data:

Formation tested: MDSN. DST: 2.
Interval tested: 9,580 to 9,750 feet.
Recovery period: 26.4 minutes, I.
Flow rate: 70 gal/min, 9.4 ft³/min.
Final flow pressure: 3,603 lb/in².
Total time of test: 215 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0.00	3,603	0.44	3,939	3.54	4,148
.04	3,649	.66	3,997	4.86	4,168
.15	3,707	.82	4,055	12.6	4,183
.22	3,765	1.33	4,084	20.6	4,186
.29	3,873	2.21	4,131	26.4	4,189
.33	3,881				

Well: 08S54E21ADA.
Date: 6-27-70.
PRD: 6,878 feet.
Flow period: 60 minutes.
Initial flow pressure: Unknown.
Hydraulic pressure: Unknown.
Recovery data: (1).

Formation tested: MSNC. DST: Production test.
Interval tested: 6,990 to 7,190 feet.
Recovery period: 20 minutes.
Flow rate: 1,300 gal/min, 170 ft³/min.
Final flow pressure: 2,976 lb/in².
Total time of test: Unknown.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	2,976	0.50	3,017	20	3,017

[1]Data from Sam Gary Production Co.

Well: 09S53E22AB.
Date: 2-18-71.
PRD: 6,964 feet. Altitude: 3,466 feet, G.
Flow period: 60 minutes.
Initial flow pressure: Unknown.
Hydraulic pressure: Unknown
Recovery data: (1).

Formation tested: MSNC. DST: Production test.
Interval tested: 6,964 to 7,170 feet.
Recovery period: 30 minutes.
Flow rate: 990 gal/min, 30 ft³/min.
Final flow pressure: 3,025 lb/in².
Total time of test: Unknown.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	3,025	2.00	3,069	15.00	3,093
.25	3,045	4.00	3,078	20	3,097
.50	3,055	6.00	3,082	25	3,098
1.00	3,063	10.00	3,088	30	3,098

[1]Data from Sam Gary Production Co.

TABLE 3.—*Selected yield and recovery data from drill-stem tests*—Continued

Well: 06N59E29AA.
Date: 1-2-66.
PRD: 7,336 feet. Altitude: 3,237 feet, G.
Flow period: 60 minutes.
Initial flow pressure: 128 lb/in².
Hydraulic pressure: 4,041 lb/in².
Recovery data: (1).

Formation tested: MSNC. DST: 1.
Interval tested: 7,284 to 7,339 feet.
Recovery period: 30 minutes, F.
Flow rate: 4.3 gal/min, 0.57 ft³/min.
Final flow pressure: 366 lb/in².
Total time of test: 125 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	366	12.0	2,712	24.0	2,935
3.0	2,143	15.0	2,792	27.0	2,955
6.0	2,437	18.0	2,851	30.0	2,988
9.0	2,608	21.0	2,896		

[1]Computed by Halliburton, Inc.

Well: 08N30E07AD.
Date: 4-27-59.
PRD: 7,462 feet. Altitude: 3,343 feet, G.
Flow period: 125 minutes.
Initial flow pressure: 56 lb/in².
Hydraulic pressure: 3,648 lb/in².
Recovery data:(1).

Formation tested: CRLS. DST: 5.
Interval tested: 7,463 to 7,547 feet.
Recovery period: 30 minutes, F.
Flow rate: 6.4 gal/min, 0.86 ft³/min.
Final flow pressure: 751 lb/in².
Total time of test: 202 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	751	12	3,310	24	3,321
3	3,277	15	3,313	27	3,324
6	3,299	18	3,316	30	3,324
9	3,307	21	3,319		

[1]Computed by Halliburton, Inc.

Well: 08N40E14CD.
Date: 9-30-60.
PRD: 4,688 feet. Altitude: 2,721 feet, DF.
Flow period: 30 minutes.
Initial flow pressure: 330 lb/in².
Hydraulic pressure: 2,623 lb/in².
Recovery data:

Formation tested: MSNC. DST: 2.
Interval tested: 4,698 to 4,725 feet.
Recovery period: 30 minutes, F.
Flow rate: 100 gal/min, 14 ft³/min.
Final flow pressure: 1,269 lb/in².
Total time of test: 155 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	1,269	.59	1,575	1.05	2,282
.15	1,283	.62	1,621	1.13	2,359
.16	1,306	.64	1,667	1.28	2,374
.17	1,329	.73	1,744	3.64	2,389
.18	1,360	.86	1,821	8.21	2,396
.19	1,398	.93	1,897	14.1	2,402
.21	1,436	.96	2,013	29.9	2,387
.32	1,483	1.00	2,128	---	2,406
.50	1,529	1.02	2,205		

TABLE 3.—*Selected yield and recovery data from drill-stem tests*—Continued

Well: 09N60E04C.
Date: 12-29-71.
PRD: 8,094 feet. Altitude: 3,193 feet, KB.
Flow period: 23 minutes.
Initial flow pressure: 205 lb/in^2.
Hydraulic pressure: 4,407 lb/in^2.
Recovery data:

Formation tested: MSNC. DST: 1.
Interval tested: 8,055 to 8,094 feet.
Recovery period: 59.6 minutes, F.
Flow rate: 5.6 gal/min, 0.74 ft^3/min.
Final flow pressure: 523 lb/in^2.
Total time of test: 147 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0	195.4	0.83	1,680	13.6	6,813
.06	438	1.37	1,988	21.6	7,009
.16	673	2.39	2,477	29.6	7,122
.35	1,019	4.60	2,676	42.9	7,226
.54	1,383	8.79	2,851	59.6	7,311

Well: 10N24E36AA.
Date: 4-28-56.
PRD: 7,537 feet. Altitude: 3,747 feet, KB.
Flow period: 59.3 minutes.
Initial flow pressure: 83 lb/in^2.
Hydraulic pressure: 4,156 lb/in^2.
Recovery data: ([1]).

Formation tested: MSNC. DST: 2.
Interval tested: 7,554 to 7,583 feet.
Recovery period: 20 minutes, F.
Flow rate: 11 gal/min, 1.5 ft^3/min.
Final flow pressure: 616 lb/in^2.
Total time of test: 100 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0	616	8.0	3,206	16	3,258
2.0	2,778	10.0	3,225	18	3,267
4.0	3,114	12.0	3,242	20	3,273
6.0	3,176	14.0	3,250		

[1]Computed by Halliburton, Inc.

Well: 10N27E18DA.
Date:3-8-69.
PRD: 4,403 feet. Altitude: 3,265 feet, KB.
Flow period: 20 minutes.
Initial flow pressure: 120 lb/in^2.
Hydraulic pressure: 2,367 lb/in^2.
Recovery data: ([1]).

Formation tested: MSNC. DST: 2.
Interval tested: 4,375 to 4,407 feet.
Recovery period: 60 minutes, I.
Flow rate: 24 gal/min, 3.2 ft^3/min.
Final flow pressure: 690 lb/in^2.
Total time of test: 230 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0	690	0.72	1,599	5.33	2,070
.37	737	.80	1,666	9.12	2,097
.39	791	1.12	1,733	[1]12	2,098
.41	825	1.33	1,774	[1]18	2,101
.43	859	1.64	1,814	[1]24	2,104
.47	926	1.75	1,855	[1]30	2,106
.51	1,060	1.90	1,895	[1]36	2,109
.54	1,195	2.08	1,935	[1]42	2,111
.60	1,330	2.22	1,969	[1]48	2,114
.67	1,464	2.86	2,003	[1]54	2,116
.69	1,532	3.70	2,036	[1]60	2,119

[1]Computed by Halliburton, Inc.

TABLE 3.—*Selected yield and recovery data from drill-stem tests*—Continued

Well: 10N27E18DA.
Date: 3-11-69.
PRD: 4,641 feet. Altitude: 3,265 feet, KB.
Flow period: 45 minutes.
Initial flow pressure: 448 lb/in².
Hydraulic pressure: 2,491 lb/in².
Recovery data:

Formation tested: MSNC. DST: 3.
Interval tested: 4,600 to 4,645 feet.
Recovery period: 60 minutes, F.
Flow rate: 19 gal/min, 5 ft³/min.
Final flow pressure: 994 lb/in².
Total time of test: 150 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	994	0.61	1,607	1.60	2,219
.01	1,058	.68	1,676	2.42	2,225
.06	1,195	.79	1,745	14.5	2,230
.09	1,332	.88	1,813	36.6	2,233
.22	1,401	.93	1,985	50.4	2,233
.33	1,470	1.05	2,157	60	2,234
.44	1,539	1.10	2,191		

Well: 10N27E18DA.
Date: 3-16-69.
PRD: 5,043 feet. Altitude: 3,265 feet, KB.
Flow period: 45 minutes.
Initial flow pressure: 623 lb/in².
Hydraulic pressure: 2,469 lb/in².
Recovery data: ([1]).

Formation tested: LDGP. DST: 4.
Interval tested: 5,050 to 5,110 feet.
Recovery period: 45 minutes, F.
Flow rate: 40 gal/min, 5.4 ft³/min.
Final flow pressure: 1,753 lb/in².
Total time of test: 130 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	1,753	20	2,389	35	2,393
5	2,380	25	2,391	40	2,393
10	2,387	30	2,393	45	2,393
15	2,387				

[1]Computed by Halliburton, Inc.

Well: 11N27E13DA.
Date: 7-25-58.
PRD: 5,419 feet. Altitude: 3,364 feet, KB.
Flow period: <1 minute.
Initial flow pressure: Unknown.
Hydraulic pressure: 2,964 lb/in².
Recovery data:

Formation tested: MDSN. DST: 2.
Interval tested: 5,405 to 5,482 feet.
Recovery period: 30 minutes, I.
Flow rate: 9.7 gal/min, 1.3 ft³/min.
Final flow pressure: 585 lb/in².
Total time of test: 181 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0.06	667	0.42	1,828	7.52	2,439
.09	749	.47	1,930	[1]9.00	2,450
.13	801	.76	2,033	11.02	2,442
.18−	903	.80	2,136	[1]12.00	2,455
.18+	1,006	1.00	2,239	[1]15	2,456
				17.2	2,447
.22	1,109	1.19	2,290	[1]18	2,457
.23	1,211	1.34	2,341	[1]21	2,458
.25	1,365	2.14	2,393	[1]24	2,458
.27	1,520	2.98	2,418	[1]27	2,458
.29	1,622	[1]3.00	2,412	30	2,458
.33	1,725	[1]6.00	2,442	[1]30	2,458

[1]Computed by Johnston Testers, Inc.

TABLE 3.—*Selected yield and recovery data from drill-stem tests*—Continued

Well: 15N37E33AA.
Date: 12-6-59.
PRD: 5,980 feet. Altitude: 3,134 feet, DF.
Flow period: 120 minutes.
Initial flow pressure: 28 lb/in^2.
Hydraulic pressure: 3,147 lb/in^2.
Recovery data: ([1]).

Formation tested: CRLS. DST: 5.
Interval tested: 5,990 to 6,036 feet.
Recovery period: 60 minutes, F.
Flow rate: 0.2 gal/min, 0.03 ft^3/min.
Final flow pressure: 68 lb/in^2.
Total time of test: 245 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0	68	24	2,269	48	2,515
6.0	367	30	2,370	54	2,542
12	1,639	36	2,433	60	2,563
18	2,107	42	2,479		

[1]Computed by Halliburton, Inc.

Well: 15N37E33AA.
Date: 12-8-59.
PRD: 6,049 feet. Altitude: 3,134 feet, DF.
Flow period: 60 minutes.
Initial flow pressure: 73 lb/in^2.
Hydraulic pressure: 3,200 lb/in^2.
Recovery data: ([1]).

Formation tested: CRLS. DST: 6.
Interval tested: 6,068 to 6,176 feet.
Recovery period: 30 minutes, F.
Flow rate: 20 gal/min, 2.7 ft^3/min.
Final flow pressure: 1,062 lb/in^2.
Total time of test: 155 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0	1,062	12	2,695	24	2,729
3.0	2,620	15	2,705	27	2,734
6.0	2,659	18	2,716	30	2,739
9.0	2,680	21	2,724		

[1]Computed by Halliburton, Inc.

Well: 15N37E33AA.
Date: 12-11-59
PRD: 6,220 feet. Altitude: 3,134 feet, DF.
Flow period: 60 minutes.
Initial flow pressure: 118 lb/in^2.
Hydraulic pressure: 3,263 lb/in^2.
Recovery data: ([1]).

Formation tested: MSNC. DST: 7.
Interval tested: 6,234 to 6,315 feet.
Recovery period: 30 minutes, F.
Flow rate: 17 gal/min, 2.3 ft^3/min.
Final flow pressure: 983 lb/in^2.
Total time of test: 125 minutes.

Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)	Time since recovery began	Recovery (lb/in^2)
0	983	12	2,601	24	2,695
3	2,370	15	2,632	27	2,708
6	2,492	18	2,658	30	2,716
9	2,555	21	2,679		

[1]Computed by Halliburton, Inc.

TABLE 3.—*Selected yield and recovery data from drill-stem tests*—Continued

Well: 16N40E15BA.
Date: 3-8-64
PRD: 6,433 feet. Altitude: 2,892 feet, KB.
Flow period: 120 minutes.
Initial flow pressure: 29 lb/in².
Hydraulic pressure: 3,326 lb/in².
Recovery data:

Formation tested: CRLS. DST: 1.
Interval tested: 6,451 to 6,483 feet.
Recovery period: 46.3 minutes.
Flow rate: 0.99 gal/min, 0.13 ft³/min.
Final flow pressure: 62 lb/in².
Total time of test: 217 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	70.1	5.18	596	23.2	2,129
.12	81.9	8.0	1,197	28.8	2,244
.69	99.6	11.9	1,683	34.4	2,336
1.81	197.5	17.2	1,957	46.3	2,396
2.94	437				

Well: 16N54E17BAD.
Date: 8-24-61
PRD: 7,965 feet. Altitude: 2,465 feet, KB.
Flow period: 192 minutes.
Initial flow pressure: 138 lb/in².
Hydraulic pressure: 4,601 lb/in².
Recovery data: ([1]).

Formation tested: MSNC. DST: 1.
Interval tested: 7,920 to 7,972 feet.
Recovery period: 59 minutes, F.
Flow rate: 0.15 gal/min, 0.02 ft³/min.
Final flow pressure: 552 lb/in².
Total time of test: 298 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
0	552	25	3,734	45	3,783
5	2,855	30	3,751	50	3,790
10	3,608	35	3,766	55	3,797
15	3,674	40	3,775	59	3,801
20	3,710				

[1]Computed by Johnston Testers, Inc.

Well: 19N44E10BD.
Date: 11-2-62.
PRD: 7,632 feet. Altitude: 2,700 feet, KB.
Flow period: 60 minutes.
Initial flow pressure: 138 lb/in².
Hydraulic pressure: 4,247 lb/in².
Recovery data:

Formation tested: MSNC. DST: 2.
Interval tested: 7,654 to 7,689 feet.
Recovery period: 90 minutes, F.
Flow rate: 9.1 gal/min, 1.2 ft³/min.
Final flow pressure: 577 lb/in².
Total time of test: 200 minutes.

Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)	Time since recovery began	Recovery (lb/in²)
[1]0	589	[1]90	3,632	8.45	3,579
[1]9	3,605	0	577	11.7	3,582
[1]18	3,616	.20	1,185	17.1	3,585
[1]27	3,620	.28	1,986	22.6	3,588
[1]35	3,622	.40	2,984	33.4	3,589
[1]45	3,626	.63	3,423	44.3	3,590
[1]54	3,628	1.08	3,483	55.1	3,591
[1]63	3,628	2.48	3,537	66.0	3,591
[1]72	3,630	4.10	3,562	76.9	3,591
[1]81	3,630	6.28	3,572		

[1]Computed by Halliburton, Inc.

TABLE 4.—*Summary of transmissivities estimated from drill-stem tests*

Location number: See text for explanation of location-numbering system.
Formation: CRLS, Charles Formation; MSNC, Mission Canyon Limestone; LDGP, Lodgepole Limestone; MDSN, Madison Group undivided.
Estimated transmissivity: Viscosity of produced fluids not considered in calculation.
Remarks: Q is yield of well in gallons per minute and cubic feet per minute.

Well No.	Formation	Tested interval (feet)	Estimated transmissivity [(ft³/day)/ft]	Yield of test (Q)	
				Gal/min	Ft³/min
01S60E20DB	LDGP	6,293-6,340	0.25	5.2	0.69
07S59E03AB	MSNC	4,496-4,650	(1)	39	5.2
08S46E11AA	MDSN	9,580-9,750	11.3	70	9.4
08S54E21ADA	MSNC	6,990-7,190	(1)	1,300	17.0
09S53E22AB	MSNC	6,964-7,170	5,400	990	130
06N59E29AA	CRLS MSNC.	7,284-7,339	.07	4.3	.57
08N30E07AD	CRLS	7,463-7,547	2.7	6.4	.86
08N40E14CD	MSNC	4,698-4,725	[2]27	100	14
09N60E04C	MSNC	8,063-8,098	.05	5.6	.74
10N24E36AA	MSNC	7,554-7,587	.88	11	1.5
10N27E18DA	MSNC	4,375-4,407	5	24	3.2
10N27E18DA	MSNC	4,600-4,645	14	19	2.5
10N27E18DA	LDGP	5,050-5,110	29	40	5.4
11N27E13DA	MDSN	5,405-5,482	(3)	9.7	1.3
15N37E33AA	CRLS	5,990-6,036	.01	.2	.03
15N37E33AA	CRLS	6,068-6,176	2.2	20	2.7
15N37E33AA	MSNC	6,234-6,315	.97	17	2.3
16N40E15BA	CRLS	6,451-6,483	.03	.99	.13
16N54E17BAD	MSNC	7,920-7,972	.01	.15	.02
19N44E10BD	MSNC	7,654-7,689	4.6	9.1	1.2

[1]Recovery too rapid to compute transmissivity.
[2]Recovery curve has unusual shape.
[3]Insufficient data to compute transmissivity.

To show the altitude to which water would actually rise in a tightly cased well, the pressure heads would have to be corrected for density variations due to increases in temperature and dissolved-solids concentration. Equation 6 can be modified to reflect density corrections as:

$$h = (2.307 + C_T - C_S)\,FSIP - PRD + LSD, \qquad (7)$$

where C_T is the temperature correction, C_S is the dissolved-solids correction, and the other symbols are as given in equation 6. The temperature correction, C_T, is positive and in the English system ranges from 0.0001 foot/(lb/in^2) for each 1°F change at 50°F to 0.0011 foot/(lb/in^2) for each 1°F change at 250°F. In the metric system C_T ranges from 0.0002 m/(kg/cm^2) for each 1°C change at 10°C to 0.0026 m/(kg/cm^2) for each 1°C change at about 120°C. C_T can be determined from the following table:

Temperature		C_T (correction factor at indicated temperature)	
°F	°C	Feet/(lb/in²)	Metres/(kg/cm²)
39.2	4	0	0
50	10	.001	.004
60	15.6	.002	.009
70	21.1	.005	.022
80	26.7	.008	.035
90	32.2	.012	.052
100	37.8	.016	.069
110	43.3	.021	.091
120	48.9	.027	.117
130	54.4	.033	.143
140	60	.039	.169
150	65.6	.046	.199
160	71.1	.054	.234
170	76.7	.062	.269
180	82.2	.070	.303
190	87.8	.079	.342
200	93.3	.088	.381
210	98.9	.098	.425
220	104.4	.108	.468
230	110	.119	.516
240	115.6	.130	.564
250	121.1	.141	.611

The dissolved-solids correction, C_S, is negative and is 0.007 foot/(lb/in²) for each 5,000 mg/l change in dissolved solids, assuming sodium and chloride are the major constituents. In the metric system C_S is 0.0030 m/(kg/cm²) for each 5,000 mg/l change in dissolved solids.

The net result of correcting the data for density would be a map similar to plate 1*A*, but the surface on the west side of the study area would be elevated because temperature in the aquifer increases faster than the dissolved-solids concentration, and the surface to the northeast would be depressed because the dissolved-solids concentration increases more rapidly than the temperature. The resultant map could be used to indicate actual water-level altitudes or depths to water in wells but would not show the true hydraulic gradient.

The hydraulic gradient (pl. 1*A*) is away from the outcrop or recharge areas and is generally toward the north and northeast. The potentiometric surface of the Madison is below land surface on the high interstream divides south of the Yellowstone River. On the Little Bighorn–Tongue River divide the potentiometric surface is as much as 1,200 feet (370 m) below land surface. However, the potentiometric surface is above land surface along all the major streams that cross the southern part of the area and is as much as 1,000 feet (300 m) above land surface along the Yellowstone River. Except for some high buttes and interstream areas, the potentiometric surface is above land surface in all the area north of the 46th parallel.

Some features on the potentiometric map (pl. *1A*) correlate with features on the structure maps (fig. 3; pl. *1D*). A potentiometric low occurs southeast of the Cat Creek anticline and north and west of the Porcupine dome. Other potentiometric lows not apparently related to structural features occur at the north end of the Powder River basin and along the Bighorn River. The lows are places where water could discharge from the Madison aquifer. Potentiometric highs occur along the Cedar Creek anticline and between the Tongue, Bighorn, and Yellowstone Rivers. Other highs occur around the outcrop areas. Another noticeable feature is the decrease in gradient toward the Williston basin.

Several mechanisms or combinations of mechanisms can explain some of the features on plate *1A*. For example, the potentiometric low that extends about 60 miles (100 km) northeast from the Cat Creek anticline probably results from pumping by wells, folding and faulting of rocks, and upward leakage through the overlying beds. Several water wells (table 5) have been completed along the Cat Creek anticline and related structures and on the north and east sides of the Porcupine dome. Because these wells are mainly in two small areas on the south and west sides of the low, it appears unlikely that pumping by wells could account for the extensive but relatively shallow low.

Folding and faulting in the Cat Creek anticline–Porcupine dome area have been mapped by Sandberg (1959), Smith (1962), and Johnson and Smith (1964); the Blood Creek syncline is north of this area. Deformation of the rocks by folding and faulting has probably created permeable zones where upward leakage could occur.

Upward leakage through the overlying beds can be significant where a large head difference occurs over a large area, even though the vertical permeabilities are low. In the area of the Cat Creek anticline–Porcupine dome low, the potentiometric head in the Madison ranges in altitude from about 3,400 to 3,600 feet (1,040 to 1,100 m). The potentiometric heads in the overlying rocks are lower; the potentiometric head of the Big Snowy Group rocks ranges in altitude from 2,300 to 2,800 feet (700 to 850 m), and the potentiometric heads of basal and middle Cretaceous rocks range from 3,000 to 3,300 and 2,300 to 2,600 feet (910 to 1,010 and 700 to 790 m), respectively. South of the potentiometric low near the Cat Creek anticline–Porcupine dome area, the Big Snowy Group rocks are absent, and Pennsylvanian rocks unconformably overlie the Madison. In this area the potentiometric heads of the Madison and Pennsylvania rocks are nearly the same, which probably indicates that the rocks are hydraulically connected. However, better definition of the distribution of potentiometric heads between the Madison and Pennsylvanian rocks in the Cat Creek anticline–Porcupine dome and adjacent areas will require further study.

The potentiometric low at the north end of the Powder River basin and apparently extending across the north end of the Cedar Creek anticline could also be an area where water is discharging from the Madison. The potentiometric heads of the Madison in this area are as much as 1,000 feet (300 m) higher than those in the overlying beds, but insufficient data are available to define the distribution of head in the overlying beds or the vertical movement of water. Faults can also affect the potentiometric surface. However, except for the Weldon fault to the north and a fault associated with the Cedar Creek anticline on the east, the only evidence for faulting in this area is Zietz, Hearn, Higgins, Robinson, and Swanson (1971) and Brinkworth and Kleinkopf (1972). Their aeromagnetic and gravity maps show anomalies that might be interpreted as faults, which occur along the western and southwestern parts of the potentiometric low on plate 1*A*.

The potentiometric low along the Bighorn River suggests that Bighorn Canyon and the Bighorn River just north of the canyon are discharge points. In fact, before construction of Yellowtail Reservoir, several springs issued from Madison Group rocks in Bighorn Canyon at an altitude of about 3,300 feet (1,010 m). Several test holes in the immediate vicinity of the dam also indicated similar water-level altitudes. Since the reservoir has filled, water levels in some observation wells have risen to about 3,600 feet (1,100 m), which is somewhat lower than the maximum lake altitude. The hydraulic gradient in this area is northward. The implication is that the reservoir reduced discharge from the springs and that water from the reservoir recharges the Madison, thereby altering the dynamic equilibrium of the system. The actual locations of the contours in this area are uncertain as few reliable data exist.

The anomalies along the Cedar Creek anticline might be related to oil production; the highs correspond to locations of water injection for secondary recovery of oil, and the lows correspond to areas of withdrawal of water from oil fields by pumping.

The potentiometric highs near the Bighorn Mountains, at the north end of the Black Hills, and east of the Big Snowy Mountains are caused by recharge in the outcrop areas. The high between the Bighorn, Tongue, and Yellowstone Rivers can be interpreted as a ground water divide between the Powder River basin to the east and the Cat Creek anticline–Porcupine dome area to the northwest. Vertical movement of water along faults can affect the potentiometric surface. The only evidence of faulting in this area is the Lake Basin fault zone, which can be extended (Zietz and others, 1971) across the southern part of the high. The potentiometric high in the central part of the Powder River basin along the Montana-Wyoming boundary might be due to permeability differences in the deeper part of the basin or it could be related to recharge from the Black Hills. It also might reflect the lack of data in southern Montana.

The potentiometric high in the north-central part of the study area is near the south end of the Weldon fault (Brinkworth and Kleinkopf, 1972) and the east end of the Blood Creek syncline. Zietz and others (1971) extended the Weldon fault to the southwest based on aeromagnetic interpretation. Northeast of the study area along the Weldon fault other pressure heads determined from drill-stem tests were also higher than those some distance away from the fault zone.

RECHARGE AND DISCHARGE

Few data are available that define recharge to, or discharge from, the aquifer. However, from the map of the potentiometric surface, a limited amount of well data, and data from other studies, some general interpretations can be made.

Recharge to the Madison occurs in outcrop areas in the Pryor and Bighorn Mountains in the study area, and in the Black Hills southeast of the study area, Big Snowy Mountains west of the study area, and smaller mountainous areas nearby. The most obvious source of recharge is streams that cross outcrop areas and lose water to the rocks. However, most of the recharge probably occurs in the interstream areas of the outcrops. Studies by the Wyoming State Engineer (1974) and Feltis (1973) indicate that 3.5 and 58 percent, respectively, of the average annual precipitation on the outcrop areas recharges the aquifer. Yellowtail Reservoir may also be an important source of recharge to the aquifer. The amount of recharge that occurs in the outcrop areas is presently (1976) unknown, but data are being collected in the Bighorn and Laramie Mountains in Wyoming and in the Black Hills to determine the amount.

Recharge also occurs as subsurface inflow from outside the study area and may occur as leakage from underlying or overlying beds or through fractures caused by folding and faulting. The amount of recharge from these sources is unknown and cannot be determined without complex testing.

The amount of discharge from the Madison is unknown, but it occurs as springs, as gains in streamflow where streams cross the outcrops, as upward leakage, as subsurface outflow from the area, and as withdrawal by wells. Much of the major natural discharge is thought to be upward leakage into overlying rocks through permeable beds or through folded and faulted zones. This may occur at the north end of the Powder River basin, along the Yellowstone River, and in the Cat Creek anticline–Porcupine dome area. Few wells tap the Madison, so withdrawal by wells is not precisely known, but it is probably small compared to other discharge from the aquifer.

AVAILABILITY OF WATER

The availability of water in the Madison can be generalized from the discharges by wells, which are poorly documented. From August 1970 through December 1974 about 12,000 acre-feet (14.8 million m^3) of water was withdrawn from the Bell Creek oil field. The amount withdrawn by wells at Colstrip and Sarpy Creek for coal mining, from the Soap Creek oil field, and from other wells in the area is estimated to be less than 200 acre-feet (0.25 million m^3) per year. Discharge from eight industrial and stock wells in the Cat Creek anticline–Porcupine dome area is estimated to be about 800 acre-feet (0.99 million m^3). Well 11N32E08DCB produced about 800 acre-feet (0.99 million m^3) from January 1969 through June 1975. Production of water for secondary recovery of oil is reported from the Madison in the Cedar Creek anticline area, but the amount is unknown.

Yields from wells range from about 50 gal/min (3 l/s) to a reported 1,400 gal/min (88 l/s) from a flowing well on the north side of the Porcupine dome. Yields estimated or reported from drill-stem tests range from about 1 to 157 gal/min (0.1 to 9.9 l/s); some yields were probably greater, but data are insufficient for a reliable estimate. Well and drill-stem-test yields are summarized in table 5.

WATER QUALITY

Forty-two water-quality analyses within the study area are considered to be representative of water from the Madison Group; these chemical analyses plus others in eastern Montana are presented in a report by Hopkins (1976). Nine samples are from the Charles Formation; 20, from the Mission Canyon Limestone; 3, from the Lodgepole Limestone; and 10, either from more than 1 formation or from the Madison Group undifferentiated. Other chemical analyses exist but are of questionable validity, are confidential, are proprietary information belonging to oil companies, or are not otherwise available.

Many variables influence the validity of interpretation based on these water-quality data. Many analyses are of water recovered from drill-stem tests, which sometimes are not representative of water from a given formation because of contamination by drilling fluid. Samples from each formation are not evenly distributed geographically, or in the time of collection. Moreover, some samples are from more than one formation or at least from more than one porous zone. However, the analyses appear to indicate the general dissolved-solids concentrations that can be expected from the Madison and the relative amounts of major anions and cations present.

General variations in dissolved-solids concentrations are shown on plate 1*B*. In the southern part of the study area the water contains less than 1,500 mg/l dissolved solids. In the central and northwestern parts

TABLE 5.—*Summary of yields from supply wells and drill-stem tests*

Location: See text for explanation of location-numbering system.
Formation: CRLS, Charles Formation; MSNC, Mission Canyon Limestone; LDGP, Lodgepole Limestone; MDSN, Madison Group undivided; DVNN, Devonian rocks undivided.
Remarks: IW, industrial well; WSW, water-supply well for secondary recovery of oil; WTS, water to surface in indicated time, in minutes. Leaders (----) indicate no data available.

Location	Producing interval (feet below surface reference)	Formation	Reported yield, flowing (gal/min)	Remarks
Supply wells				
01N37E26CAA	7,596–7,850	MDSN	50	IW, Sarpy Creek.
02N41E34BA	7,406–8,635	MDSN	100	IW, Colstrip; also used for public supply.
10N39E09BBB	3,146–3,671	MDSN	250	Lost-circulation zone at 3,190 feet reportedly flowed at 2,900 gal/min.
11N30E35AD	6,074–6,448	MSNC	160	WSW, Keg Coulee oil field.
11N30E36CAC	5,871–6,478	MDSN	120	Do.
11N31E11DD	6,797–7,212	MSNC	270	WSW, Stensvad oil field.
11N32E08DCB	6,109–6,199	MDSN	1,200	WSW, West Sumatra oil field.
11N32E15AB	6,080–6,770	MDSN	840	WSW, Sumatra oil field.
11N32E24AD	6,153–6,833	MDSN	150	Do.
11N43E21CD	8,183–8,230	LDGP, DVNN	1,400	Stock-water well.
12N39E09AA	5,040–5,103	MSNC	100	Do.
08S54E21ADA	6,990–7,190	MDSN	----	WSW, Bell Creek oil field:
			670	6–19–70, initial yield.
			1,300	6–27–70, after acidification.
			750	12–14–70, after 6-month flow period.
08S54E27CB	6,960–7,170	MDSN	260	WSW, Bell Creek oil field.
08S54E29CD	7,056–7,292	MDSN	640	Do.
09S53E22AB	6,964–7,170	MDSN	980	Do.
Drill-stem tests				
01N28E01BA	4,026–4,034	CRLS	----	WTS, 14 min.
	4,052–4,070	CRLS	----	WTS, 15 min.
01N28E06AA	4,500–4,534	MSNC	----	WTS, 70 min.
01N29E18DC	5,135–5,195	CRLS	----	Flowed.
02N61E06AA	7,440–7,460	MSNC	4	WTS, 235 min.
03N33E13BA	6,054–6,097	CRLS	26	WTS, 75 min.
04N37E14CC	7,365–7,385	LDGP	120	WTS, 37 min.
05N33E16BB	6,825–6,895	MSNC	----	WTS, 110 min.
05N40E20DA	6,777–6,897	CRLS	----	WTS, 80 min.
05N59E11AA	7,568–7,602	MSNC	----	Flowed.
05N61E06DC	6,950–6,969	MSNC	21	WTS, 85 min.
	7,675–7,710	LDGP	42	WTS, 25 min.
08N32E33DC	6,587–6,650	CRLS	----	WTS, 45 min.
08N40E14CD	4,698–4,725	MSNC	----	WTS, 25 min.
08N59E14AD	8,097–8,165	LDGP	5	WTS, 35 min.

TABLE 5.—*Summary of yields from supply wells and drill-stem tests*—Continued

Location	Producing interval (feet below surface reference)	Formation	Reported yield, flowing (gal/min)	Remarks
08N61E19CC	8,553–8,564	LDGP	----	WTS, 38 min.
09N39E21CC	3,920–3,965	CRLS	60	WTS, 17 min.
10N27E18DA	5,237–5,287	LDGP, DVNN.	----	WTS, 25 min.
10N39E09BBB	3,561–3,628	MSNC	----	WTS, 22 min.
11N30E35AD	5,980–6,513	MDSN	157	WTS, 17 min.
11N39E03DD	3,972–3,990	MSNC	----	WTS, 21 min.
11N43E21CD	8,183–8,230	LDGP	35	WTS, 57 min.
12N34E06AA	5,906–5,938	MSNC	----	WTS, 124 min.
	6,053–6,085	MSNC	----	WTS, 27 min.
	6,936–6,966	LDGP	----	WTS, 120 min.
12N34E23DD	6,085–6,135	MSNC	----	WTS, 55 min.
12N39E09AA	5,040–5,103	MSNC	----	WTS, 15 min.
13N32E01CB	5,750–5,799	CRLS	11	WTS, 108 min.
	6,078–6,120	MSNC	18	WTS, 50 min.
13N39E35DA	5,278–5,310	CRLS	18	WTS, 90 min.
13N56E15BA	8,014–8,139	LDGP	----	WTS, 50 min.
14N32E30CCB	4,980–5,116	MDSN	----	WTS, 27 min.
15N30E16CC	3,375–3,431	CRLS	----	WTS, 11 min.
16N26E06DC	2,885–2,913	CRLS	----	Flowed.
16N26E18BC	2,804–2,820	CRLS	----	WTS, 120 min.
16N31E23DC	6,077–6,120	MSNC	----	WTS, 18 min.
06S35E03CC	5,039–5,066	MDSN	----	WTS, 28 min.
06S35E17AA	4,915–4,968	CRLS	100	WTS, 19 min.

of the area dissolved-solids concentrations range from 1,500 to 10,000 mg/l. To the northeast, in the Williston basin, the dissolved-solids concentrations increase to more than 100,000 mg/l.

The distribution of major ions occurring in water from the Madison Group is shown on plate 1*C*. Calcium, magnesium, and sulfate are the major ions in the southern and western parts of the area. Calcium, magnesium, sodium, potassium, sulfate, and chloride, in subequal amounts, are the major ions in the central part of the area. Sodium, potassium, and chloride are the major ions in the Williston basin.

Calcium, magnesium, and sulfate ions constitute more than 75 percent of the dissolved constituents, in milliequivalents per litre, in water from the Madison in the southeastern and southwestern parts of the study area. Northward to about T. 8 N., calcium, magnesium, and sulfate ions constitute more than 50 percent of the dissolved constituents. North of this line the water contains mainly sodium, potassium, and chloride, and in the Williston basin sodium, potassium, and chloride ions constitute more than 75 percent of the total.

Sulfate is more abundant than carbonate or bicarbonate presumably because of the large amount of anhydrite in Madison rocks. Anhydrite is much more soluble than limestone.

The lines indicating the 10,000 mg/l dissolved-solids concentration (pl. 1*B*) and the concentration of 75 percent sodium plus potassium plus chloride (pl. 1*C*) roughly coincide. This location is the approximate western limit of significant halite deposits in the Madison shown in figure 4. Sandberg (1962) indicated that salt beds were present in the northeastern part of the study area (fig. 4). Nordquist (1953) and Andrichuk (1955) also mention halite in the northeastern part of the study area. Two oil tests have penetrated halite deposits in the upper part of the Charles Formation; the deposits were more than 200 feet (60 m) thick in a test about 12 miles (19 km) north of the study area in sec. 25, T.22 N., R.48 E., and more than 60 feet (18 m) thick in sec. 25, T.15 N., R.55 E.

The dissolved-solids concentration and selected ratios of reacting values of water samples from different formations penetrated by the same well are listed in the following table. The ratios indicate that no apparent relation exists among formation, depth, and dissolved-solids concentration. Similar variations occur in samples from adjacent wells in different formations and, in places, in samples from adjacent wells in the same formation.

Well No.	Formation[1]	DS[2]	Ratios[3] $\frac{Na+K}{Ca+Mg}$	Ratios[3] $\frac{Cl}{SO_4+HCO_3}$	Ratios[3] $\frac{SO_4}{HCO_3}$	Sampling depth (feet)
01N28E01BAC	CRLS	2,780	0.63	0.02	6.17	4,010–4,293
	MSNC	2,740	.13	.03	38.0	4,300–4,479
06N32E02CC	CRLS	2,800	1.62	.10	6.80	6,565–6,647
	MSNC	6,450	1.74	.09	13.7	6,930–6,973
07N59E01BBB	CRLS	59,400	4.17	14.0	16.0	6,734–6,773
	MSNC	36,200	5.11	6.09	16.2	7,155–7,200
	LDGP	4,230	1.05	.77	5.50	7,855–7,891
19N34E32BD	CRLS	6,220	2.00	1.22	4.11	5,787–5,818
	MSNC	5,240	2.15	1.00	5.14	6,002–6,076

[1]CRLS, Charles Formation; MSNC, Mission Canyon Limestone; LDGP, Lodgepole Limestone.
[2]DS, dissolved-solids concentration, in milligrams per litre.
[3]Na, sodium; K, potassium; Ca, calcium; Mg, magnesium; Cl, chloride, SO_4, sulfate; HCO_3, bicarbonate

POROSITY FROM GEOPHYSICAL LOGS

One aspect of this study was the evaluation of geophysical logs to determine which logs and interpretation techniques would be best suited for a detailed geohydrologic study of the Madison Group. No attempt was made to analyze and tabulate all available geophysical logs of test holes that have penetrated the Madison. Instead, a brief description is given of the types of logs and interpretation techniques that appear most promising.

The relation of porosity to the electrical, nuclear, and acoustic properties of rocks has been described in detail by Archie (1942), Guyod (1944), Lynch (1962), Pirson (1963), Wylie (1963), and Schlumberger, Ltd. (1972a). A discussion on the practical application is given in the above references and in Chombart (1960), Connolly (1968), Dorin, Chase, and Linke (1968), Raymer and Biggs (1963), and Savre and Burke (1963).

ELECTRIC LOGS

Electric logs have been described by Pirson (1963, p. 65–177) and Schlumberger, Ltd. (1972a, p. 7–36). Basically, electric logs measure the resistivity of rocks and their contained fluids, which are related to porosity. The only electric log evaluated in this report is the microlog, which has been described in detail by Doll (1950), Pirson (1963, p. 117–125), and Lynch (1962, p. 167–174).

The microlog can be used in carbonate rocks to delineate permeable zones, to estimate porosity in granular carbonates, and to define boundaries between beds accurately for use with other geophysical logs. Interpretation of microlog curves can be illustrated with a suite of logs from well 03S37E03BC (fig. 6), which includes microcaliper, microlog, gamma-ray, and neutron logs of a typical section of the Charles Formation.

In general, permeable zones are indicated by the buildup of mud cake in the borehole adjacent to permeable beds, as shown on the microcaliper log and by positive separation of the microlog curves. Positive separation is defined as the 2-inch (50.8 mm) normal curve registering a higher resistivity than the 1-inch (25.4mm) inverse curve. According to Lynch (1962, p. 169) positive separation occurs when mud filtrate invading part of the formation has a higher resistivity than the mud cake. Even though the principal criterion for forming a mud cake is that the permeability of the formation be greater than that of the mud cake, the formation does not necessarily have to be permeable enough to produce fluid.

Some of the intervals that have large positive separations on the micrölog are 7,243–7,253, 7,290–7,325, 7,362–7,396, and 7,404–7,418 feet (2,208–2,211, 2,222–2,233, 2,244–2,254, and 2,257–2,261 m). Porosity in these zones is also indicated by the neutron curve; left deflections indicate porosity and right deflections indicate dense zones. The gamma-ray curve indicates some shaliness in these zones by right deflections. The evenly spaced, symmetrical false deflections on the gamma-ray and neutron curves that occur about every 40 feet (12 m) may be caused by magnetization of the cable drum.

In vuggy or fractured carbonate rocks, mud cake normally does not occur, and the presence of permeable zones is indicated by the relative low resistivities of both curves, not by their separation. Impermeable rocks are generally indicated by negative separation of the microlog curves or by resistivities of both curves being nearly equal but very high. Some of the factors that may adversely affect the interpretation of

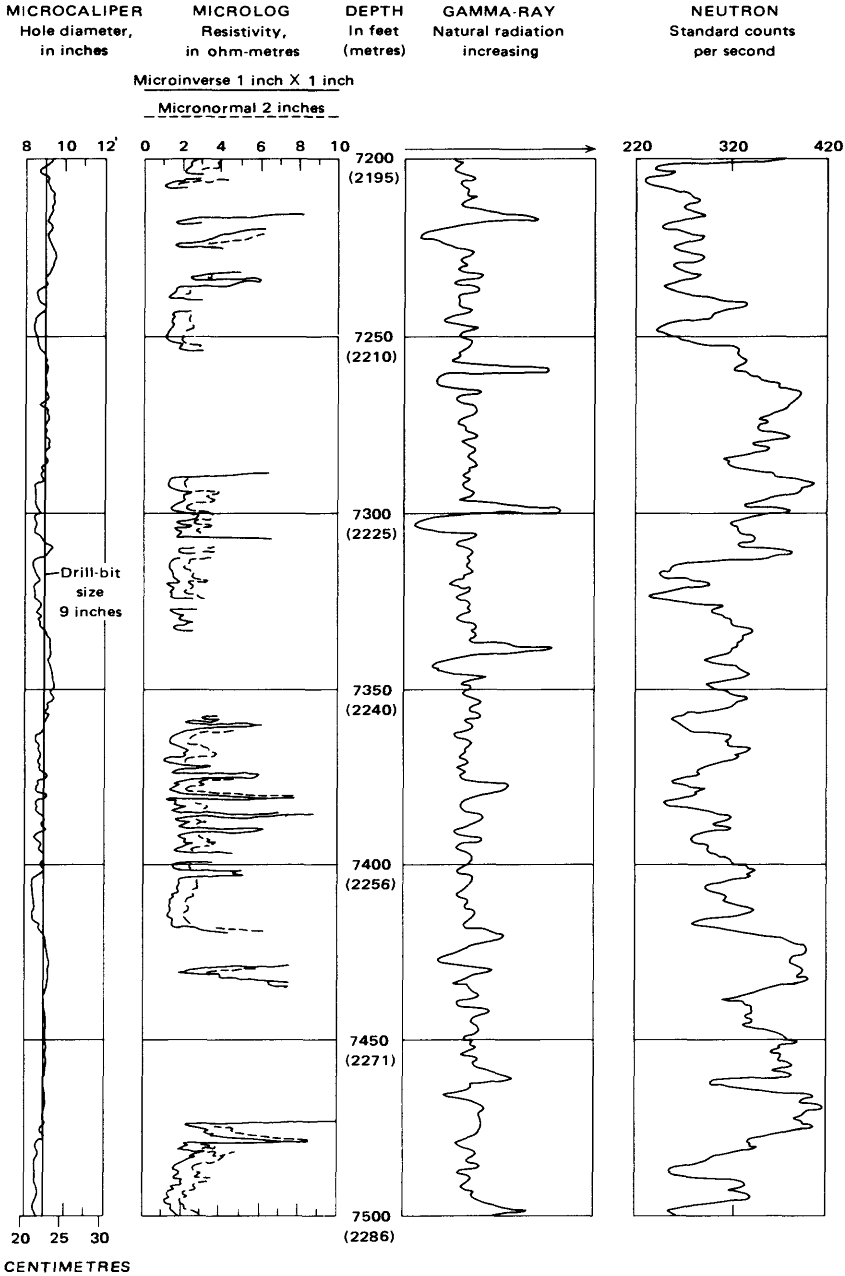


FIGURE 6.—Microcaliper, microlog, gamma-ray, and neutron logs of Charles Formation in well 03S37E03BC. Parts of the microlog curve that do not indicate good porosity have been omitted for clarity.

the microlog curves are the diameter and rugosity of the borehole; the mud-cake thickness; and the resistivity of the formation, the drilling mud, and the water in the formation.

Porosity can be estimated from micrologs, using analytical procedures outlined by Pirson (1963, p. 117–125) and from nomograph C–12 and chart C–4 of Schlumberger, Ltd. (1972b, p. 15, 42) and from figure 10–9 of Pirson (1963, p. 123). However, according to Pirson (1963, p. 125) and Schlumberger, Ltd. (1972a, p. 34), for optimum quantitative interpretation the porosity should be greater than 15 percent, the mud cake thickness should be less than 0.5 inch (1.27 cm), and the ratio of the resistivity of the flushed zone to the resistivity of the mud cake should be less than 25. Even with the above limitations and inherent errors, porosity of the Madison can still be estimated. For example, the average porosity of the zone from 7,410–7,418 feet (2,259–2,261 m) is about 6 percent assuming:

Rmc, resistivity of the mud cake, is 0.51 ohm-m at formation temperature,
Rmf, resistivity of the mud filtrate, is 0.23 ohm-m at formation temperature,
$R_{2\text{-inch}}$, resistivity measured by 2-inch normal curve, is 2.4 ohm-m at formation temperature,
$R_{1\text{-inch}}$, resistivity measured by 1-inch inverse curve, is 1.4 ohm-m at formation temperature,
t_{mc}, mud-cake thickness, is 0.375 inch (0.95 cm),
FT, formation temperature, is about 152°F (67°C), and is 0 percent.
S_{OR}, residual oil saturation,

RADIATION LOGS

Radiation logs have been described by Pirson (1963, p. 177–220), Schlumberger, Ltd. (1972a, p. 43–68), and Chombart (1960, p. 835–840). The neutron and density logs measure induced radiation, whereas the gamma-ray log measures natural radiation. The gamma-ray log is used for correlation and lithologic determinations.

NEUTRON LOGS

Neutron logs (Pirson, 1963, p. 193–213) measure the amount of capture or moderation of artificially produced high-energy neutrons mainly by hydrogen. When porous rocks containing hydrogen-rich fluids, such as water, hydrocarbons, or water of crystallization, are bombarded by artificially produced neutrons, some of the neutrons are moderated by the hydrogen and do not reach the detector. The fewer neutrons reaching the detector, the more hydrogen contained in the rocks and, hence, the greater the porosity.

An example of a neutron log of the upper part of the Madison Group and a correlation of porosity determined in the laboratory versus neutron deflection are shown in figures 7 and 8, respectively. Laboratory core porosity plotted at the same vertical scale as the logs indicates only fair correlation because (1) the actual position of cores

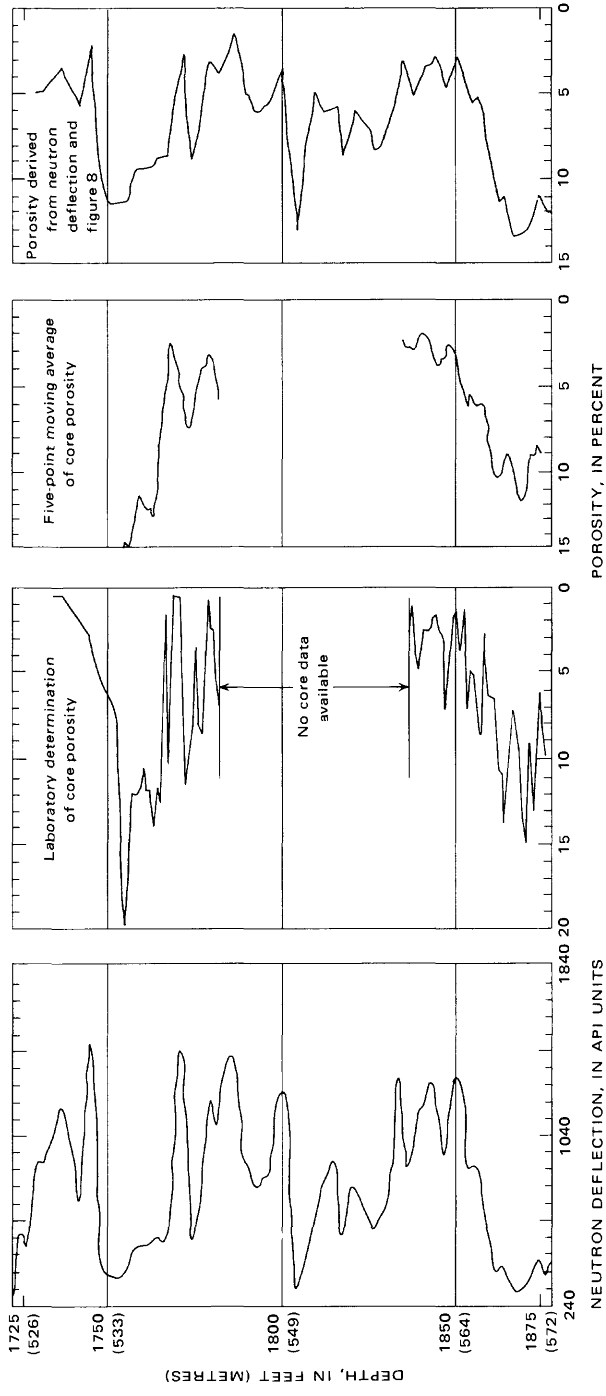


FIGURE 7.—Correlation of neutron curve with laboratory core and derived porosities of the Madison Group in well 06S32E27CDA.

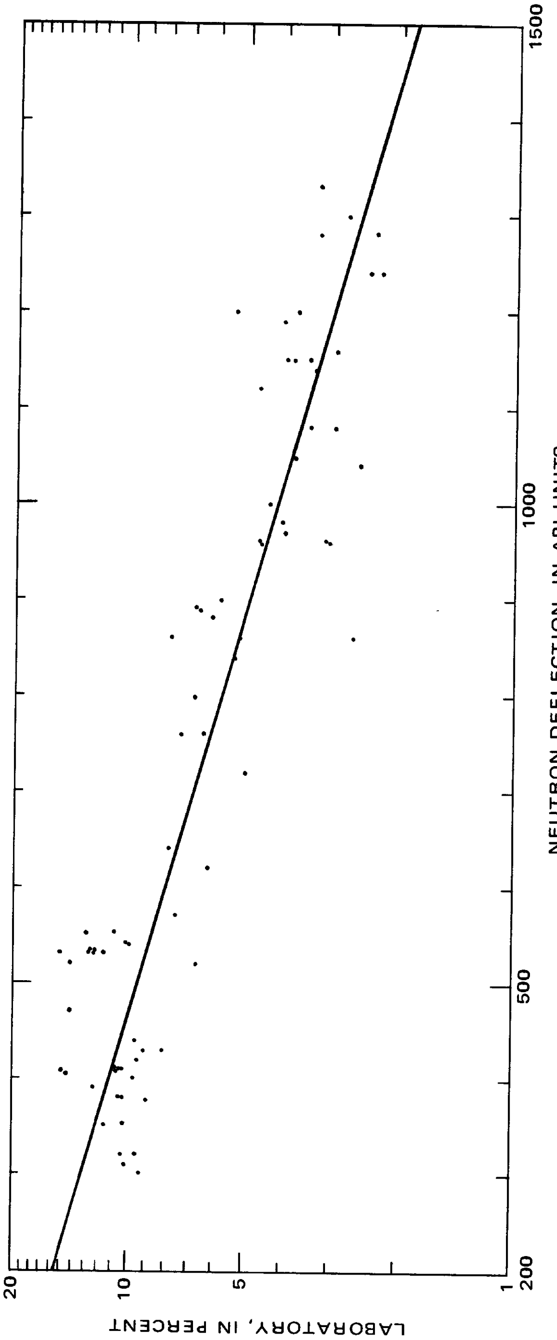


FIGURE 8.—Relation of average core porosity with neutron deflection for well 06S32E27CDA.

within the cored interval can vary by at least several inches, owing to fractures, vugs, and missing core; (2) the small plugs taken from the core for laboratory porosities may not represent the effective porosity of the interval sampled; (3) the neutron log averages the effective porosity of a volume greater than that of the core; and (4) the position of the sonde with respect to the center of the borehole will affect the resultant log. To minimize these problems, the porosity-depth and neutron-depth curves were manually aligned to correct obvious correlation errors, and a five-point moving average of porosity was calculated to compensate statistically for errors due to depth and normal instrumental and statistical fluctuations. The derived porosity of the uncored section, which is also plotted in figure 7, was determined by measuring the deflection of the neutron curve for each foot of depth and converting the values to porosity, using figure 8.

DENSITY LOGS

The density or gamma-gamma log (Pirson, 1963, p. 187-192) measures the effect of the density of rocks and their contained fluids on artificially produced gamma rays. The log records apparent bulk density, which is related to porosity by the following equation:

$$\theta=\frac{\rho_{ma}-\rho_b}{\rho_{ma}-\rho_f}, \tag{8}$$

where

θ = porosity of the rock,

ρ_{ma} = density of the matrix, in grams per cubic centimetre,

ρ_b = bulk density of the rock as measured by the log, in grams per cubic centimetre, and

ρ_f = density of the fluid contained in the rock, in grams per cubic centimetre.

A suite of geophysical logs from well 05N37E26AA (fig. 9) shows a typical density log as well as gamma-ray, caliper, and acoustic logs of the upper Charles Formation. For example, two zones in the Charles Formation indicated in figure 9 to have relatively good porosity are 5,992–6,002 and 6,084–6,104 feet (1,826–1,829 and 1,854–1,860 m). In these zones the rock is assumed to be limestone having a grain density of 2.71 g/cm^3 and the fluid is assumed to be water, having a density of 1.00 g/cm^3. The apparent bulk density is 2.52 and 2.47 g/cm^3, respectively, resulting in porosities of 11 and 14 percent. The section from 6,222 feet (1,896 m) to the bottom of the log is anhydrite, as indicated by an average bulk density of 2.90 to 2.95 g/cm^3.

ACOUSTIC LOGS

Acoustic logs have been described by Pirson (1963, p. 221–237) and Schlumberger, Ltd. (1972a, p. 37–43). These logs measure the transit time of artificially produced elastic waves through rocks adjacent to a

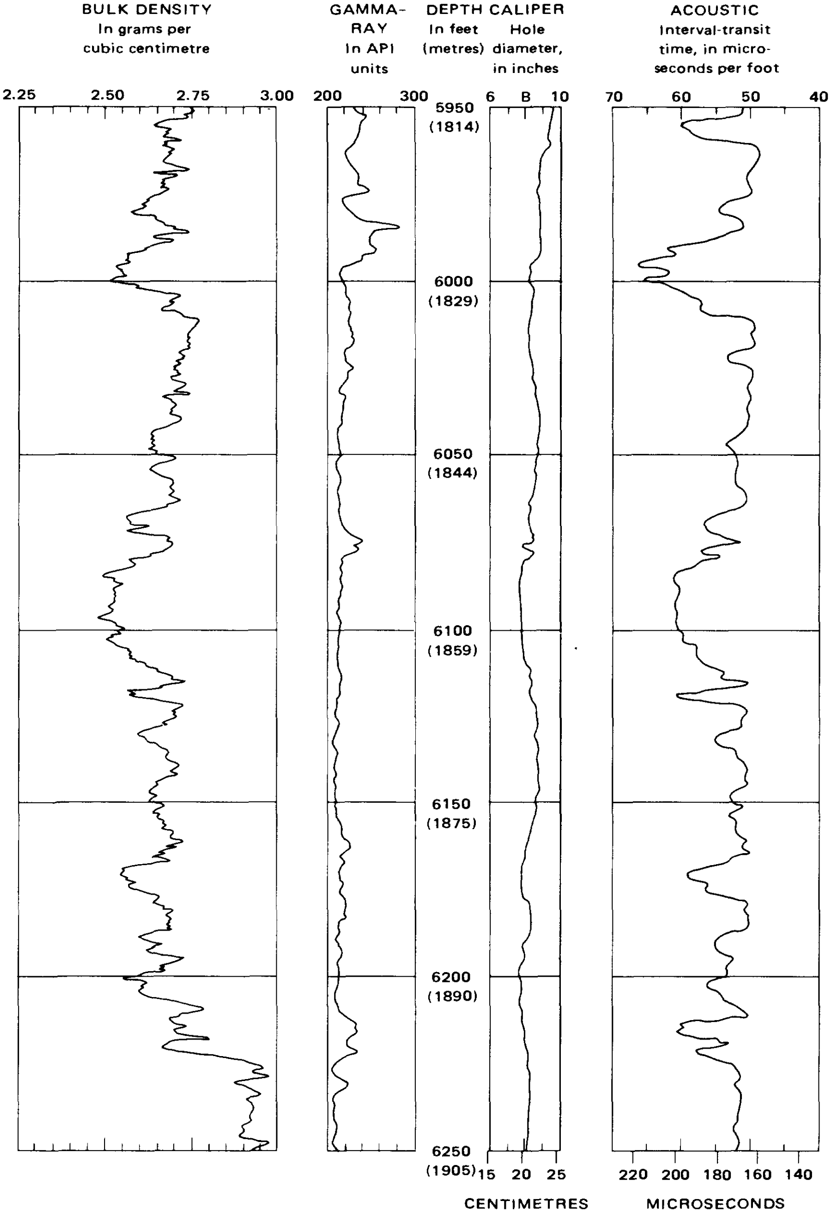


FIGURE 9.—Density, gamma-ray, caliper, and acoustic logs of the upper part of the Charles Formation in well 05N37E26AA.

sonde. The transit time is dependent on the elastic properties of the rock matrix and the type and amount of fluid contained in the rocks, which are related to porosity by the following equation:

$$\theta=\frac{\Delta t_l-\Delta t_{ma}}{\Delta t_f-\Delta t_{ma}}, \tag{9}$$

where

θ = porosity of the rock,

Δt_l = interval-transit time measured by the log, in microseconds per foot.

Δt_{ma} = interval-transit time of the matrix, in microseconds per foot, and

Δt_f = interval-transit time of the fluid contained in the rocks, in microseconds per foot.

Equation 9 can be described in the metric system if interval-transit time is given in units of microseconds per metre. Interval-transit time is the reciprocal of acoustic velocity.

The main uses of acoustic logs in carbonate rocks are determination of porosity and delineation of fractures within the rock framework adjacent to the borehole. For example, analysis of the acoustic log of well 05N37E26AA (fig. 9) indicates several porosity zones, which are confirmed by the density log. The porosities of two of these zones, 5,992–6,002 and 6,084–6,104 feet (1,826–1,829 and 1,854–1,860 m) were estimated to be 15 and 12 percent, respectively. These calculations are based on average interval-transit times measured from the log of about 65 μs/ft (213 μs/m) for the upper zone and 61 μs/ft (200 μs/m) for the lower zone. The calculations are also based on the assumptions that the rock matrix is limestone with an acoustic velocity of 23,000 ft/s (7,010 m/s) or an interval-transit time of 43.5 μs/ft (143 μs/m), and the fluid is water with an acoustic velocity of 5,400 ft/s (1,650 m/s) or an interval-transit time of 185 μs/ft (607 μs/m).

USE OF LOGS IN HETEROGENEOUS ROCKS

The preceding discussion of geophysical logs and techniques for their interpretation assumes that the rocks are homogeneous. However, carbonate rocks generally have complex lithologies, and the distribution of porosity in carbonate rocks is not predictable. Therefore, quantitative analysis of the lithologic and hydrologic characteristics of the Madison using a single geophysical log is difficult. Wrong assumptions about the lithologies and physical properties of the rocks will result in erroneous estimates of porosity. The oil industry has done much research on this problem. For example, Raymer and Biggs (1963) showed that plots of acoustic-interval transit time versus bulk density will indicate porosity and lithology. Plots of these values from the logs of well 05N37E26AA (fig. 9) for the zone 5,992–6,002 feet (1,826–1,829 m) indicate that the porosity is about 11 percent and the rock is dolomitic limestone. Similarly, the zone 6,084–6,104 feet (1,854–1,860 m) has a porosity of about 14 percent and the rock is mainly limestone also.The porosities derived from the log density, acoustic-interval transit time, and a cross-plot of both values are listed below. Similar techniques using acoustic and neutron or density and neutron logs are available. Other workers who have discussed the use of geophysical logs for interpreting carbonate rocks that have more than one type of porosity are Baird (1968), Chombart (1960), Dorin, Chase, and Linke (1968), Pirson (1963), and Savre and Burke (1963).

Interval (feet)	Porosity		
	Density derived	Acoustic derived	Plot derived
5,992–6,002	11	15	11
6,084–6,104	14	12	14

Other factors, such as the number of logs and their quality, can affect the quantitative analysis of geophysical logs. More than 200 wells in southeastern Montana have penetrated at least part of the Madison, and more than one log is available for most of the wells. The amount of time necessary for manual interpretation of all the data would be considerable. A practical approach to data analysis would be to use computers. Dawson-Grove and Palmer (1968) and Poupon, Hoyle, and Schmidt (1970) have discussed computer application in detail and the major service companies offer this service.

Connolly (1968) indicated that the main causes of poor quality logs are the variety of logs available, the difference in ages of the wells that have been logged, and the many instrumental and operator errors that occur when the logs are made. Therefore, standardization of logs is necessary before any quantitative analysis can be made. The logs used in this report appear to have been properly calibrated and appear to be of good quality, except as noted.

Based on this study and studies by other authors, geophysical logs would be useful in an evaluation of the hydrology of the Madison Group. The main value of these logs would be for correlation and determination of porosity and lithology. Logs of most probable benefit would be electric, gamma ray, neutron, density, caliper, and acoustic.

ADDITIONAL STUDY

Detailed conjunctive surface and subsurface studies could define the hydrology of the Madison in enough detail to determine the optimum locations for obtaining large water supplies from the Madison and to predict the effects of large-scale development. Some possible studies are briefly outlined below.

1. A detailed petrologic study of surface and subsurface sections could define the relations between environments of deposition, lithology, geochemistry of the water and rocks, and the development of porous and permeable zones. Definition of these relations might make possible a prediction of the distribution of permeability in the aquifer and, hence, the most probable locations for obtaining large water supplies.
2. A detailed study of borehole geophysical logs could help relate concepts determined in petrologic studies of cored test holes to uncored holes. The information obtained would include porosity and lithology determined from electric, gamma-ray, density, neutron, caliper, and acoustic logs. Because of the large number of well logs and the lengthy methods of analysis, digitization and computer analysis would be most practical.
3. Results of studies using seismic and other surface geophysical methods might show the interrelationships of the following: the "grain" or fabric of the basement rocks and the major structures, such as lineaments, folding, and faulting; the development of porous and permeable zones; the features of the potentiometric surface; and the areal distribution of selected ionic ratios.
4. Hydrologic testing is necessary to define the head relations within the Madison and between the Madison and the overlying and underlying rocks. These tests would also help to define the porosity and permeability distribution, and possibly the chemical characteristics of water in the Madison. These tests would require test drilling, which could (1) determine the feasibility of completing large-diameter production wells in the Madison and (2) permit installation of casing for observation wells to monitor the hydrologic effects of water-supply developments.
5. A detailed analysis of the temperature and hydraulic gradients of the Madison Group and underlying and overlying rocks might be useful in locating zones of ground-water circulation and areas of upward and downward leakage.
6. A detailed study of drill-stem tests is necessary to relate their yields and recovery data to the hydraulic characteristics of the aquifer. The study would entail detailed field testing that would emphasize the effect of drilling fluid on the completion and interpretation of drill-stem tests.
7. A series of hydrogeologic maps and sections showing the horizontal and vertical distribution of lithology, porosity and permeability, potentiometric head, and quality and quantity of water, as well as the configuration and thicknesses of the overlying and underlying rocks, could be used to refine, and to some degree quantify, the existing preliminary concepts about the characteristics of the hydrologic system.

SUMMARY

The Madison Group aquifer is a thick sequence of carbonate rocks that has undergone several periods of deformation and karstification. Water in the aquifer is under artesian conditions. The aquifer is assumed to be bounded at the base by Cambrian, Ordovician, Silurian, or Devonian rocks and at the top by the Mississippian Big Snowy Group or by Pennsylvanian or Jurassic rocks. Some data suggest that locally the Madison may be hydraulically connected with porous and permeable zones of the underlying and overlying rocks, mainly Ordovician and Pennsylvanian rocks.

The Madison Group consists of the Lodgepole Limestone, Mission Canyon Limestone, and Charles Formation. The Lodgepole Limestone consists of thin-bedded argillaceous dense to crystalline and fragmental or oolitic limestone and dolomitic limestone and crystalline dolomite. Several facies changes occur in the area. Porosity and permeability development is in fragmental or oolitic limestone in the upper part and coarsely crystalline dolomite in the lower part.

The Mission Canyon Limestone consists of dense to crystalline thick-bedded to massive and fragmental to oolitic or pisolitic limestone and dolomitic limestone, and crystalline dolomite. Locally, anhydrite occurs. Porosity and permeability development occurs in coarsely crystalline oolitic to pisolitic or fragmental limestone and in coarsely crystalline dolomite.

The Charles Formation consists of anhydrite and halite with restricted-marine limestone and dolomite. Porosity and permeability are mainly in dolomite and fragmental limestone and in some evaporites.

The Madison Group consists of cyclically deposited normal-marine carbonates and restricted-marine carbonates and evaporites. The rocks range in thickness from about 700 feet (210 m) in the Bighorn Mountains to about 2,000 feet (610 m) in the Williston basin. The depth to the top of the Madison ranges from land surface in the Bighorn Mountains to about 10,000 feet (3,000 m) on the Montana-Wyoming border. Along the perimeter of the Fort Union coal region (fig. 1), the Madison is about 6,000 feet (1,800 m) below land surface.

The major structures in the study area are the Bighorn and Black Hills uplifts, the Porcupine dome, the Cedar Creek anticline, and the Powder River, Bull Mountains, and Williston basins. A zone of intensive deformation lies in the northwestern part of the area, and the Lake Basin fault zone extends into the area from the west.

Contours on the potentiometric surface, which are based on data from drill-stem tests and wells, indicate that movement of water in the Madison is to the north and northeast. The gradient slopes away from the outcrop areas and flattens toward Williston basin. Potentiometric lows occur in the Cat Creek anticline–Porcupine dome area, along the Bighorn River, and at the north end of the Powder River basin. In addition to potentiometric highs in the outcrop areas, one occurs between the Bighorn, Yellowstone, and Tongue Rivers. Other smaller anomalies, which occur on the Cedar Creek anticline, may be the result of injection and pumping of water in the production of oil in that area.

The potentiometric surface is as much as 1,200 feet (370 m) below land surface on the divide between the Little Bighorn and Tongue Rivers. It is as much as 1,000 feet (300 m) above land surface along the Yellowstone River.

Recharge to the Madison occurs in the structurally high outcrop areas. Some of the recharge is from losing streams where they cross the outcrop areas. Some of the recharge is in the interstream areas where Feltis (1973, p. 29) estimated that as much as 58 percent of the average annual precipitation recharges the aquifer. Subsurface inflow from outside the area and leakage from underlying or overlying beds also recharge the aquifer.

Discharge from the aquifer is from springs, to gaining streams in the outcrop areas, by upward leakage to overlying beds through locally permeable beds or through faulted zones, by subsurface outflow, and by pumping from wells. The availability of water in the Madison must be generalized from the few known producing wells. Withdrawals by individual industrial wells generally are less than 200 acre-feet (0.25 million m^3) per year. Yields from wells range from about 50 gal/min (3 l/s) in several places to a reported 1,400 gal/min (88 l/s). Yields from drill-stem tests range from about 1 to 157 gal/min (0.1 to 9.9 l/s).

South of about T. 1 N., water in the Madison Group generally contains less than 3,000 mg/l dissolved solids. North of this line the dissolved-solids concentrations range from 3,000 to 10,000 mg/l, except in the Williston basin, where the concentrations appear to exceed 100,000 mg/l. In the southeast and southwest, calcium, magnesium, and sulfate ions constitute more than 75 percent of the dissolved constituents, in milliequivalents per litre. North of about T. 8 N., sodium, potassium, and chloride ions constitute more than 50 percent of the dissolved constituents; in the Williston basin sodium, potassium, and chloride ions constitute more than 75 percent of the total.

Porous and permeable zones occur in most of the Madison but their locations are difficult to predict and they are difficult to correlate from place to place. Analysis of geophysical logs and related interpretive techniques indicates that the logs of most probable benefit for identifying and determining the characteristics of porous and permeable zones in a detailed geohydrologic study of the Madison would be electric, gamma-ray, neutron, density, caliper, and acoustic.

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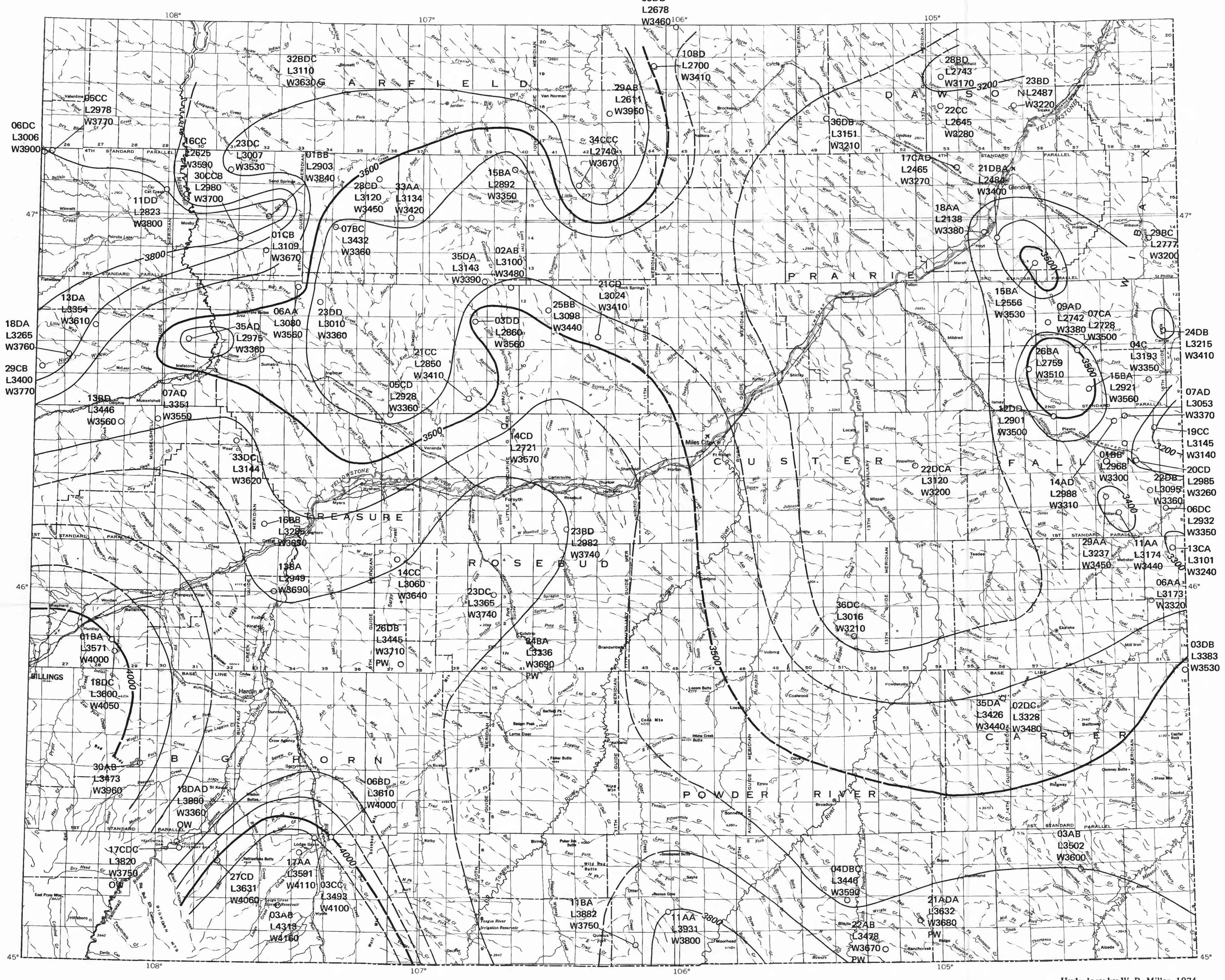


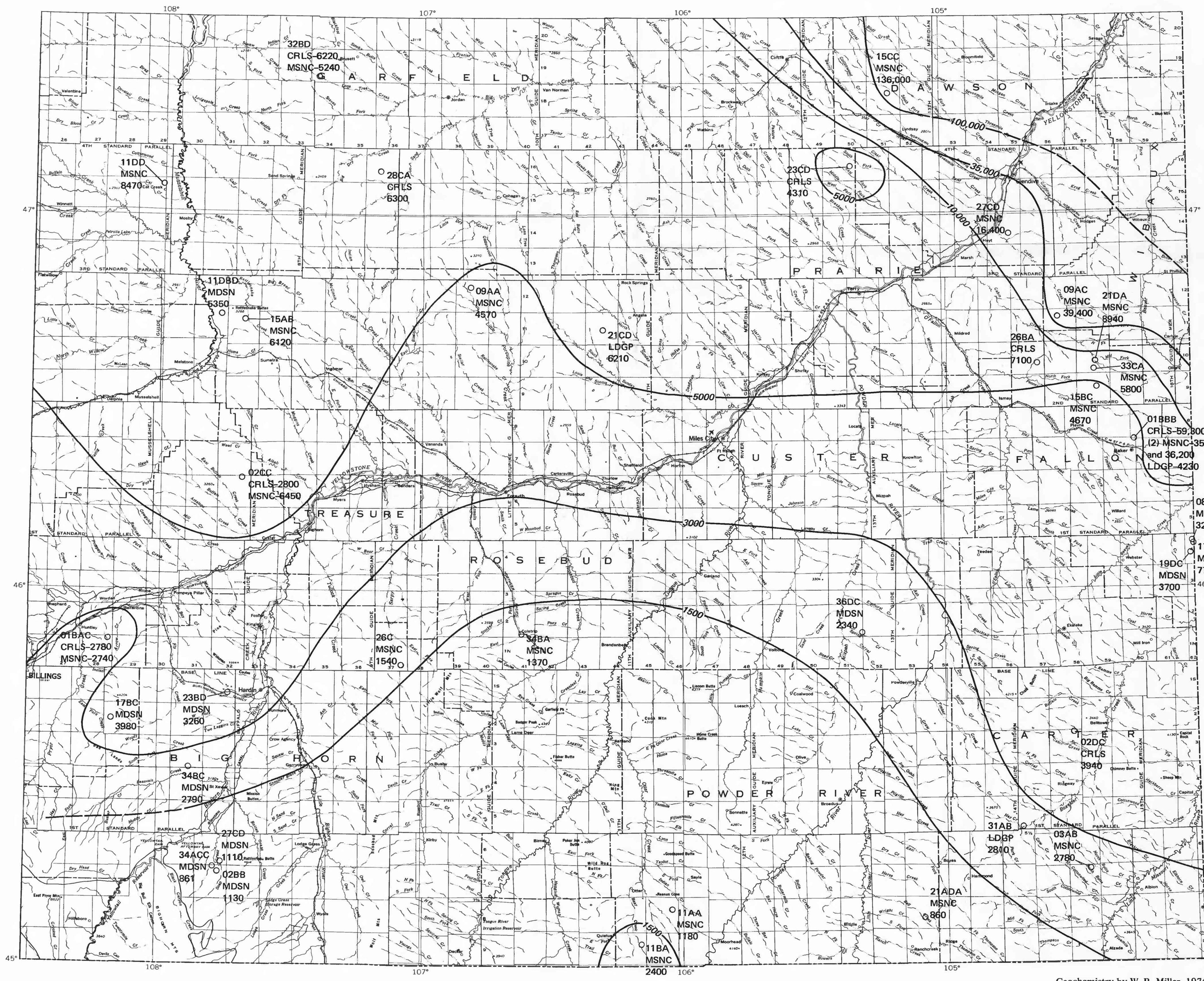
Hydrology by W. R. Miller, 1974

EXPLANATION

—3500— GENERALIZED POTENTIOMETRIC CONTOURS— Show altitude at which water level would have stood in tightly cased wells in the Madison Group if the water had a density of 1.00 g/cm^3. Dashed where approximately located. Contour interval 100 feet (30.5 m). Datum is mean sea level. Data from drill-stem tests and water-level measurements in production and observation wells made from 1946 to 1974

○34BA L3236 W3690 PW — WELL USED FOR CONTROL POINT – Upper number is section-number part of well-location number. Number prefixed with L is altitude of land surface, in feet above datum. Number prefixed with W is altitude of water level, in feet above datum. PW indicates data from production well; OW indicates data from observation well; all other data from drill-stem tests

A. GENERALIZED POTENTIOMETRIC SURFACE



Geochemistry by W. R. Miller, 1974

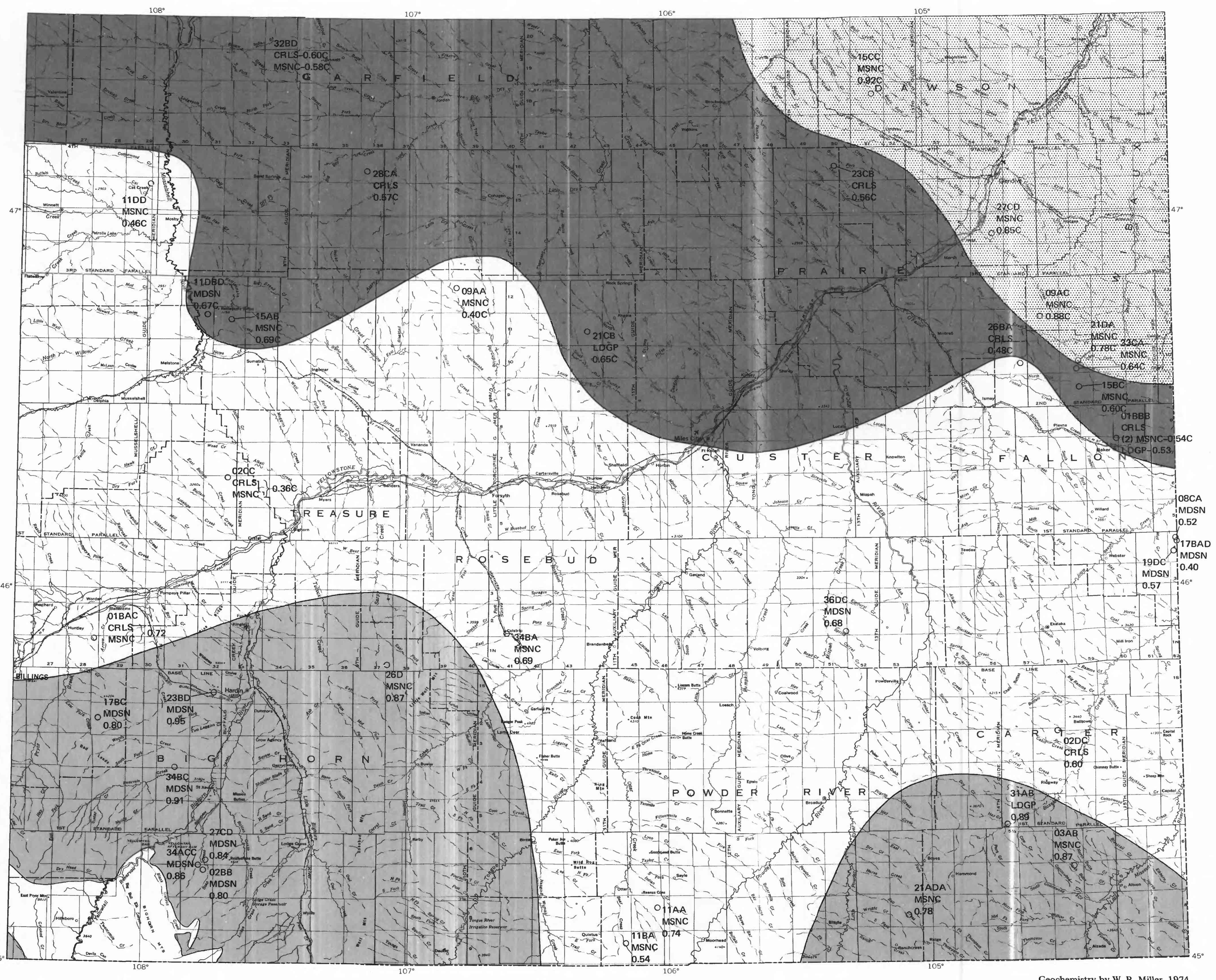
EXPLANATION

—5000— LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION (SALINITY) – Dashed where approximately located. Intervals, in milligrams per litre, are variable. Where analyses are available from several formations in the same well, lines are drawn to MSNC or LDGP analysis

○28CA CRLS 6300 — WELL USED FOR CONTROL POINT – Oil-test or production well. Upper number is section-number part of location number. Letters are geologic unit. CRLS is Charles Formation, MSNC is Mission Canyon Limestone, LDGP is Lodgepole Limestone, and MDSN is Madison Group undivided. Lower number is calculated dissolved-solids concentration (salinity) of water sample from indicated geologic unit, in milligrams per litre

——— BOUNDARY – Top or basinward limit of exposed Madison Group rocks

B. DISSOLVED-SOLIDS CONCENTRATION OF WATER



Geochemistry by W. R. Miller, 1974

EXPLANATION

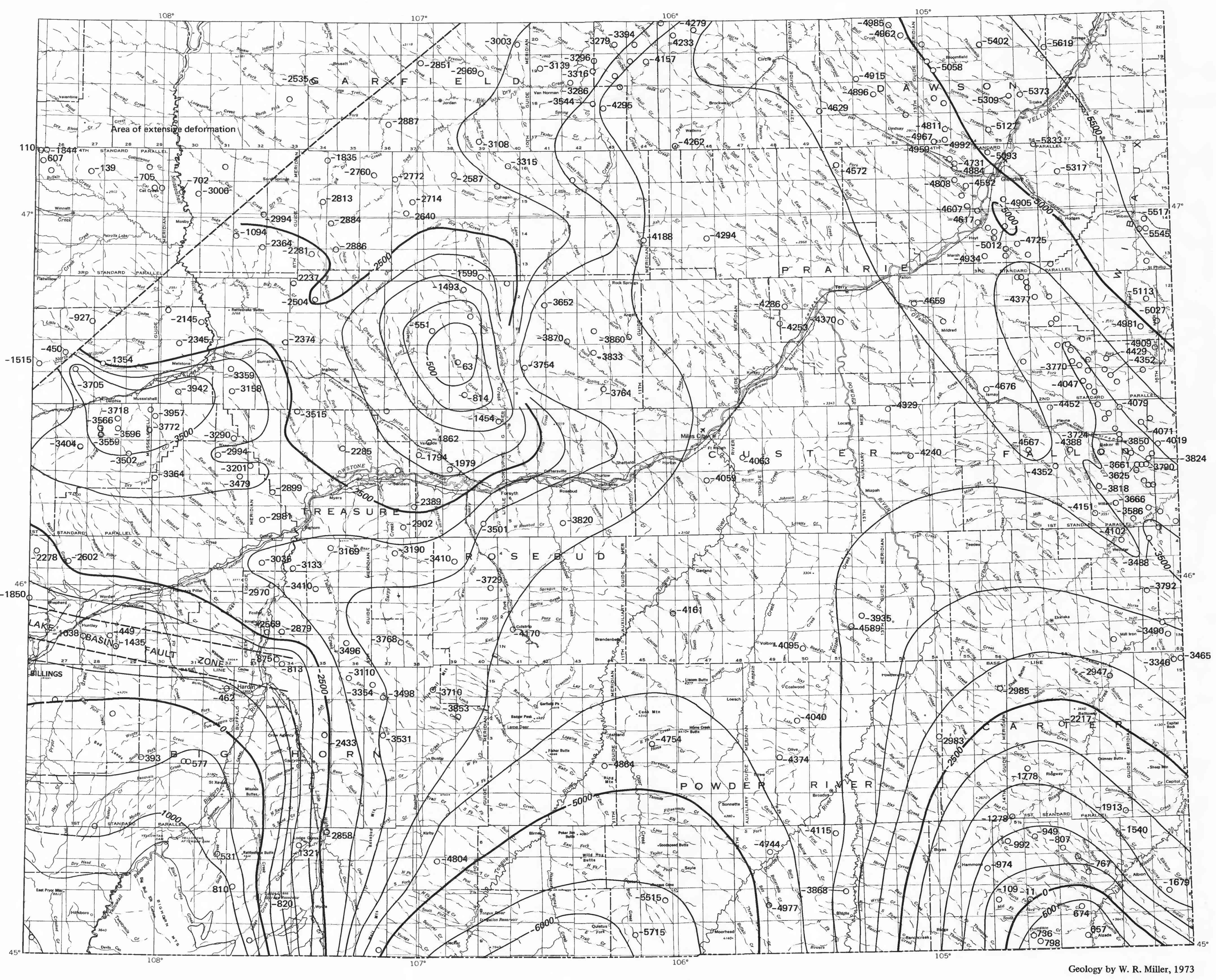
GENERALIZED AREAS WHERE WATER CONTAINS INDICATED PERCENTAGE OF MAJOR CONSTITUENTS

- Water contains more than 75 percent calcium + magnesium + sulfate ($Ca + Mg + SO_4$) and less than 25 percent sodium + potassium + chloride ($Na + K + Cl$)
- Water contains between 50 and 75 percent calcium + magnesium + sulfate ($Ca + Mg + SO_4$) and less than 50 percent sodium + potassium + chloride ($Na + K + Cl$)
- Water contains between 50 and 75 percent sodium + potassium + chloride ($Na + K + Cl$) and less than 50 percent calcium + magnesium + sulfate ($Ca + Mg + SO_4$)
- Water contains more than 75 percent sodium + potassium + chloride ($Na + K + Cl$) and less than 25 percent calcium + magnesium + sulfate ($Ca + Mg + SO_4$)

○15AB MSNC 0.69C — WELL USED FOR CONTROL POINT – Oil-test or production well. Upper number is section-number part of location number; see text for explanation of location-numbering system. Letters are geologic units. CRLS is Charles Formation, MSNC is Mission Canyon Limestone, LDGP is Lodgepole Limestone, MDSN is Madison Group undivided. Lower number is ratio of calcium + magnesium + sulfate ($Ca + Mg + SO_4$) to sum of all constituents; when followed by C, is ratio of sodium + potassium + chloride ($Na + K + Cl$) to sum of all constituents. Ratio is dimensionless, calculated from values in milliequivalents per litre

——— BOUNDARY – Top or basinward limit of exposed Madison Group rocks

C. GENERAL CHEMICAL CHARACTER OF WATER



Geology by W. R. Miller, 1973

EXPLANATION

—-5000— STRUCTURE CONTOURS – Show altitude of top of Madison Group. Dashed where approximately located. Contour interval 500 feet (152 metres). Datum is mean sea level

○-4295 WELL USED FOR CONTROL POINT – Oil test or production well. Number is altitude of top of Madison Group, in feet above or (-) below datum

BOUNDARIES

- - - - - - Limit of extensive deformation zone or fault zone

——— Top or basinward limit of exposed Madison Group rocks

D. CONFIGURATION OF THE TOP OF THE MADISON GROUP

Base from U.S. Geological Survey
State base map, 1975

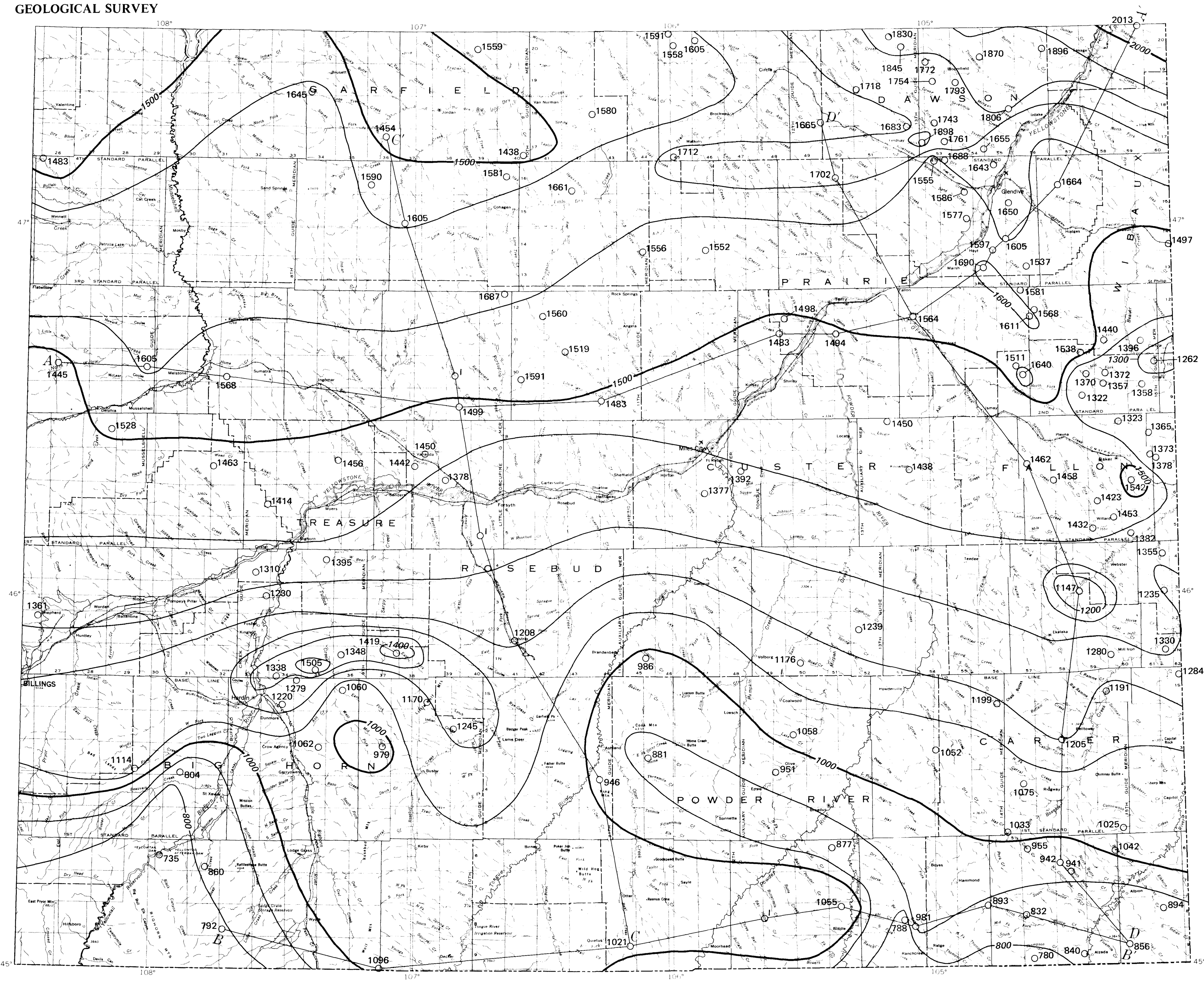
SCALE 1:1 000 000

25 0 25 50 75 100 MILES

25 0 25 50 75 100 KILOMETRES

MAPS SHOWING THE GENERALIZED POTENTIOMETRIC SURFACE, DISSOLVED-SOLIDS CONCENTRATION, AND GENERAL CHEMICAL CHARACTER OF THE WATER AND THE CONFIGURATION OF THE TOP OF THE MADISON GROUP IN SOUTHEASTERN MONTANA

Prepared in cooperation with the
MONTANA BUREAU OF MINES AND GEOLOGY



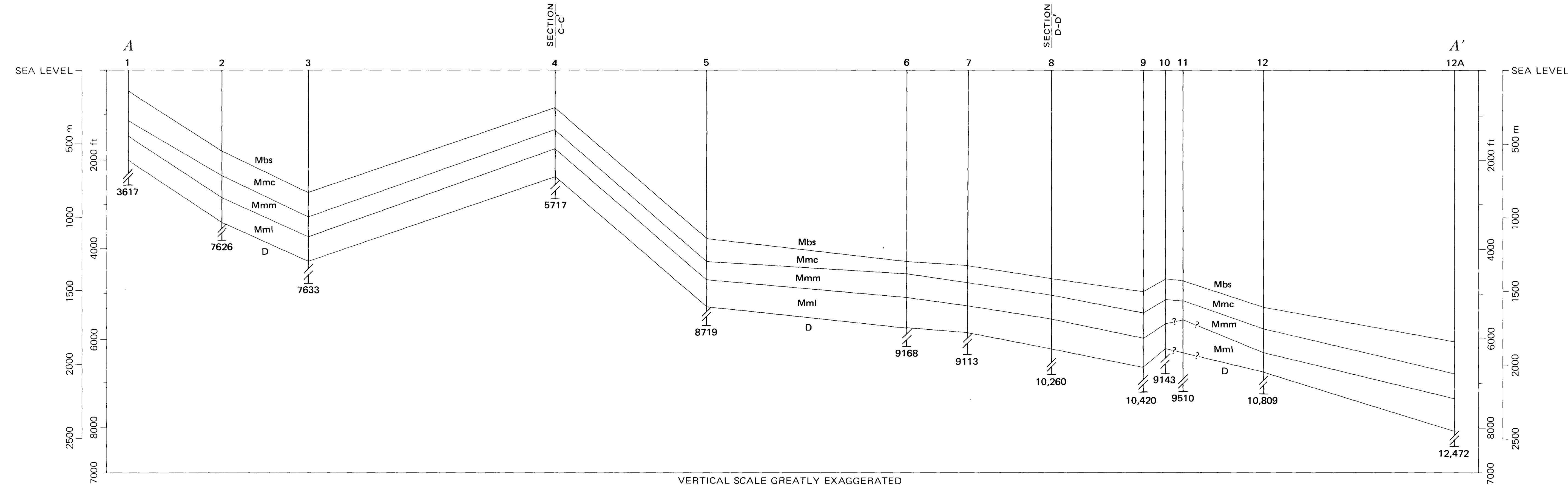
Base from U.S. Geological Survey State base map, 1975

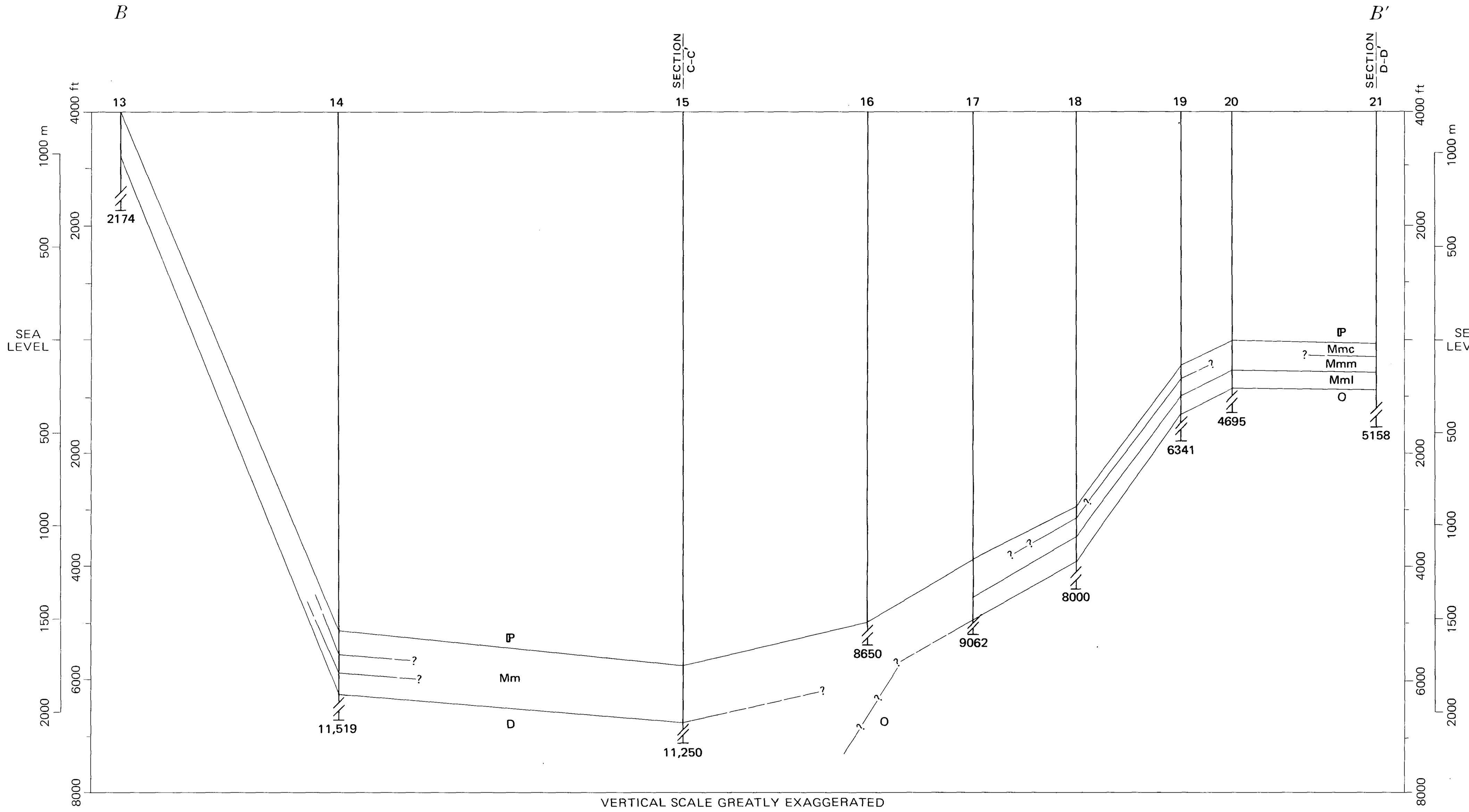
SCALE 1:1 000 000

25 0 25 50 75 100 MILES

25 0 25 50 75 100 KILOMETRES

Thickness from Andrichuk (1955) and Nordquist (1953); modified by W. R. Miller, 1973





EXPLANATION

—1000— LINES OF EQUAL THICKNESS OF THE MADISON GROUP – Interval 100 feet (30.5 metres). May include Devonian and Mississippian Bakken Formation in northern part of study area

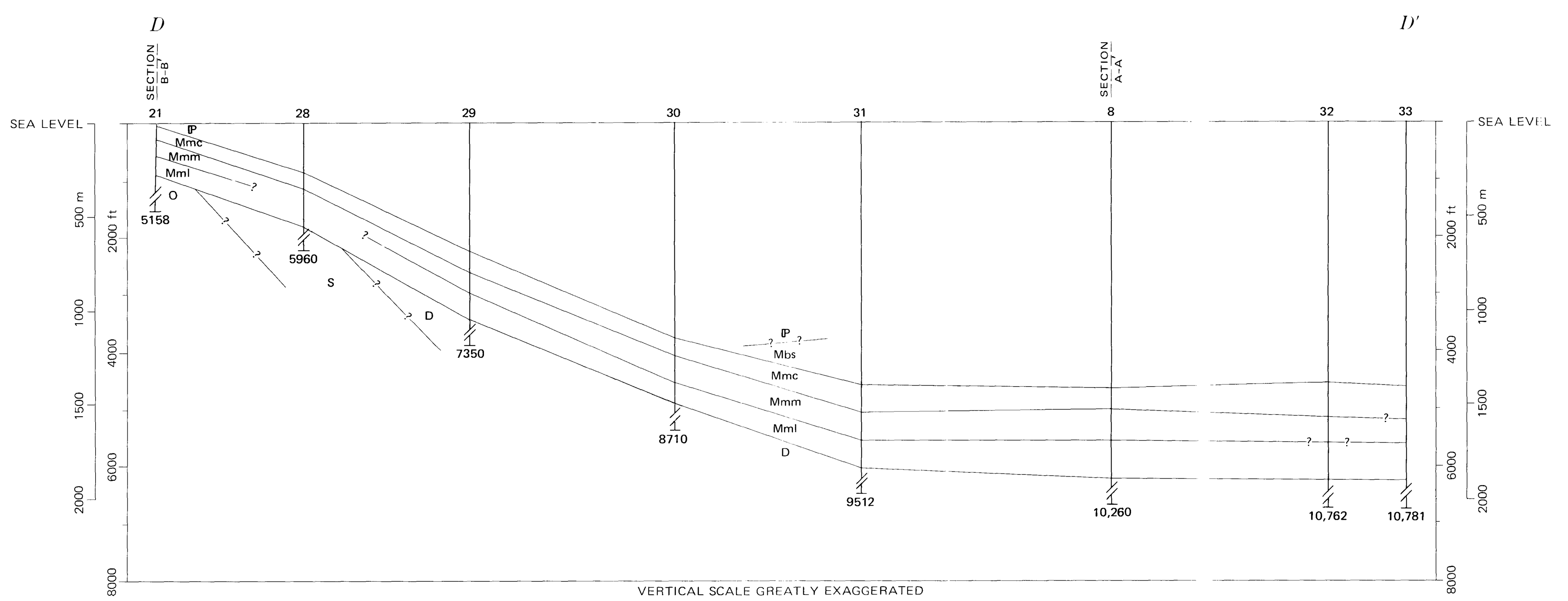
○1559 WELL USED FOR CONTROL POINT – Oil-test or production well. Number is thickness of Madison Group, in feet. ׀ indicates well did not completely penetrate Madison Group

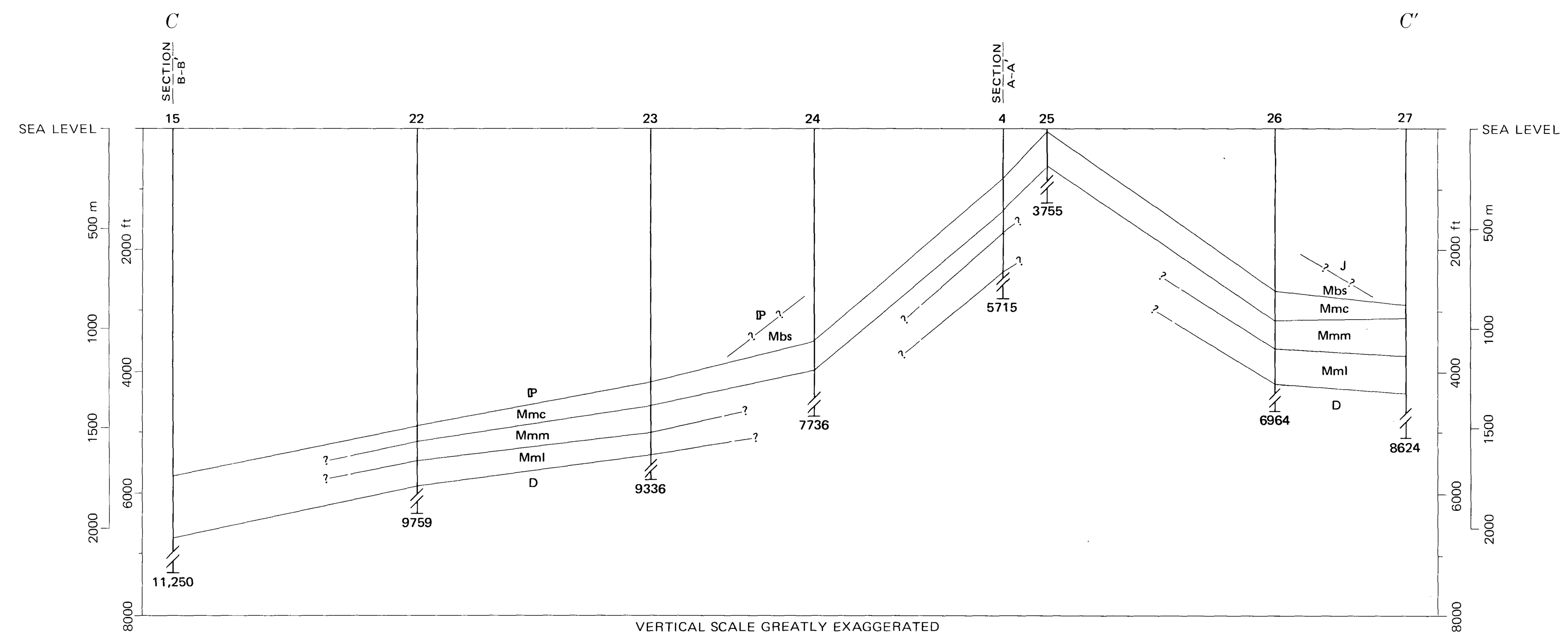
A —— A′ Line of correlation section

11 Numbers at top of section correspond to well numbers in table below.

9510 Number is total depth of well, in feet

Well no.	Location
1	10N27E18DA
2	10N29E23DB
3	10N32E29BD
4	09N39E21CC
5	09N43E14DB
6	11N49E17BB
7	11N51E18BCB
8	12N53E33AB
9	13N55E17AB
10	14N55E34CBD
11	14N55E24ABD
12	16N57E34DD
12A	20N59E02AD
13	08S33E30BAA
14	09S37E36AAA
15	09S45E11BA
16	08S50E18CB
17	08S52E04DBC
18	08S54E27CB
19	08S56E01CA
20	08S58E18CBA
21	09S61E17DBA
22	04S44E03DA
23	02N41E34BA
24	05N40E20DA
25	10N39E20DB
26	15N37E33AA
27	17N36E10DC
28	06S59E30DDA
29	03S58E02DCB
30	03N59E19AD
31	07N57E20AA
32	16N50E23CB
33	18N49E36DB





ERATHEM	SYSTEM	GROUP	FORMATION
MESOZOIC	JURASSIC J		
PALEOZOIC	PENNSYLVANIAN IP		
	MISSISSIPPIAN	Big Snowy Group Mbs	
		Madison Group Mm	Charles Formation Mmc
			Mission Canyon Limestone Mmm
			Lodgepole Limestone Mml
	DEVONIAN D		
	SILURIAN S		
	ORDOVICIAN O		

MAP SHOWING GENERALIZED THICKNESS OF THE MADISON GROUP AND CORRELATION SECTIONS OF MISSISSIPPIAN ROCKS IN SOUTHEASTERN MONTANA

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TABLE 3.—*Ratio of mean annual discharge to the average for the 30-year reference period 1941–70, for long-term stream-gaging stations in the upper Ohio River basin, Pennsylvania, New York, Maryland, northern West Virginia, and Ohio*

[Italic and boldface numbers indicate ratios computed from prior station site data which have been adjusted by a drainage area ratio]

Abbrev. station No.	1904	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940
0105																		0.78					0.84	1.16	1.26	1.05	1.03	0.67	0.88	0.88	0.61	0.81	0.92	1.18	1.03	0.77	1.01
01102	1.28	0.86	0.82	1.09	1.30	1.04	1.11	1.10	1.10	1.21	0.94	0.92	1.51	1.05	1.04	0.99	0.78	.78	.99	0.72	0.94	0.74	.93	1.18	1.31	1.25	.97	.65	.95	.81	.67	.85	.93	1.23	.97	.80	1.06
01255																																	.95	1.23	1.01	.81	1.06
0130																																				.78	1.13
0145																																	.89	1.12	1.19	.82	1.05
0150																																					1.05
0155							.92	1.28	1.39	1.29	.96	.82	1.22	1.09	.87	.92	.96	.85	.88	.74	.97	.71	1.00	1.24	1.29	1.01	.86	.53	.78	.64	.59	.69	.92	1.17	1.03	.86	1.01
0160																																					
0175																																			1.11	.82	1.08
0200							.85	.99													1.09	.75	1.03	1.43	1.46	1.30	1.06	.60	.93	.75	.60	.87	.95	1.39	1.04	.75	1.05
0205							.88	1.07	1.32	1.25	1.01	.77	1.08	1.05	.92	.91	.80	.81	.83	.68	.84	.62	.89	1.23	1.14	1.15	.88	.62	.83	.72	.65	.72	.93	1.31	1.02	.88	.97
02152							.91	1.26	1.40	1.39	1.10	.98	1.17	1.06	.86	.87	.59	.92	.81	.62	.85	.63	.97	1.21	1.22	1.03	.93	.57	.77	.70	.70	.69	.88	.98	1.11	.82	1.02
0240						.98	.88	1.27	1.46	1.40	1.18	.90	1.14	1.05	.91	.89	.77	.88	.85	.66	.95	.73								.66	.64	.68	.80	1.16	1.03	.83	.91
0250																														.63	.57	.63	.88	1.46	1.09	.91	.91
0255												.84	1.27	1.05	.99	.97	.80	.84	.96	.72	.95	.75	1.06	1.27	1.31	1.21	.98	.62	.89	.76	.66	.78	.91	1.27	1.06	.84	1.03

Abbrev. station No.	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
0105	0.70	1.28	1.50	0.79	1.41	1.21	1.20	1.06	0.78	1.00	1.43	1.22	0.97	0.80	0.75	1.42	0.91	0.90	1.00	1.08	0.87	0.70	0.75	0.94	0.74	0.85	0.94	1.06	0.78	1.01	1.07	1.63	1.16	1.27	
01102	.75	1.07	1.45	.79	1.29	1.13	1.28	1.05	.77	1.01	1.31	1.17	.93	.80	.77	1.49	.94	.87	1.00	1.17	.88	.73	.76	.86	.76	.88	1.02	1.12	.98	1.00	1.11	1.44	1.14	1.21	
01255	.76	1.05	1.48	.78	1.28	1.12	1.25	1.06	.78	1.03	1.33	1.15	.92	.79	.79	1.49	.94	.88	1.00	1.17	.90	.76	.76	.88	.78	.90	.99	1.08	.95	.98	1.06	1.33	1.12	1.14	
0130	.81	.94	1.39	.96	1.16	.97	1.35	.92	.74	1.01	1.16	1.03	.80	.83	.95	1.36	.98	.98	1.10	1.12	.92	.72	.77	.85	.84	1.05	.94	1.05	1.23	1.08	1.20	1.25	1.11	1.02	
0145	.74	.98	1.46	.95	1.13	.92	1.35	1.01	.77	1.17	1.22	.99	.76	.77	.92	1.34	.95	.88	1.08	1.13	.86	.68	.74	.87	.98	.96	1.17	1.00	1.20	1.05	1.17	1.38	1.14	1.01	
0150	.77	.94	1.44	.94	1.13	.96	1.31	.94	.75	1.09	1.23	1.03	.81	.80	.97	1.42	.99	.89	1.11	1.13	.83	.68	.74	.85	.92	.98	1.05	1.06	1.21	1.03	1.18	1.27	1.13	1.02	
0155	.74	.87	1.39	.79	1.07	1.03	1.31	.94	.86	1.20	1.30	1.15	.88	.79	.95	1.48	.95	.95	1.05	1.11	.77	.65	.72	.89	1.00	.91	1.13	.98	1.18	.91	1.15	1.27	1.08	1.03	
0160		.97	1.46	.82	1.22	1.09	1.27	1.02	.81	1.08	1.32	1.12	.90	.79	.85	1.52	.96	.89	1.03	1.16	.85	.71	.73	.87	.84	.92	.99	1.03	1.05	.99	1.12	1.35	1.10	1.09	
0175	.75	.89	1.42	.75	1.18	1.14	1.13	.98	.73	1.12	1.49	1.22	.99	.79	1.10	1.60	.89	.94	1.09	1.08	.86	.73	.71	.87	.83	.93	.92	.95	.94	.98	1.12	1.31	1.08	1.11	
0200	.70	.91	1.44	.79	1.15	1.19	1.11	.96	.75	1.17	1.49	1.20	.97	.73	1.06	1.54	.89	.95	1.07	1.06	.88	.73	.72	.87	.85	.98	.93	.97	.96	.98	1.15	1.35	1.13	1.15	
0205	.68	.93	1.37	.76	.96	1.15	1.16	.88	.89	1.27	1.39	1.29	1.00	.83	1.09	1.43	.95	.97	1.11	1.14	.73	.58	.68	.89	.98	.93	1.04	.94	1.11	.90	1.12	1.29	1.16	1.13	
02152	.73	.93	1.32	.90	1.01	.94	1.40	1.01	.93	1.16	1.25	1.01	.82	.84	.99	1.30	.94	.90	1.08	1.10	.78	.68	.74	.92	1.06	.86	1.16	1.01	1.18	1.07	1.01	1.40	1.09	1.05	
0240	.72	.95	1.29	.81	.92	1.05	1.25	.87	.90	1.28	1.27	1.14	.87	.79	1.03	1.42	.95	.90	1.10	1.19	.76	.65	.71	.95	1.03	.91	1.09	1.03	1.20	.98	1.14	1.29	1.09	1.10	
0250	.74	.97	1.41	.84	.88	1.11	1.14	.89	.89	1.30	1.31	1.34	.95	.67	1.13	1.53	.93	.93	1.11	1.23	.73	.61	.63	.93	.97	.94	.90	.96	1.13	.85	1.10	1.48	1.28	1.08	
0255	.76	.96	1.44	.81	1.12	1.10	1.23	.96	.81	1.15	1.33	1.16	.91	.78	.95	1.50	.96	.91	1.05	1.15	.84	.68	.75	.89	.90	.91	1.00	.99	1.05	.96	1.11	1.33	1.11	1.09	

Abbrev. station No.	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940
0285																																				
0295																																			0.72	1.01
0305																																				
0315																													0.76	0.62	0.80	0.91	1.26	1.05	.80	.99
0325															0.97	1.14	0.91	1.04	0.82	1.21	0.62	0.94	1.39	1.54	1.22	0.95	0.56	0.85	.91	.52	1.02	1.08	1.49	1.16	.76	.89
0340																																			.70	.86
0345																																				.79
0360																																			.79	.87
0365	0.95	0.88	1.12	1.29	0.94	0.82	1.11	1.38	1.28	1.15	0.85	1.37	1.10	1.03	.99	.88	.87	.98	.77	1.08	.75	1.09	1.41	1.50							.82	.92	1.27	1.07	.83	.98
0380																																		1.06	.89	.91
0390						.74	.97	1.66	1.40	1.15	1.02	1.41	1.01	.95	1.16	1.23	.96	1.12	.76	1.51	.61	1.12	1.38	1.76	.81	.82	.47	.65	1.06	.73	1.01	1.00	1.37	1.01	.85	.90
0400										1.03	.81	1.24	.98	.88	.78	1.31	.92	1.05	.79	1.47	.59	.83	1.43	1.48	.84	.68	.64	.76	1.00	.64	.99				.80	.99
0410																																				.94
0415																																			.81	.94
0430	1.05			1.37	.97	.96	.98	1.71	1.18	1.10	.84	1.41	.97	.93	.93	1.14	.91	.94	.73	1.30	.58	.92	1.31	1.56	.82	.84	.56	.74	1.00	.82	1.09	1.23	1.47	1.08	.76	.86
0440																																				.91
0450																																				.94
0470																																				1.00
0485				1.51	.85	.92	.98	1.65	1.01	1.13	.86	1.33	.96	.88	.90	1.25	.94	1.05	.89	1.44	.68	1.02	1.38	1.59	.95	.85	.65	.80	1.05	.81	1.12	1.21	1.59	.99	.78	.96
0490																																				
0495																																			.81	.98

Abbrev. station No.	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
0285						1.13	1.10	1.03	0.79	1.15	1.45	1.21	1.10	0.82	0.87	1.47	0.89	0.91	0.98	1.08	0.89	0.77	0.76	0.88	0.83	0.95	0.95	0.99	0.82	1.07	1.06	1.38	1.17	1.37	
0295	0.80	0.93	1.44	0.68	1.21	1.14	1.09	.97	.83	1.16	1.45	1.22	.99	.81	.99	1.48	.87	.98	1.00	1.09	.83	.83	.77	.85	.83	.93	.96	.99	.83	1.04	1.11	1.42	1.17	1.32	
0305					1.16	1.12	1.05	.95	.83	1.19	1.47	1.23	.94	.77	1.03	1.47	.88	.97	1.02	1.10	.83	.77	.73	[illegible]	.86	.97	.99	1.06	.86	1.05	1.09	1.44	1.20	1.32	
0315	.77	.95	1.42	.79	1.12	1.10	1.19	.96	.84	1.17	1.36	1.18	.92	.78	.98	1.50	.93	.91	1.04	1.13	.82	.69	.72	.89	.90	.92	1.00	1.01	1.03	.98	1.13	1.35	1.15	1.14	
0325	.78	.81	1.36	.78	1.23	1.11	1.02	1.04	.93	1.14	1.50	1.22	.89	.75	1.07	1.53	.87	1.05	.93	1.08	.90	.84	.64	.95	.88	.95	1.00	.97	.79	1.00	1.16	1.49	1.26	1.29	
0340	.77	.81	1.33	.72	1.20	1.09	1.05	.94	.87	1.05	1.44	1.20	.94	.72	1.02	1.66	.94	1.15	1.03	1.10	.92	.80	.68	1.00	.85	.94	1.08	.95	.74	1.05	1.23	1.49	1.32	1.52	
0345	.72	.86	1.29	.87	1.37	1.12	.97	1.00	.81	1.08	1.54	1.19	.90	.74	1.06	1.66	.84	1.03	.90	1.10	1.03	.86	.88	.88	.79	.86	.92	.88	.74	1.08	1.12	1.43	1.37	1.30	
0360	.77	.85	1.34	.83	1.30	1.15	1.04	.97	.85	1.03	1.47	1.18	.92	.72	1.01	1.61	.90	1.14	1.00	1.08	.94	.82	.69	.96	.84	.91	1.00	.91	.70	1.03	1.16	1.45	1.28	1.39	
0365	.74	.95	1.42	.80	1.14	1.11	1.18	.98	.85	1.14	1.37	1.17	.92	.77	.98	1.48	.93	.95	1.06	1.14	.85	.73	.70	.88	.89	.92	.98	.99	.98	.99	1.11	1.34	1.15	1.15	
0380	.65	.82	1.30	.83	1.45	1.16	.89	1.06	.86	1.03	1.63	1.15	.89	.75	1.17	1.86	.87	.94	.87	1.15	.95	.84	.79	.88	.80	.81	.94	.85	.62	1.15	1.32	1.36	1.28	1.31	
0390	.64	.81	1.35	.83	1.50	1.18	.89	1.11	.89	1.03	1.58	1.15	.89	.75	1.21	1.83	.89	1.00	.85	1.13	.95	.85	.75	.87	.82	.80	.95	.87	.62	1.00	1.18	1.39	1.17	1.21	
0400	.87	.89	1.27	.85	1.17	.99	.80	1.01	.97	1.14	1.36	1.19	1.05	.53	1.33	1.23	.88	1.01	.82	1.18	1.19	.93	.87	1.02	.84	.70	.99	.82	.70	1.37	1.52	1.47	1.21	1.13	
0410	.85	.93	1.24	.83	1.17	1.06	.77	1.04	.97	1.13	1.54	1.20	1.07	.65	1.34	1.28	.81	.87	.81	1.25	1.12	.84	.81	.98	.86	.78	1.04	.85	.73	1.18	1.41	1.60	1.28	1.15	
0415	.88	.88	1.27	.86	1.16	1.01	.82	1.03	.98	1.13	1.40	1.19	1.06	.57	1.32	1.28	.91	.99	.83	1.19	1.15	.92	.86	.98	.83	.75	.98	.82	.69	1.25	1.45	1.45	1.21	1.15	
0430	.71	.84	1.26	.86	1.33	1.16	.90	1.10	.96	1.17	1.67																								
0440	.80	.87	1.26	.87	1.26	1.08	.86	1.08	.99	1.17	1.53	1.19	.99	.63	1.27	1.33	.87	.97	.86	1.14	1.10	.89	.83	.96	.80	.80	.98	.79	.69	1.15	1.32	1.41	1.21	1.19	
0450	.88	.89	1.20	.83	1.19	1.00	.93	.97	.98	1.19	1.42	1.25	.89	.57	1.25	1.38	.90	.92	.84	.97	1.09	.89	.90	1.11	.88	.82	.98	.82	.77	1.30	1.58	1.46	1.11	1.19	
0470	.90	.89	1.27	.85	1.24	1.03	.89	1.07	1.02	1.16	1.60	1.19	.88	.59	1.34	1.42	.85	.94	.84	.95	1.08	.90	.86	.97	.83	.79	.98	.82	.64	1.20	1.60	1.56	1.16	1.27	
0485	.85	.90	1.32	.85	1.27	1.08	.86	1.04	.96	1.13	1.53	1.18	.96	.62	1.29	1.37	.87	.96	.85	1.11	1.11	.92	.86	.97	.81	.78	.97	.79	.66	1.13	1.35	1.48	1.22	1.22	
0490	.82	.88	1.36	.80	1.38	.99	1.00	1.01	.85	1.07	1.46	1.33	.86	.68	1.24	1.70	.90	1.04	.91	1.09	.91	.83	.69	.99	.98	.87	.92	.86	.74	.89	1.06	1.34	1.27	1.37	
0495	.75	.93	1.39	.82	1.18	1.10	1.12	1.00	.87	1.14	1.41	1.17	.92	.74	1.04	1.48	.92	.96	1.01	1.13	.88	.74	.72	.90	.89	.90	.99	.97	.93	1.00	1.14	1.34	1.14	1.14	

Abbrev. station No.	1899	1900	1901	1902	1903	1904	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935
0500															1.23	1.20	1.23	0.94	1.29	0.70	1.44	1.09	1.48	0.78	1.19	1.60	1.32	1.06	0.76	0.79	1.11	1.18	0.77	1.28
0505																																		
0510							1.52	0.73	1.04	1.07	1.39	1.02	1.25	0.72	1.19	1.08	1.08	.87	1.20	.76	1.23	.93	1.42	.80	1.16	1.59	1.32	1.05	.78	.76	1.08	1.21	.82	1.30
0520																																		
0535															1.27	1.18	1.05	1.00	1.31	.75	1.20	.93	1.32	.75	1.17	1.61	1.17	.96	.78	.67	.96	1.18	.82	1.12
0545																																		
0560																																		
0570																																		
0585															1.32	1.16	1.06	1.01	1.30	.68	1.17	1.00	1.45	.95	1.24	1.75	1.24	.83	.74	.50	.83	1.25	.79	1.17
0590																							1.59	.80	1.22	1.66	1.20	.85	.74	.49	.83	1.12	.74	1.08
0610							1.24	.67	.71	.92	1.21	.89	1.12	.76	1.52																		.74	1.14
0615							1.41								1.19	1.00	.84	.84	1.31	.91	1.28	.78										1.29	.58	1.03
0620															1.24	1.09	.93	.84	1.22	.72	1.23	.90	1.36	.73	1.16									
0650																																		
0660																					1.14	.82	1.28	.75	1.19	1.31	1.09	1.05	.79	.77	.93	1.14	.77	1.07
0690										1.15	1.81	1.18	1.19	.80	1.14	1.06	1.25	1.06	1.32	.76	1.33	.89	1.37	.74	1.16									
0695													1.24	.91	1.40	1.10	1.07	.92	1.26	.96	1.16	.85	1.35	.75	1.14	1.40	1.07	.86	.69	.76	.96	1.11	.76	1.20
0700																							1.31	.74	1.18	1.39	1.13	.92	.75	1.01	1.10	.76	1.16	1.07
0705									1.05	1.38	1.73	1.17	.97	.86	1.16	1.23					1.30	.86	1.37	.73	1.22	1.41	1.36	.87	.93	.74	.94	1.10	.70	1.10
0720																																		
0725																																		
0730																															.80	1.12	.66	.96
0745																																		
0750																																	.72	1.09
0755																																		
0765	1.55	0.97	1.35	1.35	1.78	0.96																												
0775																																		
0785																																1.21	.68	1.10
0790																				1.03	1.04	.77	1.62	.54	1.15	1.26	1.28	.91	.80	.74	.83	1.13	.74	1.06
0800																		.74	1.27	.93	1.00	.86	1.32	.73	1.12	1.31	1.33	.94	.85	.63	.87	1.00	.81	1.19
0810																																		
0825								.81	.93	1.12	1.60	1.02	1.09	.86	1.21	.98	.87	.82	1.25	.95	1.04	.75	1.27	.48	1.16	1.28	1.29	.87	.77	.67	.87	1.03	.70	1.08
0830																																		
0835																				.93	1.02	.74	1.18	.51	1.17	1.24	1.22	.85	.80	.69	.84	1.03	.70	1.12
0840																																		
0850																																		

Abbrev. station No.	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
0500	1.21	1.08	1.09	1.06	0.81	0.56	0.84	1.31	0.89	1.07	0.87	0.70	1.08	1.13	1.40	1.25	0.94	0.79	0.76	1.10	1.27	1.02	1.30	0.69	1.06	1.18	1.04	1.15	0.90	0.93	0.68	1.34	0.98	0.78	1.03	1.30	1.62	1.40	1.40	
0505										1.11	.92	.70	1.05	1.12	1.39	1.21	.92	.80	.73	1.13	1.31	1.03	1.33	.68	1.04	1.17	1.04	1.16	.88	.94	.66	1.30	.97	.79	.99	1.26	1.58	1.34	1.38	
0510	1.22	1.08	1.15	1.03	.90	.68	.84	1.24	.92	1.17	.96	.74	1.08	1.13	1.37	1.21	.93	.85	.71	1.07	1.25	.96	1.30	.69	1.03	1.16	1.01	1.13	.88	.93	.67	1.26	.99	.84	.99	1.21	1.52	1.39	1.41	
0520								1.28	.95	1.23	1.00	.80	1.14	1.12	1.41	1.14	.90	.85	.70	1.03	1.21	.99	1.27	.74	.98	1.22	1.03	1.17	.85	.90	.62	1.17	.95	.85	.99	1.25	1.54	1.39	1.55	
0535	1.07	1.09	1.21	.93	.91	.75	.76	1.31	.87	1.27	.92	.77	1.17	1.14	1.54	1.20	.92	.80	.72	1.07	1.21	1.04	1.32	.74	.96	1.15	1.01	1.18	.80	.90	.62	1.16	.89	.85	.96	1.15	1.42	1.28	1.32	
0545						.70	.83	1.30	.93	1.25	.95	.77	1.14	1.12	1.42	1.20	.94	.83	.74	1.09	1.24	1.01	1.32	.71	1.01	1.18	1.00	1.15	.83	.89	.62	1.16	.92	.83	.93	1.15	1.45	1.29	1.36	
0560				.96	.89	.72	.79	1.32	.91	1.25	.91	.72	1.17	1.10	1.41	1.23	.95	.81	.69	1.08	1.28	1.00	1.33	.71	1.01	1.19	1.00	1.17	.85	.91	.64	1.16	.94	.82	.96	1.18	1.41	1.26	1.32	
0570					.95	.75	.81	1.32	.90	1.32	.92	.71	1.16	1.09	1.40	1.26	.98	.80	.66	1.09	1.30	1.00	1.31	.73	1.02	1.20	.99	1.16	.83	.89	.63	1.14	.91	.78	.96	1.13	1.38	1.23	1.29	
0585	1.10	1.16	1.26	.97	.99	.68	.69	1.35	.84	1.51	.95	.69	1.24	1.27	1.72	1.32	.95	.72	.58	1.10	1.21	.94	1.30	.72	1.08	1.22	1.07	1.26	.71	.88	.51	1.08	.83	.64	.92	1.14	1.26	1.20	1.31	
0590	1.08	1.15	1.13	.91	1.01	.69	.74	1.47	.92	1.67	1.01	.67	1.18	1.17	1.63	1.40	1.02	.72	.52	1.12	1.28	.97	1.39	.70	1.05	1.15	.96	1.10	.70	.85	.50	1.01	.87	.63	.89	1.12	1.34	1.29	1.37	
0610	1.15	1.22	1.14	1.01	1.01	.72	.77	1.43	.85	1.68	1.00	.63	1.23	1.14	1.48	1.48	1.09	.72	.49	1.15	1.34	.97	1.34	.73	.98	1.11	1.00	1.12	.72	.89	.53	1.00	.92	.62	.85	1.06	1.28	1.21	1.28	
0615	1.08	1.34	1.09	1.22	.86	.79	.98	1.51	.88	1.54	1.09	.73	1.21	1.08	1.25	1.58	1.12	.83	.52	1.26	1.56	.94	1.26	.73	.78	1.16	1.02	.99	.68	.82	.59	.88	.86	.51	.84	1.09	1.16	1.22	1.39	
0620				.97	.96	.75	.81	1.35	.88	1.43	.96	.70	1.18	1.10	1.48	1.32	1.02	.78	.59	1.09	1.32	.97	1.33	.74	1.00	1.17	1.01	1.17	.79	.92	.59	1.08								
0650						.80	.80	1.16	.89	1.11	.87	.76	1.06	1.13	1.24	1.18	.98	.88	.79	1.24	1.35	.97	1.26	.70	1.17	1.17	1.03	1.13	.91	.93	.72	1.15	.91	.79	.94	1.16	1.38	1.35	1.33	
0660	1.05	.93	1.06	.94	.96	.78	.79	1.09	.91	1.14	.80	.72	1.01	1.06	1.16	1.03	1.02	.86	.79	1.30	1.37	1.03	1.23	.65	1.14	1.17	.98	1.32	.95	.94	.77	1.15	1.01	.87	1.04	1.20	1.35	1.35	1.27	
0690						.77	.97	1.18	.85	1.17	.92	.78	1.07	1.15	1.29	1.17	.98	.87	.83	1.08	1.20	.95	1.26	.71	1.07	1.19	1.02	1.08	.94	.89	.77	1.12	.89	.86	.97	1.15	1.35	1.30	1.26	
0695	1.05	1.05	1.16	1.06	.96	.79	.84	1.15	.87	1.16	.88	.76	1.06	1.13	1.25	1.14	.98	.88	.81	1.18	1.29	.98	1.25	.69	1.14	1.16	1.01	1.14	.92	.90	.74	1.15	.92	.83	.96	1.14	1.38	1.31	1.34	
0700	1.04	1.11	1.11	1.06	.95	.80	.87	1.16	.89	1.19	.86	.74	1.09	1.13	1.26	1.17	.98	.89	.77	1.15	1.32	.97	1.23	.72	1.10	1.17	.95	1.18	.93	.91	.73	1.12	.93	.81	.96	1.15	1.36	1.31	1.34	
0705	1.11	1.32	1.10	1.03	1.14	1.04	.90	1.23	.85	1.40	.88	.78	1.13	1.00	1.28	1.24	1.13	.85	.62	1.16	1.46	.93	1.09	.85	.91	1.30	.89	.96	.92	.82	.70	1.04	.98	.78	.90	1.32	1.37	1.18	1.34	
0720						1.01	.99	1.61	.73	1.50	1.10	.75	1.13	1.00	1.14	1.73	1.14	.83	.40	1.16	1.57	.95	1.12	.80	.77	1.14	1.08	.95	.75	.82	.57	.98	.87	.53	.85	1.12	1.30	1.22	1.44	
0725				1.01	.99	.82	.85	1.31	.89	1.37	.94	.71	1.16	1.09	1.33	1.32	1.05	.82	.65	1.12	1.36	.98	1.27	.74	.99	1.19	1.01	1.10	.81	.89	.64	1.06	.91	.73	.91	1.13	1.35	1.23	1.27	
0730	1.31	1.48	1.04	1.05	1.26	1.02	.86	1.64	.72	1.38	.97	.83	1.00	1.01	1.19	1.81	1.09	.72	.32	1.29	1.78	.81	.89	.82	.85	1.36	1.15	.84	.75	.77	.68	.94	.78	.69	1.03	1.28	1.28	1.22	1.22	
0745								1.35	.92	1.62	1.26	.94	1.13	1.07	1.12	1.56	1.17	.89	.47	1.26	1.38	.85	.91	.90	.85	.93	.86	.79	.80	.80	.62	.99	.92	.68	.95	1.07	1.63	1.22	1.26	
0750	1.09	1.18	1.08	1.01	.98	.79	.85	1.34	.87	1.39	.95	.73	1.14	1.08	1.32	1.35	1.06	.81	.61	1.13	1.40	.98	1.23	.76	.97	1.16	1.00	1.05	.80	.87	.67	1.10	.91	.73	.95	1.13	1.38	1.22	1.30	
0755							.83	1.20	.85	1.31	.82	.69	1.19	1.14	1.19	1.17	1.04	.88	.69	1.17	1.38	.94	1.14	.72	1.03	1.21	.98	1.17	.90	.86	.77	1.07	.91	.74	1.06	1.11	1.37	1.33	1.23	
0765						.94	.88	1.15	.85	1.32	.85	.73	1.19	1.12	1.20	1.15	1.07	.87	.64	1.18	1.35	.96	1.16	.75	1.04	1.20	.97	1.08	.88	.86	.76	1.05	.94	.74	1.14	1.22	1.38	1.30	1.19	
0775					.97	.93	.86	1.14	.84	1.32	.86	.73	1.19	1.12	1.24	1.22	1.13	.87	.64	1.27	1.37	.97	1.11	.72	.98	1.19	.94	1.07	.92	.83	.73	1.04	.96	.75	1.07	1.27	1.38	1.29	1.23	
0785	1.29	1.35	.94	.79	1.02	.78	1.00	1.38	.88	1.30	.94	.74	.97	.95	.99	1.36	1.22	.94	.57	1.63	1.04	.92	1.36	.65	1.25	1.23	.89	.78	1.02	.85	.67	.99	.95	.59	1.19					
0790	1.12	1.22	.91	.87	1.06	.92	.89	1.26	.86	1.21	1.02	.91	1.05	1.02	1.09	1.28	1.17	.98	.53	1.37	1.23	.90	1.09	.75	1.15	1.22	.91	.86	1.06	.86	.67	1.02	.84	.71	1.17	1.39	1.44	1.26	1.12	
0800	1.12	1.31	1.00	.85	1.04	.95	.93	1.20	.99	1.25	1.00	.90	1.03	1.05	1.12	1.15	1.14	.89	.67	1.24	1.30	.85	1.03	.83	1.01	1.13	.91	.88	1.04	.83	.81	1.02	.87	.91	1.15	1.34	1.39	1.12	1.09	
0810						.94	.86	1.18	.90	1.25	.95	.81	1.11	1.09	1.19	1.27	1.14	.92	.61	1.32	1.28	.93	1.10	.77	1.06	1.19	.91	.94	.96	.82	.72	1.03	.90	.77	1.13	1.33	1.40	1.26	1.18	
0825	1.07	1.23	.97	.88	1.02	.92	.86	1.18	.88	1.24	.96	.81	1.08	1.02	1.15	1.24	1.12	.90	.60	1.31	1.31	.91	1.06	.78	.99	1.18	.99	.97	1.02	.84	.73	1.06	.92	.80	1.16	1.38	1.45	1.25	1.20	
0830							.88	1.30	.86	1.48	1.16	.91	1.03	1.03	1.14	1.32	1.17	.91	.63	1.14	1.46	.82	.90	.93	.90	1.02	.89	.89	1.07	.96	.76	.98	.83	.77	1.02	1.41	1.52	1.17	1.06	
0835	1.08	1.27	.99	.91	1.06	.96	.90	1.27	.90	1.32	.98	.85	1.10	1.03	1.15	1.29	1.13	.89	.59	1.29	1.36	.91	1.04	.80	1.02	1.15	.92	.91	.98	.83	.70	1.01	.86	.75	1.12	1.34	1.47	1.22	1.19	
0840														.99	1.20	1.80	1.28	.84	.55	1.20	1.30	.84	.94	.96	1.01	1.24	1.19	.87	.92	.88	.78	1.06	.74	.52	.90	1.04	1.31	1.05	1.06	
0850				.97	1.03	.88	.89	1.35	.89	1.39	1.00	.77	1.15	1.07	1.26	1.39	1.09	.82	.59	1.14	1.38	.93	1.16	.76	.98	1.16	.99	1.02	.85	.87	.67	1.02	.87	.69	.97	1.16	1.37	1.21	1.24	

Abbrev. station No.	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942
0855									1.36	1.09	1.34	0.86	1.86	0.80	1.30	1.68	2.00	1.09	0.90	0.50	0.76	1.16								0.88	0.95
0860																							0.66	0.94	1.01	1.24	1.04	0.86	0.98	.80	.91
0865																															.80
0895																															.89
0905																				.50	1.03	.91	.41	.80	1.05	1.63	1.44	1.08	1.05	.77	.86
0915																			1.16	.46	1.08	.95	.32	.87	1.08	1.62	1.39	1.17	1.11	.82	.86
0920																														.79	.88
0925																1.36	1.31	1.36	.91	.44	.81	.80	.35	.65	.81	1.22	1.17	.95	1.12	.73	.92
0930																1.39	1.38	1.39	.91	.49	.81	.69	.33				.98	.84	1.04	.67	.96
0940																														.72	.93
0955																1.39	1.45	1.51													
0980											.94	.62	1.33	.66	1.14	1.47	1.54	1.41	1.03	.44	.89	.87	.31	.81	.99	1.50	1.20	.99	1.04	.69	.95
0995																															
1015																								.67	.72	1.24	.99	.77	.85	.64	1.28
1025			1.15	0.96	1.06	0.96	0.91	0.93	.91	.89	.93	.68	1.20	.81	1.12	1.31	1.50	1.37	1.17	.47	.90	.85	.57	.63	.84	1.37	1.07	.82	.86	.70	1.04
1030			1.22	1.10	1.17	.97	1.11	.94	.96	1.05	1.07	.66	1.41	.92	1.42	1.70	1.56	1.79	1.17	.49	.81	.78	.38	.61	.91	1.39	.96	.88	.91	.64	1.11
1035																												.81	.86	.67	1.07
1055				.71	1.09	.82	1.00															.69	.39	.74	.84	1.33	1.10	.91	.96	.65	.95
1060									1.00	.90	1.17	.71	1.59	.80	1.12	1.69	1.85	1.09	1.16	.50	.87	.96	.57	1.09	1.12	1.53	1.21	.89	1.01	.83	.96
1065	1.64	1.36	1.30	.99	1.28	1.03	1.06	.88	.89	.72	.98	.69	1.30	.68	1.12	1.44	1.55	1.33	1.03	.40	.86	.93	.51	.95	.96	1.49	1.18	.90	.93	.82	.93
1080																															.99
1095					1.19	.83	.83	.82	1.06	.97	1.08	.66	1.47	.65	1.16	1.61	1.65	1.30	1.26	.43	.89	1.01	.45	.91	1.18	1.86	1.29	1.16	1.02	.83	.90
1100																														.78	.84
1115																															.87
1120																														.90	.93
1145					1.67													.87	.80	.41	.82	1.12	.60	1.14	1.10	1.31	1.18	1.11	1.01	.82	.89

Abbrev. station No.	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
0855	1.49	0.87	1.47	0.93	0.78	0.97	0.99	1.17	1.87	1.21	0.78	0.50	1.04	1.95	0.94	0.99	0.88	0.90	1.06	0.92	0.83	0.77	0.78	0.80	0.93	0.82	0.68	0.91	1.19	1.17	1.33	0.98	
0860	1.38	.84	1.27	1.06	.99	1.06	.96	1.22	1.42	1.17	.88	.68	1.08	1.44	.93	1.03	.91	1.06	.99	.84	.84	.88	.86	.79	.99	.91	.82	.97	1.14	1.34	1.17	1.17	
0865	1.22	.56	.97	1.18	1.20	.95	.93	1.23	1.61	1.49	.85	.60	1.23	1.66	.96	1.31	1.30	1.17	.84	.61	.67	.81	.74	.64	.96	.92	.74	1.06	1.16	1.07	1.49	1.55	
0895	1.39	.57	1.00	1.26	1.29	.83	.81	1.21	1.40	1.59	.79	.50	1.38	1.85	.96	1.29	1.34	1.12	.84	.67	.59	.92	.63	.63	.87	.85	.64	1.04	1.32				
0905	1.30	.54	.95	1.08	1.34	.87	.90	1.33	1.55	1.50	.80	.63	1.23	1.65	.96	1.25	1.29	1.22	.84	.65	.62	.85	.73	.64	.94	.89	.82	.99	1.10	1.20	1.57	1.50	
0915	1.06	.62	.90	1.16	1.30	.91	.88	1.27	1.55	1.54	.82	.59	1.31	1.61	1.00	1.21	1.45	1.24	.84	.75	.59	.78	.81	.55	.86	.81	.78	1.11	1.13	1.14	1.63	1.53	
0920	1.41	.64	.81	.94	1.36	.78	.69	1.29	1.39	1.53	.63	.67	1.26	1.78	.96	1.18	1.42	1.36	.73	.64	.53	1.01	.76	.72	.92	.79	1.01	1.11	1.06	1.39	1.47	1.75	
0925	1.34	.65	1.01	1.03	1.29	.78	.78	1.28	1.31	1.58	.63	.66	1.20	1.64	1.06	1.03	1.46	1.29	.81	.67	.75	.88	.78	.79	.87	.88	.97	.91	1.07	1.29	1.31	1.36	
0930	1.33	.66	.86	1.07	1.35	.78	.80	1.27	1.34	1.43	.46	.66	1.16	1.62	1.13	1.03	1.46	1.20	.94	.71	.66	.86	.86	.91	.92	.92	1.21	.84	1.09	1.21	1.38	1.39	
0940	1.24	.62	.91	1.12	1.34	.83	.83	1.31	1.46	1.51	.67	.63	1.28	1.66	1.07	1.13	1.46	1.28	.85	.69	.62	.83	.81	.72	.81	.79	.97	.93	1.07	1.15	1.47	1.49	
0955		.60	.85	1.05	1.68	.74	.77	1.45	1.50	1.39	.58	.81	1.23	1.95	.86	.90	1.30	1.16	.80	.42	.46	.84	.83	.69	.89	.92	1.36	.67	.88	1.13	1.25	1.25	
0980	1.32	.56	.80	1.10	1.37	.78	.77	1.29	1.49	1.49	.68	.63	1.25	1.72	1.07	1.04	1.43	1.29	.90	.69	.60	.92	.91	.73	.87	.83	.99	.86	1.09	1.15	1.53	1.45	
0995	1.29	.56	.82	1.13	1.31	.81	.81	1.25	1.46	1.44	.71	.64	1.30	1.74	1.10	1.09	1.40	1.26	.87	.69	.81	.87	.90	.78	.86	.84	.95	.88	1.04	1.12	1.47	1.38	
1015	1.27	.71	.92	1.01	1.47	.85	.78	1.32	1.37	1.26	.72	.74	1.07	1.73	.91	.82	1.20	1.26	.81	.55	.56	.90	.92	.79	1.02	.96	1.30	.85	1.05	1.26	1.14	1.15	
1025	1.43	.77	.85	1.12	1.33	.84	.91	1.26	1.34	1.36	.77	.65	1.24	1.56	.99	1.01	1.24	1.16	.76	.58	.63	.93	1.04	.86	.85	.88	1.11	.84	.94	1.27	1.17	1.19	
1030	1.45	.71	.84	1.02	1.42	.82	.80	1.29	1.37	1.40	.68	.73	1.22	1.72	.93	.83	1.25	1.13	.82	.51	.51												
1035	1.35	.72	.88	1.04	1.32	.82	.85	1.30	1.39	1.38	.73	.72	1.24	1.73	.97	.92	1.21	1.18	.82	.55	.56	.87	.95	.84	.92	.94	1.22	.86	1.02	1.23	1.22	1.27	
1055	1.37	.64	.90	1.06	1.28	.81	.83	1.25	1.42	1.39	.73	.67	1.29	1.73	1.00	1.05	1.27	1.22	.87	.65	.57	.93	.90	.82	.90	.91	1.04	.90	1.04	1.26	1.36	1.39	
1060	1.39	.83	1.35	1.06	1.03	.91	.93	1.18	1.49	1.32	.79	.68	1.16	1.71	.93	1.15	.93	1.14	.82	.72	.66	.88	.88	.90	.90	.89	.74	.82	1.07	1.29	1.32	1.43	
1065	1.46	.74	1.13	1.08	1.01	.88	.88	1.21	1.49	1.33	.91	.77	1.20	1.70	.91	1.09	1.00	1.12	.75	.67	.58	.89	.94	.82	.87	.96	.87	1.01	1.19	1.41	1.39	1.36	
1080	1.31	.92	1.56	1.04	.91	.98	1.03	1.18	1.73	1.36	.82	.50	1.10	1.67	.92	.96	.93	1.02	.91	.78	.75	.78	.77	.88	1.08	.85	.55	.82	1.12	1.13	1.33	1.25	
1095	1.29	.72	1.19	1.25	1.04	.87	.89	1.15	1.53	1.37	.93	.59	1.26	1.67	.94	1.35	1.17	1.14	.86	.70	.67	.80	.80	.77	.85	.89	.70	.88	1.22	1.18	1.49	1.39	
1100	1.24	.80	1.41	1.17	1.12	.95	1.17	1.10	1.74	1.45	.75	.51	1.08	1.58	.85	1.18	.94	.98	1.06	.84	.80	.74	.81	.88	.97	.72	.63	.95	1.11	.93	1.26	1.21	
1115	1.45	.88	1.39	1.07	.94	1.02	1.34	1.36	1.66	1.37	.71	.39	1.02	1.45	.86	.87	1.03	.81	1.09	.81	.97	.71	.81	.95	1.02	.86	.64	.91	1.22	1.02	1.21	1.27	
1120	1.87	.89	1.27	.91	.75	.82	.96	1.15	1.59	1.04	.67	.36	10.5	1.73	.95	1.09	1.00	.88	1.37	1.05	.91	.75	.81	.74	.96	.87	.71	1.05	1.18	1.35	1.37	1.28	
1145	1.44	.84	1.56	1.12	.64	1.20	1.08	1.36	1.42	1.08	.75	.49	1.19	1.29	.90	1.31	.73	.96	1.12	.96	1.18	.77	.97	.64	.96	.98	.63	.72	1.22	1.30	1.19	1.43	