Fracture-Controlled Ground-Water Circulation and Well Siting in the Vicinity of Laramie, Wyoming

by Peter W. Huntoon[a] and Don A. Lundy[b]

ABSTRACT

The artesian Casper aquifer, comprised of 700 ft of interbedded limestones and sandstones, currently supplies 70 percent (3.5 Mgal/d) of the municipal-water needs of Laramie, Wyoming. Large transmissivities occur in fracture zones associated with faults and folds in the area, and water discharges from several springs localized along these structures. Transmissivities in fracture zones are 100 times greater than those in unfractured parts of the aquifer. The overlying Satanka Shale is a regional confining unit even in most areas of fracturing, and is a source of poor quality ground water. Prospecting for new ground-water supplies near Laramie involves mapping the tectonic structures and drilling into them once they are identified.

OBJECTIVE

It is the purpose of this paper to document that zones of large transmissivities in the Casper aquifer in the vicinity of Laramie, Wyoming, are fracture-controlled and that the fracture zones have transmissivities which are two orders of magnitude greater than unfractured parts of the aquifer. By using this information, new well sites have been located by mapping favorable structures.

PHYSIOGRAPHIC SETTING

Laramie, a town of approximately 26,000 people, is situated on the eastern side of Laramie basin, an intermontane structural depression that contains a 12,000-ft-thick section of Paleozoic, Mesozoic, and Cenozoic sediments which rest on Precambrian crystalline rocks (Figure 1). The Laramie range, east of town, trends north-south and is characterized by outcrops of west-dipping Paleozoic strata. Precambrian rocks crop out along the highlands of the range, having been exposed by erosion. Elevations range from 7,100 ft in Laramie to 8,800 ft in the Laramie range 6 mi to the east. Precipitation increases with elevation from 11 to 20 in/yr. Natural vegetation consists of grasses and sage, and scattered pines in the highlands.

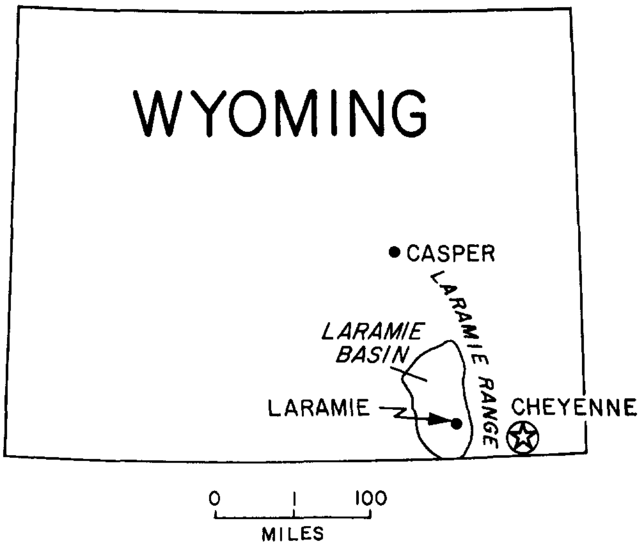

Fig. 1. Location of the Laramie Basin and Laramie in Wyoming.

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[a] Associate Professor, Department of Geology and Water Resources Research Institute, University of Wyoming, Laramie, Wyoming 82071.

[b] Ground-Water Hydrologist, Brown and Caldwell Consulting Engineers, Bin 83, Arroyo Annex, Pasadena, California 91109.

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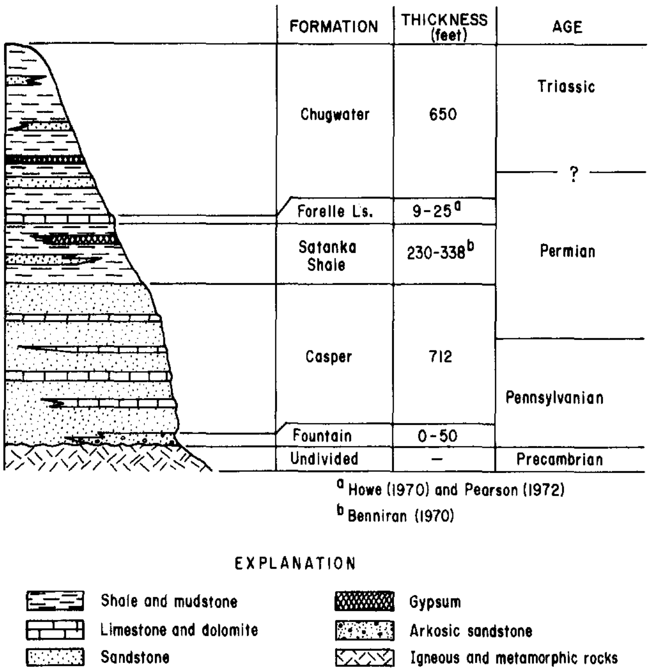

Fig. 2. Generalized lithologies, thicknesses, and ages of the Precambrian through Triassic rocks in the vicinity of Laramie, Wyoming.

CASPER AQUIFER

The Casper aquifer is the principal aquifer in the area and includes the Permian-Pennsylvanian Casper Formation and the underlying Pennsylvanian Fountain Formation (Figure 2). Outcrops of these rocks east of Laramie serve as the recharge area for the aquifer. The Casper aquifer dips below the land surface one-half mile east of the city and is confined by the Satanka Shale to the west. Water in the aquifer is under artesian conditions throughout the Laramie basin.

The Casper Formation is comprised of a series of permeable sandstones and virtually impermeable interbedded limestones, whereas the Fountain Formation contains permeable arkosic sandstones and lenses of sandy shale. These rocks are 700 ft thick under Laramie. The presence of the limestone confining beds creates a series of interbedded confined sandstone subaquifers within the Casper aquifer that are hydraulically integrated into one system by several faults (Boos, 1940 and 1941; Huntoon, 1976; Lundy, 1978).

The Casper Formation is divided herein into 5 informal members named in ascending order: alpha, beta, gamma, delta, and epsilon. Figure 3

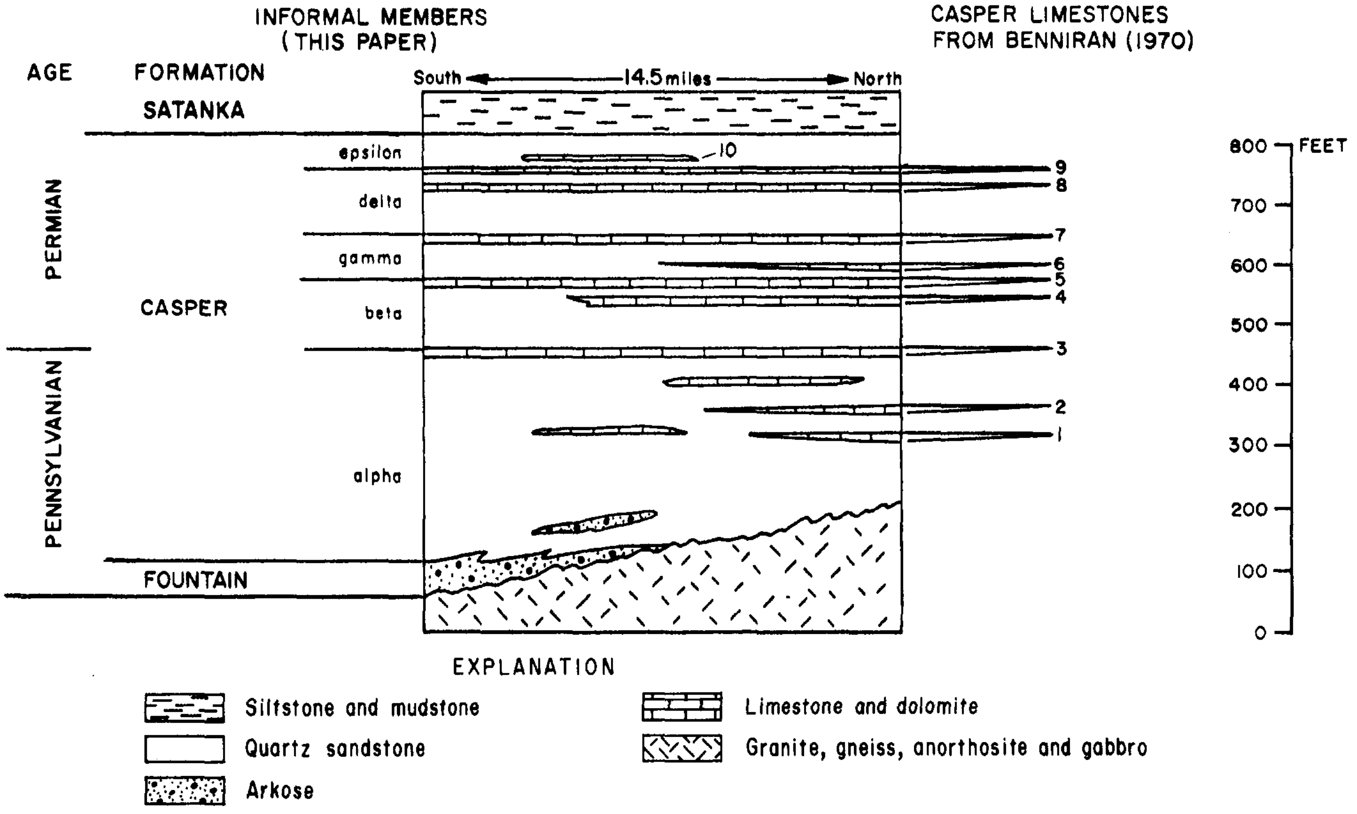

Fig. 3. The relationship between informal members of the Casper Formation defined herein and the Casper limestones of Benniran (1970) in the vicinity of Laramie, Wyoming.

Table 1. Transmissivities, Hydraulic Conductivities, and Storage Coefficients for the Casper Aquifer in the Vicinity of Laramie, Wyoming

Well[a]	*Name*	*Thickness of Producing Zone*[b] *(ft)*	*Producing Zone*[c] *(inclusive)*	*Storage Coeff.*	*Transmiss. (ft^2/day)*	*Hydraulic Conduct. (ft/day)*	*Test Method*	*Source of Data*
Wells completed in Casper sandstones with intergranular and limited joint permeability								
1	Cathedral Home 1	60	epsilon	–	80	1.3	specific capacity	State Engineer (various)
2	Wyo Tech Inst	50	epsilon	–	130	2.6	specific capacity	State Engineer (various)
3	Retort 1	180	gamma-epsilon	–	18	0.10	Jacob solution	Dana (1969)
4	Wyo Central	385	gamma-epsilon	–	50	0.13	Van Everdingen sol.	Evers (1973)
5	Huntoon 1	38	gamma	–	57	1.5	Jacob recovery sol.	Lundy (1978)
6,7	Monolith 1 & 2	575	alpha-epsilon	–	186	0.32	closed contour	Lundy (1978)
8	Ideal 2	580	alpha-epsilon	–	130	0.21	Jacob solution	Davis (1976)
Wells completed in proximity of faults where rocks have significant joint and fracture permeability								
9,10,11	Turner 1, 2 &3	650	alpha-epsilon	0.001	18,000	28	Theim solution	Morgan (1946)
10	Turner 2	650	alpha-epsilon	–	14,000	22	specific capacity	Goodrich (1942)
11	Turner 1	650	alpha-epsilon	0.0005	21,000	33	Theis solution	Banner Assoc. (1978)
12	Pope 2	700	alpha-epsilon	0.001	20,000	29	Theis solution	Banner Assoc. (1978)

[a] Numbers correspond to Figure 4.

[b] Length of slotted casing or open hole in unfaulted areas; total thickness of Casper aquifer in faulted areas.

[c] See Figure 3.

shows the approximate thicknesses of the members along a schematic north-south cross section centered about Laramie. As shown on Figure 3, a tongue of the Fountain Formation extends 8 mi into the study area from the south and is included in the alpha member for the purposes of this study. Figure 3 also shows that the contacts between members are located at the tops of laterally continuous limestones. Limestone beds in the Casper Formation become thicker north of Laramie and pinch out to the south and west.

FRACTURE PERMEABILITY

The Casper Formation is faulted and folded as shown on Figure 4. Styles of deformation include high-angle normal faults with displacements up to 400 ft, and monoclines (step-line folds) with structural offsets as large as 600 ft. The monoclines overlie high-angle reverse faults in the basement rocks. Gently folded anticlines and synclines also occur in the area.

The Casper aquifer occupies a position between a brittle crystalline basement complex and a thick, tectonically incompetent section of overlying redbeds and shales. The Casper and Fountain Formations themselves are comprised of brittle limestone layers sandwiched between indurated clastic rocks. The mechanisms by which faults in the basement have propagated upward into the sedimentary section are of major importance to transmissivity distributions and vertical circulation within the Casper aquifer.

Faults, both normal and reverse, in the crystalline basement offset the basal Fountain-Casper contact and have propagated upward into the sedimentary section by fracturing of the brittle units, and by a combination of fracturing and folding of the intervening clastic units. The Casper limestones (Figure 3), and Forelle Limestone (Figure 2) tended to fracture, whereas the Casper and Fountain clastics, and Satanka and Chugwater shales deformed by folding and jointing. Faults traced upward from the basement therefore tend to merge into folds, and the widths of the folds widen with elevation in the sedimentary section. The net result is that the incompetent members in the section absorbed the deformation, and the offsets associated with the structures attenuate with elevation. Because of this, most faults in the area die out below the level of the Forelle Limestone, notable exceptions being the large displacement Sherman Hill and Laramie faults (Figure 4) which offset the Chugwater Formation.

The reverse faults underlying the monoclines usually did not result in offsets in the beds above the Casper Formation. Rather the Satanka Shale and younger rocks are folded over the Casper aquifer.

The rocks comprising the Casper Formation are intensely fractured along the faults and monoclines. Enhanced fracture permeabilities extend several tens of feet on either side of the structures. Table 1 summarizes the aquifer parameters computed for the Casper aquifer and demonstrates clearly that fractures associated with the faults and monoclines significantly enhance transmissivities. The gently folded anticlines and synclines in the area have lesser effects on transmissivities because

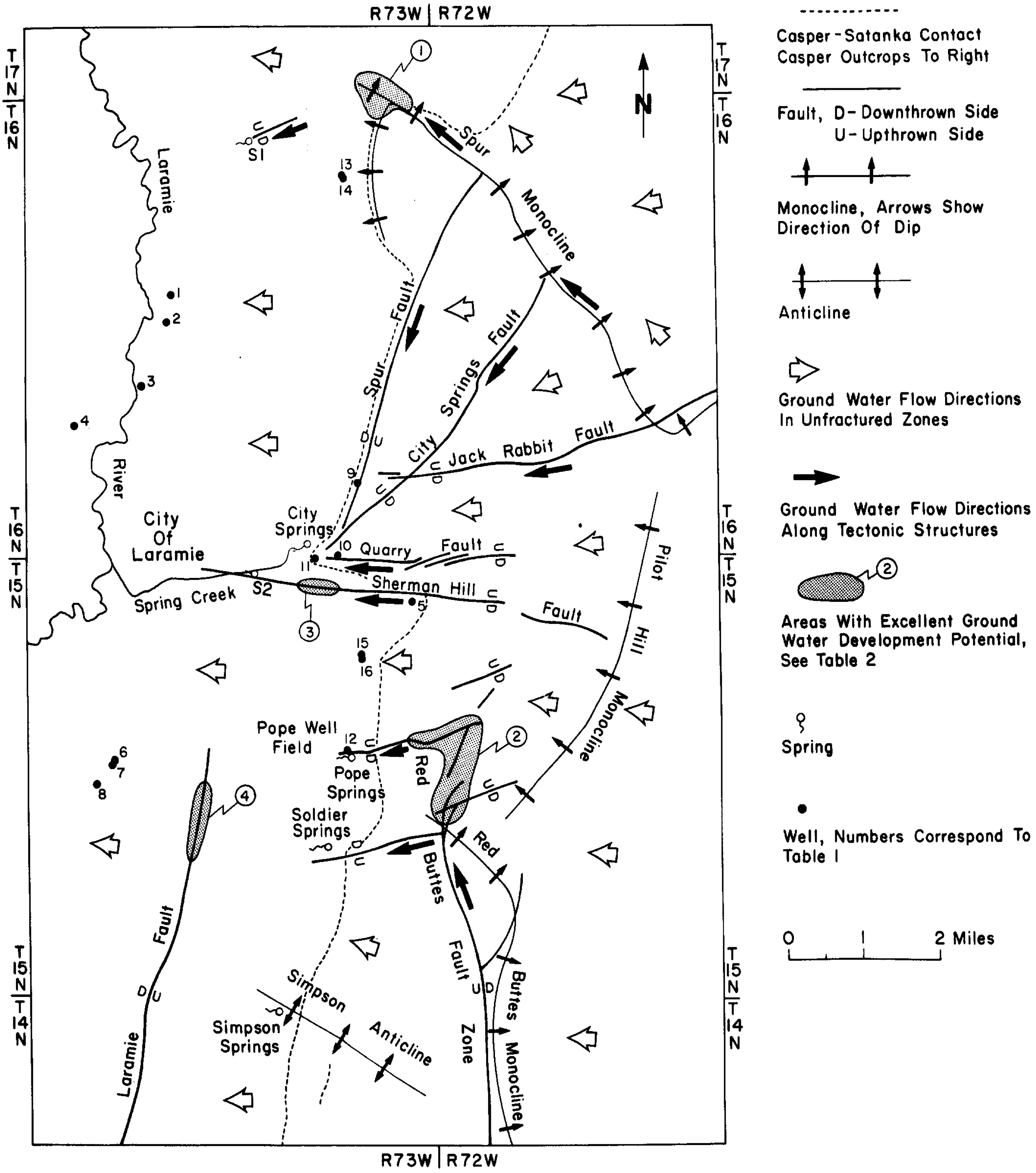

Fig. 4. Locations of tectonic structures, selected wells and springs, and ground-water flow directions in the vicinity of Laramie, Wyoming.

the rocks are not as intensely fractured by these structures. Simpson Spring (Figure 4) is localized on fractures associated with the minor Simpson anticline.

The vertical continuity of faults and monoclines is of major importance when considering circulation in the Casper aquifer because they sever the confining limestones. The associated fractures form hydraulic links between the sandstone subaquifers, but generally die out or close upward in the overlying shales. The result is that the fractures are usually sealed above, thus confining the circulation system to the Casper and Fountain formations.

Fracture zones account for the largest transmissivities found in the Casper aquifer; however, they contain only small volumes of water. The interbedded sandstones in unfractured areas account for most of the water in storage.

CONFINING LIMESTONES

No quantitative data are available on the hydraulic conductivities of the Casper limestones. Field observations demonstrating that the hydraulic conductivities of the limestones are negligible include: (1) ponded water on jointed limestone, (2) no visible loss of water from ephemeral streams that flow over limestone outcrops, and (3) head differences across limestone beds at several locations.

Evidence that the limestones locally confine the water in the Casper sandstones is provided by pairs of wells completed respectively above and below specific limestone beds. For example, wells 15 and 16 (Figure 4) are located within 150 ft of each other, but were drilled respectively, 100 and 135 ft deep. Well 15 is completed in the epsilon member of the Casper Formation whereas well 16 is completed in the delta member. The water level in well 16 is 25 ft higher than in well 15, proving that the intervening limestone is a confining bed. Similar evidence is provided by head differences in wells 13 and 14 (Figure 4), which are respectively completed above and below the same limestone. We conclude that limestones 3, 5, 7, 8 and 9 (Figure 3) also serve as regional confining beds.

FRACTURE-CONTROLLED SPRINGS

All the major springs that discharge from the Casper aquifer are located on or near faults or folds, including City, Soldier, and Simpson springs with respective average discharges of 2.4, 2.3 and 0.4 ft^3/sec. Several smaller springs also occur along faults, including S1 and S2 (Figure 4). The primary controls for the locations of the springs are faults and fractures associated with folds. Valleys and canyons have characteristically eroded along the structures, thus providing the springs with topographically low positions relative to the surrounding Casper outcrops.

The stratigraphic locations of the springs on the dip slopes are typically fixed by the intersections of fractures, and the contact between the Casper Formation and overlying Satanka Shale. The springs occur at or near the contact because the controlling fractures die out or close upward in the shale. Otherwise the springs would occur along the fractures at points higher in the stratigraphic section but at lower elevations in the basin. Exceptions to this pattern include spring S2 along the Sherman Hill fault and a series of seeps along the Laramie fault (Figure 4) which discharge, in part, Casper waters that have leaked upward along through-cutting faults to the level of the Chugwater Formation.

REGIONAL CIRCULATION

Ground-water flow in the unfractured parts of the Casper aquifer, as shown on Figure 4, parallels the westward gradient. However, faults and fractures along fold axes, by offering zones of large transmissivity, intercept and divert the westward circulating ground water to springs along the fractures. The Spur, Jackrabbit, City Springs, and Quarry faults divert ground water to City Springs (Figure 4). Similarly, the Red Buttes fault functions as a collector structure for Soldier Springs and the Pope well field. Perennial discharge into Spring Creek originates in part from the Quarry and Sherman Hill faults. In fact, upward leakage of ground water along the Sherman Hill fault contributes to wet basement problems along Spring Creek in wet years.

The hydraulic gradient associated with the Casper aquifer potentiometric surface flattens from about 400 to 25 ft/mi near the Casper-Satanka contact (Lundy, 1978, Figure 8). The change in gradient is attributed to (1) loss of water from the aquifer through springs and wells, and (2) an increase in the saturated thickness of the aquifer toward the west.

WATER QUALITY

Lundy (1978) found that the Casper aquifer contains potable ground water having among 38 samples a total dissolved solids concentration that ranges from 139 to 285 mg/l. The gross chemical character of Casper water is controlled by dissolution of calcite and dolomite from the aquifer matrix. A representative group of Casper samples is plotted on the trilinear diagram on Figure 5 in order to classify the water according to relative proportions of major ions. Figure 5 shows that Casper water is of the calcium-bicarbonate type in the outcrop area, but becomes a calcium-magnesium-bicarbonate water to the west. As the water moves westward in the aquifer, there is an

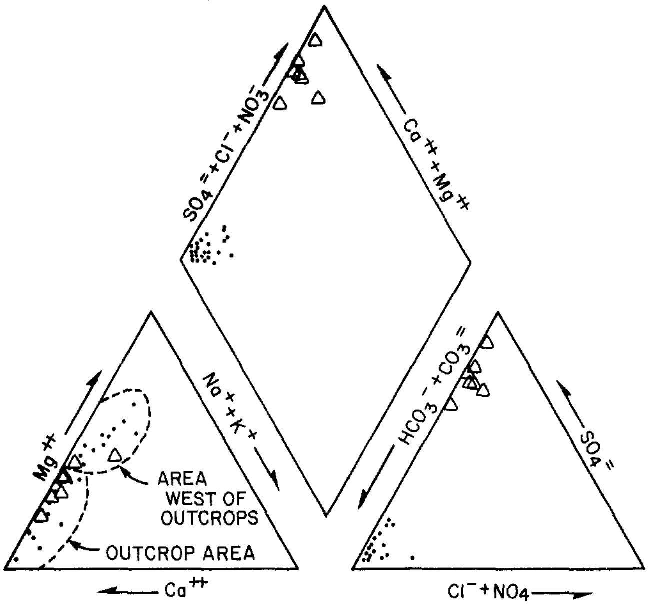

Fig. 5. Chemical character of ground water in the vicinity of Laramie, Wyoming. Dots are Casper aquifer waters; triangles are Permo-Triassic redbed waters. Coordinate axes are the percentages of milliequivalents/liter concentrations; method after Piper (1944).

increase in the relative proportions of SO_4^{-2} and Na^{+}, and a corresponding decrease in the relative proportions of Ca^{+2} and HCO_3^{-}.

Ground water in the Satanka Shale and younger rocks, herein referred to as the Permo-Triassic redbeds, is of poor quality based on total dissolved solids concentrations ranging from 926 to 2,300 mg/l in 5 samples (Lundy, 1978). The gross chemical character of the Permo-Triassic redbed water is controlled by dissolution of gypsum, anhydrite, calcite, and dolomite from the rocks. As shown on Figure 5, the water is of the calcium-magnesium-sulfate type. Permo-Triassic redbed waters in the area are readily differentiated from Casper waters by SO_4^{-2} concentrations that are more than 10 times greater than the highest SO_4^{-2} concentrations measured in Casper samples. Similarly, mixtures of waters in wells and springs deriving water from both the Casper aquifer and the Permo-Triassic redbeds can be detected by intermediate concentrations of SO_4^{-2}.

The contrasts between the water qualities found in the Casper aquifer and the Permo-Triassic redbeds will eventually lead to a deterioration of the quality of water withdrawn from the Casper aquifer. This will occur in areas where the Casper aquifer is overlain by the redbeds because leakage of poor quality water from the redbeds will take place as heads are lowered in the Casper aquifer as a result of large-scale pumpage.

WELL SITING

Because faults and folds have created zones of large transmissivities in the Casper aquifer, the problem of locating large-capacity wells is reduced to identifying favorable structures. Exploration for large-capacity well sites in the vicinity of Laramie is readily accomplished by detailed mapping of faults and folds, and extrapolation of them into the basin under the Satanka Shale and younger rocks.

Tectonic maps for the Laramie area were compiled for this purpose by Huntoon (1976) and Lundy (1978). In addition, Lundy (1978) prepared a structural contour map of the top of the Casper Formation. Using these data, Banner Associates (1978) recommended to the City of Laramie a list of well sites that are situated over known faults and monoclines and located so as to minimize conflicts in existing ground-water rights. We have identified additional sites which are shown, along with the Banner sites, on Figure 4 and which have the advantages and disadvantages listed in Table 2.

Site 3 along the Sherman Hill fault is one of the more interesting sites in Table 2. Water that is now wasting from this fault through springs along Spring Creek could be pumped from wells directly into the city distribution system. With pumpage, the potentiometric surface could be lowered sufficiently to reduce or stop upward leakage of water along the fault and alleviate the troublesome problem of wet basements in the area.

CONCLUSIONS

Through a combined program of (1) assembling aquifer transmissivities using available data and (2) mapping of faults and folds, we are able to document that zones of large transmissivities correlate with tectonic structures in the Casper aquifer. Table 1 demonstrates conclusively that fractures associated with faults and folds in the Laramie area resulted in transmissivities that are two orders of magnitude greater than the transmissivities in the undeformed areas. With this insight, it is obvious that chances for completing large-capacity wells are improved significantly in fractured areas. Prospecting for feasible well sites in the area can be accomplished by mapping the faults and folds, and selecting drilling sites along them. Because faults usually do not propagate upward through the Satanka Shale, the problem of locating well sites will become complicated when wells are required west of the outcrop area. It will be necessary to project the trends of structures westward using geophysical or subsurface geologic methods.

Table 2. Promising Areas for Ground-Water Development in the Vicinity of Laramie, Wyoming

Site[a]	*Advantages/Problems*	*Source*
1	Located in major fracture zone associated with Spur monocline which drains rocks to the north and east. No major ground-water developments nearby. Elevation allows for gravity flow to Laramie. Will require long pipeline.	Banner Associates (1978)
2	Located in major fracture zone associated with Red Butte fault zone. No Permo-Triassic redbeds overlie the site so problem of vertical leakage of poor quality water is eliminated. Will affect Pope well field and Soldier Springs.	Banner Associates (1978)
3	Located along Sherman Hill fault which discharges water to Spring Creek. Pumpage would alleviate wet basement problems in the area. Close to existing distribution system. Could affect nearby domestic wells.	This study
4	Located along Laramie fault which should intercept significant quantities of westward flowing ground water. Close to developing parts of Laramie. There is potential for vertical leakage of poor-quality ground water from the Permo-Triassic redbeds.	This study

[a]Numbers correspond to areas with excellent ground-water development potential shown on Figure 4.

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Peter W. Huntoon, Ph.D., University of Arizona, 1970, is an Associate Professor of Geology with the Department of Geology and the Wyoming Water Resources Research Institute, University of Wyoming. He specializes in ground-water exploration, the occurrence of water in fractured sedimentary rocks, digital modeling of aquifers, and the tectonics of the Colorado Plateau. Before joining the University of Wyoming, he was an Assistant Professor with the Conservation and Survey Division and Department of Geology, University of Nebraska-Lincoln, 1971-1974.

Don A. Lundy, M.S., University of Wyoming, 1978, is a ground-water hydrologist with Brown and Caldwell Consulting Engineers, Pasadena, California. Lundy specializes in the development of ground-water supplies, ground-water quality problems, and basinwide assessment studies.