THE DAKOTA AQUIFER NEAR PUEBLO, COLORADO:

FAULTS AND FLOW PATTERNS

By Edward R. Banta

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METRIC CONVERSIONS

The inch-pound units used in this report may be converted to SI (International System of Units) by use of the following conversion factors:

Multiply	*By*	*To obtain*
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
square foot per day (ft^2/d)	0.09290	square meter per day

Temperature in degree Celsius (°C) may be converted to degree Fahrenheit (°F) by use of the following formula:

$$°F = 9/5\ °C+32$$

The following term and abbreviation also is used in this report:

microsiemens per centimeter (μS/cm)

THE DAKOTA AQUIFER NEAR PUEBLO, COLORADO: FAULTS AND FLOW PATTERNS

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ABSTRACT

The Lower Cretaceous Dakota Sandstone and underlying Purgatoire Formation (Dakota aquifer) form a broad outcrop at the southeastern margin of the Cañon City Embayment just west of Pueblo, Colorado. Five large faults and several small faults, all apparently of high angle, have been found to affect ground-water flow patterns in the Dakota aquifer and adjacent strata. Analysis of lithology, structure, ground-water levels, and water quality indicates areas of restricted flow and of interformational flow.

The transmissivity of the Dakota aquifer is extremely variable, but in most of the study area it ranges from 50 to 200 square feet per day. Net recharge in the outcrop area is estimated to be about 920 acre-feet per year, as calculated by a flow-net analysis.

INTRODUCTION

The Lower Cretaceous Dakota Sandstone and Purgatoire Formation (Dakota aquifer) supply water for domestic, stock, irrigation, and municipal purposes in much of southeastern Colorado as well as other areas of the Great Plains physiographic province. In Colorado, recharge to the Dakota aquifer occurs primarily in the outcrop areas, because the overlying Graneros Shale (Upper Cretaceous) and underlying Morrison Formation (Upper Jurassic), typically effective confining beds, greatly retard interformational flow. The presence of faults in, and downgradient from, the outcrops causes the question to arise: Do the faults affect the hydraulic flow regime to such a degree that they hinder or enhance the rates of recharge or control the direction of flow? The question of how ground-water flow is affected here as well as in other areas where equivalents of the Dakota and Purgatoire are faulted is of importance to the Central Midwest Regional Aquifer System Analysis, a U.S. Geological Survey project concerned with the geohydrology of the Dakota aquifer and underlying aquifers of the Great Plains physiographic province.

A 12-township area in Pueblo and Fremont Counties near Pueblo, Colo., was selected for the purpose of exploring this question (see fig. 1). Here the Dakota Sandstone and Purgatoire Formation, due to generally gentle dip, form broad outcrop areas (fig. 2) in contrast to the more common hogback-shaped outcrops found along the mountain flanks where the strata dip steeply. Scott and others (1978) and Stout (1958) have mapped several high-angle faults which have stratigraphic offsets as much as 250 ft in places.

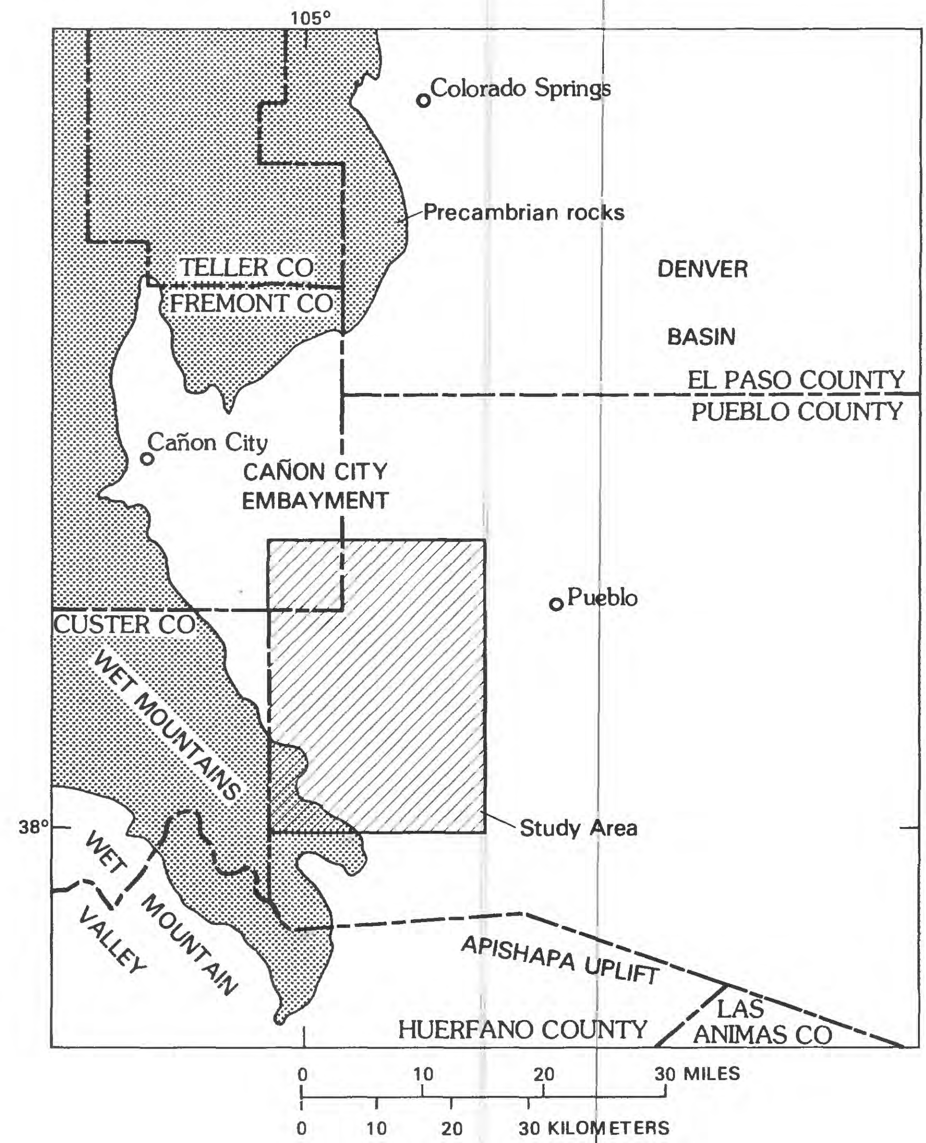


Figure 1.--Location of study area.

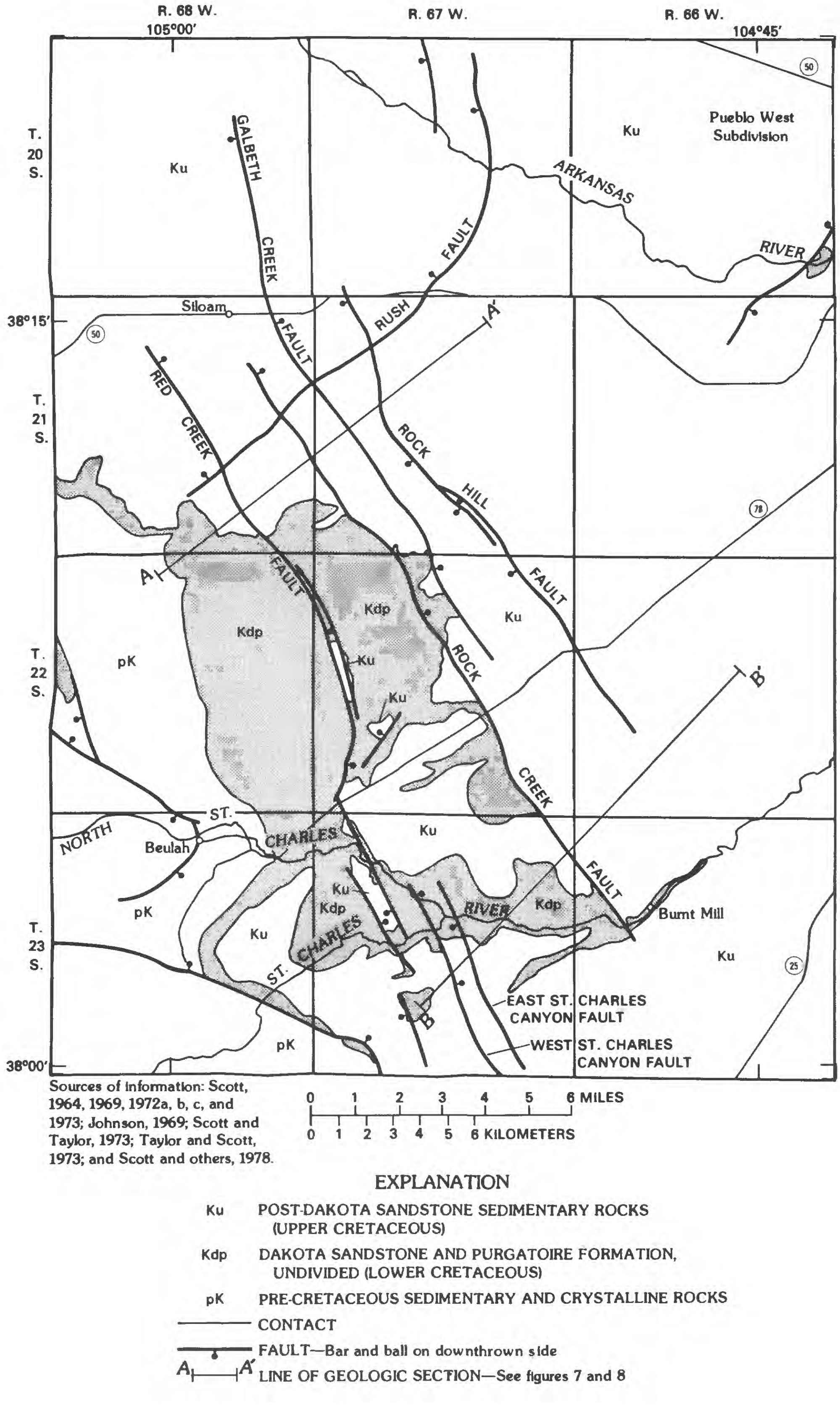


Figure 2.--Generalized geology.

Data used to infer the effects of geologic controls on the ground-water flow patterns were stratigraphic and lithologic descriptions, water levels in wells, and specific conductance of ground water. The geologic controls analyzed in this report are in two categories: Lithology and structure (fault-associated). Stratigraphic descriptions in published and unpublished reports and lithologic descriptions from water-well drillers' logs and one oil test well log provided the basis for the lithologic characterization of the strata of the Dakota Sandstone, the Purgatoire Formation, and adjacent units. The map showing the structure of the top of the Dakota Sandstone (fig. 3) was drawn using altitudes of "tops" interpreted from water-well drillers' logs and outcrop altitudes of the Dakota Sandstone and younger units. This map was used to estimate the magnitude of the offset along the various faults (fig. 4). Water-level data were obtained from water-well drillers' logs and U.S. Geological Survey ground-water files. The effects of pumping from the aquifer on water-level data were minimized by selecting water-level data recorded before the extensive development of the aquifer. With ground-water pumping at a negligible level, the ground-water flow characteristics in the Dakota aquifer primarily were affected by geologic factors. Water-level contours were derived from water levels in selected wells. Specific-conductance data, obtained from U.S. Geological Survey ground-water files and a report by Crouch and others (1982), were used as an indication of the concentration of dissolved solids in the ground water. The configuration of the potentiometric surface and the distribution of dissolved solids were used to infer ground-water flow patterns in the Dakota aquifer. The geology and the flow patterns were compared in order to infer a cause-and-effect relation between the geologic controls and the ground-water flow patterns.

GEOLOGY OF THE DAKOTA SANDSTONE, THE PURGATOIRE FORMATION, AND ASSOCIATED ROCKS

Stratigraphy

The thickness of the Dakota Sandstone and underlying Purgatoire Formation ranges from less than 200 ft in the east-central part of the mapped area to 340 ft in the west-central part (fig. 5). Sedimentary rocks ranging from fluvial sandstones and conglomeratic sandstones to marine shales are found within this sequence. For descriptive purposes, the rocks are divided into three major units in ascending order: The Lytle Sandstone and Glencairn Shale Members of the Purgatoire Formation, and the Dakota Sandstone (fig. 6).

The Purgatoire Formation is underlain by the Jurassic Morrison Formation, a series of sandstone, argillaceous limestone, varicolored shale, and siltstone, all lenticular in nature (Malek-Aslani, 1952) that is over 300 ft thick.

The Graneros Shale overlies the Dakota Sandstone and is approximately 105 to 115 ft thick (Scott, 1972a and 1973; Scott and Taylor, 1973; Taylor and Scott, 1973).

The Lytle Sandstone Member of the Purgatoire Formation is the most variable in thickness of the three rock units. The maximum measured thickness is 190 ft in section 25, T. 21 S., R. 68 W.

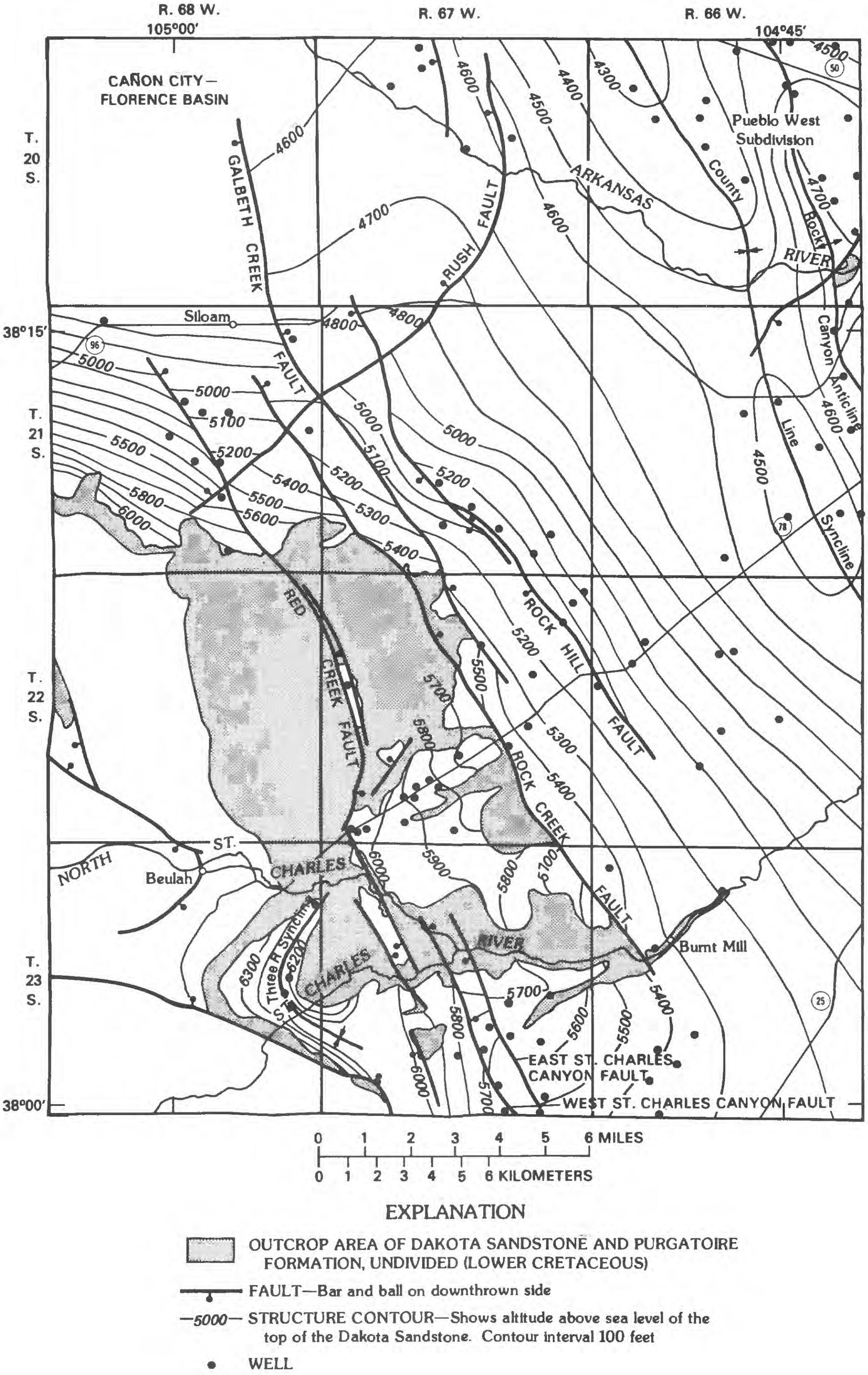


Figure 3.--Altitude and configuration of the top of the Dakota Sandstone.

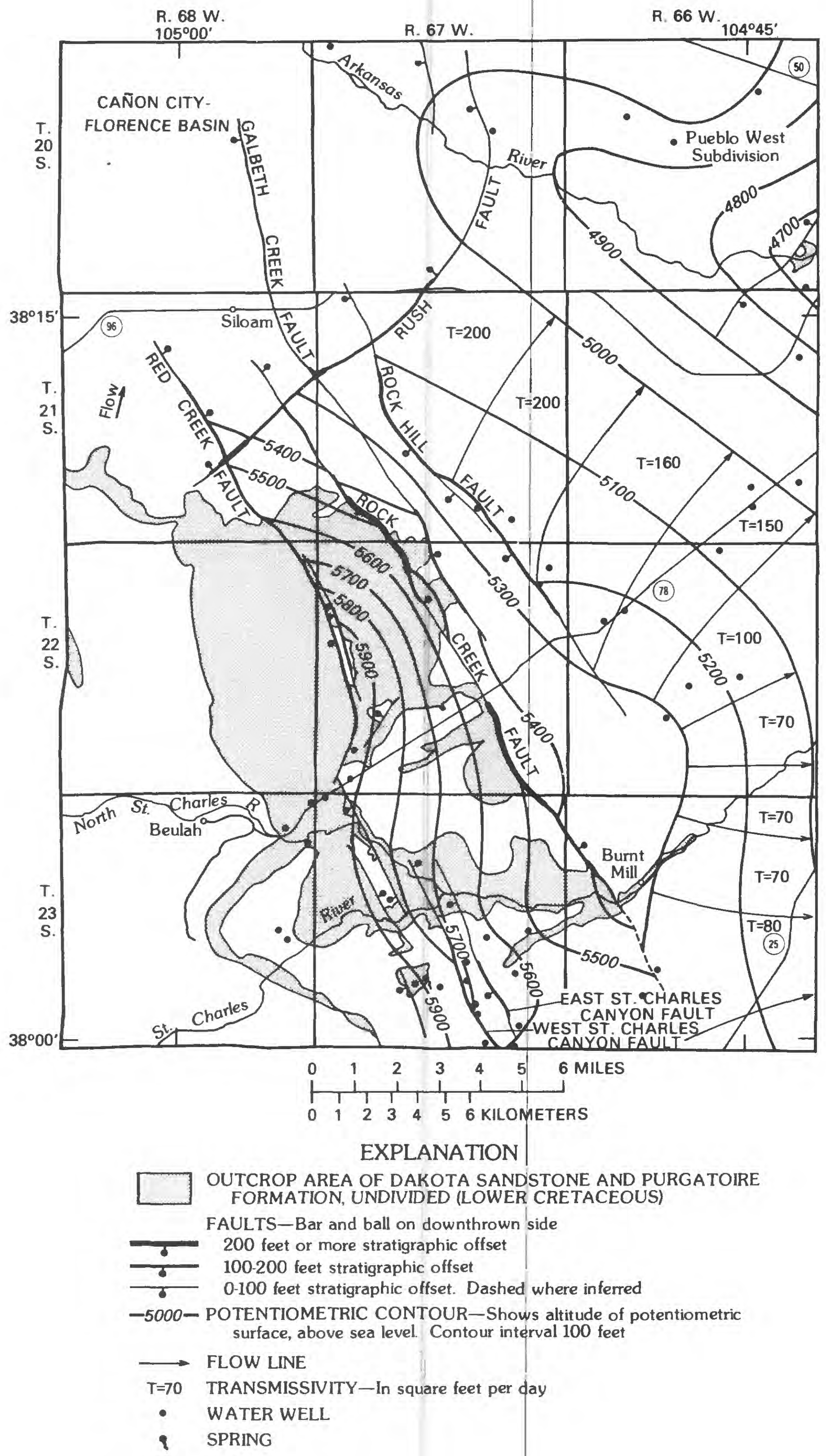


Figure 4.--Altitude and configuration of the potentiometric surface and flow net for the Dakota aquifer.

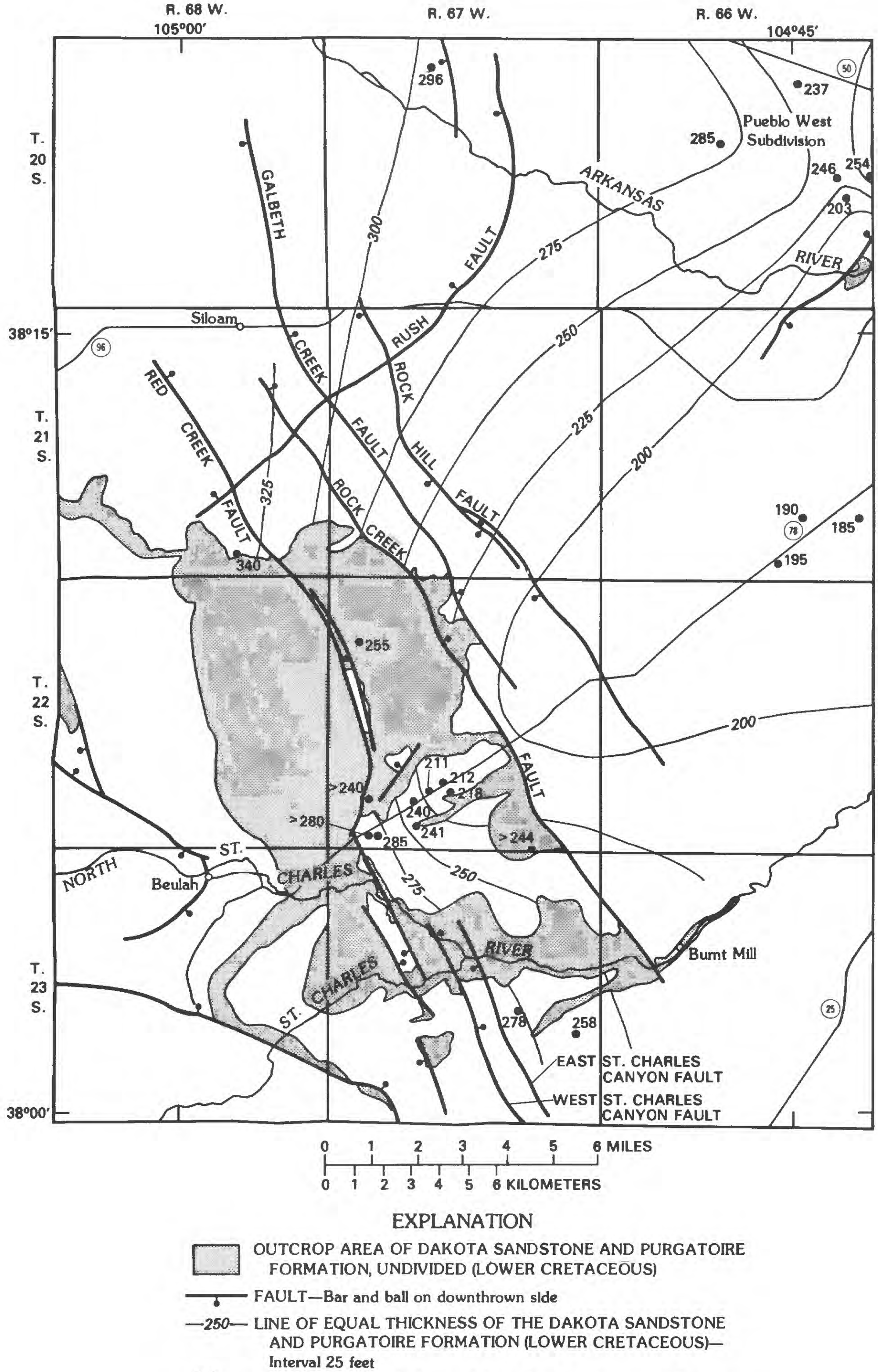


Figure 5.--Thickness of the Dakota Sandstone and Purgatoire Formation.

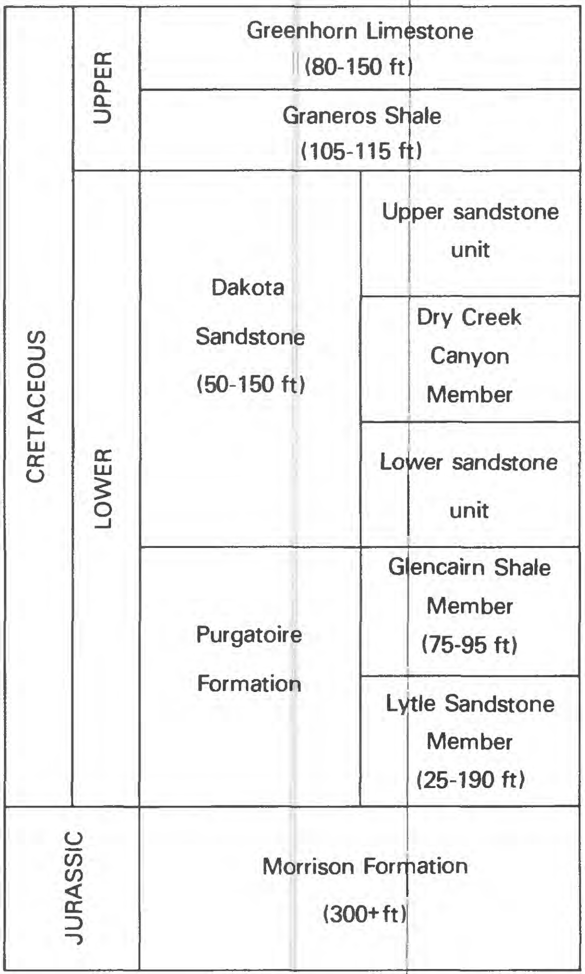


Figure 6.--Stratigraphy of the Dakota Sandstone, Purgatoire Formation, and associated rocks.

Weimer (1970, p. 161) describes the Lytle Sandstone Member as follows:

> The unit consists of white to light-tan fine- to medium-grained lenticular conglomeratic quartzose sandstone bodies which are surrounded by red to green siltstone and claystone layers. The individual sandstone bodies are fluvial channel deposits that vary in width from a few hundred to a few thousand feet and vary in thickness from a few feet to as much as 60 feet.

Water-well drillers rarely differentiate between siltstone and sandstone in their well construction logs, so the Lytle Sandstone Member typically is described as a massive sandstone bed, although red and green shales are reported in places. No drillers' logs record a conglomerate in this part of the stratigraphic section.

The Glencairn Shale Member of the Purgatoire Formation in the study area ranges in thickness from 75 to 95 ft (Vinckier, 1978). Both Weimer (1970) and Vinckier (1978) describe the Glencairn Shale Member as a series of alternating shale and marine sandstone locally underlain by a massive, locally conglomeratic sandstone. Weimer (1970) calls this lowermost sandstone the Plainview Sandstone Member of the South Platte Formation; Vinckier (1978) calls it the basal Glencairn sandstone. Hydrologically, there is no reason for distinguishing between Vinckier's basal Glencairn sandstone and the underlying Lytle Sandstone Member. Therefore, for the purposes of this report, Vinckier's basal Glencairn sandstone, where it occurs, is included with the Lytle Sandstone Member. The composition of the Glencairn Shale Member varies; shale and siltstone are dominant in some areas and fine-grained sandstone is dominant in others (Vinckier, 1978).

Both Waagé (1953) and Vinckier (1978) describe three distinct units in the Dakota Sandstone: The lower sandstone, the middle Dry Creek Canyon Member, and the upper sandstone. The thickness of the Dakota Sandstone generally increases toward the southern part of the mapped area where it exceeds 150 ft. The unit thins to less than 50 ft in the northeastern part of the area.

The textures of both sandstone units in the Dakota Sandstone range from fine-grained to locally conglomeratic. The lower sandstone unit tends to be medium-grained, whereas in the upper sandstone unit fine- to medium-grained sandstone alternates with shale layers. In particular, the deposits near the top of the upper sandstone unit generally are transitional into the overlying Graneros Shale and as such tend to contain the shale layers, although shale streaks are common throughout the upper sandstone unit. The Dry Creek Canyon Member consists of shale, claystone, and sandstone layers. Waagé (1953), in his description and interpretation of the geology of the Dakota Sandstone in outcrops, concluded that two phases of channeling removed all but a limited distribution of remnants of the Dry Creek Canyon Member. According to Waagé (1953), the channels formed by erosion into, and occasionally through, the Dry Creek Canyon Member were filled with deposits of the upper sandstone unit. In outcrops where channeling has removed the entire Dry Creek Canyon Member, the Dakota Sandstone is one massive sandstone bed. Likewise, in the subsurface, the Dry Creek Canyon Member was found to be nonpersistent in the study area.

The depositional environments of the Dakota Sandstone are deltaic, coastal, fluvial, and littoral (Waagé, 1953; Long, 1966; Weimer, 1970). This range of depositional environments is responsible for the complex lithology of the Dakota Sandstone.

Structure

The study area is located on a broad structural saddle between the Cañon City Embayment to the west and the southern end of the Denver basin to the east (fig. 2). To the southwest are the Wet Mountains and the subsurface Apishapa uplift, which together form a northwest-trending, southeast-plunging arch (Oborne, 1956).

Four major northwest-striking faults and one northeast- to north-striking fault offset the sedimentary rocks in this area (fig. 3). From southwest to northeast the four northwest-striking faults are: The Red Creek fault, the Rock Creek fault, the Galbeth Creek fault, and the Rock Hill fault. The northeast- to north-striking fault is the Rush fault.

The Red Creek fault, the Rock Creek fault, and for most of its length, the Galbeth Creek fault are downthrown on the northeast, forming a series of steps. The throw of the northern end of the Galbeth Creek fault is reversed for a short distance (Scott and others, 1978). The Rock Hill fault is downthrown on the southwest, forming a graben between it and the Galbeth Creek fault (fig. 7). The Rush fault is downthrown on the northwest.

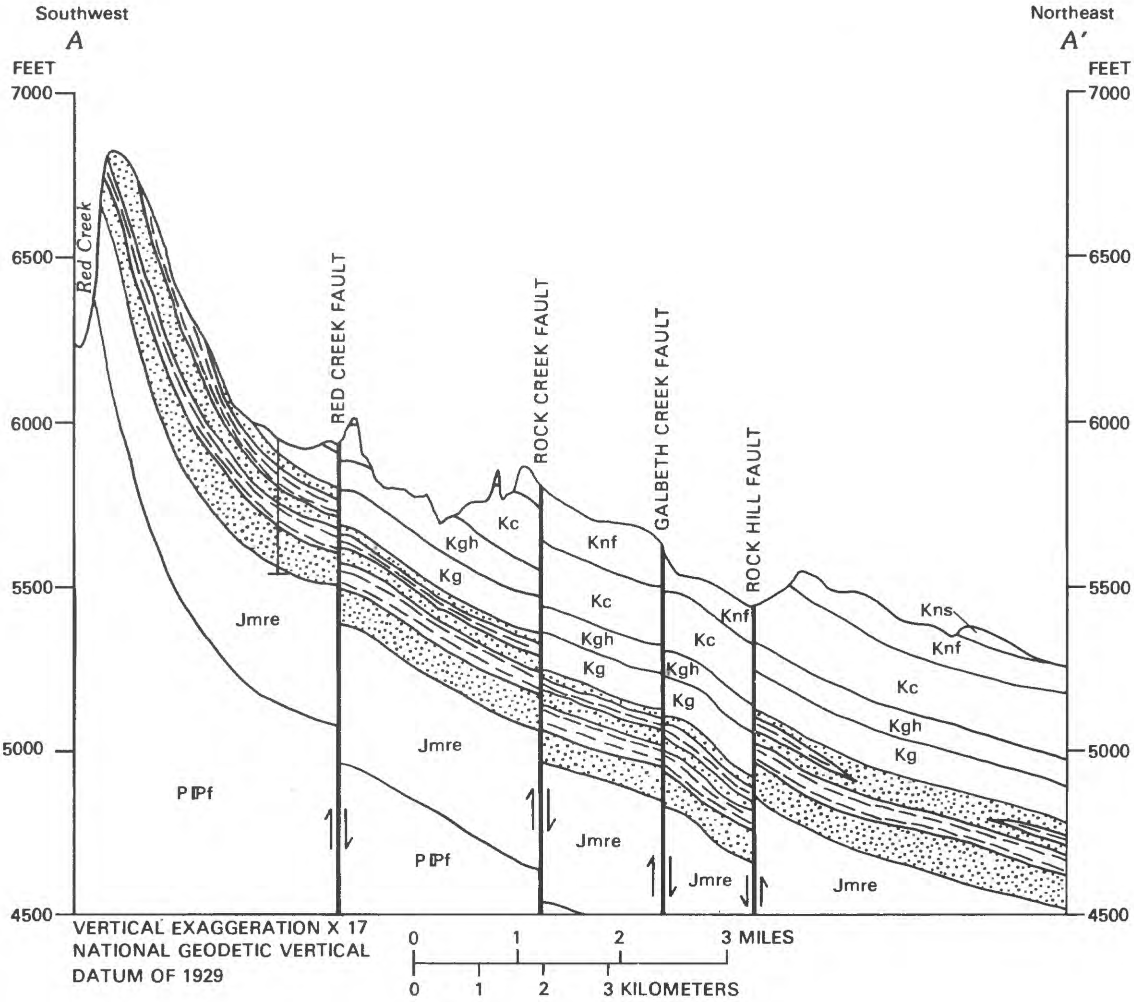
The Rock Creek fault is the most laterally extensive of the five faults named above and also has the largest stratigraphic displacement. Stratigraphic displacements along the faults exceeding 100 and 200 ft, inferred from the structure contours, are shown in figure 5. The Rock Creek fault has an offset greater than 200 ft for about 5 mi of its length in two segments located between the southwest part of T. 21 S., R. 67 W. and the northwest part of T. 23 S., R. 67 W. Interspersed segments of this fault, however, have little or no offset. The only other fault that has more than 200 ft of offset is the Rush fault, where large offsets are inferred for short distances at the intersections with the Red Creek and Galbeth Creek faults.

In addition to these major faults there are three other unnamed faults that have at least 100 ft of offset. The northernmost fault is just east of the Red Creek fault and is downthrown on the west, forming a long, narrow graben between these two faults. Maximum offset is about 150 ft, judging from water-well and outcrop information on either side of the fault.

Two faults in the south-central part of the study area have displacements exceeding 100 ft along parts of their extents. These faults, which form a graben trending southeast across the center of T. 23 S., R. 67 W., are called the East and West St. Charles Canyon faults in this report (fig. 2). Other faults shown in figure 2 either have offsets less than 100 ft or occur where the Dakota Sandstone and Purgatoire Formation are absent.

In the central and southeast parts of the study area the Dakota-Purgatoire sequence dips generally to the northeast at a moderate 80 to 150 ft/mi. This trend continues to the northeast into the north- to northwest-trending County Line syncline (Scott and others, 1978; see fig. 3). Continuing to the east-northeast, the sequence rises more steeply to the Rock Canyon anticline (Scott and others, 1978), the axis of which crosses the extreme northeast corner of the mapped area, approximately parallel to the County Line syncline.

The southeast margin of the Cañon City-Florence basin (Scott and others, 1978) occupies the northwest part of the mapped area. Here, west of the Red Creek and Rush faults, the Dakota-Purgatoire sequence dips northward at 300 ft/mi to more than 1,000 ft/mi at the outcrop, where the dip is approximately 11 degrees, the steepest in the study area.



EXPLANATION

UPPER CRETACEOUS

Kns Smoky Hill Member of the Niobrara Formation

Knf Fort Hays Limestone Member of the Niobrara Formation

Kc Carlile Shale

Kgh Greenhorn Limestone

Kg Graneros Shale

LOWER CRETACEOUS

Upper unit of the Dakota Sandstone

Dry Creek Canyon Member of the Dakota Sandstone

Lower unit of the Dakota Sandstone

Glencairn Shale Member of the Purgatoire Formation

Lytle Sandstone Member of the Purgatoire Formation

UPPER JURASSIC

Jmre Morrison Formation, Ralston Creek Formation, and Entrada Sandstone

PERMIAN AND PENNSYLVANIAN

P IPf Fountain Formation

CONTACT

FAULT—Arrows show direction of displacement

WELL

Figure 7.--Geologic section A-A'. (See fig. 2 for line of section.)

The south-central part of the study area is characterized by more complex folding than is the rest of the area. The most prominent fold is the L-shaped Three-R syncline (Scott and others, 1978; see fig. 4).

HYDROLOGY WITH RESPECT TO FAULTS AND FLOW PATTERNS

Water-bearing properties of the formations

The Morrison Formation underlies the Purgatoire Formation. In at least one area, the fine sediments generally present in the upper part of the Morrison form an effective barrier to vertical ground-water flow. Evidence of the nearly impermeable nature of these upper strata is from a well in section 31, T. 21 S., R. 67 W. This well was drilled through 75 ft of Dakota Sandstone, 67 ft of the Glencairn Shale Member, and 28 ft of the Lytle Sandstone Member, both of the Purgatoire Formation all of which yielded no water. Water was encountered at 380 ft below the top of the Morrison Formation and flowed at the surface. To the south and east of this well, there are other wells completed in the lower strata of the Morrison Formation; in these wells the water rises well above the top of the Morrison Formation, although the Dakota-Purgatoire sequence was reported not to have yielded water. The Morrison Formation is an important aquifer in the study area; many wells are completed in both the Morrison Formation and the Dakota-Purgatoire sequence. The Ralston Creek Formation does not yield water to wells in the study area. The Entrada Sandstone is only of minor importance as an aquifer. The Pennsylvanian and Permian Fountain Formation is important as an aquifer within the study area only in the area near Beulah, Colo., where the Dakota-Purgatoire sequence and the Morrison Formation have been removed by erosion.

The Lytle Sandstone Member of the Purgatoire Formation is the source of water for many of the domestic and stock wells in the study area. The properties of the Glencairn Shale Member as a permeability (hydraulic conductivity) barrier between the Dakota Sandstone and the Lytle Sandstone Member are not consistent. In some areas the sandstone laminae of the Glencairn Shale Member are sufficiently permeable to yield water to wells in quantities suitable for stock or domestic purposes. In other areas the Glencairn Shale Member is a massive shale and forms a confining bed. Overall, however, the variability in the composition of the Glencairn Shale Member is such that it should be described as a leaky confining layer. The Dakota Sandstone is the source of water for most of the domestic and stock wells in the study area. In many local areas, though, the shale layers in the Dry Creek Canyon Member and in the upper sandstone unit are effective confining beds. However, because of some hydraulic connection between all the units in the Dakota Sandstone and the Purgatoire Formation, they are treated as a single aquifer called the Dakota aquifer in this report.

The overlying Graneros Shale forms a nearly impermeable barrier, except in parts of the Arkansas River valley where erosion of this unit allows some hydraulic connection between the Dakota aquifer and the river-alluvial aquifer system.

Because no aquifer-test data were available for the Dakota aquifer in the study area, transmissivity values were estimated from specific capacities of wells. Specific capacity is defined as the ratio of discharge to drawdown in a pumped well. In the interest of accuracy, specific capacities resulting from bailer tests were not used for estimating transmissivities due to the difficulty in measuring the discharge and drawdown in a bailed well.

Meyer (1963) provides a method for estimating transmissivity from well specific capacity using Theis' (1935) nonequilibrium formula to construct a family of curves relating transmissivity to 1-day specific capacity, well-bore diameter, and storage coefficient. The method used in this report is virtually Meyer's (1963) method, modified so that tests for which pumping time was other than 1 day may be used. See Banta (1983) for details of this method.

The storage coefficient used in estimating transmissivity of the Dakota aquifer is 5.0×10^{-5}. This value was selected because it is typical of the values of the storage coefficient estimated using methods outlined in Vinckier (1978) and in Lohman (1972).

The faulting and channeling previously discussed, in addition to localized fracturing, probably cause much of the great variability observed in the estimated transmissivity values (fig. 8). Although many of the wells tested penetrate only a part of the Dakota aquifer, the effect of partial penetration would be small in comparison with the three-order-of-magnitude variability in the values shown. Indeed, the estimated transmissivity values seem to be unrelated to depth of penetration. Most of the large transmissivity values shown in figure 8 are not contoured because they probably reflect local fracturing.

Ground-Water Flow

Recharge and Discharge Areas

The map of the Dakota aquifer potentiometric surface (fig. 4) indicates that recharge occurs in the southwest part of the study area. This recharge occurs intermittently by infiltration of excess precipitation either through the soil zone or from the numerous ephemeral streams that traverse the outcrop area. Infiltration of excess irrigation water is only a small contribution because most of the land is used for ranching.

Most of the outcrop area shown in figure 5 serves as a recharge area, with the following exceptions: The St. Charles Canyon (fig. 9) and North St. Charles Canyon, which have been eroded deeply into the Dakota-Purgatoire sequence; the outcrop in section 28, T. 23 S., R. 67 W., in which there is a spring; and the outcrop on the Arkansas River at sections 25 and 36, T. 20 S., R. 66 W. These areas serve as discharge zones.

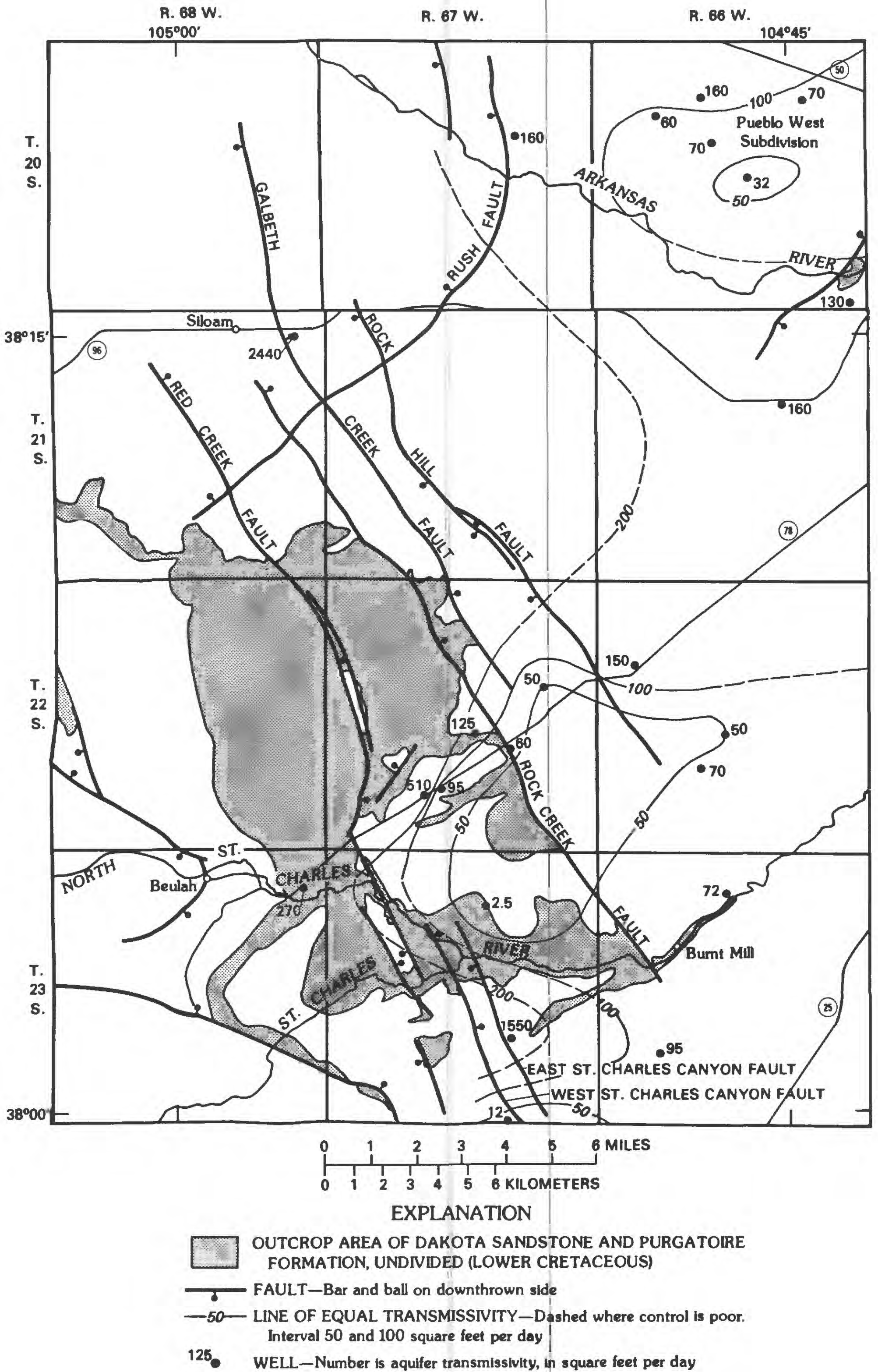
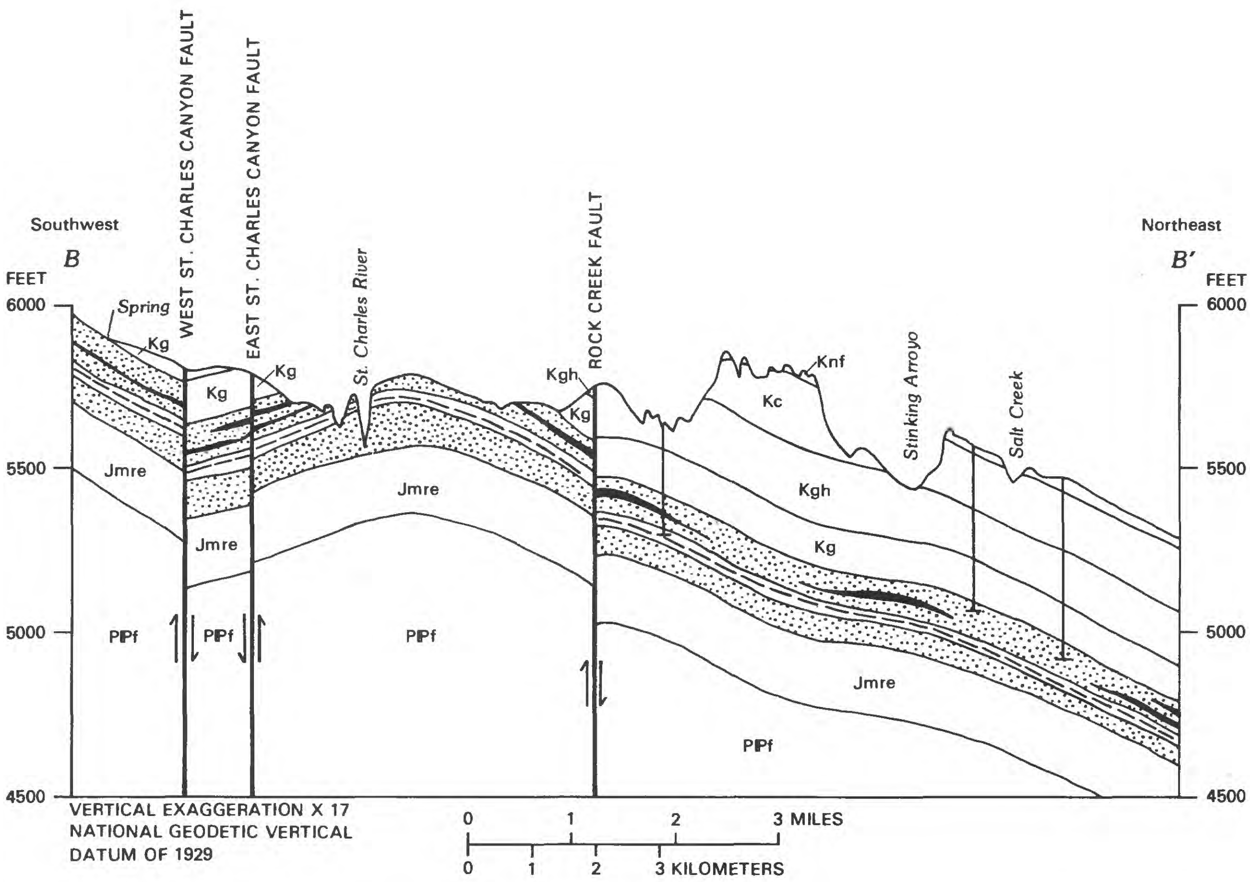


Figure 8.--Transmissivity of the Dakota aquifer.



EXPLANATION

UPPER CRETACEOUS

Knf	Fort Hays Limestone Member of Niobrara Formation
Kc	Carlile Shale
Kgh	Greenhorn Limestone
Kg	Graneros Shale

LOWER CRETACEOUS

Dakota Sandstone with shale layers

Glencairn Shale Member of Purgatoire Formation

Lytle Sandstone Member of Purgatoire Formation

UPPER JURASSIC

Jmre	Morrison Formation, Ralston Creek Formation, and Entrada Sandstone

PERMIAN AND PENNSYLVANIAN

PIPf	Fountain Formation

CONTACT

FAULT—Arrows show direction of displacement

WELL

Figure 9.--Geologic section B-B'. (See fig. 3 for line of section.)

Although the Dakota Sandstone and Purgatoire Formation are treated as one aquifer in this report, limited data show that the Glencairn Shale Member of the Purgatoire Formation is a relatively impermeable bed in at least one area. This is an elongate area of approximately 5 mi^2, approximately 4 to 5 mi long and 1 or more mi wide, trending northwest between section 31, T. 22 S., R. 67 W. and section 10, T. 23 S., R. 67 W. In this area, the potentiometric surface in the Lytle Sandstone Member of the Purgatoire Formation is approximately 100 ft lower than that in the Dakota Sandstone. The potentiometric-surface map (fig. 4) shows only the hydraulic head in the Dakota Sandstone in this area. The difference in hydraulic head probably is due to the difference in exposures of the two formations. Because the Dakota Sandstone overlies the Purgatoire Formation, it is exposed on the dip slopes of the cuestas and hogbacks, whereas the Purgatoire is exposed on the escarpment sides where the availability of water for recharge is limited.

In other areas where wells are completed in only the Lytle Sandstone Member, the potentiometric surface does not differ appreciably from that in the Dakota Sandstone. Although this does not necessarily mean that the two formations are in direct hydraulic connection, it is evidence that the entire Dakota-Purgatoire sequence is one aquifer.

From the outcrop area of the Dakota aquifer, ground water generally flows downdip, northeastward and eastward, across the central and eastern parts of the study area. The potentiometric contours (fig. 4) show that water is being discharged to the Arkansas River in spite of the presence, along most of the reach shown, of overlying strata that are confining beds elsewhere. Much of the water recharged to the aquifer in the outcrop area flows out of the study area across its east border.

Some of the water in the aquifer is discharged by wells. Irrigation and municipal supply wells, however, are the only wells having discharges large enough to be capable of having a significant effect on water levels and flow patterns. According to available records, there were just three irrigation wells and no municipal wells completed in the Dakota aquifer in the study area before 1969. During 1969 and 1970 the number of wells, in particular large-capacity wells, completed in the the Dakota aquifer more than doubled.

The potentiometric-surface map is based on water-level data only from 1970 and earlier in order to minimize the effects on water levels due to pumping from these large-capacity wells. The flow patterns thus inferred should reflect a near-equilibrium predevelopment state.

Flow-Net Analysis

A flow net (fig. 4) was constructed to estimate the rate at which net recharge to the Dakota aquifer is occurring in the outcrop and faulted areas. Normally, a flow net is drawn as a grid covering the area of interest, and construction of the net requires that transmissivity is everywhere equal. For this study, the equipotential lines are drawn as if the faults in most areas are lines of greater resistance to flow.

The trend in potentiometric surface indicates a comparatively low area in the area northeast of the Rock Hill fault and southeast of the Rush fault. This is interpreted as being a result of the four northwest-trending major faults collectively forming a barrier to flow. Toward the southeast, the offset of these faults generally decreases and eventually disappears completely. Where there is very little offset, these faults probably do not affect the flow of ground water.

The shapes and spacing of the potentiometric contours (fig. 4) reflect trends in transmissivity as well as the effects of the faults. In the area where flow lines are drawn, potentiometric contours are more widely spaced in areas of greater transmissivity.

In order to complete the flow-net analysis, transmissivity values need to be assigned to individual "squares," or elements, in the flow net. These were assigned on the basis of the mapped transmissivity values (fig. 9). Flow through each flow-net element can be computed by the following equation, derived from Darcy's Law:

$$Q = T\Delta h$$

where Q = discharge through an individual grid element;
T = transmissivity for the element;
Δh = potentiometric-contour interval.

For example, flow through a grid element where the transmissivity is 150 ft^2/d and the potentiometric-contour interval is 100 ft was calculated as 15,000 ft^3/d. Summing the flows in the nine grid elements gives a total flow through this zone of 110,000 ft^3/d or approximatley 920 acre-ft/yr. Note that this value takes into account discharge to the St. Charles River, but not to the Arkansas River.

Water Quality

Specific conductance, an indicator of overall water quality, helped define the ground-water flow patterns. Crouch and others (1982) present a least-squares regression relation between specific conductance and dissolved-solids concentration of the water from the Dakota aquifer in the Cañon City Embayment. Their regression equation, based on laboratory determinations of 80 samples, is:

$$DS = 0.748 \times SC - 81.6$$

where DS = dissolved-solids concentration, in milligrams per liter; and
SC = specific conductance, in microsiemens per centimeter at 25°C.

The correlation coefficient (R) for this relation is 0.98, indicating a significant degree of correlation between dissolved-solids concentration and specific conductance.

Data on the quality of water from the other aquifers in the study area, summarized in table 1, are sparse.

Table 1.--*Specific-conductance data for water from aquifers other than the Dakota aquifer in the study area*

[μS/cm, microsiemens per centimeter]

Aquifer	Mean specific conductance (μS/cm)	Standard deviation (μS/cm)	Number of samples
Greenhorn Limestone	2,310	467	2
Morrison Formation	949	207	6
Fountain Formation	1,947	528	3

Because the study area is not near an ocean, it is expected that the specific conductance of rainwater and snowmelt recharging the aquifers is well below 100 μS/cm (see Hem, 1970, p. 102).

The specific-conductance map (fig. 10) has several features of interest. A lobe of relatively fresh water extends from the outcrop northeastward across T. 22 S., R. 67 W. as far as the Rock Hill fault. Water on the northeast side of this fault shows an abrupt increase in dissolved-solids concentration. This area of more mineralized water extends northeastward, indicating flow in that direction. The fault seems to affect the water-quality trend either by being a barrier, inducing a stagnant area downgradient, or by allowing water with greater dissolved-solids concentration to leak into the Dakota aquifer from another source. The Rock Hill fault is downthrown on the southwest approximately 140 ft in this vicinity. This offset is sufficient to place the Greenhorn Limestone (Upper Cretaceous) on the southwest opposite the Dakota Sandstone on the northeast, because the thickness of the intervening Graneros Shale is about 115 ft here (Scott, 1972a). Although no water-level data exist for aquifers other than the Dakota aquifer in the area of greater specific conductance northeast of the Rock Hill fault, a comparison of hydraulic heads in the Morrison Formation, the Dakota aquifer, and the Greenhorn Limestone in nearby areas indicates that a vertical hydraulic-head gradient exists that would tend to drive flow downward. On the basis of the vertical hydraulic-head gradient and the relatively large specific conductance of water in the Greenhorn Limestone, it would seem that the Rock Hill fault is a conduit for flow from the Greenhorn Limestone to the Dakota Sandstone in this area. Similar fault geometry is present at the East St. Charles Canyon fault. An anomalously large specific-conductance value (2,500 μS/cm) was measured on the east side of this fault, indicating that it, too, may be a conduit for leakage from the Greenhorn Limestone to the Dakota Sandstone. The relatively small specific-conductance value of 496 μS/cm in section 13, T. 23 S., R. 67 W. apparently is a result of recharge, and thus dilution, by the infiltration of precipitation on the fairly large outcrop area of the Dakota aquifer there.

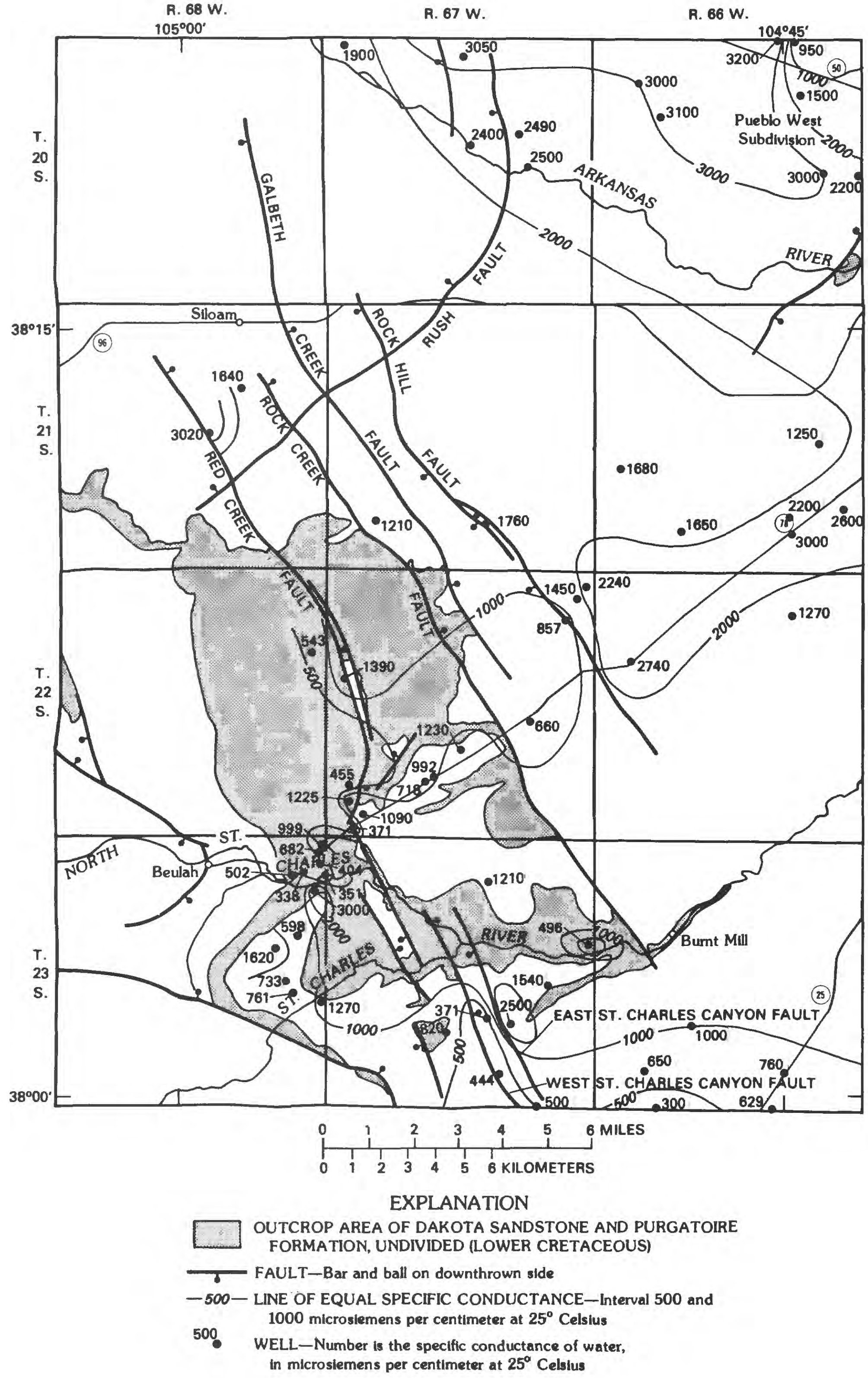


Figure 10.--Specific conductance of water in the Dakota aquifer.

A large specific-conductance value for water in the Dakota aquifer in an area where it is exposed at the surface would indicate that upward leakage may occur from Jurassic or deeper rocks. The value of 3,000 μS/cm in section 12, T. 23 S., R. 68 W., as well as water-level data from a nearby well completed in the Morrison Formation indicating a potential for upward flow, show that this may be a place where upward leakage occurs. Because water from the Morrison Formation generally is fresh in this area, it may be that the source of the more mineralized water is deeper than the Morrison Formation. Other anomalously large values of specific conductance also may be due to vertical leakage, but the lack of water-level data prevents inferring the direction of leakage.

Effect of Fault Offset on Flow Patterns

Geologic section A-A' (fig. 7) shows four major northwest-trending faults. Here, the Galbeth Creek fault has very little offset, and as a result has little potential for affecting ground-water flow. The other faults, however, have a much greater offset. As shown on the geologic section, the Red Creek fault allows some flow of water between the lower sandstone unit of the Dakota Sandstone on the southwest and the upper sandstone unit of the Dakota Sandstone on the northeast. Likewise, the upper few tens of feet of the Lytle Sandstone Member of the Purgatoire Formation are in partial contact with the lower sandstone unit of the Dakota Sandstone. Overall, however, the fault restricts ground-water flow. The geometry of the Rock Creek fault is almost the same as that of the Red Creek fault, further restricting the flow. Fault gouge, if present, would result in additional restriction to flow. The development of fault gouge is expected to be greatest in areas where the Dakota-Purgatoire sequence is shaliest.

Displacement at the Rock Hill fault is in the direction opposite to, and of greater magnitude than, the other three faults. Here, water may flow from the upper sandstone unit of the Dakota Sandstone into the Lytle Sandstone Member. In addition, the Greenhorn Limestone abuts against the Dakota Sandstone, indicating the possibility of flow from one to another. Offset along these faults varies, of course, so that the net effects are an overall restriction of ground-water flow and a mixing of the waters of the various strata.

As shown on geologic section B-B' (fig. 9), offset on the East St. Charles Canyon fault is small, only about 30 ft. The presence of several shale layers and likely associated fault gouge, however, makes this small offset a potentially effective barrier to flow, at least in the Dakota Sandstone. Flow in the Lytle Sandstone Member, however, probably is not significantly affected. The larger offset of the West St. Charles Canyon fault renders it a more effective barrier, as evidenced by the large difference in hydraulic head on either side of this fault (fig. 5). The slight eastward bulge of the 5,700-ft potentiometric contour in the graben between the East and West St. Charles Canyon faults may be due to an offset of a part of the West St. Charles Canyon fault that allows flow between the Lytle on the west and the Dakota Sandstone on the east. Similarly, the 5,600-ft potentiometric contour bulges eastward east of these faults, possibly indicating flow across the East St. Charles Canyon fault. This flow apparently is maximum where offset along this fault ranges from 100 to 200 ft.

Fault-associated fracturing, if present, would increase the degree to which the faults act as a conduit for flow. The orientation of the 5,600-ft potentiometric contour, nearly perpendicular to the southern end of this fault, indicates flow here is parallel to the two faults, most likely because the faults act as barriers. These variable effects of the faults are interpreted to be a combination of the effects of variable offset, strata of differing lithology, and variable development of fault gouge along the faults.

CONCLUSIONS

Even in simple hydrologic systems, ground-water flow patterns are controlled by many factors, among them: Size, shape, location, and altitude of recharge and discharge areas; recharge and discharge rates; leakage; and variations in aquifer thickness and hydraulic conductivity. The complicated lithology of the Dakota Sandstone and the Purgatoire Formation, resulting from deposition and erosion in environments ranging from marine to fluvial, compounds the problem of determining ground-water flow patterns. In the study area, faulting and possible associated fracturing have added two more variables to take into consideration.

If only the various effects of recharge and discharge areas and the areal pattern of transmissivity were to be considered, most of the ground-water flow would be expected to occur northeastward across the central part of the study area, and the area of low aquifer transmissivity in the southeast quadrant would be expected to hamper the flow of water. Instead, the potentiometric surface indicates that flow is restricted in the central part relative to the southeast quadrant.

Although the apparent difference between expected flow patterns and flow patterns inferred from the potentiometric surface may be due to undetected high-transmissivity zones in the southeast part of the study area, the trend of the data belies this hypothesis. Instead, the four major northwest-trending faults studied apparently tend to restrict flow, especially where offset is such that relatively impermeable strata are opposite relatively permeable strata. Fault-associated fracturing, if present, seems to be limited to relatively localized intervals along the faults.

The abrupt changes in dissolved-solids concentration of water in the Dakota aquifer associated with two of the faults indicate areas where flow from the Greenhorn Limestone (Upper Cretaceous) to the Dakota aquifer may occur.

Upward interformational flow may occur in areas where potentiometric-surface differences favor that flow and the confining beds are leaky. This type of flow is indicated in at least one place near the axis of the Three-R syncline. In general, however, the fine-grained sediments above and below the Dakota aquifer have too little permeability to allow significant interformational flow, except near the faults.

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