Permeability Architecture and Groundwater Circulation Along a Fault-Severed Margin, Northern Hanna Basin, Carbon County, Wyoming

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1994
Final Report WWRC-94-27

Final Report

Submitted to

Wyoming Water Resources Center
University of Wyoming
Laramie, Wyoming

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1994

ABSTRACT

Groundwater circulation through the aquifers of the Troublesome-Difficulty Creek area in the hanging wall of the Shirley thrust fault is primarily parallel to bedding. Cross-stratigraphic circulation between aquifers occurs only through faults and fractures that crosscut permeable and confining layers. The interconnection of geologic features having bedding-parallel or bedding-perpendicular permeabilities results in a permeability architecture through which groundwater circulates downgradient from recharge areas to points of discharge.

Water entering Madison Formation in the Shirley Mountains circulates downgradient but upsection into the overlying Tensleep aquifer. The water discharges as rejected recharge from the lowest topographic exposures of the Tensleep Sandstone along the perimeters of the Hanna Basin due to a basinward reduction in hydraulic gradients and permeability.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. James I. Drever, Dr. Victor R. Hasfurther, Dr. Lisa Stillings, and W. Todd Jarvis of Weston Engineering, Inc. for providing assistance on this project.

For assistance in the field, thanks to Claudia Stewart. Thanks to the ranchers of the study area, John and Bill Ellis, Robert Korkow, Mr. Hoffman, Casey Palm, and Martin Sullivan of the Williams Ranch Company. Thanks to Rob Garland and Mark Stacy for their time and assistance.

Funding for this report was provided by the Wyoming Water Resources Center.

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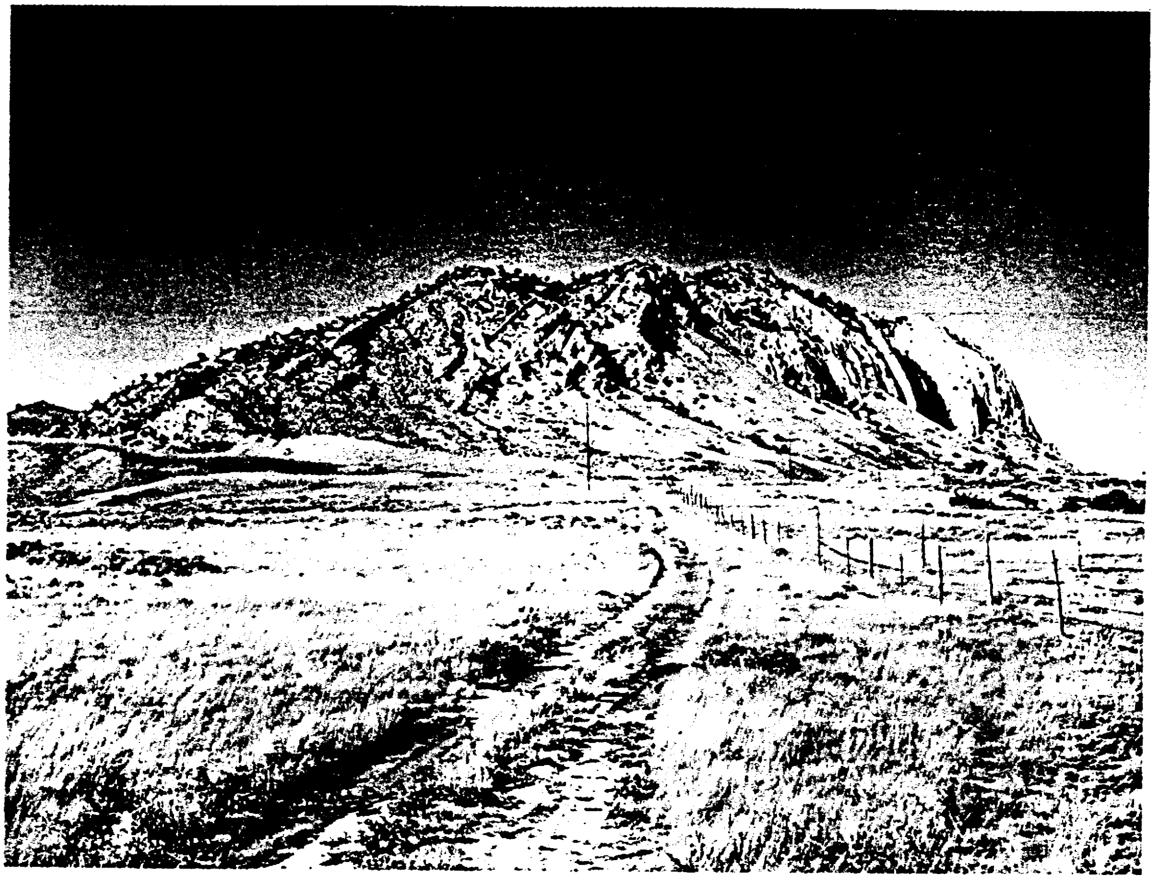


Frontispiece. The Beer Mug anticline. An asymmetrical anticline with limbs composed of the Tensleep Formation at the leading edge of a small thrust fault which splays off the Shirley thrust fault.

CHAPTER I
INTRODUCTION

Purpose

This study examines the permeability architecture in the Paleozoic stratigraphic units along the fault-severed margin between the Shirley Mountains and the northern Hanna Basin. The purpose of the study is to (1) document the directional permeabilities of various geologic features, (2) demonstrate how interconnected permeabilities affect groundwater circulation within the Paleozoic aquifers in the hanging wall of the Shirley thrust fault, and (3) identify favorable groundwater exploration targets in the study area.

Statement of the Problem

Half the mountain flanks in Wyoming are bounded by thrust faults that sever the hydraulic continuity of the major aquifers between the upland recharge areas and the basin interiors (Huntoon, 1993)(Figure 1). Permeability enhancement along extensional zones (Morgan and others, 1977; Huntoon 1986, 1993) within the hanging wall block of these thrust faults has prompted groundwater explorationists to target these areas of extension for potential development. However, merely drilling into highly transmissive extensional zones does not guarantee good-quality, large-yield water supplies. Groundwater exploration efforts into extensional zones in the hanging wall block have failed to produce significant quantities of water because the permeable zones in the recharge area are in poor hydraulic connection with permeable zones basinward. The poor hydraulic connection

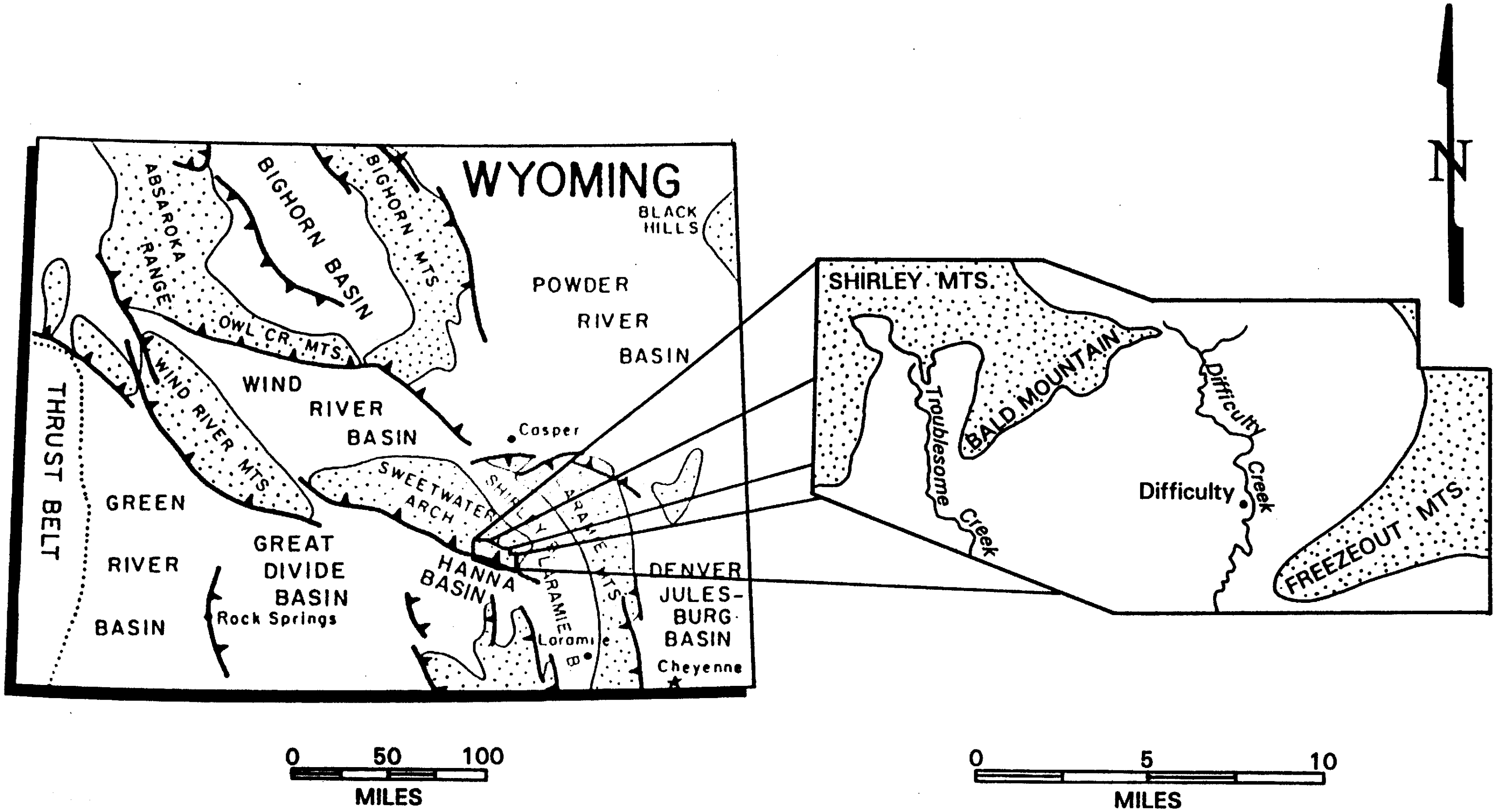


Figure 1. Map showing the location of the Troublesome-Difficulty Creek area and of the foreland uplifts (stippled) and basins in Wyoming. Notice that approximately half of the basin margins are bound by thrust faults which sever the Paleozoic and Mesozoic strata between the recharge areas in the uplifts and the artesian aquifers in the basins. (Modified from Huntoon, 1985a.)

exists because diagenetic processes have destroyed the permeability of the aquifer basinward of the recharge area.

Groundwater circulation in the Paleozoic rocks in the Wyoming foreland basins has been strongly affected by directional permeabilities imparted on the rocks during Laramide deformation and subsequent diagenesis. In this study, preferred flow pathways in regional aquifers will be identified by documenting the directional permeabilities of geologic structures and the variables that cause enhancement and reduction of permeability.

Location and Geographic Setting

The study area, 20 miles northwest of the town of Medicine Bow, Wyoming, is located along the south flank of the Shirley Mountains and extends east to the Freezeout Mountains of north-central Carbon County (Figure 1). The area is sparsely populated, includes no towns, and encompasses approximately 167 mi^2.

The topography is characterized by alternating steep ridges and small flat valleys. Elevations range from a maximum of 8895 feet at Bald Mountain to a minimum of 6500 feet at Difficulty Creek south of the Beer Mug Ranch. Topographic relief rarely exceeds 800 feet over a one mile distance.

The climate of the basin is semi-arid with increased precipitation occurring along the mountain flanks. Precipitation in the study area averages 14 inches/year (National Oceanic and Atmospheric Administration, 1982-1992).

The study area lies within the North Platte River drainage basin. Difficulty Creek, Troublesome Creek, and Cottonwood creeks are the largest streams which drain the area. Only Difficulty and Troublesome creeks are perennial.

Geologic Setting

The Wyoming foreland of the central Rocky Mountains is the classic example of basement-involved Laramide deformation. The foreland uplifts in Wyoming are characterized by a large asymmetrical anticline bounded by a fault-severed margin on one flank and a continuous homocline on the other (Huntoon, 1993). Fault-severed margins are defined by large-displacement thrust faults paralleling the mountain fronts. These thrust faults dip beneath the mountain range and have displacements as great as several miles (Gries, 1983). A cross section through a typical Wyoming mountain uplift having this type of deformation is shown in Figure 2.

Thrust faults are important because they sever the hydraulic continuity of aquifers between the upland recharge areas and the basinward subcrops. The Shirley thrust fault severs the Paleozoic aquifers in the study area, precluding groundwater circulation from the mountain uplift into the northern Hanna Basin. The result is that two completely different circulation systems develop, one restricted to the hanging wall and the other to the footwall block. Conversely, homoclinal margins are characterized by strata that dip gently and continuously basinward. Hydraulic continuity is maintained within the permeable strata between the recharge area and the basin interior along a homoclinal margin.

The Shirley Mountains-Freezeout Mountains occupy the southeast-plunging nose of the Sweetwater Arch, a basement-cored uplift in south-central Wyoming. The Troublesome-Difficulty Creek area lies along the southern flank of the Shirley Mountains in the hanging wall block of the Shirley thrust fault. This hanging wall block contains Laramide compressional faults, and a series of tightly folded and faulted anticlines at the end of the Shirley thrust which dip toward the range. The form of these anticlines range

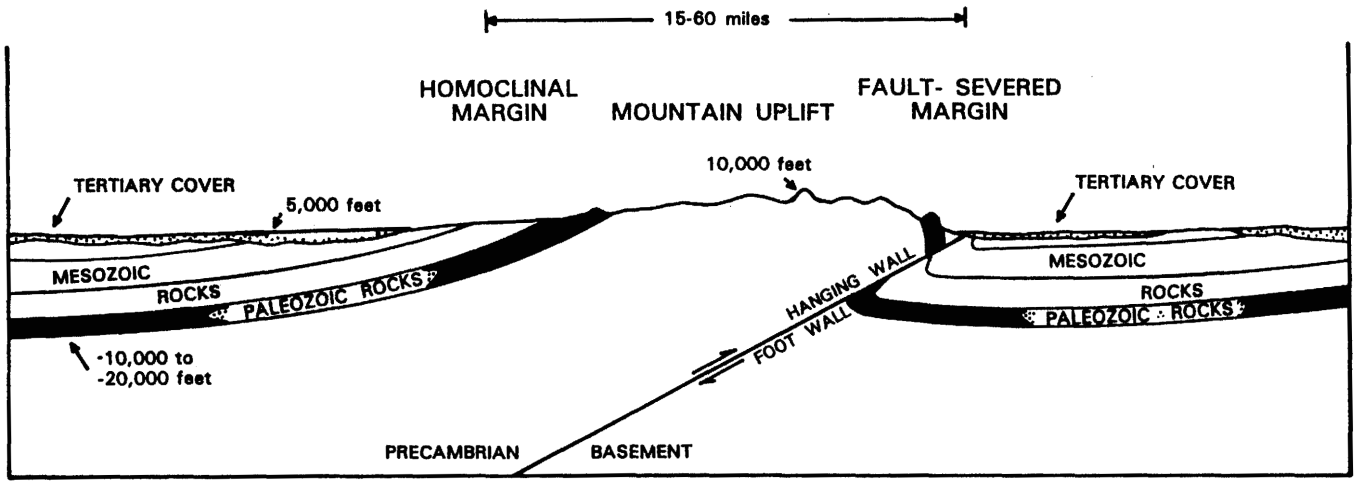


Figure 2. Cross section through a Wyoming foreland uplift showing the style of deformation that produces fault-severed and homoclinal basin margins. Notice that the thrust fault severs the Mesozoic and Paleozoic rocks in the hanging wall from those in the footwall. (Reprinted from Huntoon, 1993.)

from gently-dipping broad warps to sharply folded asymmetrical folds only hundreds of feet across (Figure 3).

Figure 4 shows the thicknesses and lithologies in the 28,000-foot sedimentary section, ranging in age from Mississippian to Tertiary, that is exposed in the study area.

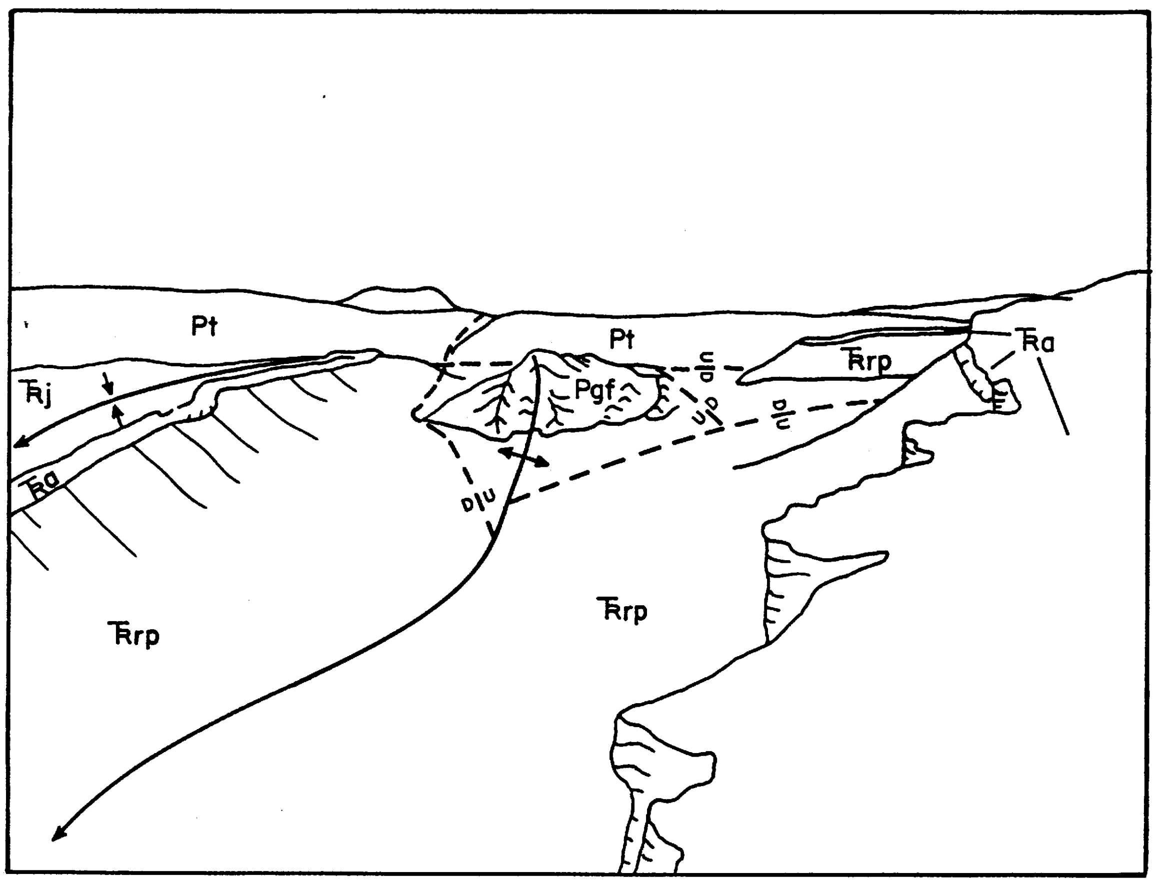
Tensleep Aquifer Overview

The Tensleep Formation, where it is saturated, is the major aquifer in the region. It consists of 580 feet of fine-grained, carbonate and silica cemented, cross-bedded quartz sandstone (Todd, 1964). Recharge to the aquifer from precipitation and snowmelt is by direct infiltration through intergranular pores, fractures, and joints in surface exposures over the 23 mi^2 recharge area exposed on the Shirley Mountains, Freezeout Mountains, and Tensleep outcrops in the basin.

Recharge to the Tensleep aquifer is also derived from precipitation and runoff into sinkholes and fractures in the 6 mi^2 outcrop of the Madison Limestone exposed in the Shirley Mountains. Inclusion of the Madison Limestone outcrops in the recharge area of the Tensleep aquifer is appropriate because (1) the Madison and Tensleep formations are hydraulically interconnected through extensional fractures and faults along the flanks of the basin, and (2) streams lose water and disappear into sinkholes in the lower strata of the Madison Formation in the Shirley Mountains indicating recharge water infiltrates the limestone, however, no springs discharge from the upper strata of the Madison Limestone.

The rocks comprising the Tensleep aquifer are stratigraphically sealed by confining shales of the overlying Goose Egg Formation. These confining shales localize Tensleep springs along the basin margins and at the margins of the Tensleep outcrops in the basin.

Figure 3. Core of the Troublesome Creek anticline, a typical Laramide anticline within the study area. Rocks exposed in the center of the valley are the Opeche, Minnekahta, Glendo, and Forelle members of the Goose Egg Formation. The interesting aspects of this anticline are (1) the dip angles of the limbs of this anticline differ radically from the overlying redbeds and Alcova limestone, (2) two reverse faults traverse the length of the anticline which displace the anticlinal core upward. View is to north. Pt, Pennsylvanian Tensleep Sandstone; Pgf, Permian Glendo Shale and Forelle Limestone; Trp, Triassic Red Peak Shales; Tra, Triassic Alcova Limestone; Trj, Triassic Jelm Formation; U, upthrown side; D, downthrown side.


Pt
Pt
TRj
TRa
Pgf
TRrp
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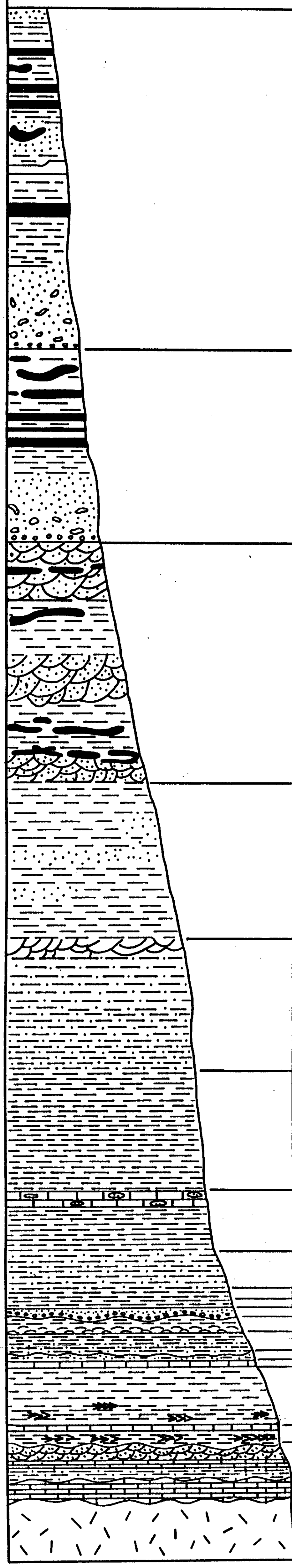
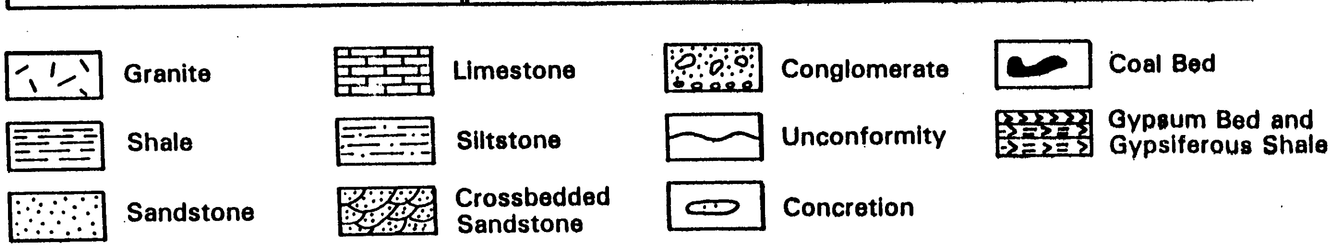
TRrp

Figure 4. Lithology, thicknesses and ages of rocks exposed in the northern Hanna Basin, Carbon County, Wyoming.

LITHOLOGY



THICKNESS (FEET)	AGE	UNIT	REFERENCES
0-8000	TERTIARY	HANNA	BOWEN (1918) GILL (1970)
0-6500		FERRIS	BOWEN (1918) GILL (1970)
4000-6200		MEDICINE BOW	BOWEN (1918) GILL (1970)
2300-2600	CRETACEOUS	LEWIS	CROSS (1899) GILL (1970)
2300-3000		MESAVERDE	PIPIRINGOS (1968)
2400-3800		STEELE	DARTON (1909) DOBBIN (1929)
1165-1475		NIOBRARA	MEEK (1962) FATH (1924)
761-790		FRONTIER	BROWN (1935) COBBAN (1951)
150-219		MOWRY	DARTON (1904) BERG (1956)
125-210		THERMOPOLIS	LUPTON (1916) EICHER (1962)
53-75		CLOVERLY	DARTON (1904) ESPENSCHIED (1957)
251-295	JURASSIC	MORRISON	CROSS (1894) BAKER (1965)
200-354		SUNDANCE	BARTRAM (1930) PIPIRINGOS (1968)
80-148	TRIASSIC	JELM	KNIGHT (1917) LOVE (1957)
10-30		ALCOVA	LEE (1927) LOVE (1957)
1100-1400		CHUGWATER	DARTON (1904) LOVE (1957)
250-460	PERMIAN	GOOSE EGG	BURK (1956) LANE (1973)
580-838	PENNSYLVANIAN	TENSLEEP	DARTON (1904) MALLORY (1967)
250-280	MISSISSIPPIAN	MADISON	MAUGHN (1963) WY STATE ENG. (1974)
PRECAMBRIAN (UNDIFFERENTIATED)			



The No. 1 Young-State oil exploration well in section 36, T. 25 N., R. 81 W., encountered artesian conditions after penetrating the aquifer revealing that the Tensleep aquifer is confined within the basin interior (See Deer Creek Anticline Well Drillers Report in Appendix E).

No quantitative data are available for hydraulic conductivities, transmissivities, and porosities of the Tensleep aquifer due to the lack of well tests in the study area. However, work by Todd (1964), Morgan and others (1978), and Mankiewicz and Steidtmann (1979) on the Tensleep Formation in the Bighorn Basin shows that the permeability varies horizontally and vertically due to (1) variations in primary and secondary silica, carbonate, and anhydrite cements; (2) fracturing and faulting; and (3) compaction with depth. Bredehoeft (1964) concluded from an analysis of drill stem tests that the transmissivity of the Tensleep aquifer progressively decreases basinward along the perimeters of the Bighorn Basin.

Groundwater Compartments

Groundwater circulation within the Tensleep aquifer of the Troublesome-Difficulty Creek area is restricted to the hanging wall of the Shirley thrust fault as a result of aquifer-severing displacements along the fault. The hydraulic continuity of the Tensleep aquifer in the hanging wall is severed by the Troublesome Creek and Paradise faults. These faults trend obliquely across the uplifted Tensleep Formation in the Shirley Mountains, south, to the Shirley thrust fault (Plate I). Stratigraphic displacements up to 1000 feet along the Troublesome Creek and Paradise faults preclude groundwater circulation perpendicular to the trend of the faults.

The Troublesome Creek and Paradise faults have divided the Tensleep aquifer in the hanging wall of the Shirley thrust fault into three hydraulically disconnected groundwater compartments (Plate III). Groundwater compartments are segments of an aquifer bounded by groundwater flow barriers that preclude circulation perpendicular to the trend of the barriers. These compartments have hydraulic heads and circulation systems that differ from other segments of the regional aquifer. Compartmentalization of the Tensleep aquifer by the Troublesome Creek and Paradise faults is demonstrated by (1) 400 foot hydraulic head differences across the faults (Plate III), and (2) differing chemical analyses of groundwater samples from the Tensleep aquifers in the individual compartments (Plate IV). The groundwater compartments in the hanging wall of the Shirley thrust fault are herein referred to as the (1) Troublesome Creek, (2) Hay Slough, and (3) Difficulty Creek compartments. These compartments contain groundwater circulation systems characterized as less-active circulation systems, an inactive-circulation systems, and an active circulation systems, respectively.

Active groundwater circulation systems have large circulation rates, steep hydraulic gradients, and good water qualities. Inactive groundwater systems are characterized as having small hydraulic gradients, poor water qualities, and small transmissivities. Less-active circulation systems are a combination of active and inactive circulation systems. The Troublesome Creek groundwater compartment is a less-active circulation system because the flanks of the Troublesome Creek groundwater compartment, updip of the springs, are zones of active groundwater circulation, whereas the basin portion of the groundwater compartment is a zone of inactive groundwater circulation.

Methodology

The geology and hydrogeology of the study area must be accurately defined before the groundwater circulation in the Tensleep aquifer can be described. The following procedures were used to develop critical data for this report.

An extensive field program was undertaken to locate and gauge all groundwater discharge locations in the study area. Spring discharges were calculated by use of a calibrated bucket and stopwatch. Flow rates of springs discharging from the streambed of Difficulty Creek were identified by increases in streamflow. Flow velocities in Difficulty Creek were calculated by use of a current meter. Recharge rates to the aquifer were calculated by summing the discharge of the springs and dividing by the recharge area.

Most of the springs were sampled and their waters analyzed for the major cations Na, K, Ca, Mg, and the major anions Cl, HCO_3, and SO_4. These water quality data were plotted on trilinear, fingerprint, and composition diagrams to identify individual aquifers, and to determine if mixing of groundwaters between individual aquifers is occurring. Trilinear, fingerprint, and composition diagrams visually display differences in the major-ion chemistry of groundwater flow systems. Groundwater of a particular flow system will have a similar water composition and plot as a group on each of the geochemical diagrams. Mixing of waters between flow systems in trilinear and composition diagrams is shown as a geochemical group which plots on a straight line between aquifer groups. Fingerprint diagrams indicate the mixing of waters from two aquifer systems when a geochemical group plots at an intermediate position between the aquifer groups.

A map of the potentiometric surface of the Tensleep aquifer was developed from water levels measured in oil exploration wells and the elevations of the springs having

Tensleep water chemistry. The potentiometric map was used to deduce groundwater circulation patterns from areas of recharge to areas of discharge.

A map showing the exposed faults and folds (Plate I) and a map of the top of the Tensleep Formation (Plate II) were prepared for the study area using (1) high altitude aerial photography, (2) published and unpublished geologic maps, and (3) reported formation tops from well logs. These maps were used in conjunction with the potentiometric and water quality data to interpret (1) the geologic and hydrogeologic controls on the localization of springs, and (2) the structural geologic controls on groundwater circulation and mixing.

CHAPTER II

PERMEABILITY ARCHITECTURE

Permeability is a measure of the ability of a porous media to allow the movement of water through it. This chapter describes the geologic features that contribute permeability to the Paleozoic rocks in the study area and the consequent influences of that permeability on groundwater circulation. The hydrologic roles of the Paleozoic rocks exposed in the Troublesome-Difficulty Creek area are summarized on Figure 5.

A discussion of permeability, hydraulic gradient and rejected recharge will preface this chapter and provide the necessary background for a subsequent discussion of the regional groundwater circulation in the Tensleep aquifer.

Groundwater Circulation Predicated on Permeability

Groundwater circulates downgradient to points of discharge through preferred flowpaths within individual geologic formations and structures. Preferred flowpaths have permeabilities larger than the primary permeabilities of their host rocks. These increased permeabilities develop as dissolution accompanies circulation. Dissolution enlarges flowpaths oriented parallel to the hydraulic gradient, thus increasing transmissivities. However, because water discharges at the perimeter of the basin through springs, circulation rates in the aquifer diminish basinward. Hence, gradients decrease basinward, and basinward recharge is small.

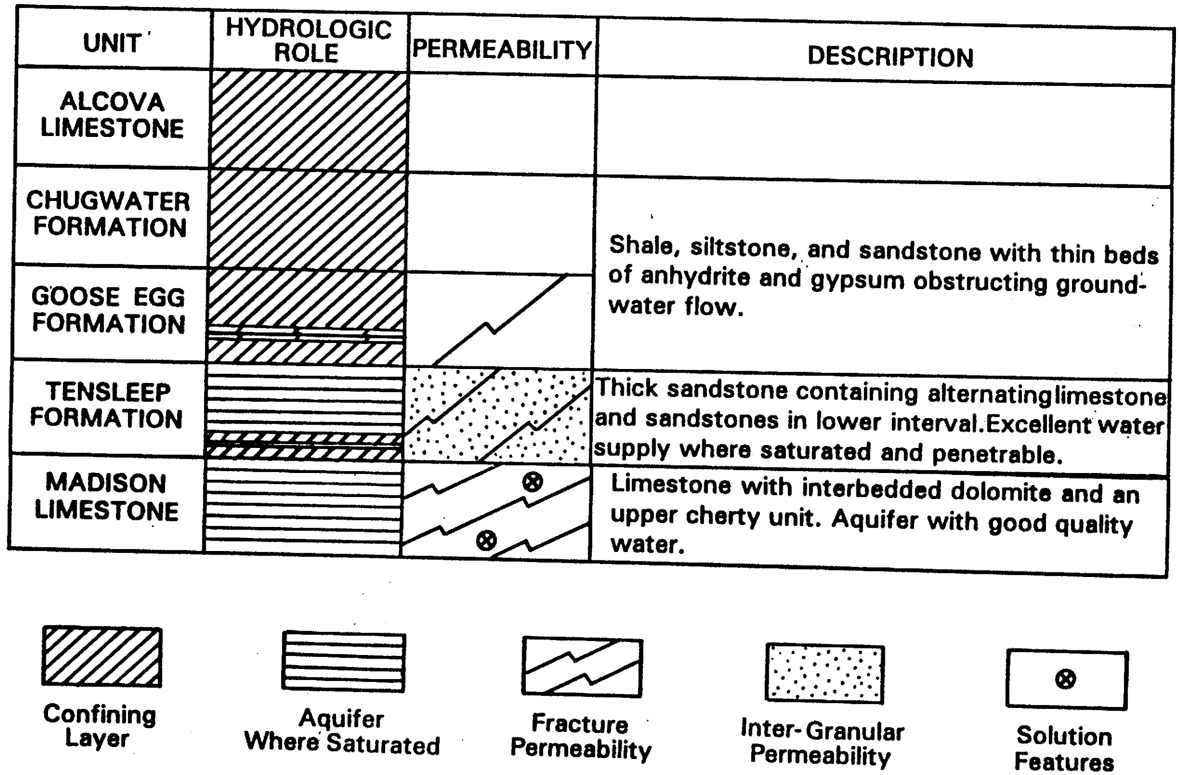


Figure 5. Hydraulic characteristics of rock units in the Troublesome-Difficulty Creek area, Carbon County, Wyoming.

Groundwater Circulation and Hydraulic Gradient

The contrast in hydraulic gradients between the upland and basin regions of the confined Tensleep aquifer in part regulates groundwater circulation into and through the aquifer. Small hydraulic gradients imply (1) small quantities of water are flowing through a unit, or (2) the transmissivities in a unit are large (Huntoon, 1987).

The small hydraulic gradients in the basin portion of the Troublesome Creek groundwater compartment reveal that small quantities of water are circulating through the aquifer. This conclusion is based on (1) the rejection of water from the aquifer through springs along the perimeter of the basin, and (2) a lack of springs discharging from the fully saturated aquifer in the basin.

Rejected Recharge

Rejected recharge is the expulsion of groundwater from a confined aquifer due to a basinward decrease in transmissivity and/or hydraulic gradient (Mancini, 1974). The basinward decrease in both transmissivity and gradient results in the rejection of the majority of the upland recharge from the aquifer above the point where the aquifer dips beneath the overlying confining layer on the flanks of the basin.

Rejected recharge can be quantified using the Darcy equation:

$$q=T(dh/ds) \qquad [1]$$

where

q = specific discharge,

T = transmissivity,

dh/ds = hydraulic gradient.

From Equation 1 it can be seen that as transmissivity and/or hydraulic gradient are reduced basinward the volume of groundwater circulating into the basin is proportionally reduced. Consequently, groundwater moving down gradient toward the basin cannot circulate laterally beneath the overlying confining bed and is rejected to springs along the contact of permeable unit and the confining bed.

Permeability Architecture

Permeability architecture is herein defined as the spatial arrangement of permeable zones emplaced in a formation or group of formations by physical and chemical processes. Permeable zones consist of faults, fractures, joints, and interconnected pores in rock units, which allow for the down gradient movement of water. Inherent in the definition of permeability architecture is the understanding that several distinct permeable zones will be superimposed within a formation, and the interconnectedness of the various permeable zones yields a network of permeable pathways for groundwater circulation. These permeable pathways are commonly oriented either parallel to bedding or perpendicular to bedding.

Bedding-Parallel Permeabilities

Wyoming foreland artesian basins consist of permeable strata interbedded among confining surfaces. A confining surface is the interface between a permeable unit and a lower permeability confining layer. The permeability of a confining layer is at least three orders of magnitude less than those of aquifers (Aldam and Kuang, 1989). This reduced permeability inhibits vertical circulation. Consequently, groundwater circulation in the interbedded permeable strata in the Wyoming foreland artesian basins is primarily parallel to bedding (Huntoon, 1993).

Intergranular Permeability

Bedding-parallel circulation in the Tensleep aquifer is demonstrated by springs discharging from the unfractured sandstone at the toe of the Tensleep Formation dip slope along the Shirley Mountains in the Troublesome Creek groundwater compartment (Plate III). Recharge water infiltrates the upturned edges of the Tensleep Formation along the perimeter of the artesian basin in the hanging wall of the Shirley thrust fault and circulates downward to the saturated part of the aquifer above the Madison Limestone. The water flows downgradient parallel to the bedding. Where fully saturated, the Tensleep aquifer is confined above by the Goose Egg Formation throughout the Troublesome-Difficulty Creek area. The negligible permeability of the Goose Egg Formation prevents cross-stratigraphic circulation of groundwater from the Tensleep aquifer into overlying units. Consequently, the recharge water ultimately discharges from the Tensleep Formation through springs located at the topographically lowest exposure of the unit on the flanks of the basin.

Mancini (1974) reports similar bedding-parallel circulation in the confined aquifers of the Powder River Basin. He states that where an artesian aquifer is flat lying or folded into anticlines and synclines, water moves parallel to the overlying and underlying confining beds. Similarly, Morgan and others (1977) report that non-reservoir material and bedding cause the flow of fluids to be mostly horizontal in the Tensleep Formation in the Oregon Basin oil field in the Bighorn Basin.

Intercrystalline Permeability

The intercrystalline permeability of the Madison Limestone in the Troublesome-Difficulty Creek area is extremely small. This is demonstrated in the field by (1) ponded water lying on unfractured limestone outcrops in the Shirley Mountains, and (2) no visible loss of streamflow as water discharging from Withrow Spring flows across the limestone. Reports by Richter (1981a,b) on the Laramie, Hanna, Shirley, and Wind River basins, and reports by Huntoon (1976b, 1993) on the eastern flank of the Bighorn Mountains and on Sheep Mountain anticline in the Bighorn Basin state that the intercrystalline permeability of the Madison Limestone is very small to negligible. Richter (1981b) attributes the negligible interstitial permeability of the Madison Limestone to the finely crystalline rock fabric.

Because the intercrystalline permeability of the Madison Limestone is extremely small, permeable zones in the Madison Limestone must result from nonstratigraphic elements. Richter (1981b) reports that permeable zones in the Madison Limestone are the result of fractures, joints, and solution cavities.

Fractures

Fractures are hydraulically important because of their capability to establish zones of large bedding-parallel and/or bedding-perpendicular permeabilities in rocks. Huntoon (1976a) and Lundy (1978) found that permeabilities in fractured rocks near Laramie were 100 times larger than those in unfractured rock. However, not all fractures provide permeable zones within the host rock. Fractures developed as a result of extension are generally more permeable than fractures formed through compression. Extensional fractures along which open separations have developed provide zones of large bedding-parallel and bedding-perpendicular permeability, whereas fractures infilled by cementation, or that have undergone compression, have negligible permeabilities.

Vertical Joints

Vertical joints are a class of fractures along which open separations develop as a result of the extension of strata during folding. As shown in Figures 6 and 7, numerous small- and large-scale vertical joints can be found in the Madison and Tensleep formations in the crestal parts of exposed folds within the study area. These vertical joints parallel the axial trace of folds and penetrate most of the way through outcrops before terminating at the intersection of bedding planes or simply closing downward. Joints observed in the Madison and Tensleep outcrops extend from between 10 and 100 feet vertically, and are spaced from inches up to a 100 feet apart.

Bedding-parallel permeabilities associated with extensional joints are qualitatively revealed in the Madison Limestone by solutional widening along the fractures. Figures 6 and 8 show solution widened vertical joints and keyhole-shaped solution tubes localized on bedding planes in Madison outcrops in the Shirley Mountains. The orientations of the solution-widened vertical joints and solution tubes parallel to the trend of the folds indicate that groundwaters have circulated through these features parallel to trend. The large permeabilities associated with dissolution-widening of the fractures and solution tubes parallel to trend produces a maximum permeability tensor that is oriented parallel to both trend (Jarvis, 1986) and bedding (Huntoon, 1993). Thus vertical joints located along the crests of anticlines provide highly transmissive lateral circulation pathways parallel to trend and parallel to bedding.

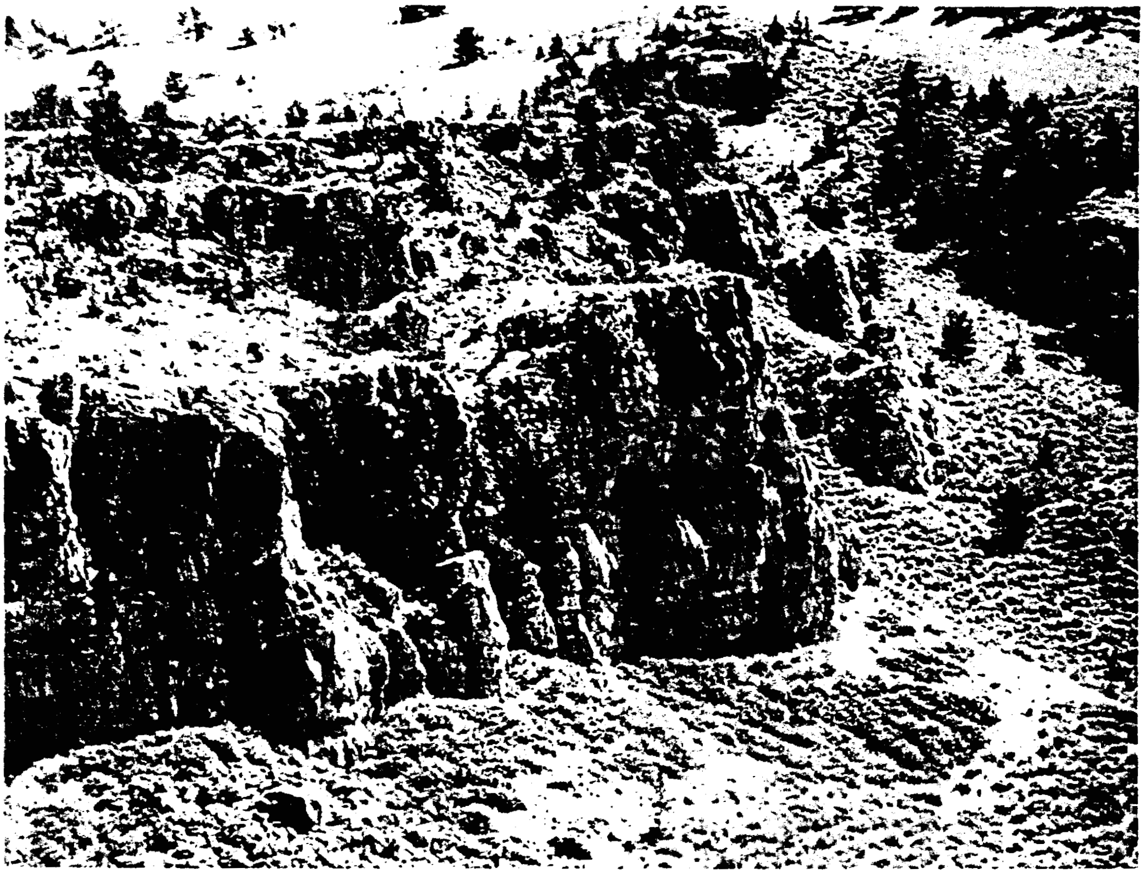


Figure 6. Outcrop of the Madison Limestone in the Shirley Mountains with prominent dissolution cavities localized along bedding planes and through-going vertical joints. View is to the east in sec. 12, T. 25 N., R. 81 W., Carbon County, Wyoming

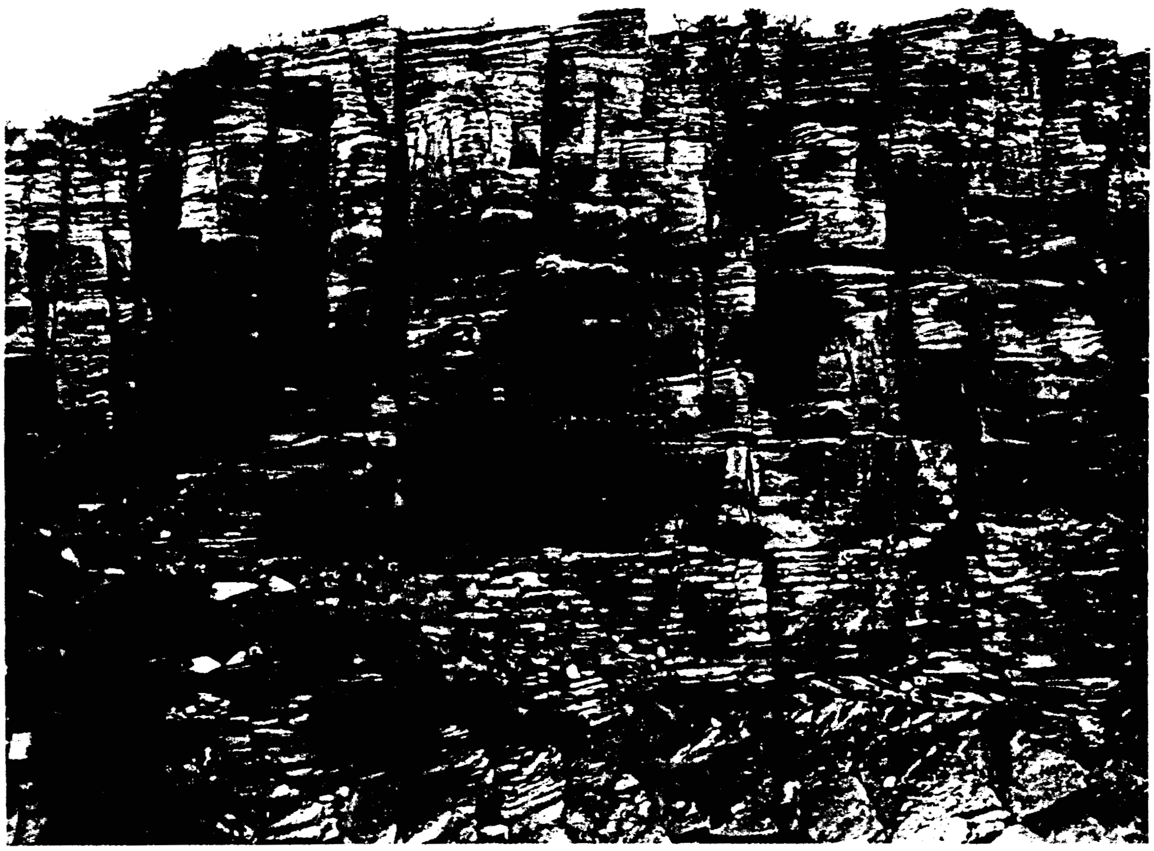


Figure 7. Large exposure of through-going vertical faults and fractures in the cross-bedded sandstone of the Tensleep Formation in section 35, T. 25 N., R. 80 W., Carbon County, Wyoming. View is to the west.

Figure 8. Solution enlarged vertical fracture in the Mississippian Madison Limestone in section 12, T. 25 N., R. 81 W., Troublesome-Difficulty Creek area, Carbon County, Wyoming. Fracture crosscuts the bedding of the limestone. Although it is a vertical feature groundwater circulation through the fracture in a confined aquifer is parallel to the walls of the fracture, parallel to bedding. Numerous solution enhanced fractures were observed, however no springs were observed discharging from the limestone.

No springs were observed that discharge from solution-widened fractures or solution tubes in the Madison Limestone. However, alteration halos observed along the base of several large fractures indicate past groundwater circulation through the fractures in the limestone. Alteration halos consist of chemically reduced zones that penetrate a few inches into the rock from the surfaces of the fractures.

Huntoon (1993) reports joints similar to those described above in the Madison Limestone in Sheep Mountain anticline in the Bighorn Basin. He found that groundwaters that have circulated along strike through vertical joints in the anticline, widened joints and localized bedding-parallel solution tubes on through-going joints. Similarly, work by Emmet and others (1971), Jarvis (1986), Spencer (1986), and Doremus (1986), in the Bighorn Basin, has shown that vertically oriented joints along anticlinal crests provide highly permeable conduits allowing for lateral groundwater circulation.

Cross Joints

Cross joints are vertical fractures that trend oblique or perpendicular to the fold axis. This class of fracture results from extension of strata along doubly-plunging anticlines (Hurley, 1990). The extension of strata caused by the doubly-plunging geometries of folds creates open separations along cross joints. These open separations increase the permeabilities along the cross joints.

Cross joints are visible in the Alcova Limestone member of the Chugwater Formation on Troublesome Creek anticline and in the Tensleep Formation within the double-plunging anticlines in the Freezeout Mountains. No visible evidence of enhanced permeability associated with these features was found in the study area. However, Huntoon (1993) reports that where cross jointing is the dominant fracture within anticlines, the principal permeability tensor will be oriented perpendicular to the trends of folds and parallel to bedding.

Partings along Bedding Planes

Bedding plane partings are open fractures that develop as a result of shearing parallel to bedding during folding. These fractures are parallel to bedding and follow the trends of folds. The bedding-parallel permeability of such fractures is well developed in Cave Creek Cave in the Shirley Mountains (Hill and others, 1976). Cave Creek Cave is localized on the bedding plane contact between the Tensleep Sandstone and the underlying Madison Limestone, and dissolutional enlargement below the contact occurs along the entire 2048 foot length of the cave.

Bedding-Perpendicular Permeability

Although groundwater circulation in the Wyoming foreland artesian basins is primarily parallel to bedding, cross-stratigraphic circulation between two or more aquifers separated by a confining layer or between a confined aquifer and the land surface does occur. Extensional fractures, small-scale thrust faults, reverse faults, and normal faults, which crosscut permeable and confining strata provide bedding-perpendicular permeability pathways for cross-stratigraphic circulation. However, the cross-stratigraphic circulation occurring within Wyoming artesian basins is very limited owing to the presence of areally extensive, thick confining strata (Huntoon, 1993). The cross-stratigraphic circulation pathways that do exist usually occur along discrete vertical discontinuities (Rush and others, 1982), such as faults and fractures within Laramide anticlines. Thus in the Wyoming foreland artesian basins, bedding-perpendicular permeabilities and cross-stratigraphic circulation usually occur only in areas of structural deformation. In this project area there has been some type of structural deformation wherever cross-stratigraphic circulation between aquifers or between aquifers and the land surface occurs.

Normal Faults

Several small-scale normal faults with east-west trends occur in the study area (Plate I). The bedding-perpendicular permeabilities associated with these normal faults is attributed to small stratigraphic displacements and separations developed along the fault surfaces as a result of tectonic extension.

The bedding-perpendicular permeability of such faults is revealed by spring 4 and springs 6-10 (Plate V), which discharge from the Tensleep aquifer near normal faults and associated fractures along the toe of the recharge area in sections 20 and 31 of T. 25 N., R. 81 W. Cross-stratigraphic circulation of groundwater from the Madison Formation into the Tensleep Formation is based on the following field evidence: (1) surface drainage systems lose water to sinkholes in the basal Madison Limestone; (2) the only large volume springs in the basin discharge from the Tensleep and lower Goose Egg formations, upsection of the Madison Limestone; (3) the springs located upsection of the Madison Limestone are localized on vertical fractures and faults. From this evidence I deduce that water entering the Madison Formation circulates downward through karst features developed along bedding in the Madison Limestone. The water then crosses bedding through fractures and faults into the Tensleep aquifer and discharges from springs localized on the crosscutting faults and fractures. Similar cross-formational flow through faults and fractures crosscutting confining surfaces are documented by Stone (1967), Cooley (1986), Jarvis (1986), and Spencer (1986).

The loss of streamflow where streams cross fault zones further demonstrates cross-stratigraphic circulation through normal faults. Difficulty Creek flows across the Goose Egg Formation north of Difficulty Canyon at a rate of 1.5 ft^3/sec (672 gpm). A loss in the flow rate of 0.85 ft^3/sec (381 gpm) was recorded where the stream flows along a one-half mile segment of the normal fault in section 3, T. 24 N., R. 80 W.

Vertical Fractures

Vertical extensional fractures located along the crests of anticlines propagate upward through overlying rocks and destroy the hydraulic integrity of overlying confining layers (Jarvis, 1986). Vertical fractures are important in (1) imparting vertical hydraulic connections between aquifers within the crestal parts of anticlines, and (2) spring localization in permeable and confining strata.

Cross-stratigraphic circulation through vertical fractures is indicated (1) by the large number of springs that discharge from fractures in the lower Goose Egg confining layer along the banks of Difficulty Creek, and (2) by an increase in streamflow of 3.46 ft^3/sec (1550 gpm) along a one mile stretch of Difficulty Creek in section 16, T. 24 N., R. 80 W. This latter increase occurs near the intersection of two doubly plunging anticlines of the Tensleep Formation and the termination of a splay fault from the aquifer-severing Shirley thrust fault (Plate I).

Permeability Enhancement and Reduction

Bedding-parallel and bedding-perpendicular permeabilities are enhanced through dissolution of interstitial cements and matrix material, or are reduced by the precipitation of various cements. Permeability enhancement and reduction in stratigraphic units is dependent in part on the geochemical environment present. Typically, permeabilities in recharge areas are increasing as a result of dissolution by chemically undersaturated waters derived from snowmelt and precipitation, whereas the permeabilities in the basins are being reduced by recrystallization, cementation, and compaction (Bredehoeft, 1964; Head and Merkel, 1977; Huntoon, 1993).

The permeability of the Tensleep aquifer in the Troublesome Creek groundwater compartment is largely the result of dissolutional enlargements of fractures and bedding planes in the recharge area and along the basin margin. Fractures in these areas have been enlarged through the dissolution of matrix cements by the circulation of chemically undersaturated waters. The increase in the permeability through the fractures allows for greater volumes of water to circulate more rapidly through the fractures to remove matrix material. This process sets up a feedback mechanism that localizes zones of large permeability along the fractures, and that permeability is proportional to the total volume of water that has circulated through the rock (Huntoon, 1993).

Solution widened fractures in any kind of reservoir rock have permeabilities hundreds of times larger than those of unaltered rock (North, 1985). Oil field research has shown that a 0.5 millimeter fracture could account for more than 90 percent of the total flow in a limestone aquifer (Chilingar, 1972). The size of a fracture opening greatly enhances the ability of the aquifer to transmit water. Thus, the larger the size of a fracture opening the more permeable that fracture will be. Dissolutional enlargement of a vertical joint within the Tensleep Formation in Difficulty Canyon has produced a two-inch-wide fracture that discharges more than 120 gpm from the Tensleep aquifer (Figure 9). Similarly, dissolutional enlargement of fractures is indicated by the discharge of sand and silt from springs 4, 9, and 10 that are localized on fractures. The discharge of sand and silt from these springs reveal that waters circulating through the fractures are dissolving matrix cements from the Tensleep Formation and the large transmissivity of the water circulating in the fractures is actively removing grains of sand from the walls of the fractures.

In contrast to the permeability enhancement in the recharge area, the basin area undergoes significant permeability reduction due to recrystallization, cementation, and compaction. Basinward decreases in permeability along mountain-basin margins has been reported by Bredehoeft (1964), Huntoon (1985b), and Doremus (1986). They attribute the diminished permeabilities in the basin to (1) reduced rates of solutional enhancement, (2) reprecipitation of cements, and (3) compaction of matrix material with depth. Todd (1963), Lawson and Smith (1966), and Fox and others (1975) have shown that the interstitial porosity in the Tensleep Sandstone ranges from 20 percent in recharge areas to less than 5 percent in basins. This decrease is a result of precipitation of dolomite, silica, and anhydrite cements. Furthermore, Mankiewicz and Steidtmann (1979) report that the permeability of the Tensleep Formation in the Bighorn Basin is being reduced by the infilling of fractures with anhydrite and silica, and pore spaces infilling with calcite.

Figure 9. Hole-in-the-Wall spring, spring 30, (section 10, T. 24 N., R. 80 W.). This spring discharges 120 gpm from a two inch wide dissolution enhanced vertical fracture in the Tensleep Formation in Difficulty Canyon. The groundwater seeps from unfractured Tensleep Formation 200 feet downstream.

Permeability Architecture in the Troublesome Creek Groundwater Compartment

The characteristics of the permeability architecture present in the study area are as follows: (1) downgradient groundwater flow is through preferred flowpaths that have permeabilities larger than the interstitial permeabilities; and (2) permeable zones are oriented either parallel or perpendicular to bedding. Bedding-parallel permeabilities provide pathways for bedding-parallel circulation in aquifers whereas bedding-perpendicular permeabilities provide the only pathways for cross-stratigraphic circulation between aquifers or through confining layers (Figure 10).

The Troublesome Creek groundwater compartment serves as a good example of how the interconnection of geologic structures having either bedding-parallel or bedding-perpendicular permeabilities create an overall permeability architecture. The permeability architecture of the Troublesome Creek groundwater compartment is described below and is shown in Figure 11.

Recharge to the Madison Formation occurs by infiltration of precipitation and snowmelt into vertical fractures and sinkholes. These features act as collector structures for groundwater circulation into permeable features in the unsaturated zone. Water moves from the sinkholes and vertical fractures into bedding plane partings. Dissolution accompanying circulation creates preferred flow pathways along the bedding plane partings dipping basinward. However, groundwater circulation through the dissolution enhanced permeabilities of the bedding plane partings diminishes along the basin margin as a result of basinward permeability reduction. Extensional faults and fractures intersect the bedding plane partings along the basin margin. The bedding-perpendicular permeabilities of the

Figure 10. Outcrop of the lower Goose Egg Formation (section 10, T. 24 N., R. 80 W.) in which past bedding-parallel and cross-stratigraphic circulation are revealed by the presence of alteration halos (chemically reduced zones). Notice that past groundwater circulation through the fractured shales in the lower part of the photo paralleled the bedding contact of the underlying limestone and the overlying unfractured shales. The vertical fracture that intersects the fractured shales imparts a bedding-perpendicular permeability pathway for cross-stratigraphic circulation through the overlying confining layer.

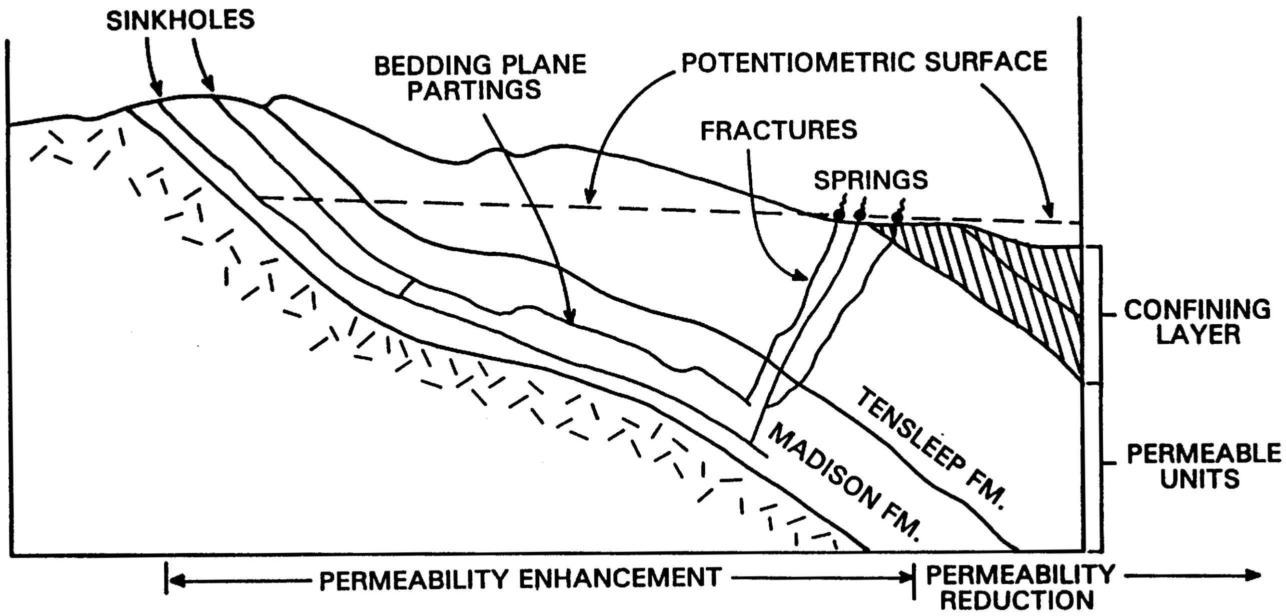


Figure 11. Diagrammatic cross-section showing groundwater circulation downgradient but upsection through permeability pathways in the Madison and Tensleep formations on the flanks of Shirley Mountains in the Troublesome Creek groundwater compartment, Carbon County, Wyoming. Permeability is enhanced by dissolution by fresh groundwaters between the recharge and discharge points. Permeability is reduced basinward of springs as a result of recrystallization, compaction, and cementation.

faults and fractures provide cross-stratigraphic circulation pathways for groundwater circulation into the overlying Tensleep aquifer. The reduction in Tensleep aquifer permeability basinward reduces the volume of groundwater entering the artesian basin, consequently the majority of recharge water is expelled from the aquifer as rejected recharge.

The enhanced permeabilities associated with different geologic features attests to the importance of dissolution in providing preferred flow pathways in this architecture. It is clear that the best model to explain the groundwater circulation from areas of recharge in the Madison Limestone to the springs discharging from the Tensleep aquifer is that of a permeability architecture dominated by interconnected fracture permeability subsequently enhanced by dissolution widening.

CHAPTER III
WATER QUALITY

The purpose of this chapter is to discuss the geochemistry of the groundwater system in the study area. The primary objectives of this chapter are to (1) identify the individual water groups in the study area, and (2) determine by chemical analysis where cross-stratigraphic circulation is occurring.

Cross-stratigraphic circulation between formations will be demonstrated using trilinear, fingerprint, and composition diagrams. These diagrams indicate mixing of waters if the chemical compositions of suspected mixed waters are at intermediate positions and they plot linearly between the chemical compositions of end member waters for the various formations. However, the actual mixing of waters does not have to occur to produce intermediate chemical compositions. Instead, geochemical processes such as dissolution and cation exchange occurring at water-rock contacts can alter water chemistry significantly and can be misrepresented as groundwater mixing (Drever and others, 1977; Mazor, 1991; Mazor and others, 1993). Regardless of which process actually occurs, groundwater mixing or geochemical reactions at water-rock contacts, an intermediate water composition between end members in the chemical analysis diagrams indicates cross-stratigraphic circulation of groundwater between rock formations.

Water quality data for select wells and springs in the study area are listed in Appendices B, C, and D. Diagrammatic representations of water chemistry and total dissolved solids of springs and wells in the study area are shown on Plate IV.

All springs discharging from fractures and faults near the Paleozoic rocks in the study area were sampled and these samples were chemically analyzed to identify the geochemistry of distinct aquifers. Geochemical analysis revealed that some of these waters discharge from minor aquifers in the Mesozoic Cloverly Formation. Because the Mesozoic Cloverly Formation is not a principal formation under investigation in this study geochemical data obtained from this formation is not discussed herein, but rather is tabulated Appendices B, C, and D for reference.

Chemistry of the Tensleep Waters

The chemical character of the Tensleep aquifer is primarily dictated by the dissolution of calcite from the aquifer matrix. Near outcrops, groundwater is of calcium-bicarbonate type, and Ca^{+2} is the dominant cation. The dominance of calcium results from the dissolution of calcite ($CaCO_3$) which is present in abundance in the cement in the unit. HCO_3^- is the dominant anion in the Tensleep aquifer.

Water quality analyses from the springs listed in Appendix C reveal low mineralized waters within the Tensleep aquifer, which range from 107 to 180 mg/l of dissolved solids. Total dissolved solid concentrations are low because residence times are short. Water analyses for the Tensleep aquifer are plotted on the fingerprint diagram in Figure 12.

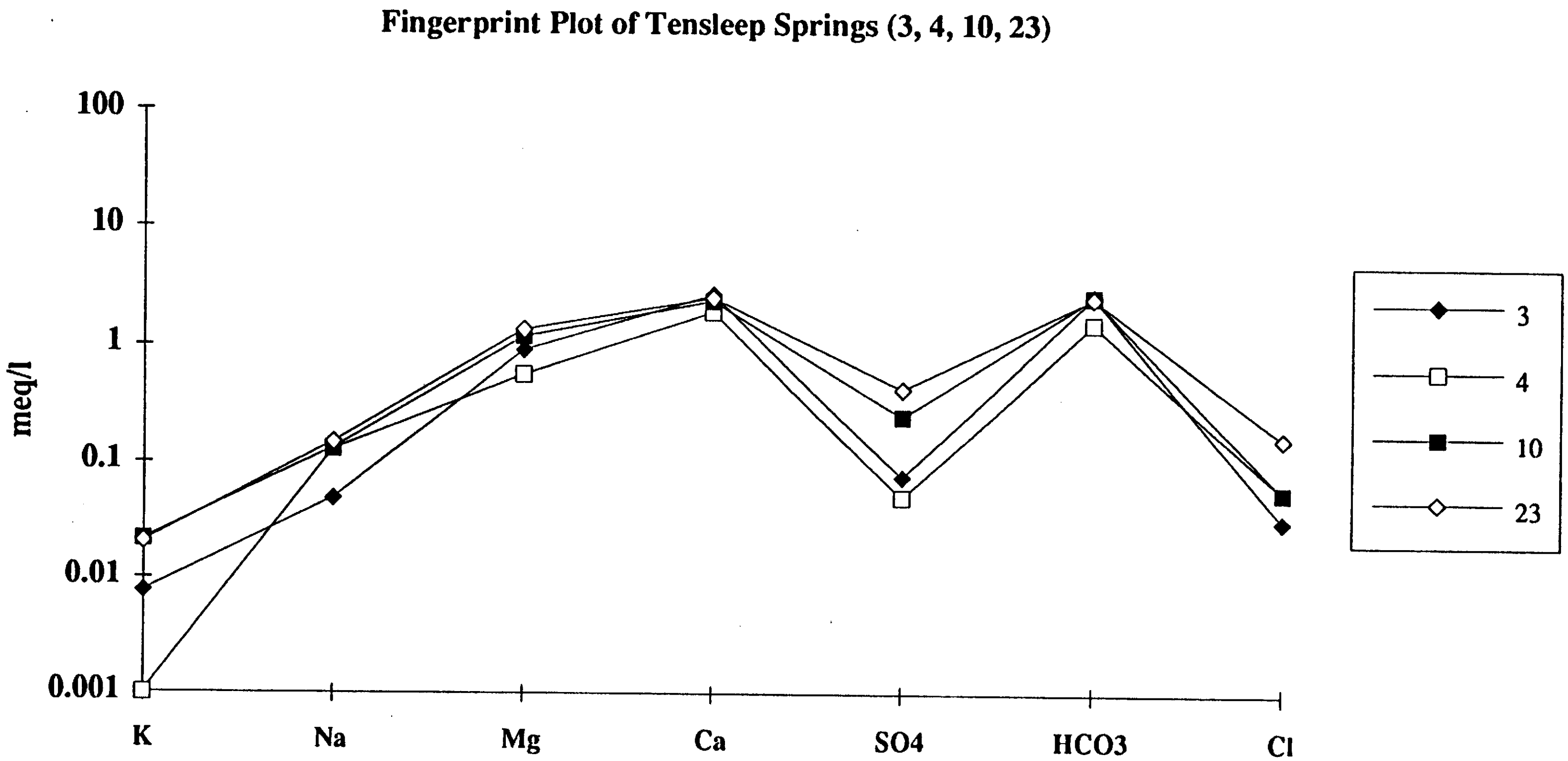


Figure 12. Fingerprint diagram showing the chemical characteristics of well and spring water derived from the Tensleep aquifer in the Troublesome-Difficulty Creek area, Carbon County, Wyoming. Numbers correspond to locations shown in Plate III and listed in Appendices B and C. Method after Mazor (1991).

Chemistry of the Redbed Waters

The Goose Egg and Chugwater Formations together compose a regional confining layer in the Troublesome-Difficulty Creek area. However, thin limestones in the lower Goose Egg Formation are considered minor localized aquifers. The waters from the localized aquifers in the lower Goose Egg Formation will be described herein as the redbed waters.

As shown in Appendix C, redbed waters have high calcium and sulfate concentrations and a total dissolved solids concentration between 1094 and 2742 mg/l. Dissolution of evaporites in the Goose Egg Formation account for the high concentration of dissolved solids. The dominance of calcium (Ca^{2+}) and sulfate (SO_4^{2-}) result from the dissolution of gypsum and anhydrite which are present in abundance as thick beds on surface exposures and at outcrops of the Goose Egg and Chugwater formations. Evidence of evaporite dissolution includes (1) collapse features in the Goose Egg Formation north of Difficulty Canyon, and (2) circular subsidence features on the surface of the Goose Egg Formation adjacent to the eastern flank of the canyon.

Water analyses for the redbeds are plotted on the fingerprint diagram of Figure 13.

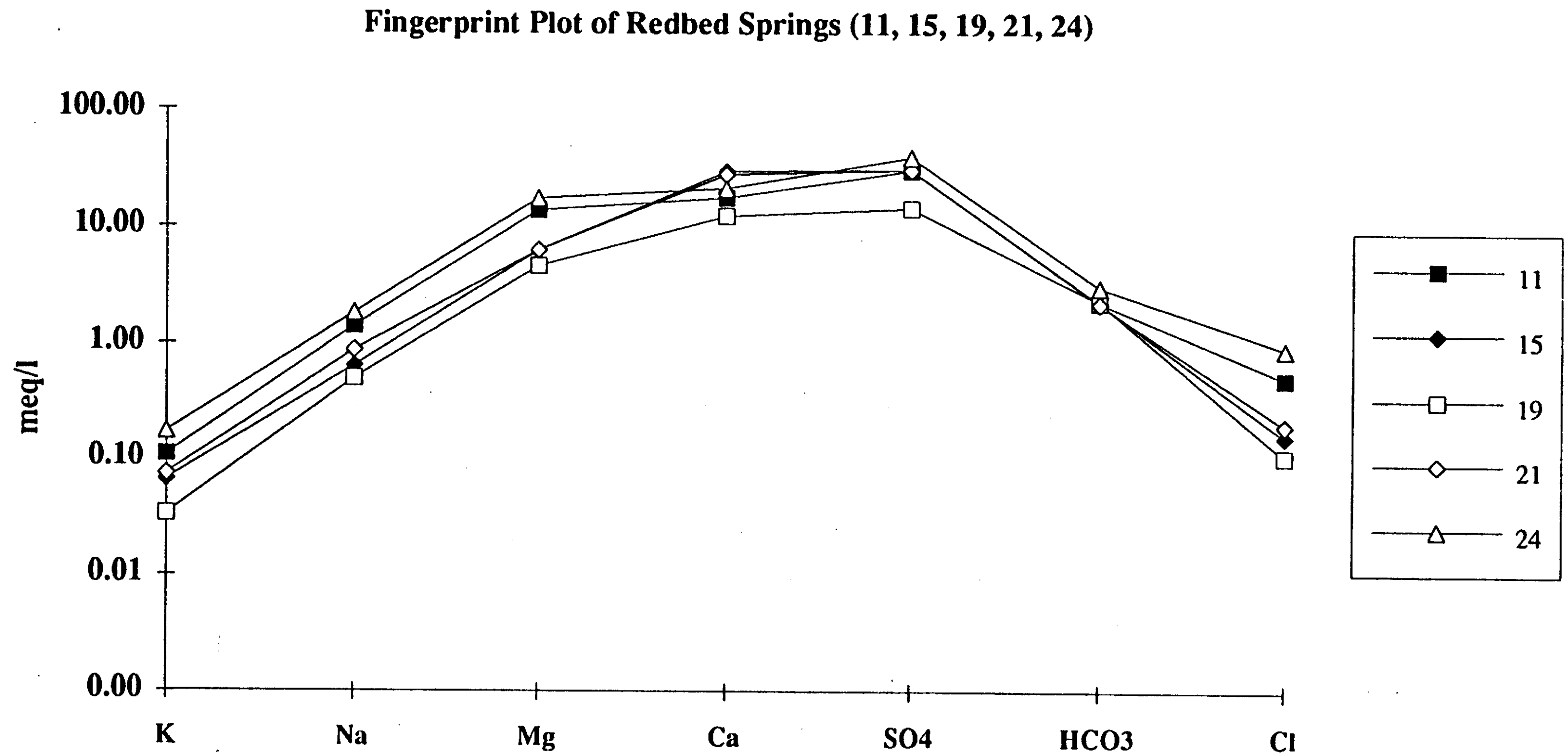


Figure 13. Fingerprint diagram showing the chemical characteristics of well and spring waters derived from the redbed aquifers in the Troublesome-Difficulty Creek area, Carbon County, Wyoming. Numbers correspond to locations shown in Plate III and listed in Appendices B and C. Method after Mazor (1991).

Mixing of Waters

The mixing of groundwater was determined from mixing lines and linear correlations between chemical data plotted on trilinear, composition, and fingerprint diagrams. The geochemical data plotted is that of springs and wells in the study area (Plate IV). The methods used in this study are those of Piper (1944) and Mazor (1991).

Trilinear diagrams (Piper, 1944) were used to characterize water groups on the basis of their cation and anion facies. Twenty-one water samples from springs and wells were analyzed for major cations and anions and plotted on the trilinear diagram of Figure 14. The analyses of these waters are listed in Appendix C.

The trilinear diagram shown in Figure 14 contains the plots of Tensleep end member waters, redbed end member waters, Cloverly waters, and plots of suspected mixed waters. Piper (1944) states that two waters are mixed if the following conditions are met: (1) the mixed waters must plot as a straight line in all three fields of a trilinear diagram, (2) the concentration of the mixed water must be intermediate between the end member water concentrations, and (3) the computed concentrations for total and individual constituents must agree with the analytical data used in the following equations:

$$V_A = [bE_B/(aE_A + bE_B)] \times 100\%, \qquad [2]$$

$$C_M = C_A V_A + C_B V_B, \qquad [3]$$

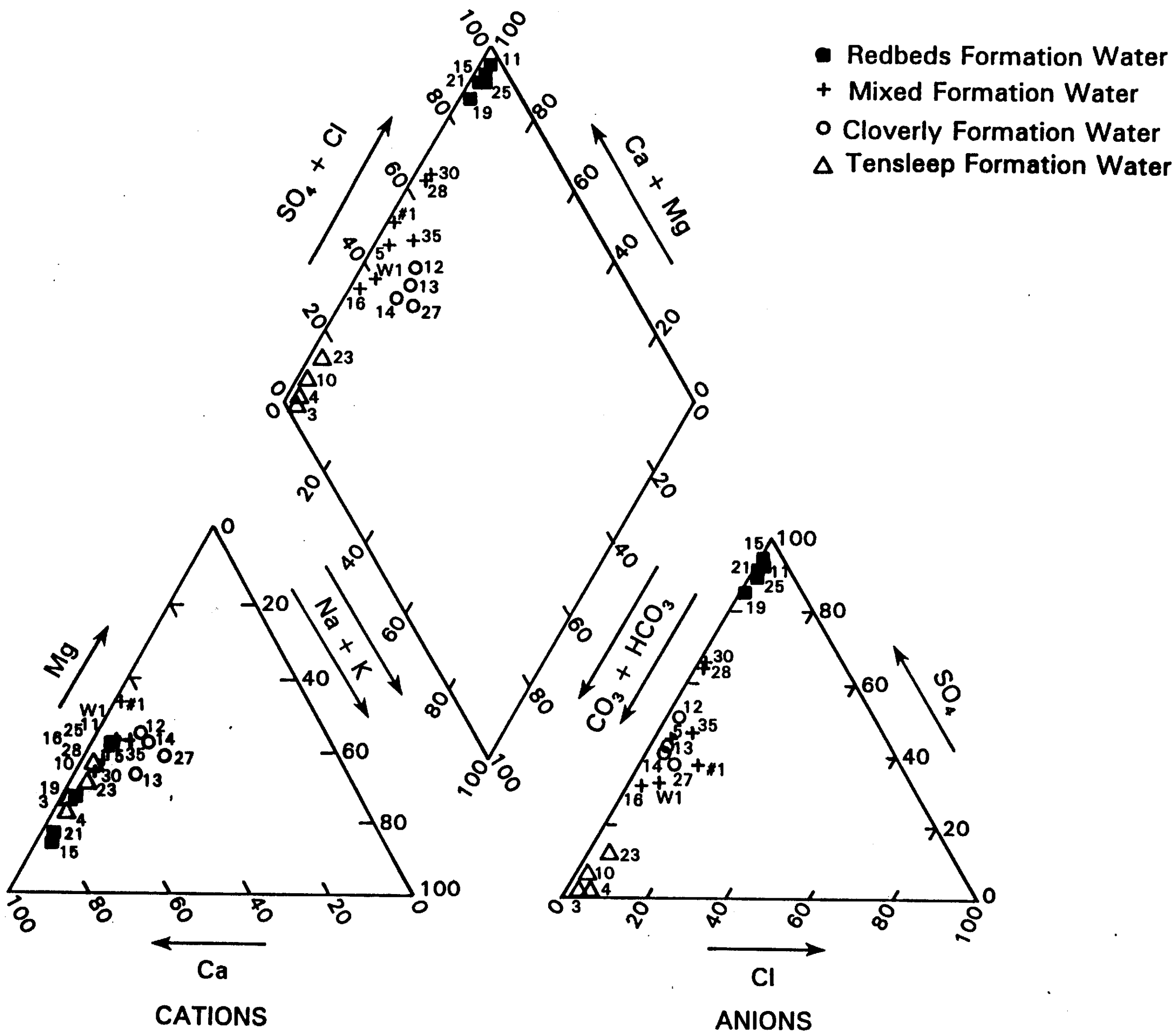
$$V_A + V_B = 100\%, \qquad [4]$$

where:

V_A = percentage of the mixture that has the composition of end member A,

V_B = percentage of the mixture that has the composition of end member B,

Figure 14. Trilinear diagram showing the chemical characteristics of all sampled spring and well waters in the Troublesome-Difficulty Creek area, Carbon County, Wyoming. Numbers correspond to locations shown on Plate III and listed in Appendices B and C. Method after Piper (1944).



Redbeds Formation Water
+ Mixed Formation Water
o Cloverly Formation Water
Δ Tensleep Formation Water
SO4 + Cl
Ca + Mg
Na + K
CO3 + HCO3
Mg
SO4
Ca
Cl
CATIONS
ANIONS

a = distance, scale arbitrary, between the plot position of mixed sample and end member A on a trilinear diagram,

b = distance, scale same as for a, between the plot position of mixed sample and end member B on a trilinear diagram,

E_A = concentrations of total cations (or anions) of end member A in milliequivalents/liter (meq/l),

E_B = concentrations of total cations (or anions) of end member B in milliequivalents/liter (meq/l),

C_M = concentration in the mixed water of total dissolved solids or of an individual constituent in meq/l,

C_A = concentration in end member water A of total dissolved solids or of an individual constituent in meq/l or mg/l,

C_B = concentration in end member water B of total dissolved solids or of an individual constituent in meq/l or mg/l.

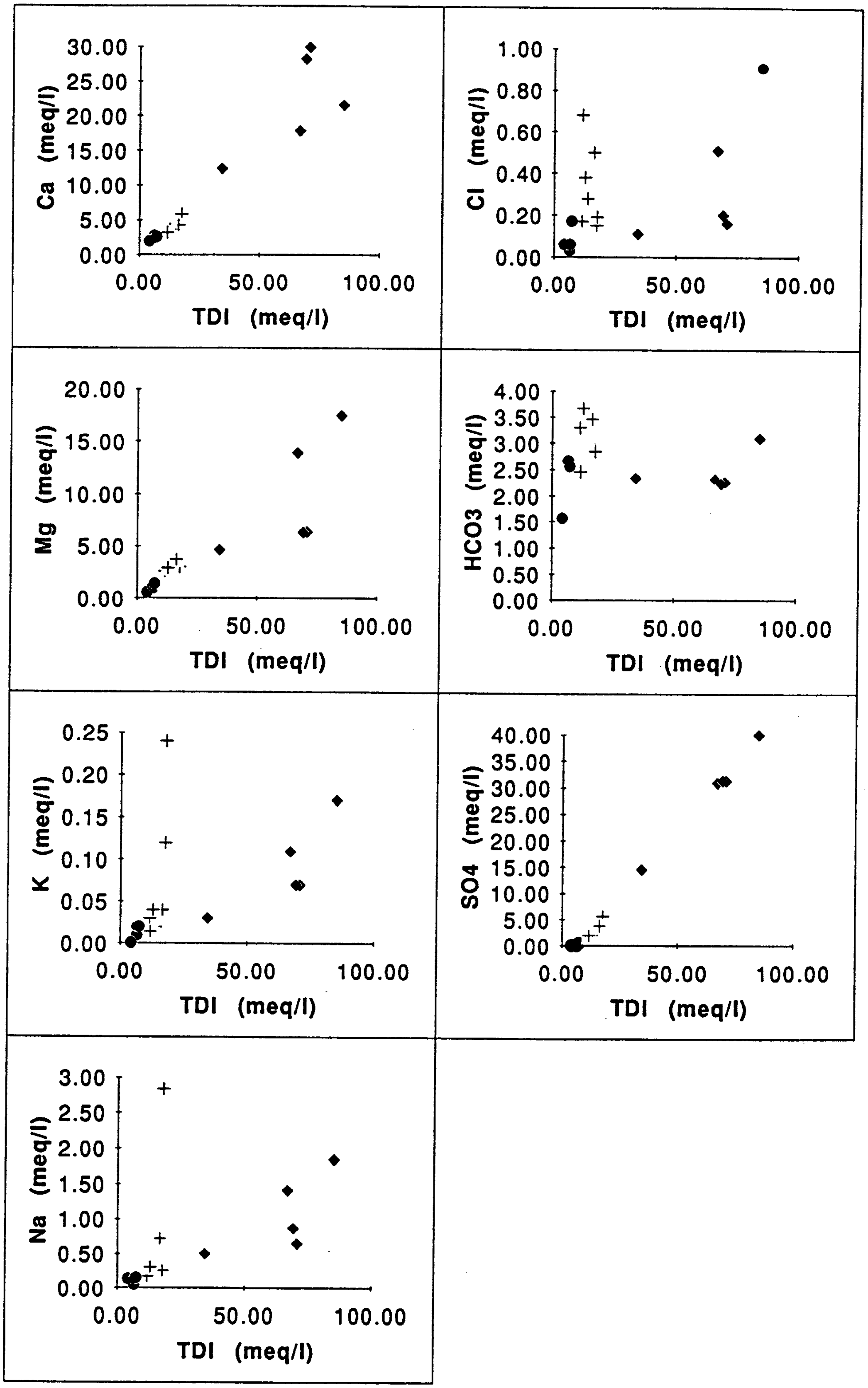
It is evident from Figure 14 that three distinct water types and a mixture of two of the three waters are present. Mixed waters plot as a line between two end member waters in all three fields of a trilinear diagram. Figure 14 reveals that a linear relationship exists between the Tensleep and redbed end members. This linear relationship is also found in the cation and anion fields, consistent with mixing occurring between these water groups. The second criterion, that the concentration of mixed water be intermediate between the end members does occur (Appendix D). The third criterion was validated using equations 2 and 3. End member springs chosen were spring 3 (Tensleep water) and spring 11 (redbed spring). Equation 2 was used to determine the percentages of each end member in the mixed water. The mixed water consisted of 81% Tensleep water and 19% redbed water. These percentages were used in equation 3 to determine if the summed percentage of individual constituents of the end member waters agreed with individual constituents in the mixed water. Using equation 3, the percent differences in measured and calculated constituents are: (1) 12% in total cations, (2) 15% in total anions, and (3) 7% in total dissolved solids. This evidence indicates that mixing of waters is occurring.

To further substantiate the mixing of Tensleep water and redbed water an identification procedure of Mazor (1991) was used. This procedure uses composition diagrams to demonstrate the mixing pattern of waters with different chemistries. Mazor (1991) reported mixing of waters from two aquifer systems occur when the values for the suspected mixed waters lie on lines connecting the values of the end member waters.

The individual chemical constituents of springs from the study area were plotted against total dissolved ions (TDI) on composition diagrams in Figure 15. The composition diagrams contain Tensleep water samples, redbed water samples, and water samples in which mixing of waters is suspected. Figure 15 shows (1) a cluster pattern of individual ions from each water type when plotted against TDI, and (2) the suspected mixed waters plot at intermediate positions between the Tensleep and redbed mixing lines. Mazor (1991) states that a clustering of data points indicates the sampled springs belong to one aquifer and the linear correlation between clusters demonstrates that two distinct water systems are locally interconnected. Thus the linear correlation between clusters in Figure 15 demonstrates that a fresh water mixes in various proportions with a water having higher TDI.

The individual chemical constituents of the end member and suspected mixed water groups from the study area were also plotted against their chemical concentrations on fingerprint diagrams. Fingerprint diagrams indicate the mixing of waters from two aquifer

Figure 15. Water composition diagrams showing the chemical concentrations of major ions versus the concentration of total dissolved ions (TDI) for groundwaters discharged from the Tensleep aquifer (solid circles), redbed aquifer (solid diamonds), and mixed waters (pluses). The clusters of points indicate waters of the same aquifer. The linear trend of the diagrams indicate a mixing of two water chemistries. Notice that mixed waters plot between the Tensleep and Redbed end members. (Method after Mazor, 1991).


Ca (meq/l)
TDI (meq/l)
Cl (meq/l)
TDI (meq/l)
Mg (meq/l)
TDI (meq/l)
HCO3 (meq/l)
TDI (meq/l)
K (meq/l)
TDI (meq/l)
SO4 (meq/l)
TDI (meq/l)
Na (meq/l)
TDI (meq/l)

systems when a geochemical group plots at an intermediate position between the end member aquifer groups. The fingerprint diagram of Figure 16 provides a visual description of the relative compositions of the Tensleep, redbed and suspected mixed water groups. Figure 16 clearly shows the suspected mixed-waters plot at intermediate positions between the Tensleep and redbed end member groundwater groups.

From the evidence provided by trilinear, composition, and fingerprint diagrams, it is concluded that Tensleep water and redbed water are mixing at some locations in the study area.

Cross-Stratigraphic Circulation in the Troublesome-Difficulty Creek Area

In the study area, springs 5, 16, 28, 30, 35 and well W1 yield mixed water chemistries. The mixed waters of these springs and wells indicate that the Tensleep and redbed groundwater systems are locally interconnected through bedding-perpendicular permeabilities associated with structurally deformed areas.

The locations of cross-stratigraphic circulation for water from the Tensleep aquifer are shown in Figure 17. The locations where cross-stratigraphic circulation occurs are (1) the flanks of the basin in the Troublesome Creek groundwater compartment, (2) the footwall of normal fault at the northern boundary of the Hay Slough groundwater compartment, (3) the normal fault in sections 17 and 18, T. 25 N., R. 81 W., (4) the normal faults that cross Smith Creek in section 35, T. 25 N., R. 80 W., (5) Difficulty Canyon, (6) the area along Difficulty Creek from the Ellis Ranch to the Beer Mug Ranch, and (7) the faulted hanging wall of the Freezeout thrust fault. These locations correspond to gaining and losing reaches of streams, structurally deformed areas and to fractures and faults that penetrate through the overlying confining strata along the flanks of the basin.

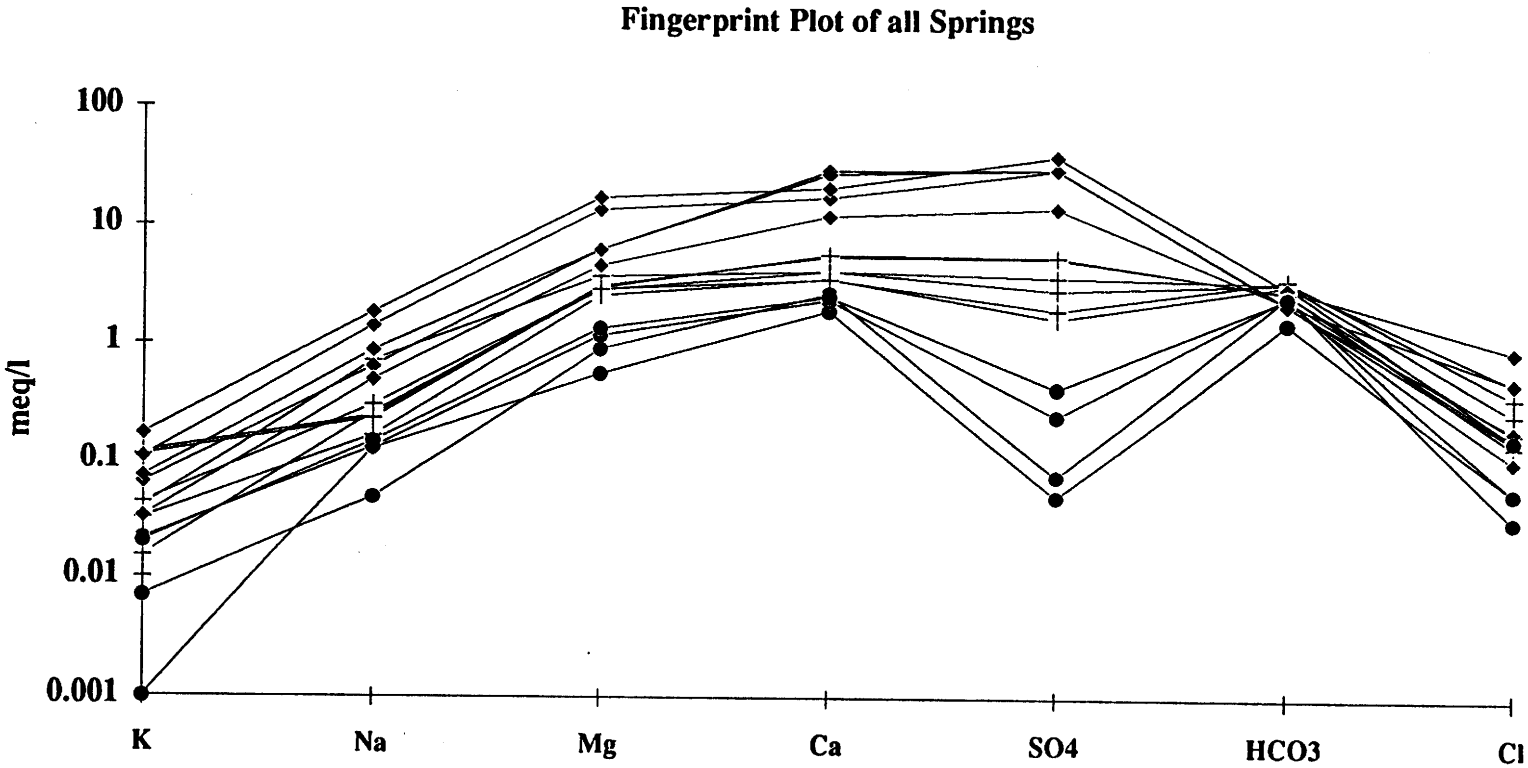
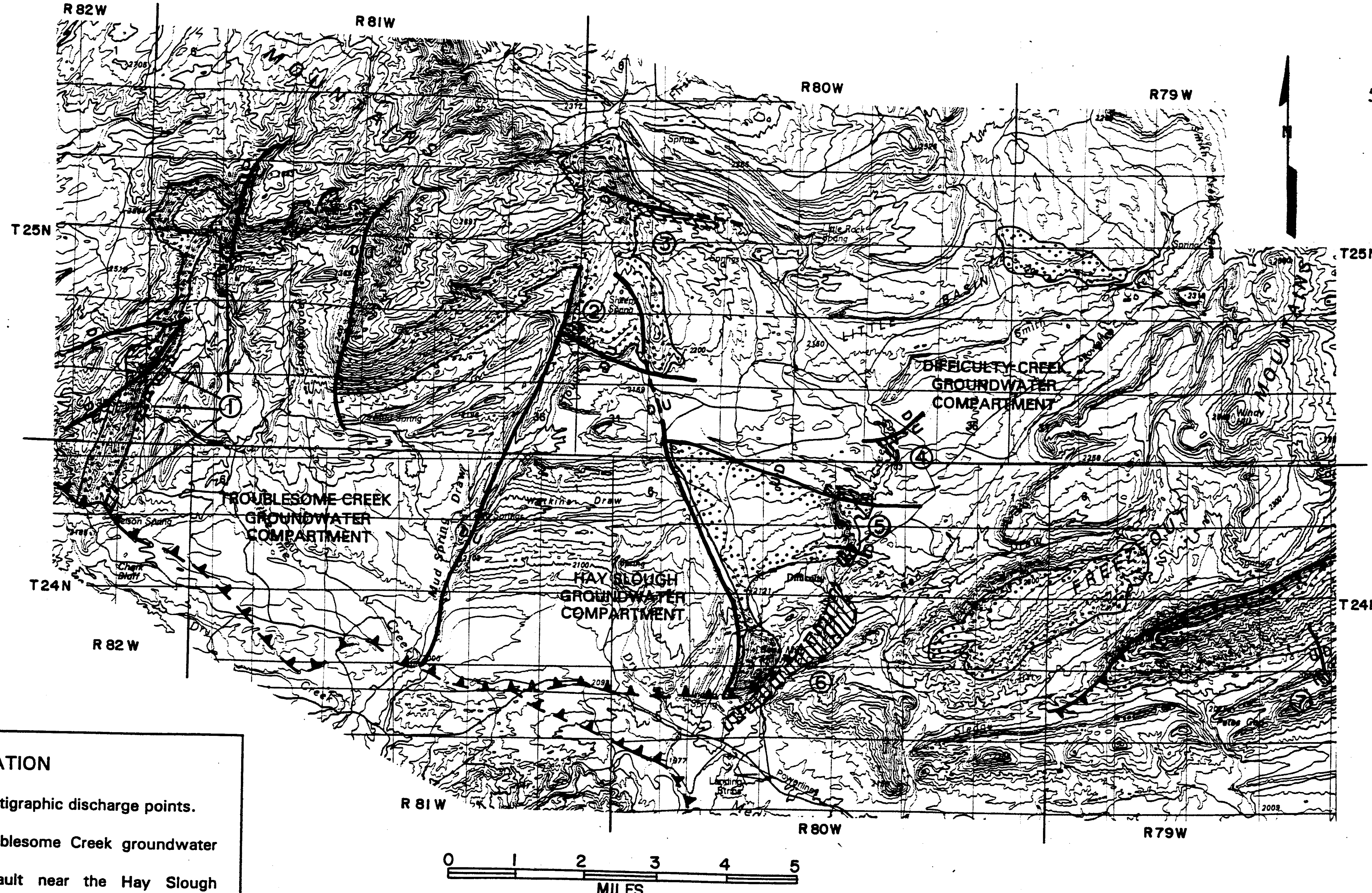


Figure 16. Fingerprint diagram showing the chemical characteristics of all sampled spring and well waters in the Troublesome-Difficulty Creek area, Carbon County, Wyoming. Tensleep aquifer (solid circles), redbed waters (solid diamonds), mixed waters (pluses). Method after Mazor (1991).

Figure 17. Map showing the present locations of sites where groundwater discharges along geologic structures through cross-stratigraphic pathways in the Troublesome-Difficulty Creek area, Carbon County, Wyoming. Notice all sites occur on or at the terminations of structurally deformed areas.



EXPLANATION

Locations of present cross-stratigraphic discharge points.

1 Flanks of the basin in Troublesome Creek groundwater compartment
2 Footwall of the normal fault near the Hay Slough groundwater compartment
3 Normal fault in Sec. 17 & 18, T. 25 N., R. 81 W.
4 Normal fault in Sec. 35, T. 25 N., R. 80 W.
5 Difficulty Canyon
6 Area between Difficult and Beer Mug Ranches
7 Faulted hanging wall block of the Freezeout thrust fault

CHAPTER IV

GROUNDWATER CIRCULATION SYSTEMS AND EXPLORATION TARGETS IN THE TROUBLESOME-DIFFICULTY CREEK AREA

This chapter describes groundwater circulation within the Troublesome Creek, Hay Slough, and Difficulty Creek groundwater compartments, and describes favorable groundwater exploration targets for each groundwater compartment.

Troublesome Creek Groundwater Compartment

The Troublesome Creek groundwater compartment is bounded by the Shirley thrust fault, the Troublesome Creek fault, and the Shirley Mountains. As shown on Plate I, the hydraulic continuity at the recharge area-basin interior contact is disrupted by the Bald Mountain high-angle reverse fault which places Precambrian rocks in the hanging wall block in fault contact with the Madison Limestone in the footwall block. Displacements up to 800 feet sever the hydraulic continuity of the Tensleep aquifer along the fault.

Two steeply-dipping homoclinal margins in which hydraulic continuity is maintained between recharge areas and the basin interior are located (1) on the backlimb of the Bald Mountain reverse fault block, and (2) along the southeast flank of the Shirley Mountains. The southeast dipping backlimb of Bald Mountain and the southeast flank of the Shirley Mountains are characterized by Madison and Tensleep outcrops that form wide continuous recharge zones that are in stratigraphic and hydraulic continuity with the basin interior.

The Troublesome Creek groundwater compartment is a less-active circulation system because the flanks of the Troublesome Creek groundwater compartment, updip of the springs, are zones of active groundwater circulation, whereas the basin portion of the groundwater compartment is a zone of inactive groundwater circulation. Active groundwater circulation systems have large circulation rates, steep hydraulic gradients, and good water qualities. Inactive groundwater systems are characterized as having shallow hydraulic gradients, poor water qualities, and small transmissivities.

Recharge to the Tensleep aquifer in this compartment is 2.3 in/year, or 16% of the mean annual precipitation (14 in/yr) on the recharge area. This rate was calculated by summing the discharge of the springs in this groundwater compartment (1068 gpm) and dividing by the Madison and Tensleep recharge areas for this compartment (5.68×10^{10} in^2). The majority of this recharge is lost to surface drainage systems as springs located at the toe of the homoclinal margin on the southeast flank of the Shirley Mountains. This rejected recharge is expelled from the aquifer primarily because of basinward decreases in permeability in the Tensleep aquifer.

Spring discharge from this groundwater compartment represents the majority of the current year's precipitation and snowmelt. This conclusion is based on (1) the proximity of the recharge area to the springs, (2) the active part of the circulation system is drained every year, and (3) the seasonal fluctuations of spring discharge. Springs 1 and 9 increased in discharge from approximately 40 gpm to 120 gpm within days of recharge events (Appendix B). In such a 'flow-through' system, rapid fluctuations in spring discharge are the result of a coincident passage of recharge water with the energy pulse caused by the recharge event (Blanchard, 1990).

Groundwater within this compartment circulates downgradient from the Madison and Tensleep outcrops on the southeastern flanks of Bald Mountain and the Shirley Mountains toward the springs 1, 4, 6-10, 22, and 23 located along the flanks of the basin (Plate III). The preferred flowpaths for groundwater circulation are through the interconnected permeabilities of karst features, solution-enhanced fractures, and normal faults located in the active portion of the groundwater compartment. The shallow hydraulic gradients in the confined basin imply small quantities of water are flowing through the aquifer. While the interbedded sandstones in unfractured areas in the confined basins have small transmissivities, they account for most of the water in storage. Conversely, the preferred flow paths along fracture zones account for the largest transmissivities in the Tensleep aquifer; however, they represent minimal storage. Because faults and folds have created zones of large transmissivity along their trend and the majority of the groundwater circulates through the active portion of the compartment along the flanks of the basin, groundwater exploration targets should be located on fractured areas located near the flanks of the basin.

Difficulty Creek Groundwater Compartment

The Difficulty Creek groundwater compartment is bounded by the Shirley thrust fault on the south, groundwater divides on the north and east, and the Shirley Mountains and Paradise fault to the west.

The Freezeout thrust fault, oblique to the basin perimeter, located along the northern flank of the Freezeout Mountains is the only hydraulic discontinuity between the recharge areas and basin in this compartment (Plate III). This fault parallels the Freezeout Mountains for more than five miles and has a displacement as great as 1800 feet.

However, the steeply-dipping back limb is in hydraulic connection with the basin interior as indicated by spring 35 and numerous seeps localized on normal faults that discharge waters having Tensleep water chemistry.

Recharge to the Tensleep aquifer in this compartment was calculated as 3.6 in/yr; (23% of the annual mean precipitation). This value is larger than that of the Troublesome Creek compartment due to (1) a 10% increase in recharge area, and (2) the existence of large volume springs that have a total discharge of 1550 gpm from the Tensleep aquifer in the basin (section 16, T. 24 N., R. 80 W.).

The Difficulty Creek groundwater compartment is an active circulation system because (1) water infiltrating the recharge area in the eastern Shirley Mountains and the Tensleep outcrops in the northern Freezeout Mountains discharges as good-quality water from springs localized on faults and fractures in the center of the basin, and (2) discharge volumes of springs in the basin are large indicating enhanced permeabilities and a short residence time

Groundwater circulation in this compartment is downgradient from numerous Tensleep outcrops toward the lowest topographic discharge points located along Difficulty Creek east of the Beer Mug anticline. The preferred flow pathways are intergranular pore spaces, dissolution enlarged fractures, and extensional faults that interconnect the confined and unconfined Tensleep aquifer. These permeable conduits facilitate the movement of groundwater downgradient from the recharge area into the basin, and eventually to the springs.

Recharge to the Tensleep aquifer in this groundwater compartment occurs in the Tensleep Formation outcrops along the Shirley Mountains and in outcrops in the basin.

The recharge water in the Shirley Mountains circulates down the hydraulic gradient until it reaches the large displacement normal fault in sections 30 and 31, T. 25 N., R. 80 W. The 800-foot stratigraphic displacement of this fault severs the hydraulic continuity of the Tensleep aquifer and prevents groundwater circulation across the trend of the fault. Consequently, the groundwater circulates parallel to the fault until it reaches the attenuated end of the fault plane. At this point the groundwater circulates downgradient to the springs discharging into Difficulty Creek from the faulted Tensleep Formation outcrop in the center of the basin (section 35, T. 25 N., R. 80 W.). Springs discharging from this faulted outcrop account for a stream flow increase in Difficulty Creek of 0.75 ft^3/sec (337 gpm). Difficulty Creek flows from the Tensleep outcrop across the Goose Egg confining layer in the basin before losing water to the normal fault at the northern entrance to Difficulty Canyon (Plate III). Water entering along this fault zone circulates downgradient to the topographically lowest discharge point of the Tensleep aquifer along the banks of Difficulty Creek east of the Beer Mug anticline. Numerous small seeps and springs occur at this location. Streamflow measurements taken of Difficulty Creek along this section of the stream course reveal a gain of 3.4 ft^3/sec (1550 gpm). A percentage of this streamflow increase is derived from groundwater flow in the Tensleep aquifer along extensional fractures that parallel the crest of the Beer Mug and Sledge Creek anticlines.

Hay Slough Groundwater Compartment

Groundwater circulation within the Hay Slough groundwater compartment is restricted as a result of aquifer-severing displacements of the faults that completely border the compartment. Vertical displacements up to 1000 feet along Troublesome Creek and

Paradise faults, between 20,000-30,000 feet along the Shirley thrust fault (Ferren, 1935, Clarey, 1984), and 700 feet along the normal fault located at the northern terminus of Hay Slough, have severed the hydraulic continuity of the Tensleep aquifer in the Hay Slough groundwater compartment from adjacent compartments, and between the recharge area and basin subcrops.

The most striking feature of the potentiometric surface shown in Plate III is the area having a static hydraulic head of 6697 feet. The hydraulic head for this area was acquired from the records of petroleum exploration wells drilled near the crest of Troublesome Creek anticline in section 36, T. 25 N., R. 81 W. The total head in this portion of the Tensleep aquifer differs significantly from head values recorded in adjacent areas. Cold Spring (spring 5) directly across Troublesome Creek fault at the western boundary of the compartmentalized aquifer has a head 403 feet higher (7100 feet elevation) than the compartmentalized aquifer (6697 feet elevation) (Figure 18).

This groundwater compartment is bounded by normal and reverse faults which fully sever the Tensleep aquifer and totally restrict groundwater flow into and out of this area. Thus, the aquifer in this compartment receives little, if any recharge, nor do any surface discharge points exist. Groundwater in this area does not circulate as a result of the lack of recharge and discharge points. Consequently, the Hay Slough groundwater compartment is a inactive groundwater system.

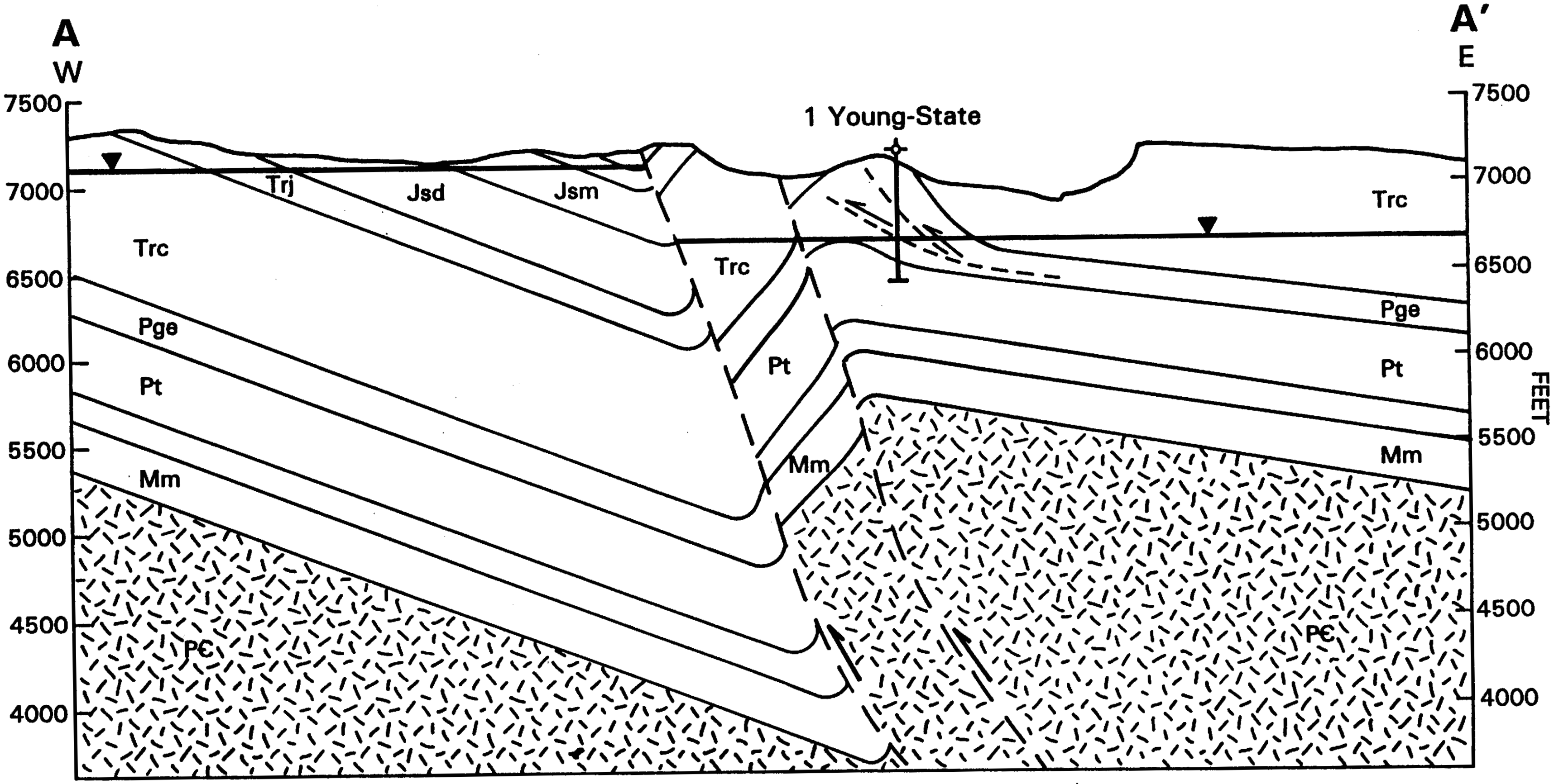


Figure 18. Cross-section A-A' through the fault-cored Troublesome Creek anticline. Notice the 400 foot difference in hydraulic head values of the Tensleep aquifer across the Troublesome Creek fault. This fault cores the anticline and is a barriers to groundwater circulation perpendicular to trend. Pc, Precambrian rock; Mm, Mississippian Madison Limestone; Pt, Pennsylvanian Tensleep Sandstone; Pge, Permian Goose Egg Formation; Trc, Triassic Chugwater Formation; Trj, Triassic Jelm Formation; Jsd, Jurassic Sundance Formation; Jsm, Jurassic Morrison Formation; arrows indicate upthrown block; 1 Young-State Oil well on crest of Troublesome anticline.

GROUNDWATER EXPLORATION SITES IN THE TROUBLESOME-DIFFICULTY CREEK AREA

The prospect of accomplishing successful groundwater development from the Tensleep aquifer in the Troublesome-Difficulty Creek area is good. The best exploration sites for groundwater development in this area are along zones of structural deformation, where faults and folds have created zones of enhanced permeability. The development sites identified by the author for the Tensleep aquifer in the Troublesome-Difficulty Creek area are depicted on Figure 19 and summarized below.

Troublesome Creek Groundwater Compartment

Site 1:	Along the fault at the plunging nose of Bald Mountain
Location:	Section 33, Township 25 North, Range 81 West Section 4, Township 24 North, Range 81 West
Siting Criteria:	Sites are located along the hanging wall of an aquifer-severing fault that intersects a major fracture zone associated with the crest of the Bald Mountain anticline which drains rocks to the north and east. This fault channels groundwater flowing westward from the recharge area on Bald Mountain.
Drilling Depths:	Steep dips of the Tensleep aquifer and the stratigraphic offset along the fault will affect well depths. Well depths could range from 300 feet to test the lower Paleozoic rocks near the flanks of the basin to over 3000 feet to test the entire saturated thickness of the Paleozoic rocks in the basin.
Potential Problems:	Close proximity to the recharge area should provide good-quality water, however, large yield wells located on this geologic structure can cause surface water interference. The loss of flow in creeks and springs could impact existing water rights.

Site 2:	Along the crest of Roaring Creek anticline
Location:	Sections 30 and 31, Township 25 North, Range 81 West Section 6, Township 24 North, Range 81 West
Siting Criteria:	Located in a zone of extensional fracture permeability on the crest of a tightly folded anticline. Extensional fractures along the crest of the tightly folded anticline will provide a zone of large transmissivity through the confined Tensleep aquifer in the basin.
Drilling Depths:	Well depths could be over 1000 feet due to steep dips.
Potential Problems:	Surface water interference. Large yield wells located on this geologic structure can cause loss of flow in creeks and springs that could impact existing water rights.

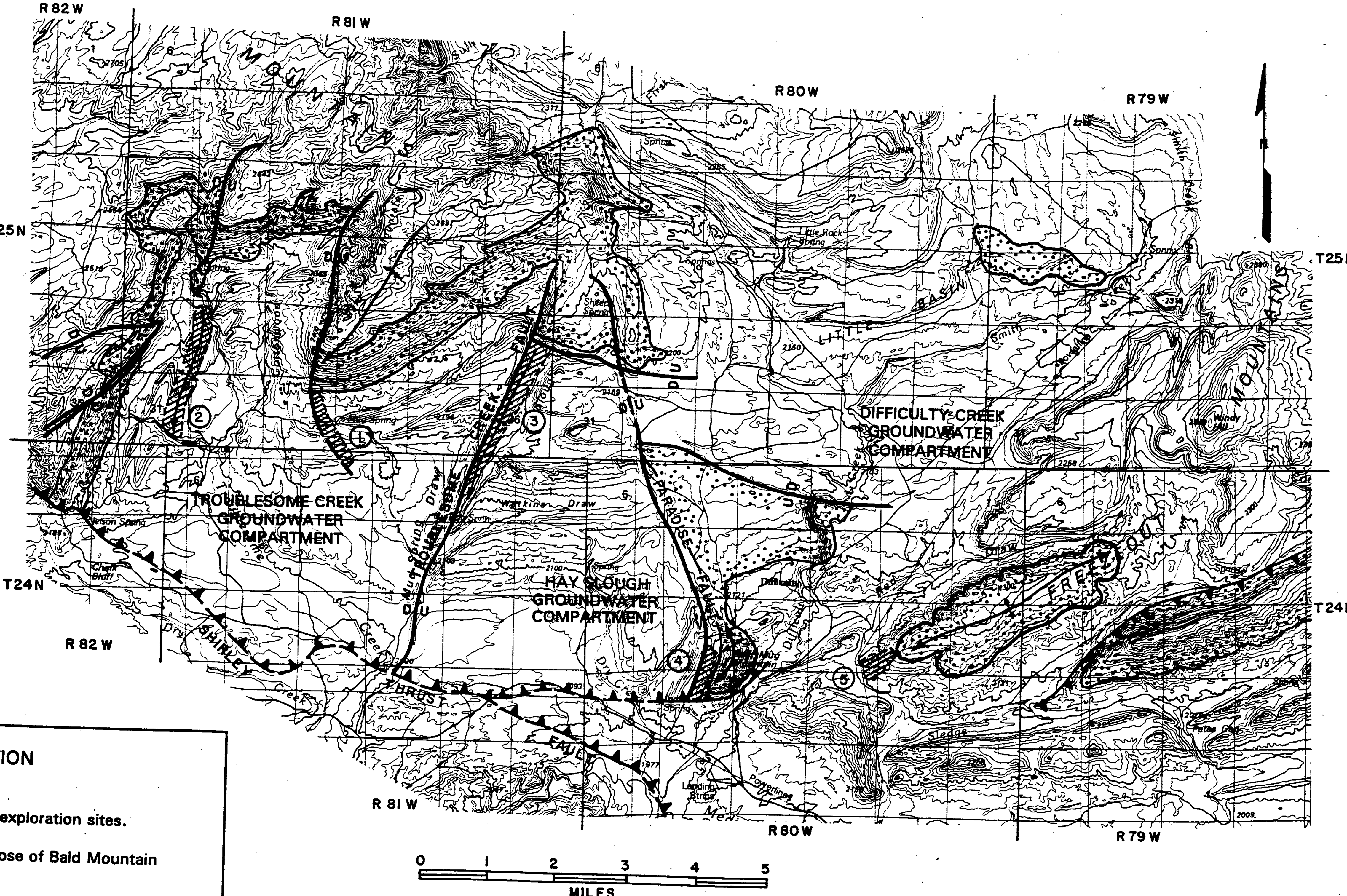
Hay Slough Groundwater Compartment

Site 3:	Troublesome Creek anticline
Location:	Sections 25 and 36, Township 25 North, Range 81 West
Siting Criteria:	Located in a zone of extensional fracture permeability on the crest of the tightly folded anticline. Extensional fractures along the crest of the tightly folded anticline will provide a zone of large transmissivity through the confined Tensleep aquifer in this compartment.
Drilling Depths:	Site was selected for development based on the shallow drilling depths (733 ft.) to the confined Tensleep aquifer along the crest of the anticline. Driller's report for the No.1 Young-State oil exploration well states water rose to 400 feet of surface after penetrating the confined aquifer.
Potential problems:	Long-term development of this groundwater compartment may be limited because there is limited potential for groundwater recharge to this compartment as a result of fault-severing of the aquifer at the boundaries of this compartment. Consequently, well development from this compartment may eventually deplete stored groundwater.

<u>Difficulty Creek Groundwater Compartment</u>

Site 4:	Along the plunging nose of the Beer Mug anticline
Location:	Section 20, Township 24 North, Range 80 West
Siting Criteria:	Located in a major fracture zone associated with the Beer Mug anticline in the hanging wall of the Shirley thrust fault and the Paradise fault. Close proximity to the recharge area should provide good-quality water. Drilling into fractures along the fault zones would place wells in a zone of large permeability.
Drilling Depths:	Large exposure of the Tensleep Formation on the Beer Mug anticline indicates the saturated portion of the aquifer will be at a shallow depth. Wells depths could be less than 200 feet.
Potential Problems:	Complex geology will require field mapping prior to final well site selection. Large yield wells located near this geologic structure can cause loss of flow in Difficulty Creek and to springs discharging near the creek. This surface water interference could impact existing water rights.
Site 5:	Along the plunging nose of Sledge Creek anticline
Location:	Sections 15 and 22, Township 24 North, Range 80 West
Siting Criteria:	Located in a zone of extensional fracture permeability at the plunging nose of the anticline. Extensional fractures along the crest of the anticline will provide a zone of large transmissivity from the recharge area to the confined Tensleep aquifer in the basin.
Drilling Depths:	Because the Tensleep Formation dips steeply on the plunging nose of the anticline wells depths could be less than 200 feet near the outcrop to over 1000 feet along the buried axis of the anticline to the southwest.
Potential Problems:	Close proximity to the recharge area should provide good-quality water, however, large yield wells located near this geologic structure may cause loss of flow in Difficulty creek and to springs discharging near the creek. This surface water interference could impact existing water rights.

Figure 19. Map showing the locations of potential drilling sites for groundwater development from the Tensleep aquifer.



EXPLANATION

Locations of groundwater exploration sites.

1 Fault zone along the plunging nose of Bald Mountain
2 Roaring Creek anticline
3 Troublesome Creek anticline
4 West flank of the Bear Mug anticline
5 Plunging nose of Sledge Creek anticline

Chapter V
CONCLUSIONS

(1) The groundwater system in the Troublesome-Difficulty Creek area is isolated from the circulation system in the northern Hanna Basin as a result of hydraulic severing of the Paleozoic rocks along the mountain-basin margin by the Shirley thrust fault. Geochemical and potentiometric data indicate the Troublesome Creek and Paradise faults structurally divide the hanging wall block of the thrust fault into three hydraulically independent groundwater compartments: the Troublesome Creek, Hay Slough, and Difficulty Creek groundwater compartments.

(2) Groundwater circulation in the Troublesome-Difficulty Creek area is primarily parallel to bedding. Bedding-parallel circulation occurs through bedding-parallel permeabilities associated with intergranular, intercrystalline, bedding plane partings, vertical joints, and cross-joints. Cross-stratigraphic circulation between aquifers in the Troublesome-Difficulty Creek area occurs only through bedding-perpendicular permeabilities of extensional faults and fractures that crosscut low permeability confining surfaces.

(3) The interconnection of geologic features having bedding-parallel or bedding-perpendicular permeabilities results in a permeability architecture through which groundwater circulates downgradient from areas of recharge to points of discharge.

(4) Water entering the Madison Formation through faults, fractures, bedding plane partings, and karst features in the Shirley Mountains circulates downgradient but upsection into the overlying Tensleep Formation through bedding-perpendicular permeabilities of faults and fractures along the flanks of the basin in the Troublesome Creek groundwater compartment. This water discharges from the Tensleep aquifer as rejected recharge due to a basinward reduction in permeability and hydraulic gradient.

(5) The Goose Egg Formation is an effective regional confining layer that inhibits cross-stratigraphic circulation from the deeper Paleozoic rocks into overlying aquifers. However, trilinear, fingerprint, and composition diagrams reveal a mixing of groundwaters from the minor localized aquifers in the lower Goose Egg Formation with groundwater of the Tensleep aquifer. Groundwater circulation between these units results from bedding-perpendicular permeabilities emplaced in the formations by extensional faults and fractures that crosscut the permeable and confining strata. The locations of springs having a mixed-water chemistry reveal that cross-stratigraphic circulation between aquifers only occurs along structurally deformed areas.

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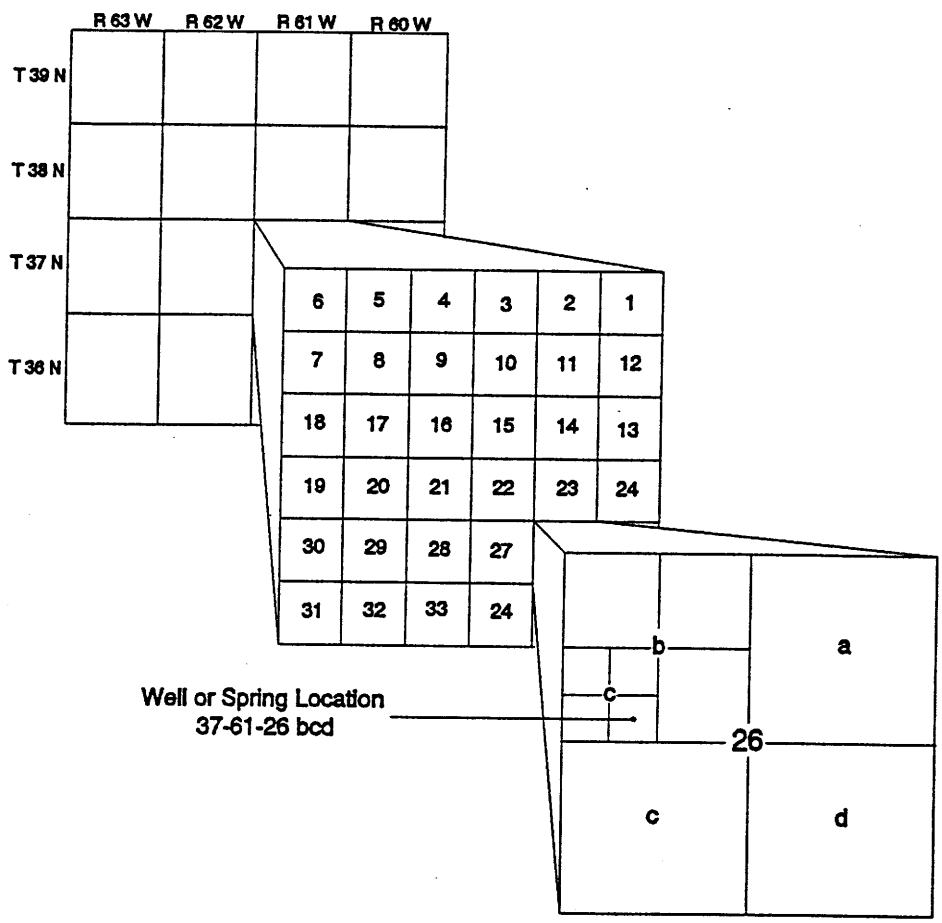
APPENDICES

APPENDIX A

U.S. GEOLOGICAL SURVEY WELL NUMBERING SYSTEM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c
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Well or Spring Location
37-61-26 bcd

APPENDIX B

SPRING INVENTORY OF THE DIFFICULTY-TROUBLESOME CREEK AREA, CARBON COUNTY, WYOMING

APPENDIX B

SPRING INVENTORY OF THE DIFFICULTY-TROUBLESOME CREEK AREA, CARBON COUNTY, WYOMING

Number (a)	Location (T-R-Sec.) (b)	Spring Name	Elevation (c)	Water Yielding Unit (d)	Discharge (gpm)	Water Analysis (e)	Comments
1	25-82-36add		7200	Pt	41		Streamflow increased after rain. 120 gpm
2	25-81-4cac	Troublesome Creek	8860	Pc	>10	Yes	Spring forms marsh. Conjugate joints @274.
3	25-81-15ddd	Withrow Spring	8620	Mm	7.88	Yes	
4	25-81-20cbb	Trout Spring	7310	Pt	>240	Yes	
5	25-81-25aca	Cold Spring	7120	Pt	>5	Yes	
6	25-81-30ccc		7200	Pt	34.2		
7	25-81-31bba		7220	Pt	26		
8	25-81-31bba	Hidden Spring	7220	Pt	48		Same as #1
9	25-81-31bba	Jarvis Spring	7200	Pt	240		
10	25-81-31bba	Jarvis' Twin	7200	Pt	240	Yes	Small springs in vicinty. <1 gpm
11	25-81-34cbb	Mud Spring	6948	Kcv	<1	Yes	

Number (a)	Location (T-R-Sec.) (b)	Spring Name	Elevation (c)	Water Yielding Unit (d)	Discharge (gpm)	Water Analysis (e)	Comments
12	25-80-8cba		7436	Jm	<2	Yes	Sand grains and small pebbles discharge from spring.
13	25-80-15cbc		7440	Jm	2	Yes	
14	25-80-15cca	Little Rock Spring	7400	Jm	48	Yes	Numerous small springs in vicinty.
15	25-80-16ccd	Difficulty Spring	7130	Pge	45	Yes	
16	25-80-19ddb	Sheep Spring	7370	Pt	5	Yes	
17	25-80-21bac		7120	Pge	<1		Several small springs in area.
18	25-80-24aba	Smith Creek #2	7200	Pge	36		
19	25-80-24aca	Smith Creek #3	7200	Pge		Yes	
20	25-79-16ccd	Smith Creek #1	7200	Pge	120		
21	25-79-21bbc		7200	Pge	120	Yes	
22	24-82-11aab		7100	Pt	NA		Ponded seep above Nelson Spring. ? Data.
23	24-82-11aaa	Nelson Spring	7040	Pt	>240	Yes	Spring is developed in 4' vertical culvert.

Number (a)	Location (T-R-Sec.) (b)	Spring Name	Elevation (c)	Water Yielding Unit (d)	Discharge (gpm)	Water Analysis (e)	Comments
24	24-81-2ccc	Palm Spring	6760	Pge	2	Yes	
25	24-81-3daa	Bog Springs	6720	Kcv	NA		Saturated ground only. Temp taken off stock tank.
26	24-81-10adb		6720	Kcv	NA		Spring is developed in stock tank. Semi-saturated ground around spring.
27	24-81-11bbc	Korkow Spring	6680	Tra	3	Yes	
28	24-80-10bcc	Ellis Spring	6700	Pt	>240	Yes	Cemented dam for use by Difficulty Ranch.
29	24-80-10bcd	Small Seeps	6700	Pt	3		Numerous small seeps along vertically jointed Pt.
30	24-80-10bca	Hole in the Wall	6700	Pt	120	Yes	Vertical joints above spring.
31	24-80-10cac	Rattlesnake Spring	6720	Pge	<1		Seep ocurrs at contact of Glendo sh.-Minnekata lmst.

Number (a)	Location (T-R-Sec.) (b)	Spring Name	Elevation (c)	Water Yielding Unit (d)	Discharge (gpm)	Water Analysis (e)	Comments
32	24-80-19add	Indian Spring	6600	Jsd	NA		Ponded and dammed for use. Unmeasurable for this reason.
33	24-80-21bbd		6700	Pt	120		Flow taken from pipe off stream.
34	24-80-21bbd	Dinky Spring	6700	Pt	4		Number of small seeps at this site.
35	24-79-22aaa	Freezout Spring	7020	Tra	<1	Yes	

a. Numbers correspond to numbered location shown on Plate III.

b. Numbering system corresponds to U.S.G.S. System as outlined in Appendix A.

c. Elevation is in feet above sea level.

d. Water yielding unit is the unit in which spring is located.

Kcv = Cloverly Formation

Jm = Morrisson Formation

Jsd = Sundance Formation

Tra = Alcova Limestone

Pge = Goose Egg Formation

Pt = Tensleep Formation

Mm = Madison Limestone

Pc = Precambrian

e. Water analyses in Appendix C.

APPENDIX C

WATER QUALITY DATA FOR SPRINGS AND WELLS IN THE TROUBLESOME-DIFFICULTY CREEK AREA, CARBON COUNTY, WYOMING

APPENDIX C

WATER QUALITY DATA FOR SPRINGS AND WELLS IN THE TROUBLESOME-DIFFICULTY CREEK AREA, WYOMING (a)

No. (b)	Location (T-R-Sec.)(c)	Water Yielding Unit (d)	Ca mg/l (meq/l)	Mg mg/l (meq/l)	K mg/l (meq/l)	Na mg/l (meq/l)	Cl mg/l (meq/l)	HCO3 mg/l (meq/l)	SO4 mg/l (meq/l)	SiO2 mg/l	F mg/l (meq/l)	Calculated % Charge Imbalance	Calculated Total Dissolved Solids	pH	Field Temp. (C)	Specific Conductance (mohm/cm @ 25 C)
2	25-81-4cac	Pc	5.86 (0.29)	1.47 (0.12)	0.33 (0.01)	2.67 (0.12)	0.57 (0.02)	21.9 (0.36)	4.11 (0.09)	7.95	0.07 (0.001)	6.9	34	6.89	7.9	50
3	25-81-15ddd	Mm-Pt	54.14 (2.71)	11.1 (0.91)	0.3 (0.01)	1.14 (0.05)	1.13 (0.03)	163 (2.67)	3.7 (0.08)	2.87	0.08 (0.001)	13.9	155	7.88	6.5	300
4	25-81-20cbb	Pt	38.5 (1.93)	6.9 (0.57)	0.1 (0.001)	3 (0.13)	2 (0.06)	95 (1.56)	2.47 (0.05)	6.8	0.08 (0.001)	20.4	107	7.17	8.4	200
5	25-81-25aca	Pt-Pge	84 (4.20)	35 (2.88)	0.6 (0.02)	6.1 (0.27)	9.7 (0.28)	209 (3.43)	139 (2.90)	6.2	0.19 (0.01)	5.4	384	7.67	13.3	640
10	25-81-31bba	Pt	47.6 (2.38)	14.4 (1.19)	0.85 (0.02)	3.07 (0.13)	2 (0.06)	162 (2.66)	12.3 (0.26)	5.18	0.15 (0.01)	11	165	7.21	7.49	300
11	25-81-34cbb	Pge	356 (17.80)	169 (13.91)	4.3 (0.11)	32.4 (1.41)	17.7 (0.51)	141 (2.31)	1480 (30.83)	4.1	0.27 (0.01)	-0.6	2133	8.04	17.7	2170
12	25-80-8cba	Jm	77.8 (3.89)	48.3 (3.98)	3.94 (0.10)	18.5 (0.80)	4.73 (0.14))	215 (3.52)	185 (3.85)	5.59	0.17 (0.01)	7.7	450	7.35	8.3	640
13	25-80-15cbc	Jm	63.5 (3.18)	25.6 (2.11)	2.73 (0.07)	19 (0.83)	6.28 (0.18)	169 (2.77)	110 (2.29)	4.44	0.2 (0.01)	8.3	315	7.32	9.6	800
14	25-80-15cca	Jm	77.3 (3.87)	49 (4.03)	4.13 (0.11)	24 (1.04)	7.16 (0.20)	249 (4.08)	155 (3.23)	6.05	0.21 (0.01)	9.2	445	7.12	8.9	920

No. (b)	Location (T-R-Sec.)(c)	Water Yielding Unit (d)	Ca mg/l (meq/l)	Mg mg/l (meq/l)	K mg/l (meq/l)	Na mg/l (meq/l)	Cl mg/l (meq/l)	HCO3 mg/l (meq/l)	SO4 mg/l (meq/l)	SiO2 mg/l	F mg/l (meq/l)	Calculated % Charge Imbalance	Calculated Total Dissolved Solids	pH	Field Temp. (C)	Specific Conductance (mohm/cm @ 25 C)
15	25-80-16ccd	Pge	598 (29.90)	77.3 (6.36)	2.61 (0.07)	14.9 (0.65)	5.62 (0.16)	138 (2.26)	1503 (31.31)	6.34	0.28 (0.01)	4.5	2276	7.7	10.5	2680
16	25-80-19ddb	Pt	72.5 (3.63)	31.3 (2.58)	1.25 (0.03)	3.91 (0.17)	5.94 (0.17)	201 (3.30)	80.7 (1.63)	4.11	0.14 (0.01)	11.3	299	8.09	9.8	500
19	25-80-24aca	Pge	247 (12.35)	56.3 (4.63)	1.3 (0.03)	11.5 (0.50)	3.77 (0.11)	143 (2.34)	697 (14.52)	6.7	0.19 (0.01)	1.5	1094	NA	9	1170
21	25-79-21bbc	Pge	565 (28.25)	76.7 (6.31)	2.9 (0.07)	20.1 (0.87)	7.04 (0.20)	136 (2.23)	1500 (31.25)	4.7	0.17 (0.01)	2.6	2243	NA	8	2230
23	24-82-11aaa	Pt	51.1 (2.56)	16.6 (1.37)	0.8 (0.02)	3.5 (0.15)	5.9 (0.17)	156 (2.56)	21 (0.44)	4.7	0.17 (0.01)	12.7	180	7.22	9.3	300
24	24-81-2ccc	Pge	430 (21.50)	212 (17.45)	6.8 (0.17)	42.4 (1.84)	31.9 (0.91)	189 (3.10)	1920 (40.0)	5.7	0.29 (0.02)	-3.5	2742	8	7.22	3170
27	24-81-11bcc	Tra-Pge	48.5 (2.43)	28.8 (2.37)	1.2 (0.03)	24.7 (1.07)	14.3 (0.41)	169 (2.77)	97.9 (2.04)	5.1	0.17 (0.01)	6.1	304	7.77	8	627
28	24-80-10bcb	Pt	112 (5.60)	37.8 (3.11)	4.73 (0.12)	5.72 (0.25)	5.13 (0.15)	175 (2.87)	260 (5.42)	4.34	0.17 (0.01)	3.6	516	6.79	13.3	830
30	24-80-10bca	Pt	116 (5.80)	36.5 (3.00)	4.43 (0.24)	5.45 (2.84)	6.69 (0.19)	173 (2.84)	267 (5.56)	4.12	0.09 (0.001)	16	525	6.5	13	800
35	24-79-22aaa	Tra	83.9 (4.20)	45.3 (3.73)	1.6 (0.04)	16.6 (0.72)	17.5 (0.50)	211 (3.46)	179 (3.73)	5.1	0.15 (0.01)	6.1	453	6.8	15.5	660
#1*	25-81-36cac	Pt-Pge	63 (3.15)	42 (3.5)	9 (0.014)		24 (0.68)	150 (2.45)	184 (1.91)			13.6				

No. (b)	Location (T-R-Sec.)(c)	Water Yielding Unit (d)	Ca mg/l (meq/l)	Mg mg/l (meq/l)	K mg/l (meq/l)	Na mg/l (meq/l)	Cl mg/l (meq/l)	HCO3 mg/l (meq/l)	SO4 mg/l (meq/l)	SiO2 mg/l	F mg/l (meq/l)	Calculated % Charge Imbalance	Calculated Total Dissolved Solids	pH	Field Temp. (C)	Specific Conductance (mohm/cm @ 25 C)
W1**	25-80-17cac	Pt-Pge	71.3 (3.57)	35.9 (2.9)	1.74 (0.04)	7.05 (0.31)	13.3 (0.38)	223 (3.66)	95.5 (1.99)	4.8	0.22 (0.01)	6.1	339	8.22	9.7	690

a. Analyses by Wyoming Analytical Laboratories, Inc. Laramie, Wyoming.

b. Numbers correspond to numbered locations shown on Plate III.

c. Numbering system corresponds to U.S.G.S. System outlined in Appendix A.

d. Water yielding unit is the unit in which spring is located.

Kcv = Cloverly Formation

Jm = Morrisson Formation

Jsd = Sundance Formation

Tra = Alcova Limestone

Pge = Goose Egg Formation

Pt = Tensleep Formation

Mm = Madison Limestone

Pc = Precambrian

* John Angwin #1 well

** Sullivan Company Well No. 1

APPENDIX D

ANALYSIS OF WATER GROUPS IN THE TROUBLESOME-DIFFICULTY CREEK AREA, CARBON COUNTY, WYOMING

APPENDIX D

ANALYSIS OF WATER GROUPS IN THE TROUBLESOME-DIFFICULTY CREEK AREA, CARBON COUNTY, WYOMING

Spring No.	TDS	TDI (meq/l)	Ca (meq/l)	Mg (meq/l)	K (meq/l)	Na (meq/l)	Cl (meq/l)	HCO3 (meq/l)	SO4 (meq/l)	SiO2 (mg/l)	F (meq/l)	Water Group
2	34	1.00	0.29	0.12	0.01	0.12	0.02	0.36	0.09	7.95	< 0 .001	Pc
3	155	6.46	2.71	0.91	0.01	0.05	0.03	2.67	0.08	2.87	< 0.001	Pt
4	107	4.29	1.93	0.57	0.00	0.13	0.06	1.56	0.05	6.80	< 0.001	Pt
10	165	6.69	2.38	1.19	0.02	0.13	0.06	2.66	0.26	5.18	0.01	Pt
23	180	7.26	2.56	1.37	0.02	0.15	0.17	2.56	0.44	4.70	0.01	Pt
5	384	13.96	4.20	2.88	0.02	0.27	0.28	3.43	2.90	6.20	0.01	Pt-Redbeds
16	299	11.55	3.63	2.58	0.03	0.17	0.17	3.30	1.63	4.11	0.01	Pt-Redbeds
28	516	17.51	5.60	3.11	0.12	0.25	0.15	2.87	5.42	4.34	0.01	Pt-Redbeds
30	525	17.74	5.80	3.00	0.24	2.84	0.19	2.84	5.56	4.12	0.00	Pt-Redbeds
35	453	16.37	4.20	3.73	0.04	0.72	0.50	3.46	3.73	5.10	0.01	Pt-Redbeds
W1	339	12.84	3.57	2.90	0.04	0.31	0.38	3.66	1.99	4.80	0.01	Pt-Redbeds
#1		11.72	3.15	3.50	0.01		0.68	2.45	1.91			Pt-Redbeds
11	2133	66.88	17.80	13.91	0.11	1.41	0.51	2.31	30.83	4.10	0.01	Redbeds
15	2276	70.71	29.90	6.36	0.07	0.65	0.16	2.26	31.31	6.34	0.01	Redbeds
19	1094	34.49	12.35	4.63	0.03	0.50	0.11	2.34	14.52	6.70	0.01	Redbeds
21	2243	69.19	28.25	6.31	0.07	0.87	0.20	2.23	31.25	4.70	0.01	Redbeds
24	2742	84.99	21.50	17.45	0.17	1.84	0.91	3.10	40.00	5.70	0.02	Redbeds
12	450	16.28	3.89	3.98	0.10	0.80	0.14	3.52	3.85	5.59	0.01	Kcv
13	315	11.42	3.18	2.11	0.07	0.83	0.18	2.77	2.29	4.44	0.01	Kcv
14	445	16.56	3.87	4.03	0.11	1.04	0.20	4.08	3.23	6.05	0.01	Kcv
27	304	11.12	2.43	2.37	0.03	1.07	0.41	2.77	2.04	5.10	0.01	Kcv

APPENDIX E

DEER CREEK ANTICLINE WELL COMPLETION REPORT

WELL COMPLETION REPORT

DEER CREEK ANTICLINE, TROUBLESOME CREEK AREA

CHARLES L. CHERRY - DON J. DESANDRO

NO. 1 YOUNG-STATE
NW NW NE SECTION 36, TOWNSHIP 25 N., RANGE 81 W.,
CARBON COUNTY, WYOMING

Prepared by:

Charles L. Cherry
Consulting
Geologist
General Partner
February 5, 1963

WELL DATA

OPERATOR:	Charles L. Cherry - Don J. DeSandro 6566 So. Elizabeth Way Littleton, Colorado
CONTRACTOR:	Work Over, Inc. 720 Patterson Building Denver 2, Colorado
WELL:	Cherry-DeSandro No. 1 Young-State
LOCATION:	512' FNL - 2356' FEL, Section 36, Township 25 North, Range 81 West, Carbon County, Wyoming.
COMMENCED DRILLING:	January 9, 1963
COMPLETED DRILLING:	January 27, 1963
STATUS:	Plugged and Abandoned on January 28, 1963.
TOTAL DEPTH:	733 feet - Driller.
CASING:	42 feet of 8-5/8 inch casing set at 43 feet below ground level with 30 sacks - 2% CaCl.
HOLE SIZE:	12-1/4 inch to 50 feet. 6-3/4 inch to 733 feet (Total Depth).
WATER SOURCE:	Surface reservoir.
LOGS:	Schlumberger Gamma Ray-Neutron 20 feet to 722 feet.
PLUGS:	Five sacks set in the top of the surface pipe.

DAILY WORK RECORD

January 6, 1963	Moved rig to location.
January 7, 1963	Rig up.
January 8, 1963	Rig up. Drill 12-1/4 inch surface hole -- 0-23'.
January 9, 1963	Drill 12-1/4 inch hole -- 23-37'.
	Drill 6-3/4 inch pilot hole -- 37-51'.
	Rear pilot hole to 12-1/4 inch hole.
	Set 42' of 8-5/8 inch surface pipe at 43' below ground level (50' below kelly bushing) with 30 sacks of cement - 2% CaCl.
	Waiting on cement.
	Nippling-up and installing blow-out preventor.
	Drill with bit #1 -- 51-54'.
January 10, 1963	Drill with bit #1 -- 54-67'.
	Mix mud.
	Repair swivel.
	Repair rotary motor.
January 11, 1963	Shut down - weather.
January 12, 1963	Shut down - weather.
January 13, 1963	Shut down - weather.
January 14, 1963	Replace rotary motor.
	Thaw lines.
	Drill with bit #1 -- 67-100'.
January 15, 1963	Drill with bit #1 -- 100-127'.
	Take drill stem test No. 1.
	Drill with bit #1 -- 127-145'.
January 16, 1963	Drill with bit #1 -- 145-185'.
	Repair swivel.
	Trip for bit #2.
	Drill with bit #2 -- 185-225'.
January 17, 1963	Drill with bit #2 -- 225-275'.
	Trip for bit #3.
	Thaw lines.
	Pick-up three collars.
	Drill with bit #3 -- 275-285'.
	Repair rotary motor.
January 18, 1963	Drill with bit #3 -- 285-337'.
	Ran out of fuel - shut down for weather.
January 19, 1963	Shut down - weather.
January 20, 1963	Shut down - weather.
January 21, 1963	Shut down - weather.
January 22, 1963	Start equipment.
	Drill with bit #3 -- 337-360'.
January 23, 1963	Drill with bit #3 -- 360-419'.
	Short on water -- hauler tied up.
	Work on swivel.
January 24, 1963	Drill with bit #3 -- 419-421'.
	Work on swivel.
	Drill with bit #3 -- 421-464'.
	Loosing fluid-mixing mud.
	Trip for bit #4

	Drill with bit #4 -- 464-520'.
January 25, 1963	Drill with bit #4 -- 520-573'.
	Repair swivel.
	Trip for bit #5.
	Drill with bit #5 -- 573-625'.
	Lost circulation temporarily at 610'.
January 26, 1963	Drill with bit #5 -- 625-661'.
	Trip for bit #6.
	Drill with bit #6 -- 661-713'.
	Lost circulation temporarily at 675'.
January 27, 1963	Lost circulation for 1.5 hours.
	Drill with bit #6 -- 713-719'.
	Lost circulation and could not regain with the equipment on location.
	Drill dry with bit #6 -- 719-733'.
	Bit dropped in cavern 721-726'.
	Logging hole.
	Wait on orders.
	Lay down drill pipe.
January 28, 1963	Plug and abandon well.
	Set 5 sacks of cement in top of surface pipe.
	Move cut rig.

INTRODUCTION

The Cherry-DeSandro No. 1 Young-State was drilled on the crest of an anticlinal nose that plunges south into the Hanna Basin trough from the Shirley Mountain uplift. The anticlinal nose is separated by faulting from the Main portion of the uplift so that the Madison limestone of Mississippian age is faulted against pre-Cambrian granite.

The primary objective of this test was the Madison limestone. The superjacent Tensleep (Casper) sandstone of Permo-Pennsylvanian age was a secondary objective.

The test was drilled with rotary tools. The rig used was a modified Franks 5000 with an 87 foot collapsing mast. Drilling fluid was circulated through the hole by a 4-1/2" x 8" pump. Extremely cold weather hampered operations and the over-all operation took considerably longer than it would have under normal conditions.

Fresh water with bentonite was used for drilling fluid. No chemicals were added. The hole was in excellent condition from start to finish. Considerable lost circulation material was maintained in the system below 425 feet to prevent the loss of fluid in minor fractures.

Sample quality was good to fair throughout the operation until complete loss of circulation prevented obtaining any cuttings below 719 feet.

Drilling time was recorded by the drillers from 67 feet to total depth. Although not too accurate, this method proved satisfactory under the circumstances.

Hole deviation was recorded by means of a Sperry-Sun Deviation instrument that was dropped in the drill stem before trips to replace worn bits.

Because of the lack of fluid in the hole due to losing circulation, the only mechanical log that could be run was a Gamma Ray-Neutron log. Such a log was made of the hole from 20 feet to 722. Fill-up of debris, cuttings and lost circulation material in a cavern in the upper part of the Madison limestone prevented logging to total depth. This log is not the most satisfactory tool for delineating fluid types, however, it does define porosity in a most satisfactory manner.

The writer served as well-site Geologist throughout the operation. Each sample of rotary cuttings was examined as it came to the surface by means of a binocular microscope and a geoscope fluorescent light.

One drill stem test was taken in the basal Embar formation and the results are recorded with the technical data.

GEOLOGY

STRATIGRAPHY

The following table lists the various formations as they were penetrated by the drill. It gives the anticipated thickness of each formation as described in the technical literature and the thicknesses as penetrated here. Also tabulated are the datums of each formation with respect to sea level.

AGE: FORMATION	PUBLISHED THICKNESS	DEPTH	THICKNESS	DATUM
PERMIAN:				
Embar? formation	50-150'	Surface	126/'	7104
PERMO-PENNSYLVANIAN:				
Tensleep (Casper) formation	450-600'	126'	580'	6985
Amsden formation	0-50'	--------	0'	--------
MISSISSIPPIAN:				
Madison formation	150-250'	706'	27/'	6405

TOTAL DEPTH: 733 feet (6378)
ELEVATION: 7104 feet ground level - 7111 feet kelly bushing

The name "Embar" has largely been abandoned, but is rejuvenated here-in to identify the sequence of rocks that is exposed at the surface on this prospect. This sequence is the southeastern wedge-edge of the Phosphoria formation of western Wyoming. It interfingers with the Minnekahta-Opeche section to the east and south of this area.

The top of the Tensleep? formation was arbitrarily called at 126 feet on the top of a fairly thick sequence of interbedded very fine grained marine sandstone, marine siltstone and silty marine shale. The entire section here-in called Tensleep is probably equivalent to the Casper formation even though the lower part appears to be Tensleep lithology. The lower part, of Tensleep lithology, is probably re-worked Tensleep sandstone deposited during Casper time. The entire formation will be referred to however, as Tensleep to correlate with other work done in the area.

The top of the Madison limestone was arbitrarily placed at 706 feet immediately subjacent to a chalky limestone bed. At 706 feet, we encountered an intensely re-worked ferruginous sandstone section that seems to have some limestone inclusion or possibly pebbles mixed with it. This section is probably Tensleep and Madison debris that had been dumped in a cavern in the Madison or that lies immediately on the top of the greatly eroded Madison surface. In any event, it is of similar lithology to the debris that would have been dumped in a cavern such as that encountered at 721 feet, so the top was called at 706 feet on this debris. A cavern that could only exist in the Madison limestone in this area, was encountered as mentioned above at 721 feet. At this point, the bit essentially fell 5 feet with very little weight on it, and at 726 feet the section drilled as though it were a debris filled cavern which it undoubtedly was. This section from 726 feet to 733 feet would drill hard for a few inches then the bit would fall for a few inches more as though it were rotating on a boulder for a while then spin it out of the way and drop to another boulder where the procedure was repeated. No samples definitive of the Madison were obtained, as circulation was lost at 713 feet. Slight returns were obtained and then it was lost again at 719 feet. It could not be regained without setting casing through the cavern. Because of the debris that filled the cavern, we could not drill any deeper with rotary tools as the debris would settle above the bit and make it very difficult and extremely expensive to remove. The only way we could drill deeper would be to use cable tools, and it might take months to bail the debris out of the cavern so the cable tool bit could penetrate the underlying rock. The cavern contained water with a piesometric surface at 414 feet, consequently there was no reason to drill deeper unless to get samples of the Madison for academic purposes.

LITHOLOGY

The Embar (Phosphoria) formation was exposed at the surface and the base was reached at 126 feet. It was composed of three units. The upper 60 feet was buff to tan dense vuggy limestone that contained live oil in some vugs, with some thin stringers of yellow to buff silty calcareous shale. Below this carbonate section was 40 feet of interbedded marine siltstone, shale and very fine grained sandstone. The basal 26 feet consisted of interbedded brown limestone, chert and stringers of very fine grained sandstone, siltstone and shale. Considerable oil was retained in vugs, fractures and streaks of intercrystalline porosity in this section. It was tested and was too tight to give up any oil.

The Tensleep (Casper) formation was encountered at 126 feet. It consisted of two basic lithologic units. The upper 146 feet was composed of interbedded very fine grained calcareous sandstone, calcareous siltstone and some calcareous to limy gray shale with a few beds of tan to brown very finely crystalline limestone. Shows of oil were encountered frequently in slightly porous streaks of the generally tight sandstone and in the limestone beds. The lower 434 feet consisted of massive calcareous sandstone beds with considerable primary and secondary clay, some thin limestone beds and some shale beds. The upper 228 feet of this section had numerous shows of oil, primarily in the limestone beds, but all were too tight to be productive. An excellent show of oil was observed from 300-312 feet in a limestone bed that had been recrystallized in part but the effective porosity was only around 3 - 4% as shown by the Gamma Ray-Neutron log. Another good show of oil was found in a tight sandstone sequence at 369-380 feet, but again, the porosity was too low (7%) to allow production of oil at such a shallow depth.

No samples were obtained of the Madison formation as the portion drilled was a debris filled cavern in which circulation was lost and no samples could be raised to the surface. The cavern was filled with water and the piesometric surface was observed at 414 feet.

STRUCTURE

The structure, as expressed at the surface, is the same on the top of the Madison formation and would undoubtedly be the same on the subjacent granite. It was anticipated that, because of the steep dips on the flanks of the anticline, the drill bit would migrate down dip considerably and we might have to drill to 1000 feet or more before penetrating the Madison formation, however, we spudded near the crest of the structure and managed to remain in the same relative position with depth so that we drilled only the true thickness of Embar and Tensleep sediments.

SUMMARY OF HYDROCARBON SHOWS

Shows of live oil were encountered in the basal Embar formation and scattered throughout the upper 374 feet of Tensleep sandstone. The oil was trapped in tight sediments, however, and could not be removed in commercial volumes. The oil was apparently indigenous to the limestone and shale units and entered the sandstone beds subsequent to a period of secondary clay filling so that, although all effective porosity was filled with oil, this oil could not be removed in commercial quantities.

CONCLUSIONS AND RECOMMENDATIONS

Considerable oil was encountered in the Embar and Tensleep formations, but it could not be removed in quantities sufficient to pay for casing and reservoir treatments.

The Madison formation had sufficient porosity to make a tremendous well, but it was filled with water.

There is no evidence to indicate that further testing could be justified.

It is recommended that no further drilling be undertaken on this prospect.

DRILLING TIME RECORD

Ten foot intervals to 700 feet
One foot intervals below 700 feet

	10	20	30	40	50	60	70	80	90	100
0-100	x	x	x	x	x	x	9	46	68	49
100-200	29	20	35	50	52	51	53	60	*103	169
200-300	210	136	131	102	114	160	167	*131	92	53
300-400	36	73	66	102	96	195	107	203	106	177
400-500	122	85	229	115	77	81	*66	56	56	76
500-600	98	100	59	113	123	120	90	*169	33	40
600-700	41	28	46	53	140	230	*165	85	77	104
700-710	6	5	5	8	4	6	5	7	7	6
710-720	7	5	8	10	10	3	7	5	10	5
720-730	5	1/2	1/2	0	0	0	2	2	1	1
730-733	3	11	2							

Drilling time starts at 66'
* -- Trip for new bit

BIT RECORD

Bit	Size	Make	Type	Depth in feet	Footage	Remarks
1	6-3/4	Sec.	M4N	36 to 185	149	Worn
2	6-3/4	Sec.	N7	185 to 277	92	Green
3	6-3/4	Hughes	CWV	277 to 464	187	Worn out
4	6-3/4	Reed	YS1	464 to 573	109	Worn out
5	6-3/4	Sec.	M4L	573 to 664	88	Worn out
6	6-3/4	Sec.	M4L	664 to 733	72	Worn

DEVIATION SURVEY

Depth	Deviation
185'	3/4°
450'	1-1/8°
545'	1-1/8°
636'	1-1/4°

DRILL STEM TESTS

D. S. T. No. 1 96-127 feet - corrected to 94-125 feet.

Tool open 45 minutes; shut-in 20 minutes.

Recovered 40 feet of water (drilling fluid) with a few specks of oil in the tool.

Tool opened with a good blow that died in five minutes.

Pressures as follows:

Initial hydrostatic -- 98#
Final hydrostatic --95#
Initial flow --136#
Final flow --136#
Final shut in --136#

Test conclusive.

SAMPLE DESCRIPTIONS

Cherry-DeSandro No. 1 Young-State
NW NW NE Section 36, T. 25 N., R. 81 W.,
Carbon County, Wyoming

0-51	Limestone buff very fine crystalline sandy to limy sand argillaceous; Chert nodular white milky scattered dead oil stain; trace live oil in vugs in limestone.
51-55	Limestone buff to light tan very fine crystalline to cryptographic micaceous scattered dead oil stain; Limestone white chalky micaceous; trace Sandstone white fine grained sub-angular scattered dead oil stain; Limestone as above; Siltstone light greenish-gray soft veri-colored grains.
55-60	Limestone buff to light tan very fine crystalline to cryptographic abundant brown and black mica trace dead oil; Limestone white chalky some mica.
60-65	Limestone as above sandy in part.
65-70	Limestone tan to brown very fine crystalline sandy slightly pyritic slightly fossiliferous some carbon fragments; Limestone buff silty argillaceous; Limestone light grayish tan very argillaceous to shaly very finely micaceous slightly pyritic; Shale light gray calcareous silty very finely micaceous slightly pyritic some green streaks.
70-75	Limestone and Shale as above.
75-80	Shale light gray calcareous silty to sandy pyritic; Siltstone light gray calcareous pyritic glauconitic? in part.
80-85	Shale as above.
85-90	Shale as above; Limestone brown very fine crystalline sandy in part with some coarse floating grains scattered dead oil rare live oil in vugs abundant brown mica; Limestone yellow very sandy and silty tight; trace Sandstone yellow very fine grained calcareous to limy tight.
90-95	Sandstone light gray very fine grained calcareous argillaceous pyritic some green clay streaks; shale light gray very finely micaceous silty to sandy soft some streaks of green shale.
95-100	Shale and Sandstone as above.
100-105	Limestone tan dense vuggy fractured free oil in vugs and fractures; Chert white to light gray some pin-point porosity filled with live oil; Sandstone white to light gray and tan calcareous very fine grained argillaceous scattered oil stain.
110-120	Limestone, Chert and Sandstone as above.

120-125	Limestone, Chert and Sandstone as above; Shale light gray silty sandy very finely micaceous; Sandstone light gray very fine grained calcareous argillaceous tight.
125-130	Sandstone light gray very fine grained calcareous argillaceous very finely micaceous light to fair scattered oil stain good spotty fluorescence good cut tight.
130-135	Sandstone as above.
135-140	Sandstone as above.
140-145	Sandstone light gray very fine grained argillaceous calcareous micaceous tight.
145-150	Sandstone as above with light scattered oil stain fair scattered fluorescence good cut tight.
150-155	Sandstone as above becoming slightly pyritic.
155-160	Sandstone as above.
160-165	Sandstone as above, no show.
165-170	Sandstone as above, some floating medium sized rounded grains rare scattered oil stain becoming silicious in part; trace Chert white dense.
170-175	Sandstone as above; increase in Chert as above; very rare Garnet?.
175-180	Sandstone and Chert as above.
180-185	Sandstone and Chert as above, becoming very pyritic.
185-190	Sandstone light gray very fine grained calcareous silicious in part micaceous tight with some streaks of brown watery oil stain slightly pyritic; Chert white to light gray trace dark gray dense.
190-195	Sandstone as above much dead oil stain; Chert white milky, light gray, black botryoidal - detrital nodules - some dead oil stain in pin-point vugs; trace Sandstone white fine grained calcareous silicious scattered dead oil stain.
195-200	Sandstone yellow very fine grained calcareous micaceous argillaceous in part; Limestone brown silicious slightly fossiliferous very hard some pin-point porosity filled with dead oil; Siltstone light gray, green very finely micaceous argillaceous.

200-205	Limestone brown very fine crystalline to lithographic fractured some vuggy porosity fractures and vugs filled with live oil; Sandstone and Limestone as above.
205-210	Limestone light tan very fine crystalline slightly fossiliferous fair pin-point porosity bleeding oil; Limestone as above; Sandstone yellow very fine grained silicious hard tight.
210-215	Sandstone yellow very fine grained calcareous silicious scattered dead oil stain; Limestone white chalky to very fine crystalline scattered dead oil stain trace live oil.
215-220	Sandstone light gray very fine grained calcareous slightly micaceous slightly pyritic hard tight trace live oil in fractures; Shale light gray to gray micaceous.
220-225	Limestone light gray very fine to fine crystalline argillaceous sandy slightly fossiliferous grace glauconite micaceous, slightly pyritic trace oil in rare pin-point vugs.
225-230	Limestone as above; Limestone light tan dense algal.
230-235	Limestone buff to brown very fine crystalline to lithographic slightly pyritic some green clay inclusions; trace Shale silver gray calcareous soft.
235-240	Limestone and Shale as above; Sandstone light gray very fine grained calcareous slightly micaceous tight.
240-245	Sandstone as above trace oil on fracture surfaces.
245-250	Sandstone as above fair to good streaked gas and oil stain.
250-255	Sandstone as above.
255-260	Sandstone as above good gas stain.
260-265	Sandstone as above rare stain; Limestone white coarse crystalline chalky in part fair pin-point porosity microscopic vugs filled with oil.
265-270	Sandstone light grayish-white very fine grained calcareous to limy micaceous lightly pyritic tight with some porous streaks showing a light gassy oil stain; Limestone white to light tan coarse crystalline chalky in part scattered pin-point vugs filled with oil.
270-275	Limestone light gray to buff very fine crystalline grading to coarse slightly fossiliferous fair pin-point porosity filled with oil sandy in part; trace Dolomite light gray medium succresic saacharoidal saturated with oil; Sandstone as above.
275-280	Limestone and Dolomite as above; Shale steel gray silty.

280-285	Shale gray calcareous grading into Limestone light gray to tan very fine crystalline abundant fractures with watery oil stain on surfaces abundant sparry calcite (fracture fill) rare vugs filled with oil.
285-290	Shale as above, slightly fossiliferous.
290-295	Shale as above.
295-300	Shale as above, abundant calcite filled fractures with a good show of oil.
300-305	Shale as above; Shale orange to reddish-brown soft looks like a regolithic shale.
305-310	Shale orange to reddish-brown calcareous to limy; Limestone white, orange coarse crystalline soft; Sandstone orange fine grained rounded calcareous to limy argillaceous soft friable.
310-315	Limestone light to dark gray very fine crystalline argillaceous fossiliferous fractured abundant sparry calcite scattered pin-point porosity filled with oil; Limestone light brown medium crystalline soft saturated with oil in part.
315-320	Limestone as above, no show.
320-325	Limestone as above; Shale silver gray calcareous micaceous.
325-330	Shale as above; Siltstone light gray calcareous micaceous; Limestone gray very fine to fine crystalline some fractures filled with dark viscous oil.
330-335	Siltstone light gray calcareous to limy; Shale light gray calcareous silty; Shale orange sandy; Sandstone white to light pink fine grained well rounded calcareous; trace Limestone buff, pink coarse crystalline.
335-340	Limestone white, buff, pink coarse crystalline fossiliferous sandy in part; Shale light gray silty to sandy calcareous; Siltstone yellow sandy calcareous to limy tight; Sandstone yellow silty very fine grained calcareous to limy tight.
340-345	Limestone, Sandstone and Siltstone as above.
345-350	Limestone as above; Shale light gray calcareous to limy sandy in part; Sandstone and Siltstone as above.
350-355	Limestone, Shale, Sandstone and Siltstone as above.
355-360	Shale, Siltstone and Sandstone as above; Shale yellow silty much free oil in sample (brown viscous blobs).

360-365	Shale, Siltstone and Sandstone as above with stringers of Limestone as above, trace loose pyrite.
365-370	Shale, Siltstone and Sandstone with stringers of Limestone as above.
370-375	Sandstone white to light tan, yellow fine grained with some coarse grains sub-rounded calcareous to limy some yellow clay fill light spotty gassey stain tight no fluorescence; Shale, Siltstone and Sandstone as above, much loose sand in the sample.
375-380	Sandstone as above.
380-385	Sandstone as above.
385-390	Sandstone white to light tan fine grained sub-rounded with some coarse grains calcareous to limy soft tight light scattered stain scattered fluorescence good cut much loose sand in sample.
390-395	Shale silver gray calcareous sandy in part; Sandstone as above; Siltstone yellow calcareous sandy in part; Limestone white, pink, light gray coarse to fine crystalline slightly pyritic sandy in part.
395-400	Sandstone white to buff fine grained sub-angular to sub-rounded some medium to coarse grains calcareous some yellow clay tight light scattered stain; Limestone white chalky; Shale light to dark gray calcareous slightly pyritic sandy in part; Shale light green calcareous sandy.
400-405	Sandstone as above; mostly loose grains few clusters with an excellent oil show; Limestone white chalky rare vugs with oil stain; Shale as above.
405-410	Sandstone as above.
410-415	Sandstone as above; stringers Limestone white chalky.
415-420	Sandstone as above.
420-425	Sandstone as above.
425-430	Sandstone white, yellow, light red fine grained sub-angular to sub-rounded calcareous slightly pyritic firm to friable tight.
430-435	Sandstone as above.
435-440	Sandstone as above.
440-445	Sandstone as above; trace Limestone brown lithographic fossiliferous some vugs filled with oil.
445-450	Sandstone as above.

450-455	Sandstone as above; trace Limestone white chalky sandy in part.
455-460	Sandstone as above.
460-465	Sandstone as above; Shale light gray to brown calcareous to limy sandy in part slightly pyritic.
465-470	Sandstone and Shale as above; trace limestone brown lithographic slightly fossiliferous scattered vugs filled with oil.
470-475	Shale gray calcareous to limy micaceous slightly pyritic; Chert light gray to white opaque to semi-translucent nodular; Sandstone and Limestone as above.
475-480	Shale light gray calcareous to limy sandy in part very finely micaceous slightly pyritic some chert pebbles; Sandstone white very fine to fine grained with some medium grains soft tight no show.
480-485	Shale as above; Limestone light gray argillaceous very fine crystalline good vuggy porosity saturated with oil in and around vugs.
485-490	Sandstone white to light gray, yellow fine to medium grained poorly sorted sub-rounded calcareous friable tight.
490-495	Sandstone as above; Limestone brown very fine crystalline silty some pin-point porosity micro-vugs filled with oil; trace Chert nodules with oil in scattered vugs; trace Siltstone brown calcareous saturated with oil tight; Shale gray silty sandy slightly pyritic.
495-500	Shale light gray to light tan calcareous silty sandy in part micaceous silicious in part with some nodular chert light oil stain on fracture faces in chert and shale.
500-505	Shale as above.
505-510	Sandstone yellow fine to medium grained sub-angular to sub-rounded calcareous argillaceous tight; Shale yellow slightly sandy silicious in part.
510-515	Sandstone and Shale as above; Shale light gray calcareous silty to sandy silicious in part.
515-520	Sandstone yellow, white, trace pink very fine to fine grained sub-angular to sub-rounded calcareous argillaceous slightly pyritic tight no show.
520-525	Sandstone as above with some yellow and pink weathered feldspar.

525-530	Sandstone as above.
530-535	Sandstone as above.
535-540	Sandstone as above.
540-545	Sandstone as above with only trace of feldspar.
545-550	Sandstone white very fine to fine grained poorly sorted sub-angular to sub-rounded calcareous argillaceous slightly friable tight trace pink feldspar.
550-555	Sandstone as above.
555-560	Sandstone as above.
560-565	Sandstone as above with slightly more pink feldspar.
565-570	Sandstone light pink very fine to fine grained poorly sorted sub-angular to sub-rounded dolomitic silicious hard tight; Sandstone as above.
570-575	Sandstone light pink as above calcareous to limy silicious in part pyritic.
575-580	Sandstone as above.
580-585	Sandstone as above.
585-590	Sandstone as above.
590-595	Sandstone as above; trace styolitic shale.
595-600	Sandstone as above.
600-605	Sandstone as above grading to limestone pink coarse crystalline sandy slightly pyritic.
605-610	Sandstone and sandy Limestone as above very silicious in part.
610-615	No sample [lost circulation].
615-620	Sandstone and sandy Limestone as above.
620-625	Sandstone as above; Sandstone light gray fine grained poorly sorted sub-rounded to sub-angular calcareous porosity est. 10-12% trace orthoclase feldspar soft friable.
625-630	Sandstone light gray as above; trace Limestone light gray very fine crystalline slightly silicious some sparry calcite.
630-635	Sandstone with trace Limestone as above.

635-640	Sandstone with trace Limestone as above.
640-645	Sandstone with trace Limestone as above; trace Shale light gray calcareous sandy in part.
645-650	Sandstone yellow fine grained sub-angular to sub-rounded calcareous slightly argillaceous (clay possibly weathered feldspar) tight.
650-655	Sandstone as above.
655-660	Sandstone as above; Limestone white, yellow chalky slightly sandy soft.
660-665	Sandstone as above.
665-670	Sandstone as above.
670-675	Sandstone yellow fine grained sub-rounded to sub-angular calcareous argillaceous friable poorly sorted in part scattered limonite stain porosity est. 5%.
675-680	Sandstone as above trace red clay in some.
680-685	Sandstone as above; trace Limestone white, light pink chalky.
685-690	Sandstone as above.
690-695	Sandstone as above; Limestone white, light pink chalky to coarse crystalline very soft.
695-700	Sandstone pale yellow, white fine to medium grained poorly sorted sub-rounded to sub-angular calcareous friable rare pink feldspar porosity est. 12-15%.
700-705	Sandstone as above; Limestone white chalky pink streaks.
705-710	Sandstone yellow very fine to medium grained poorly sorted sub-rounded to sub-angular limonitic calcareous friable porosity est. 8-10% rare pink and yellow weathered feldspar abundant chunks of limonite or jarosite; trace Limestone white medium crystalline with some floating sand grains, possibly re-crystallized.

No samples below 710 feet due to lost circulation problem.

(Retyped verbatim from original on file at Wyoming Oil and Gas Conservation Commission, Casper, Wyoming.)

APPENDIX F

CRITICAL ANALYSIS OF THE WELL COMPLETION REPORT ON THE CHERRY-DeSANDRO NO. 1 YOUNG-STATE OIL EXPLORATION WELL

CRITICAL ANALYSIS OF DRILLERS REPORT ON THE CHERRY-DeSANDRO NO. 1 YOUNG-STATE OIL EXPLORATION WELL

The Cherry-DeSandro No. 1 Young-State petroleum exploration well was spudded near the crest of the Troublesome Creek anticline on January 9, 1963, by Work Over, Inc. The target of this well was the Mississippian Madison Limestone. The Tensleep Sandstone was a secondary objective.

The following data from the well report are critical to this study: (1) fracture permeability associated with anticlinal crests, (2) electric logs taken of the completed well that provide critical evidence of the thickness of the Goose Egg Formation and the presence of numerous evaporite beds in the formation, and (3) the electric log records that show an accurate elevation of the top of the Tensleep Formation.

A brief description of the well drilling report will preface this author's interpretation of the tectonic regime and the extensional fractures within it.

The original report by the operators of this well describe several events of losing fluid and lost circulation. The first occurrence of the loss of mixing mud occurred at a well depth of 421 feet. The well operator reported the Tensleep Formation present at this level. the operator further reported, "Considerable lost circulation material was maintained in the system below 425 feet to prevent the loss of fluid in minor fractures". The drilling continued to a depth of 610 feet before circulation was lost temporarily. Circulation was regained and drilling commenced for 65 feet (675 foot well depth) before circulation was lost again. The operator showed this depth to be just above the top of the Madison

Formation. At this point the well drilling was stopped for the day. The next morning the drilling was stopped at a well depth of 713 feet. At this depth circulation was lost for 1.5 hours. The circulation was regained and drilling continued for 6 feet. The daily work record shows that the circulation was lost at this depth and could not be regained. This complete loss of circulation prevented any cuttings from being obtained below 719 feet. The operator was able to drill for 2 feet more before penetrating a 'cavern' at which point "the bit essentially fell 5 feet with very little weight on it". He reported, "The Cavern contained water with a piezometric surface of 414 feet".

The hydraulic insights that came from this report are (1) a confined aquifer exists at this location at a depth of 721 feet and, this confined aquifer has a pressure head of 319 feet; and (2) the zones of lost circulation indicate fractures along the crest of the anticline, and large hydraulic conductivities.

It is this author's opinion that the operators of the well believed they were drilling on the crest of the anticline and expected to drill through a normal sequence of stratigraphic section to their target, the Mississippian Madison Limestone. In reality the operators were drilling just east of the axis and through a thickened section of the Goose Egg Formation.

The actual depth of the Tensleep Formation can be derived by (1) subtracting the known thickness of the formations overlying the Tensleep Formation from the elevation of the surface exposure of the shallow dipping Alcova Limestone that caps the east limb of the Troublesome Creek anticline, and projecting this elevation west to its contact with the well: and (2) correlating the electric logs of the No. 1 Young-State well with an electric log from the basin in which the formation signatures are known.

Subtracting known formation thicknesses from the surface elevation of the Alcova

Limestone capping the horizontally dipping east limb of the Troublesome Creek anticline fixes the elevation of the Tensleep Formation top at 6100 feet above sea level. Projecting the elevation and dip of this bed across to the well, shows the Tensleep formation intersects the well at a depth of 700 feet (6400 feet elevation).

The correlation of electric logs reveals the contact between the Goose Egg and Tensleep formations in the No. 1 Young-State well is at a 675 feet. Figure 20 shows the electric logs from the No. 1 Young-State well and the known Tensleep Formation signature from the log of Pass Creek Basin #3 well in section 21, T. 20 N., R. 80 W. Also shown in Figure 20 are typical responses of gamma-ray and neutron curves to various types of formations penetrated by wells. The consistent sharp peaks and valleys of the Goose Egg Formation shown on the gamma-ray log from the Pass Creek #3 well correlate well with the No. 1 Young-State well. The alternating high and low recordings on the No. 1 Young-State gamma-ray log above 675 feet are representative of anhydrite and shale beds in the Goose Egg Formation. The Tensleep Sandstone is represented by continuous low gamma-ray levels following a sharp drop at the contact of the high gamma-ray levels of the lower Goose Egg Formation.

The initial lost circulation described in the drillers log was probably due to small extensional fractures or small bedding plane faults in the Goose Egg Formation. The latter episodes of lost circulation are the result of drilling into larger extensional fractures in the Tensleep Formation along the crest of the anticline. The cavern described in the report was an extensional fracture under artesian conditions within the Tensleep Formation. Huntoon (1986) documented extensional fractures having artesian conditions in the Cane Creek anticline in the Paradox Basin, Utah. The water sampled from the cavern had a mixed water chemistry (probably contaminated during extraction) when plotted on chemical analyses diagrams.

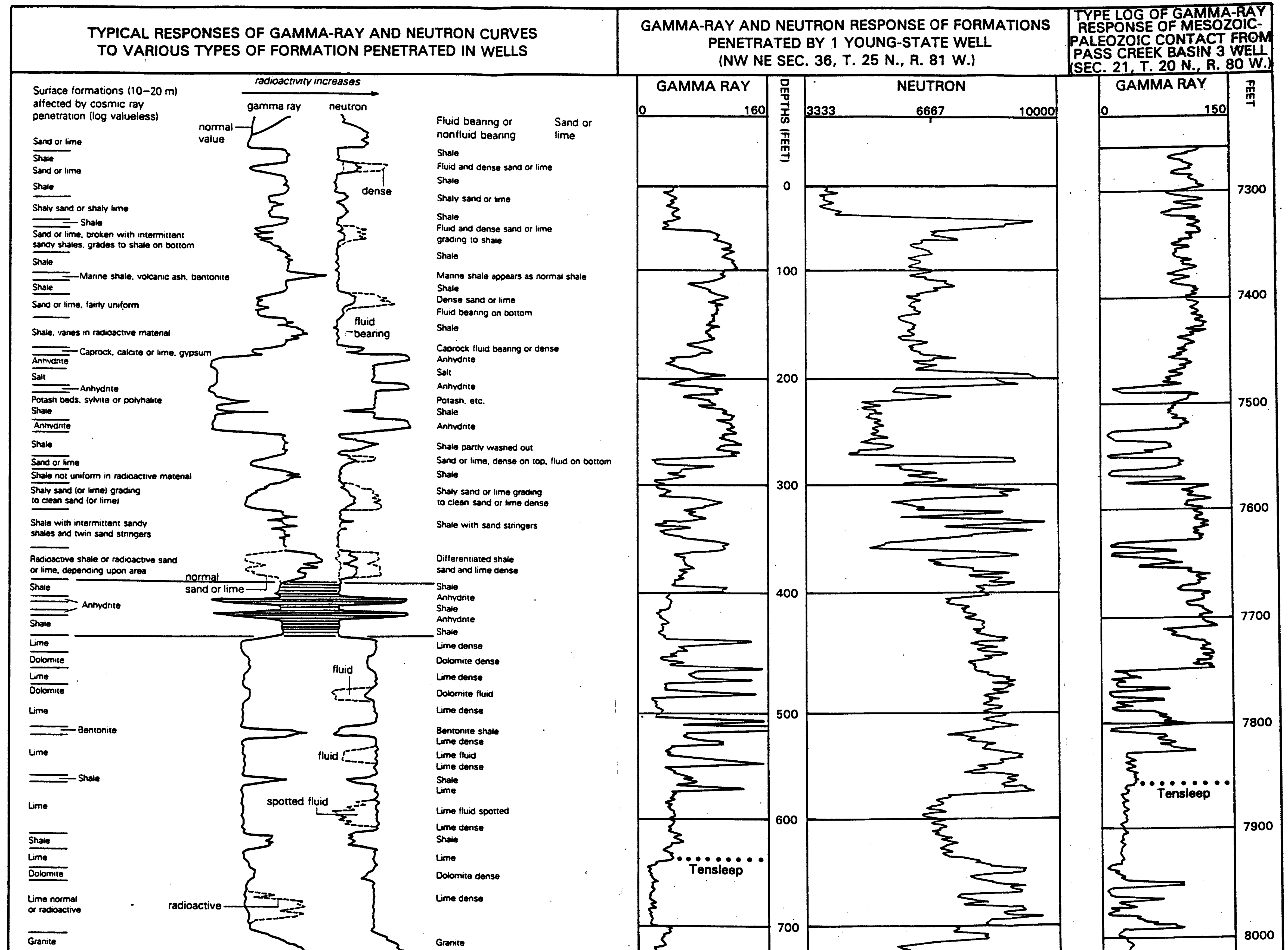
The cross section shown in Figure 18 is based on the correlation of electric logs and by projecting the known thicknesses of formations from the east-dipping limb of the Troublesome Creek anticline across the valley to the well. The projected contact of the well and the Tensleep Formation is roughly at a depth of 675 feet (6436 feet above sea level). This author believes the operators of the well misidentified this elevation to be the contact of the Madison Limestone.

The evidence provided above indicates the Goose Egg Formation in the vicinity of the No. 1 Young-State well is 675 feet thick. This is three times the thickness of a normal section of the Goose Egg Formation. The thickened formation is the result of swelling during the conversion of anhydrite to gypsum and to faulting along bedding planes.

The following is a summary of critical data obtained from the record of the No. 1 Young-State oil exploration well:

1. The Goose Egg Formation is thickened at this location by mineralization and faulting along bedding planes.
2. The Tensleep Formation top is 6400 feet above sea level.
3. The Tensleep aquifer is confined and has a potentiometric surface of 6697 feet.
4. Large permeability fractures exist along the crest of the anticline at depth.

Figure 20. Electric log correlation of No. 1 Young-State well with the Pass Creek Basin #3 well.


TYPICAL RESPONSES OF GAMMA-RAY AND NEUTRON CURVES TO VARIOUS TYPES OF FORMATION PENETRATED IN WELLS
GAMMA-RAY AND NEUTRON RESPONSE OF FORMATIONS PENETRATED BY 1 YOUNG-STATE WELL (NW NE SEC. 36, T. 25 N., R. 81 W.)
TYPE LOG OF GAMMA-RAY RESPONSE OF MESOZOIC-PALEOZOIC CONTACT FROM PASS CREEK BASIN 3 WELL (SEC. 21, T. 20 N., R. 80 W.)
radioactivity increases
gamma ray
neutron
Surface formations (10–20 m) affected by cosmic ray penetration (log valueless)
normal value
Fluid bearing or nonfluid bearing
Sand or lime
Sand or lime
Shale
Sand or lime
Shale
Shaly sand or shaly lime
Shale
Sand or lime, broken with intermittent sandy shales, grades to shale on bottom
Shale
Marine shale, volcanic ash, bentonite
Shale
Sand or lime, fairly uniform
Shale, varies in radioactive material
Caprock, calcite or lime, gypsum
Anhydrite
Salt
Anhydrite
Potash beds, sylvite or polyhalite
Shale
Anhydrite
Shale
Sand or lime
Shale not uniform in radioactive material
Shaly sand (or lime) grading to clean sand (or lime)
Shale with intermittent sandy shales and twin sand stringers
Radioactive shale or radioactive sand or lime, depending upon area
normal
sand or lime
Shale
Anhydrite
Shale
Lime
Dolomite
Lime
Dolomite
Lime
Bentonite
Lime
Shale
Lime
Shale
Lime
Dolomite
Lime normal or radioactive
radioactive
Granite
dense
fluid bearing
fluid
fluid
spotted fluid
Shale
Fluid and dense sand or lime
Shale
Shaly sand or lime
Shale
Fluid and dense sand or lime grading to shale
Shale
Marine shale appears as normal shale
Shale
Dense sand or lime
Fluid bearing on bottom
Shale
Caprock fluid bearing or dense
Anhydrite
Salt
Anhydrite
Potash, etc.
Shale
Anhydrite
Shale partly washed out
Sand or lime, dense on top, fluid on bottom
Shale
Shaly sand or lime grading to clean sand or lime dense
Shale with sand stringers
Differentiated shale sand and lime dense
Shale
Anhydrite
Shale
Anhydrite
Shale
Lime dense
Dolomite dense
Lime dense
Dolomite fluid
Lime dense
Bentonite shale
Lime dense
Lime fluid
Lime dense
Shale
Lime
Lime fluid spotted
Lime dense
Shale
Lime
Dolomite dense
Lime dense
Granite
GAMMA RAY
0
160
DEPTHS (FEET)
0
100
200
300
400
500
600
700
Tensleep
NEUTRON
3333
6667
10000
GAMMA RAY
0
150
FEET
7300
7400
7500
7600
7700
7800
7900
8000
Tensleep