AQUIFER CHARACTERISTICS

The aquifer characteristics, hydraulic conductivity, transmissivity, porosity, specific storage, and storage coefficient are important in resource evaluations and modeling. In order to define these characteristics, aquifer tests were conducted in open holes and wells completed in a single interval, using pumping-well test and slug-test techniques. Laboratory analyses of rock samples collected from outcrops and drill cores also were used to define aquifer characteristics.

Methods of Determining Characteristics

Aquifer Tests

Pumping-well aquifer tests primarily were conducted for environmental impact evaluations at large strip mines in the eastern part of the area. These tests were done during the past 5 years by the U.S. Geological Survey and by private mining concerns. Results of 22 of these tests are listed in table 5. Locations of the wells tested are shown in figure 24. Hydraulic information is restricted to the coal-bearing zones, primarily the Wadge coal seam and rocks immediately above or below the coal; no information is available on the two regional aquifers. Information about storage coefficient was obtained at only a few wells because observation wells were not available at most of the pumping-well-test sites.

Transmissivity values from pumping-well tests are shown for the Wadge coal seam and its associated overburden and underburden in the lower member east of Hayden Gulch (table 5). Values range from 0.7 to 95 ft^2/d; the mean is 17 ft^2/d and the standard deviation is 20.6. Only one value, obtained from a well completed in an unknown thickness of aquifer northwest of Dry Creek, exceeds 50 ft^2/d.

All slug-type aquifer tests were conducted during the summer of 1980, primarily on wells drilled in 1976 and 1977. In all, 24 tests were successfully completed (table 6; fig. 24). Compared with pumping-well tests, the slug tests were done in a much wider combination of geographic and stratigraphic settings with a varied depth to the potentiometric surface. Aquifers were not heavily stressed by the slug test, and the resulting information is much less representative than the pumping-well test results. One significant figure was the assumed accuracy for these slug-test results.

Slug-test data were collected using a pressure transducer connected to a strip-chart recorder that had a resolution of one-tenth of a foot of hydraulic head. To simulate an instantaneous hydraulic-head change, a weighted, 20-ft-long, 1-inch-diameter pipe was used to displace water. After installation and calibration of the pressure transducer, the 1-inch-diameter pipe was inserted into the well, displacing water and causing a rise in head. Recovery to equilibrium was recorded on the strip chart. If the aquifer transmissivity value was small, only one recovery curve was generated. In a more transmissive aquifer, several insertion-removal cycles were measured to gather replicate information.

Table 5.--Summary of data from pumping-well tests

[ft^2/d, feet squared per day; ft, feet; ft/d, feet per day; --, no data]

Well location[1]	Reported stratigraphic interval in Williams Fork Formation	Completion type	Transmissivity (ft^2/d)	Saturated thickness (ft)	Hydraulic conductivity (ft/d)	Storage coefficient	Source[2]
4/86-7DAB	Wadge overburden	Open hole	8.3	47	0.2	--	2
4/86-18BBB	|	|	34	94	0.4	--	2
4/86-18BBB	|	|	43	73	0.6	--	2
4/86-18BCB	|	|	33	53	0.6	--	2
5/85-30BBD	Wadge underburden	Unknown	10.4	--	--	--	1
5/85-30CCC	Wadge coal and overburden	|	4.2	--	--	--	1
5/85-31CDA	|	|	1.1	--	--	--	1
5/85-13ABB	Lower member	Open hole	10.5	80	0.1	--	2
5/86-13ACC	|	|	3.7	157	0.02	--	2
5/86-29CDD	Wadge overburden	Single interval	4.3	11	0.4	--	2
5/86-29CDD	|	|	6.3	20	0.3	--	2
5/86-29CDD	Lower member	Open hole	8.6	20	0.4	--	2
5/86-29CDD	Wadge overburden	|	13.6	45	0.3	--	2
5/86-29CDD	|	|	13.6	41	0.3	--	2
5/86-32BBD	|	|	15.4	60	0.3	--	2
5/86-36DDB	Wadge coal and overburden	Unknown	0.7	--	--	--	1
5/87-11BDB	Wadge underburden	Open hole	22	151	0.2	--	3
5/87-19ABB	Lower member	Single interval	3.9	24	0.2	--	3
5/88-8CDC	Upper member	Open hole	95	--	--	--	4
6/87-34ACA	Wadge coal	Single interval	3.3	9	0.4	$1x10^{-3}$	3
6/87-34DDB	Wadge overburden	Open hole	16	135	0.1	--	3
6/88-33DBB	Upper member	|	33	--	--	--	4

[x]See figure 24 for well locations.

[2]Values reported in permitting documents submitted by 1, Pittsburg and Midway Coal Mining Co.; 2, Colorado Yampa Coal Co.; 3, Peabody Coal Co.; and 4, data from U.S. Geological Survey.

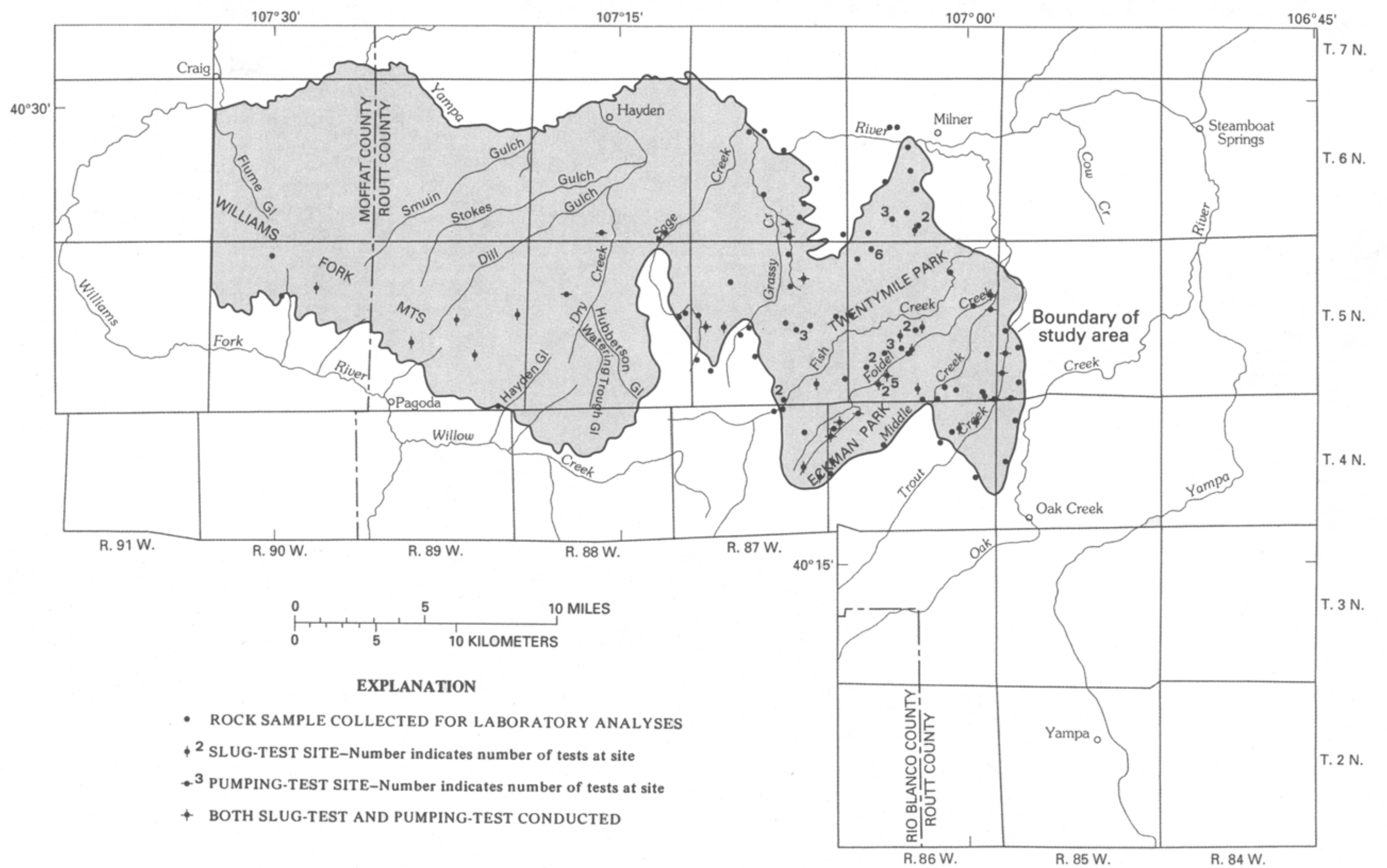

Figure 24.– location of rock-sample, slug-test, and pumping-well sites.

Table 6.--*Summary of data from slug tests in wells*
[ft^2/d, feet squared per day; ft, feet; ft/d, feet per day]

Well location[1]	Stratigraphic interval (members and coalbed are in Williams Fork or Iles Formations)	Transmissivity (ft^2/d)	Saturated thickness (ft)	Hydraulic conductivity (ft/d)
4/86-11DCC	Trout Creek Sandstone member and lower member	100-630	106	0.9-6.0
4/86-14AAA	|	3-7	143	0.02-0.05
4/86-18BBB	Lower member	210	94	2.0
4/86-18BCB	|	180-220	53	3.0-4.0
4/86-19BBD	|	1-3	44	0.02-0.07
4/86-24BCB	Wadge, overburden, lower member	4	260	0.02
4/87-24DBD	Wolf Creek coal and underburden	0.4	60	0.007
5/86-21AAA	Lewis Shale and upper member	80-250	10	8.0-25.0
5/86-21BCC	Lewis Shale	230-700	[2]188	1.0-4.0
5/86-21CDD	Lewis Shale and upper member	2.5	68	0.04
5/86-29CDD	Lower member	1.0	10	0.1
5/86-29CDD	|	5-30	45	0.1-0.7
5/86-32BBD	|	8-30	60	0.1-0.5
5/86-36CAC	Trout Creek Sandstone Member and lower member	1-4	165	0.006-0.02
5/87-11BDB	Wadge and underburden	0.4-3.0	151	0.003-0.02
5/87-19ABB	Lower member	30-90	24	1.0-4.0
5/87-20BBA	Wadge coal	0.2	10	0.02
5/89-13ACC	Upper member	70-210	50	1.0-4.0
5/89-15CAB	Upper member	6	128	0.05
5/89-20ACD	Twentymile Sandstone Member	50-130	112	0.4-1.0
5/89-23CCC	|	830	110	8.0
5/89-35ACA	Trout Creek Sandstone Member	960-2,800	304	3.0-9.0
5/90-11BCC	Twentymile Sandstone Member	1,000-3,000	210	5.0-10.0
6/86-33ADB	Trout Creek Sandstone Member and lower member	30-90	532	0.06-0.2

[1]See figure 24 for well locations.
[2]Shale interval shown for well completed only in weathered shale,

The resulting time-drawdown data were analyzed by one of two methods, depending on individual hydraulic conditions at each well. The first method, described by Cooper and others (1967), assumes a fully penetrating well in a homogeneous isotropic aquifer. The method is valid only in confined aquifers, which is a severe restriction. The solution involves a type-curve matching procedure similar to the Theis technique for pumping-test analysis. This procedure may be used for a recovering head resulting from either injection or removal of water. It yielded the best information about confined aquifers in wells that have sufficient water depth to allow the displacement pipe to be lowered beyond head fluctuation range. The procedure is sensitive to unconfined conditions and was not used in analysis of wells penetrating unconfined aquifers.

The second interpretive procedure is that of Bouwer and Rice (1976). It is based on the Theim equation and assumes the bailing of a well under homogeneous and isotropic conditions. Unlike the first procedure, the well need not fully penetrate the aquifer and, more importantly, the aquifer can be unconfined. The calculation technique is more complex than the Cooper method; however, no type-curve matching is needed. This procedure was used only for larger transmissivity tests in unconfined aquifers. Both procedures were used to interpret results of several tests. Results generally indicated agreement within at least one significant figure, the reporting accuracy for slug tests in this study.

The range in transmissivity listed for each slug test (table 6) results from the use of minimum and maximum values for well radii in the slug-test formulas. The open-hole completion wells contained no gravel packing, requiring the assumption that the maximum radius is the drilled-hole radius and the minimum radius is the inside-casing radius. The larger the transmissivity, the greater the resulting range between maximum and minimum values.

The overall transmissivity range for all slug-test wells was much greater than pumping-well-test range. There are two principal reasons for this. First, slug tests were conducted over a wider range of geological and geographical conditions. Second, slug tests displace a much smaller aquifer water volume, which produces transmissivity estimates of lesser accuracy. Many wells were completed as open holes. The aquifer penetrated by these wells varied in thickness, lithology, and in the degree of cementation and fracturing. The quantity of water removed or added for this test usually was limited to less than one well volume. The actual volume of aquifer tested is quite small, and localized irregularities do not average out as they do in the longer term pumping tests. These irregularities, particularly fracturing, may have an effect on the transmissivity near the well. Experimental error was minimized by use of an automated data-collection system and the use of only one person to perform the test and interpret the data.

The hydraulic conductivity of an aquifer is calculated by dividing the transmissivity by the saturated thickness. For a well completed in a single interval, the saturated thickness was assumed to equal the perforated interval. This thickness was used to calculate hydraulic conductivity for the single-interval wells listed in table 5. For wells completed as open holes, the water from all water-yielding intervals in the well is free to mix, regardless of perforation locations because water in the annulus is directly connected to water in the casing. The resulting transmissivity value from an aquifer test is an integrated average of all saturated intervals, which makes it impossible to distinguish between conductive and nonconductive saturated zones. In addition, most open-hole wells in the study area are not cased to the bottom of the drill hole, and few are sealed at the bottom of the casing; this may allow upward movement of water from intervals below the well casing. To simplify the calculation of hydraulic conductivity, it was assumed that the wells were sealed by collapsing at the first thick shale or mudstone below the casing, producing an impermeable seal between the well and uncased borehole below. Formational collapse could occur in cased areas containing shales; however, there is no data to document the occurrence or frequency of this condition. Therefore, it was assumed that no collapsing occurred in the cased interval. The validity of the above assumptions is unknown; therefore, these values should be used with caution. The hydraulic-conductivity values listed in tables 5 and 6 for open-hole completed wells are based on these assumptions.

Using the above assumptions, saturated aquifer thickness in open-hole completed wells was assumed to be the total thickness of all sandstones and coal in the cased interval below water level, regardless of perforated intervals. Assuming that the saturated thickness is limited to perforated intervals is incorrect because of the direct hydraulic connection between the water in the annulus and casing. Assuming the total saturated thickness of the well to be the aquifer thickness also is incorrect because of the smaller permeability values of interbedded fine-grained rocks.

Rock-Sample Analyses

The aquifer-test results provide minimal information about the aquifer characteristics of the regional aquifers. The characteristics of these aquifers in the eastern part of the area are of particular concern because determination of aquifer characteristics is requisite to successful simulation of the ground-water system. Rock samples were collected for laboratory analyses in an effort to better define the character of the regional aquifers.

Eighty-one rock samples (table 7) were collected from outcrops of the Twentymile Sandstone, Trout Creek Sandstone, and Tow Creek Sandstone Members. (The Tow Creek Sandstone Member is a potential aquifer in the middle part of the Iles Formation that subsequently was excluded from consideration in this study because of insignificant hydraulic connection with aquifers in the study area.) Twenty-two samples (table 7) also were collected from drill cores provided by the Twentymile Coal Co. The cores were obtained from depths of 301 to 1,432 ft in sandstone or siltstone of the Twentymile Sandstone Member, lower member of the Williams Fork Formation, and Trout Creek Sandstone Member. Physical characteristics of the regional aquifer samples were typical of the formational characteristics described in the "Stratigraphy" section of this report. All samples were intact, unfractured, and moderately to well indurated.

Table 7. --*Physical properties of sampled bedrock materials*

[ft, feet; g/cm^3, grams per cubic centimeter; mD, millidarcys; ft/d, feet per day; mm, millimeters; ϕ, $-\log_2$ (d), where d is grain diameter measured in millimeters; Kwt, Twentymile Sandstone Member of Williams Fork Formation; Kws, siltstone bed in the lower member of Williams Fork Formation; Kwb, sandstone bed in the lower member of Williams Fork Formation; Kit, Trout Creek Sandstone Member of Iles Formation; Kio, Tow Creek Sandstone Member of Iles Formation; --, no data]

Sample location	Formation	Depth (ft)	Bulk density (g/cm^3)	Porosity (percent)	Gas perme-bility (mD)	Hydraulic conductivity (ft/d)	Grain-size distribution (percent finer)				
							Sieve size(mm)				
							1.0 (ϕ=0)	0.5 (ϕ=1)	0.25 (ϕ=2)	0.125 (ϕ=3)	0.1 (ϕ=4)
					Williams Fork Formation						
4/86-14BAB	Kwt	0	2.16	20	4.2	1.7×10^{-3}	100	98.6	93.5	35.2	6.9
4/87-13BBA	Kwt	0	2.03	23	87	4.9×10^{-2}	100	99.0	95.1	35.3	7.9
5/86-6AAD	Kws	1,259	2.23	17	7.1	3.0×10^{-3}	100	97.8	92.1	82.3	13.7
5/86-6AAD	Kws	1,259	2.21	17	7.4	3.2×10^{-3}	–	--	--	--	--
5/86-6AAD	Kws	1,260	2.23	16	3	1.2×10^{-3}	–	--	--	--	--
5/86-6AAD	Kwb	1,375	2.25	15	1.4	4.9×10^{-4}	–	--	--	--	--
5/86-6AAD	Kwb	1,375	2.26	15	1.7	6.2×10^{-4}	–	--	--	--	--
5/86-6AAD	Kwb	1,375	2.25	16	2.2	8.3×10^{-4}	99.3	96.3	90.0	69.2	10.2
5/86-6CAA	Kwt	0	2.42	9.9	0.07	1.8×10^{-5}	–	--	--	--	--
5/86-10AAA	Kwt	0	2.21	16	18	8.5×10^{-3}	100	99.3	93.3	24.7	10.0
5/86-14ADC	Kwt	0	2.17	15	29	1.5×10^{-2}	100	99.4	96.9	90.8	24.4
5/86-18CBD	Kws	1,432	2.46	5.6	0.04	9.7×10^{-6}	–	--	--	--	--
5/86-21AAC	Kws	1,247	2.39	10	0.04	9.7×10^{-6}	–	--	--	--	--
5/86-21AAC	Kws	1,248	2.45	7.4	0.05	1.2×10^{-5}	–	--	--	--	--
5/86-21CCC	Kwt	0	--	--	--	--	99.8	99.4	94.6	26.6	8.9
5/86-25BAD	Kwt	0	2.00	25	219	1.4×10^{-1}	100	98.7	96.1	55.9	8.6
5/86-28BAB	Kwt	0	2.07	22	171	1.1×10^{-1}	100	99.6	93.6	17.3	6.9
[1]5/86-29BAA	Kwt	301	--	24	178	1.9×10^{-1}	–	--	--	--	--
5/86-29BAA	Kwt	302	2.26	24	162	9.7×10^{-2}	95.6	89.4	70.8	6.9	0.8
5/86-29BAA	Kwt	302	2.07	21	153	9.2×10^{-2}	100	98.9	94.4	33.0	12.3
5/86-30DBA	Kws	1,210	2.26	15	1.2	4.1×10^{-4}	–	--	--	--	--
5/86-30DBA	Kws	1,211	2.24	15	1	3.4×10^{-4}	–	--	--	--	--
5/86-34ABD	Kwt	0	2.03	24	244	1.6×10^{-1}	100	99.2	90.4	21.9	7.1
[1]5/86-35BCD	Kwt	0	2.05	23	49	5.1×10^{-2}	100	99.2	97	93.2	12.8
5/86-36CAB	Kwt	0	2.05	23	51	2.7×10^{-2}	99.1	97.1	92.7	68.1	9.6
[J]5/87-3ADC	Kwt	0	2.45	7.8	1	1.7×10^{-4}	100	97.8	75.5	30.8	14.8
5/87-8BDD	Kwt	0	2.41	10	0.5	1.6×10^{-4}	100	97.3	87.8	37.3	10.8
[1]5/87-10DAC	Kwt	0	1.89	29	243	3.1×10^{-1}	100	99.5	71.7	16.1	4.1
5/87-13DBC	Kwt	0	2.58	4	0.04	9.7×10^{-6}	100	77.1	59.7	46.1	11.8
[1]5/87-15DCC	Kwt	0	2.07	22	94	3.9×10^{-2}	100	99.3	68.2	19.9	5.1
5/87-18CBA	Kwt	0	2.07	22	24	1.2×10^{-2}	100	97.4	92.2	86.0	23.3
5/87-21BAB	Kwt	0	2.05	23	61	3.3×10^{-2}	100	99.6	92.6	24.7	10.0
5/87-23ABB	Kwt	0	2.15	20	16	7.3×10^{-3}	100	99.2	92	39.5	8.8
5/87-23BBC	Kws	1237	2.3	14	2.2	8.3×10^{-4}	99.7	97.5	93.2	86.0	21.8
5/87-23BBC	Kws	1238	2.31	13	1	3.4×10^{-4}	–	--	--	--	--
5/87-23BBC	Kws	1238	2.31	13	1.4	5.0×10^{-4}	–	--	--	--	--
5/87-27BBC	Kwt	0	2.04	23	72	4.0×10^{-2}	100	98.7	96.4	89.0	24.1
5/87-34DCB	Kwt	0	--	--	--		100	99.6	96.7	54.7	13.4
5/87-34DCB	Kwt	0	1.99	25	243	1.6×10^{-1}	100	99.5	96.5	37.7	11.6
[1]5/87-36AAA	Kwt	0	2.00	24	432	6.9×10^{-1}	100	99.3	72.1	18.8	8.8
5/88-13ACD	Kwt	0	2.12	20	17	8.0×10^{-3}	100	97.8	93.8	78.0	15.5
5/88-30ACC	Kwt	0	--	--	--	--	100	99.6	93.6	32.6	12.5
5/90-4BDB	Kwt	0	--	--	--	--	99.9	98.6	90.2	73.4	30
6/86-21BDD	Kwt	0	1.95	27	38	1.9×10^{-2}	100	92.7	93.6	87.5	12.5
6/86-28CDC	Kwt	0	1.98	25	231	1.4×10^{-1}	100	98.9	93.7	23.1	7.5
6/86-31DAC	Kwt	0	2.06	22	45	2.4×10^{-2}	100	99.7	93.9	29.9	5.1
[J]6/86-33ADB	Kwb	641	2.14	19	18	1.3×10^{-2}	–	--	--	--	--
6/86-33ADB	Kwb	642	2.19	17	7.3	3.2×10^{-3}	–	--	--	--	--
6/87-9DDC	Kwt	0	--	--	--	--	100	99.2	91.2	71.8	38.3
6/87-9CDC	Kwt	0	2.26	16	1.1	3.8×10^{-4}	100	90.0	76.9	40.8	7.3
6/87-28ADB	Kwt	0	2.29	14	0.5	1.6×10^{-4}	100	97.9	89.8	37.2	12.7
6/88-35DAD	Kwt	0	2.26	15	0.7	2.3×10^{-4}	100	95.9	80.4	36.0	13.6

Table 7. --*Physical properties of sampled bedrock materials*—Continued

Sample location	Formation	Depth (ft)	Bulk density (g/cm^{3})	Porosity (percent)	Gas perme-bility (mD)	Hydraulic conductivity (ft/d)	Grain-size distribution (percent finer) Sieve size(mm) 1.0 (⌀=0)	0.5 (⌀=1)	0.25 (⌀=2)	0.125 (⌀=3)	0.1 (⌀=4)
						<u>Iles Formation</u>					
4/85-7DDC	Kit	0	2.37	11	0.2	5.8x10^{-5}	98.1	86.7	72.6	54.5	9.6
5/85-19BDD	Kit	0	2.21	16	3.4	1.4x10^{-3}	100	99.2	95.2	60.0	6.4
[1]4/86-15DAB	Kit	0	2.10	21	56	1.8X10^{-2}	100	98.8	82.4	18.0	5.7
4/86-17DAB	Kit	0	2.11	20	13	6.1X10^{-3}	100	98.4	75.8	22.0	6.3
4/86-19CBC	Kit	0	1.98	25	79	4.4X10-^{2}	100	99.4	97.2	91.7	20.7
4/86-24CAA	Kit	0	2.11	19	15	6.8X10^{-3}	100	97.9	61.1	16.5	4.8
4/87-11BAB	Kit	0	--	--	--	--	100	99.7	96.9	89.0	17.7
4/87-11BCB	Kit	0	2.20	19	7.0	4.4X10^{-3}	100	99.1	94.1	38.1	15.2
5/85-19BCA	Kit	0	2.12	19	6.8	2.9X10^{-3}	100	98.3	93.2	67.4	15.5
5/85-31AAC	Kit	0	2.22	16	0.8	2.7X10^{-4}	100	91.7	78.3	66.8	30.1
5/86-33DDD	Kit	0	--	--	--	--	99.8	96.6	81.9	66.0	40.7
5/86-34CDC	Kit	0	2.68	2.2	0.02	4.4X10^{-6}	–	--	--	--	--
5/87-20ADD	Kit	0	2.22	17	5.8	2.4X10^{-3}	100	92.5	82.9	60.6	10.7
5/87-28ACB	Kit	0	2.07	22	14	6.6X10^{-3}	100	98.8	94.8	89.0	12.6
5/87-30BBD	Kit	0	2.11	21	89	5.1x10^{-2}	100	98.7	56.6	19.5	6.0
[1]5/87-30DDB	Kit	0	1.98	25	568	2.7x10^{-1}	100	99.9	97.4	28.4	5.4
5/88-13DBB	Kit	0	2.08	22	22	1.1x10^{-2}	100	98.1	93.9	63.9	15.6
5./89-36CCC	Kit	0	--	--	--	--	100	99.5	91.6	12.5	5.0
5/90-9DAC	Kit	0	--	--	--	--	99.9	98.6	88.9	62.7	26.5
[1]6/86-8DCB	Kit	0	2.01	26	35	1.5X10^{-2}	–	--	--	--	--
[1]6/86-8DDB	Kit	0	2.10	21	150	3.6X10^{-2}	100	97.0	71.5	15.3	5.6
6/86-16CAB	Kit	0	2.08	22	44	2.3X10^{-2}	100	97.5	93.4	89.2	21.4
6/86-20CDA	Kit	0	2.29	14	3.5	1.4X10^{-3}	100	99.2	94.7	44.4	17.7
6/86-28ABA	Kit	0	--	23	53	2.8X10^{-2}	100	97.8	93.3	73.7	7.6
[1]6/86-32ABD	Kit	1,151	2.28	14	2.3	1.2X10^{-3}	100	99.1	71.8	27.3	11.1
6/86-32ABD	Kit	1,152	2.26	15	4.8	1.9X10^{-3}	100	99.4	72.1	24.4	13.1
6/86-32ABD	Kit	1,153	2.25	15	9.9	4.5X10^{-3}	100	99.4	74.2	27.0	12.5
6/87-15DBB	Kit	0	2.09	21	15	7.0X10^{-3}	100	96.5	90.3	81.6	10.6
6/87-23DAD	Kit	0	2.13	20	22	1.lx10^{-2}	100	98.3	94.3	49.6	8.0
6/87-26CAA	Kit	0	2.16	19	13	6.1X10^{-3}	100	99.4	94.6	40.3	16.5
[1]6/87-35BBA	Kit	0	2.10	21	647	1.9X10^{-1}	100	99.1	57.8	6.7	2.8
6/87-36DAD	Kit	0	2.12	20	19	9.2X10^{-3}	100	96.8	91.9	86.7	17.4
6/88-35DDC	Kit	0	2.15	19	14	6.8X10^{-3}	100	95.6	89.6	83.8	44.1
4/85-8CAA	Kio	0	2.29	14	1.1	3.8X10^{-4}	100	97.6	89.0	42.9	10.2
4/85-19ADA	Kio	0	2.31	14	3.7	1.5X10^{-3}	100	96.8	87.4	41.1	10.5
4/85-19ADA	Kio	0	2.22	16	18	8.3X10^{-3}	100	98.2	72.0	24.7	9.2
4/85-30ACC	Kio	0	2.28	14	3.5	1.4X10^{-3}	100	96.3	72.8	21.3	5.8
4/85-31BAD	Kio	0	2.20	17	3.8	1.5X10^{-3}	100	98.3	85.3	33.6	7.5
4/85-31BBD	Kio	0	2.19	18	16	7.7X10^{-3}	100	97.7	91.5	49.8	11.6
4/86-22ACD	Kio	0	2.30	14	2.0	7.3X10^{-4}	100	96.4	88.5	72.0	14.2
4/86-23ACC	Kio	0	2.15	19	43	2.2X10^{-2}	100	99.8	91.2	20.0	3.9
4/86-23BAB	Kio	0	2.20	17	1.6	5.8x10^{-4}	100	99.3	77.7	24.6	5.2
4/86-28CCD	Kio	0	2.11	20	53	2.8x10^{-2}	100	99.5	76.7	24.7	8.4
4/87-10ACC	Kio	0	2.14	20	278	1.8x10^{-1}	100	99.1	84.9	21.3	7.8
4/87-34DBA	Kio	0	2.15	20	6.2	2.7x10^{-3}	100	96.5	89.2	55.6	12.5
5/85-20CAB	Kio	0	2.08	22	324	2.1x10^{-1}	100	99.0	64.7	11.1	4.5
5/86-1BAD	Kio	0	2.42	11	0.4	1.3x10^{-4}	100	98.9	92.5	29.2	9.9
5/88-25DAA	Kio	0	2.01	25	352	2.3x10^{-1}	100	98.3	92.8	35.6	8.9
6/86-23BCC	Kio	0	2.14	20	18	8.3x10^{-3}	100	99.1	94.0	43.6	15.0
6/86-25BAA	Kio	0	2.12	21	17	8.0x10^{-3}	100	98.5	94.6	82.8	15.5
6/86-25DBA	Kio	0	2.58	6.6	0.2	5.8x10^{-5}	100	96.9	87.8	72.2	24.9

[1]Data used in figure 25.

Plugs 1 in. in diameter and 1.25 in. long were cut from most samples for use in a helium gas expansion porosimeter, gas permeameter, water permeameter, and porometer. Most samples were analyzed for bulk density, porosity, and gas permeability. Grain-size distributions also were determined on a disaggregated part of each rock sample. Laboratory hydraulic-conductivity determinations were made on 14 samples in order to define a relation between gas permeability and hydraulic conductivity. This relation (fig. 25) was used to convert the determinations of gas permeability into estimates of hydraulic conductivity. The line of relation defined by the data in figure 25 is below the theoretical maximum (Klinkenberg relation; Klinkenberg, 1941) because clay in the sample reacts with water to decrease the permeability of the wetted sample.

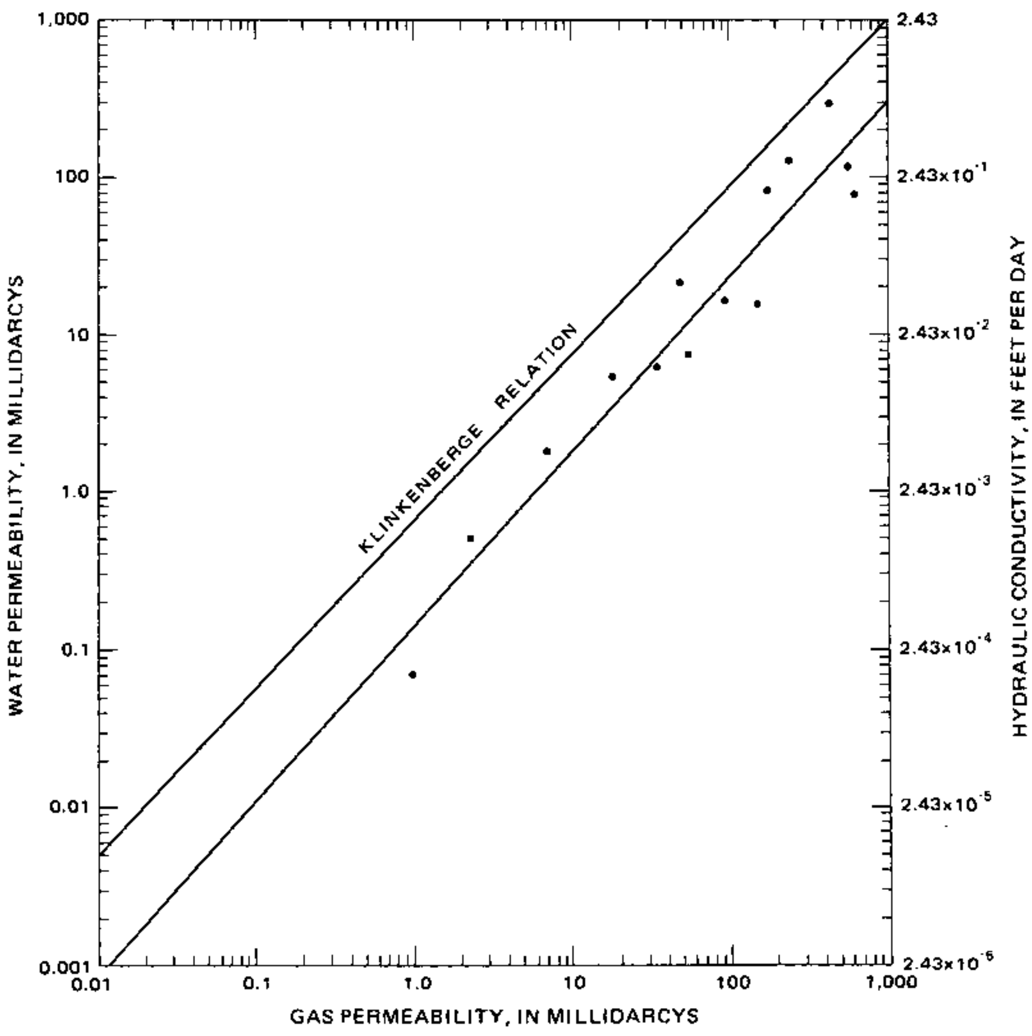

Figure 25.--Relation between gas permeability and hydraulic conductivity in samples from regional aquifers.

Hydraulic Conductivity

The hydraulic conductivity of the Trout Creek aquifer is defined for 33 data points in the eastern part of the area. The areal distribution of data values seems random, and no clear regional trend in hydraulic conductivity is evident. The data are approximately log-normally distributed, have a geometric mean of $5.1X10^{-3}$ ft/d, a standard deviation of $5.5x10^{-2}$ ft/d, and range from $4.4x10^{-6}$ to $2.7x10^{-1}$ ft/d. The hydraulic conductivity of the basal Williams Fork aquifer is defined for 53 data points. Here again, no clear pattern of regional trend in hydraulic conductivity is evident, although values seem to be larger in Eckman Park and near Trout Creek. The data are approximately log-normally distributed, have a geometric mean of $1.1x10^{-1}$ ft/d, a standard deviation of $8.3x10^{-1}$ ft/d, and range from $3.0x10^{-5}$ to 4.2 ft/d. In the Twentymile aquifer, hydraulic conductivity in the eastern area is defined for 40 data points, which indicate no regional trend in hydraulic conductivity. The data are approximately log-normally distributed, have a geometric mean of $1.4x10^{-2}$ ft/d, a standard deviation of $1.2x10^{-1}$ ft/d, and range from $9.7x10^{-6}$ to $6.9x10^{-1}$ ft/d.

The geometric mean values for the hydraulic conductivity of the three aquifers indicate that the basal Williams Fork aquifer is about 10 times more permeable than the Twentymile aquifer and is about 20 times more permeable than the Trout Creek aquifer. The difference between the mean hydraulic-conductivity values is statistically significant at the 1 percent level in a Student's t test. The difference in hydraulic conductivity may be due to the effects of secondary permeability produced by fractures in the coal beds in the basal Williams Fork aquifer. Unfractured coal is relatively impermeable. However, results of eight aquifer tests in the Wadge coal indicate that the mean hydraulic conductivity of this coal is $3.5X10^{-1}$ ft/d--about three times as large as the hydraulic conductivity of the basal Williams Fork aquifer as a whole. Although the data are few, the above results indicate that coal beds in the study area may be relatively permeable.

The effects of secondary permeability in the sandstone aquifers are more difficult to quantify. If fracturing enhances water movement in the sandstone, hydraulic conductivity based on aquifer tests could be larger than hydraulic conductivity based on laboratory analyses of unfractured rock samples. Nine aquifer tests in the Twentymile Sandstone had a mean hydraulic conductivity of $2.1x10^{-2}$ ft/d. Thirty-one hydraulic conductivity values from laboratory analyses of unfractured rock samples had a mean of $1.2x10^{-2}$ ft/d. The difference between these two numbers is not stastically significant at the 1 percent level of a Student's t test, indicating that secondary permeability in sandstone may be hydrologically insignificant or highly localized.

Fracture patterns on outcrops of Twentymile Sandstone Member indicate that joint and fracture density is highly variable in the eastern part of the study area. North of Grassy Gap (fig. 26), the sandstone forms massive cliffs that have unfractured intervals of hundreds of feet. Northwest of Twentymile Park (fig. 27), joints and fractures occur at intervals of 10 to 100 ft; to the northeast of Twentymile Park, joints and fractures are present at intervals of 10 ft or less (fig. 28). The effects of secondary permeability at depth in the sandstones likely are small because of lesser density of fracturing in the subsurface and minimal fracture interstice due to overburden load.

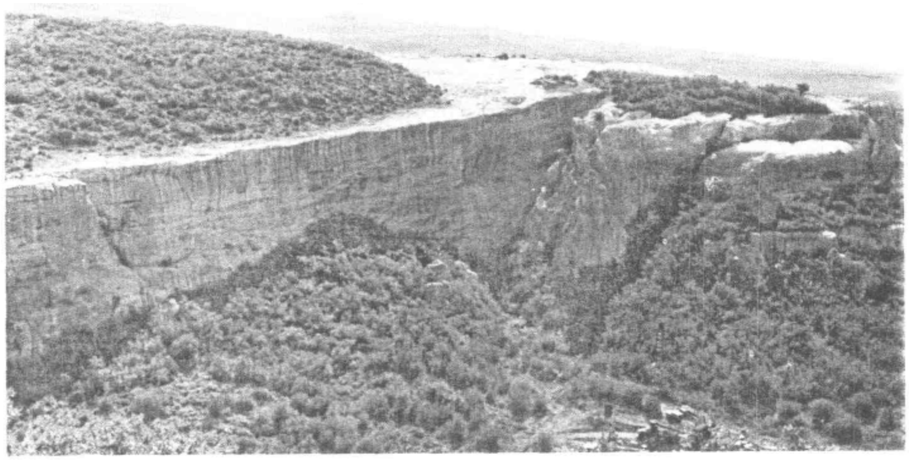

Figure 26.--Massive cliffs formed by outcrops of the Twentymile Sandstone Member of the Williams Fork Formation north of Grassy Gap.

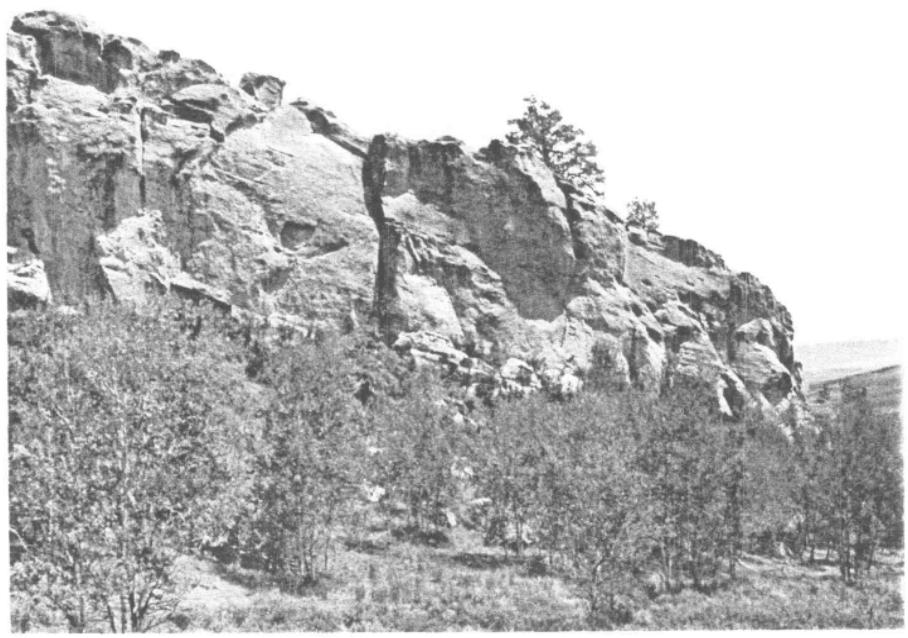

Figure 27.--Moderately fractured outcrops of the Twentymile Sandstone Member of the Williams Fork Formation northwest of Twentymile Park.

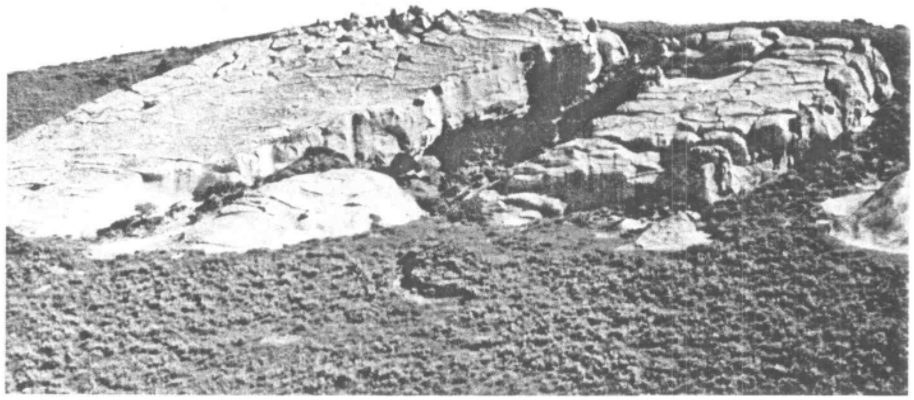

Figure 28.--Dense joint and fracture pattern enhanced by erosion on the exposed dip slope of the Twentymile Sandstone Member of the Williams Fork Formation northeast of Twentymile Park.

The hydraulic conductivity of the shale and siltstone beds that form confining layers in the study area are computed from 14 lateral hydraulic-conductivity determinations on drill-core samples of unweathered siltstone and 12 vertical hydraulic-conductivity determinations on drill-core samples of unweathered marine shale. The respective mean hydraulic-conductivity values of 8.1x10 and 4.4×10^{-4} ft/d are not statistically different at the 1 percent level of significance in a Student's t test. Both the lateral and vertical hydraulic conductivity of unfractured siltstone or shale confining layers in the eastern part of the area are assumed to be equal to the mean of the lateral and vertical values (3.6×10^{-4} ft/d). Effects of fracturing are not documented by field data.

One aquifer test in the Lewis Shale indicates a relatively large value of hydraulic conductivity (table 6, sample 5/86-21BCC). Secondary fracturing from weathering or faulty well construction may have caused this anomalously large value.

Transmissivity

The transmissivity distribution in the aquifers in the eastern part of the area was calculated as the product of mean hydraulic conductivity and the aggregate thickness of water-yielding materials in the aquifer. The resulting transmissivity of the Trout Creek aquifer ranges from 0.5 to 0.8 ft^2/d across the area. This small range is the result of the relatively uniform thickness of the aquifer (100 to 150 ft). A median value of 0.65 ft^2/d is consistent with the range and distribution of transmissivity. The 100- to 200-ft aggregate thickness of the basal Williams Fork aquifer produces transmissivity values that range from less than 10 ft^2/d to more than 25 ft^2/d. One area of small transmissivity is located in the southern part of Twentymile Park. Areas of relatively large transmissivity are near Eckman Park, Trout Creek, Grassy Gap, and Hilberry Mountain (fig. 29; pl. 1). The transmissivity of the Twentymile aquifer is irregular because of the large and inconsistent range in thickness (80 to 180 ft). The average transmissivity was 3.5 ft^2/d. In outcrops, the saturated thickness of each aquifer thins rapidly to a point of zero saturation. The rate of thinning and the location of the point of zero saturation are poorly defined by data. Consequently, the rapid decrease in transmissivity at the margin of each aquifer also is poorly defined.

Transmissivity values in the western part of the area generally are larger than transmissivity values in the eastern part of the area (tables 5 and 6). This is not a function of thickness alone because well completions varied in thickness throughout the study area. The three most plausible reasons for the differences are variation in fracturing, diagenesis, and lithology. Lithology likely is the most important of the three. Sediments in the eastern area were deposited in a lower energy, deeper water environment, and consequently contain more marine shale than the western area. The resulting average grain size of the eastern lithology would be smaller, and the resulting permeability also should be smaller. Fracturing and diagenesis are present and cause local variations in permeability, but they do not differ systematically in the two areas and probably are not an important cause of the larger transmissivity in the west.

Porosity

Porosity determinations made on 77 rock samples from outcrops and drill cores indicated regional trends in porosity in some aquifers. Although the data are sparse, the porosity of the Trout Creek aquifer seems to average about 15 percent in a broad band extending from Twentymile Park toward Hayden (fig. 30). Porosity along parts of the northern and southern margins of the aquifer averages about 22 percent. A similar pattern is indicated by the porosity data for the Twentymile aquifer, although the smaller porosity band is narrower than is indicated for the Trout Creek aquifer. Porosity averages about 12 and 23 percent in the two areas indicated in the Twentymile aquifer (fig. 31). Insufficient data are available to define trends in the porosity of the basal Williams Fork aquifer; porosity in the 16 samples ranges from 5.6 to 19 percent, has a mean of 14.1 percent, and a standard deviation of 3.6.

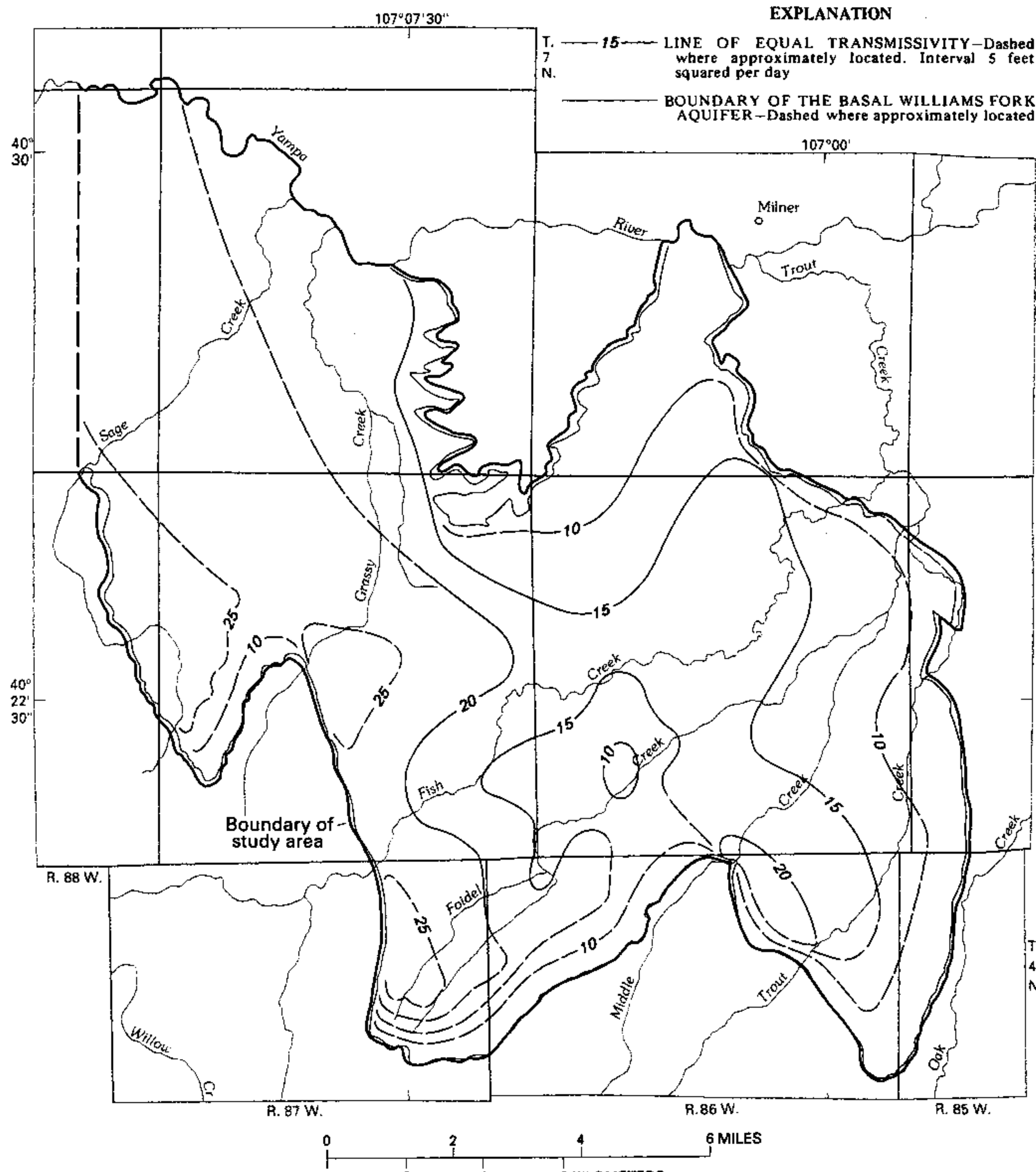

Figure 29.--Transmissivity of the basal Williams Fork aquifer in the eastern part of the study area.

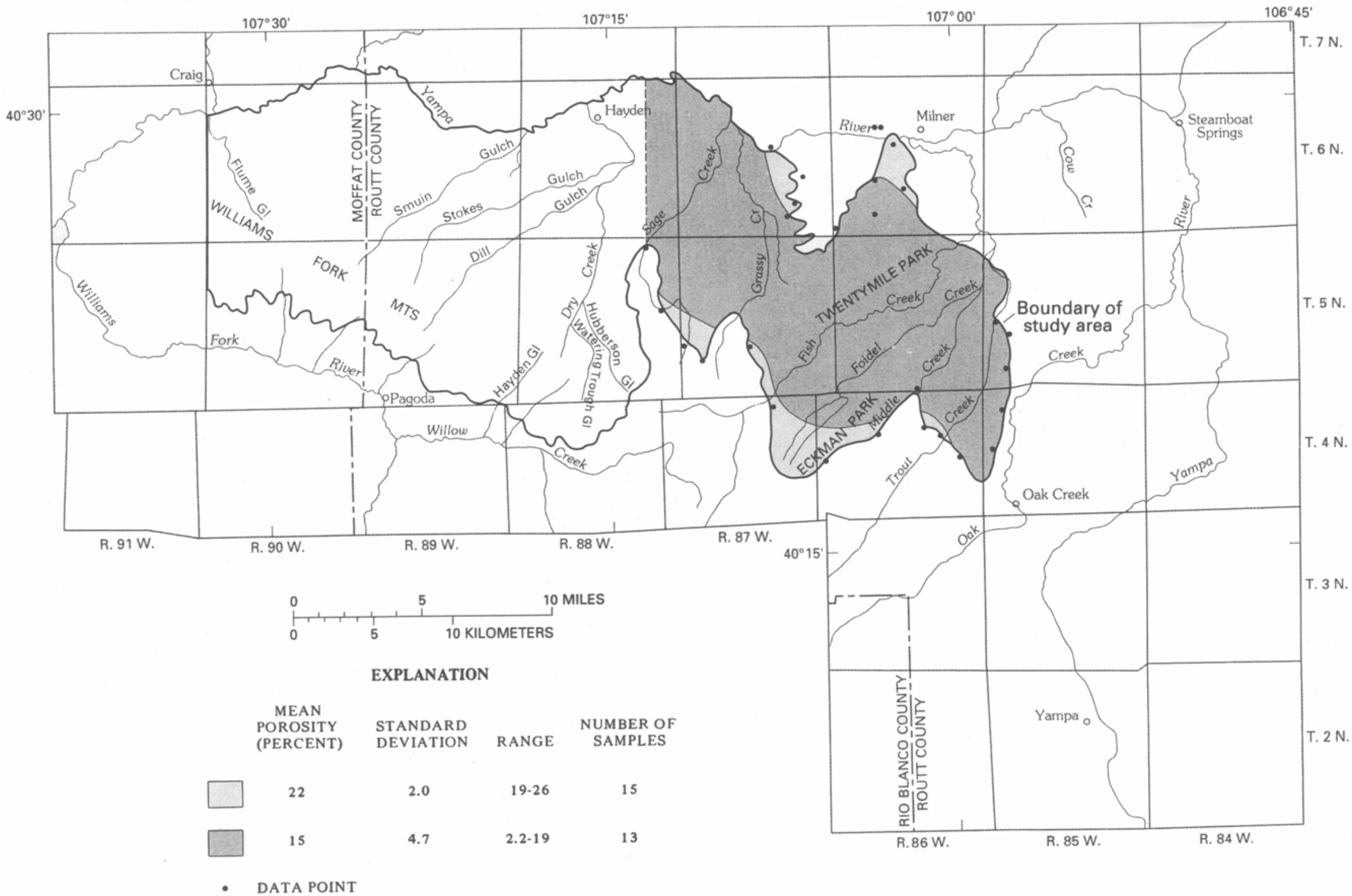

Figure 30.– Porosity of the Trout Creek aquifer in the eastern part of the study area.

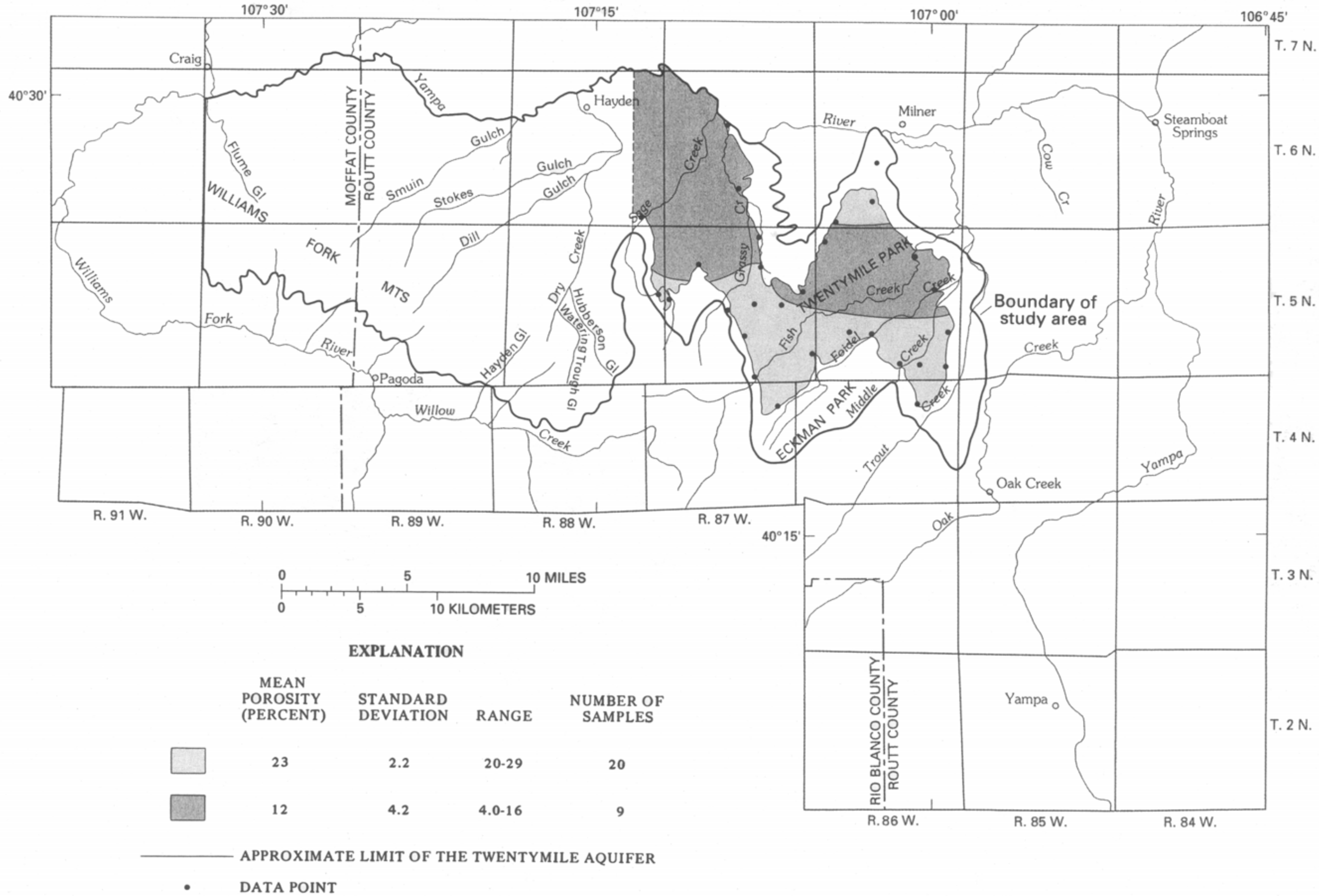

Figure 31.– Porosity of the Twentymile aquifer in the eastern part of the study area.

Specific Storage and Storage Coefficient

In a confined aquifer, the specific storage is related to the porosity and compressibility of the rock and water by the equation:

$$S_s = \gamma\,(\phi\,C_w + C_r) \qquad (1)$$

where

S_s = specific storage; s
γ = specific weight of water;
ϕ = porosity;
C_w= compressibility of water; and
C_r = compressibility of rock.

Porosity of the sandstone strata in the eastern part of the area commonly ranges from 10 to 25 percent and averages about 20 percent. Compressibility of sandstone similar to that in the study area is about 1.5 $x10^{-6}$ in^2/lb (Fatt, 1958). These data, when used with the characteristics of water in the above equation, yield a specific storage of 9 $x10^{-7}$ ft^{-1}. This value is the volume of water the confined water-yielding sandstones release from or take into storage, per unit volume of rock, per unit change in head due to the compressive character of the water and rock.

In an unconfined aquifer, the volume of water released from or taken into storage by this process is insignificant when compared to the volume of water released by gravity drainage or filling of pore space in the rock. The storage coefficient of an unconfined aquifer is approximately equal to the specific yield of the water-yielding material and may be several orders of magnitude larger than the confined storage coefficient. No data are available to define the specific yield of the sandstones in the study area. However, sandstone that has a porosity of 20 percent could be expected to have a specific yield of about $1x10^{-1}$.

Storage coefficient in a confined aquifer is equal to the product of specific storage and aquifer thickness. Thus, a 100-ft-thick confined aquifer in the Twentymile Sandstone, or Trout Creek Sandstone Members, that has a specific storage of 9 $x10^{-7}$ per foot would have a storage coefficient of 9 $x10^{-5}$. Storage coefficient in an unconfined aquifer in either unit would be about $1x10^{-1}$.

Three storage-coefficient values obtained from pumping-well aquifer tests in the basal Williams Fork aquifer ranged from $2x10^{-4}$ to $lx10^{3-}$. The accuracy of such tests generally are poor, but results indicate confined conditions exist in this aquifer.

GROUND-WATER MOVEMENT

Ground-water movement occurs as a result of hydraulic-head differences in an aquifer. The head in an aquifer at a well is calculated from water-level-measurement data and normally is expressed in terms of the altitude of the standing water level in the well. Head determinations at many different sites define the altitude and areal distribution of head in the aquifer (a