Karstic Groundwater Circulation in the Fault-Severed Madison Aquifer in the Casper Mountain Area of Natrona County, Wyoming

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ABSTRACT

Aquifer-severing displacements along thrust faults adjacent to local structural highs of the Casper Formation have disrupted the hydraulic continuity of the Madison aquifer in the Casper Mountain area and segmented the aquifer into five discrete groundwater compartments. The large permeability of the Madison aquifer in the Casper Mountain groundwater compartment is attributed to the dissolution of interstitial cements and matrix materials within the aquifer that has resulted in the development of a madison karst. Consequently, the storage capacity of the Madison aquifer is sufficient to damp out recharge pulses. The implication for groundwater prospecting is that large quantities of groundwater can be withdrawn from storage in the Madison aquifer throughout the entire southwestern homoclinal flank of Casper Mountain.

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CHAPTER I
INTRODUCTION

Purpose:

The objective of this research was to identify favorable groundwater exploration targets for the karstified Madison aquifer within the Casper Mountain area. This objective entailed delineating barriers to groundwater circulation, documenting the permeability of various geologic features, characterizing groundwater circulation patterns, and qualitatively determining the storage capacity of the Madison aquifer in the study area.

Geologic Setting:

The study area encompasses 535 mi^2 and lies at the northwestern end of the Laramie Range where the Powder and Wind River basins converge, as illustrated on Figure 1. The Powder River basin is a broad, north-northwest trending, asymmetric syncline that contains over 16,000 feet of sedimentary rocks (Feathers and others, 1981). Similarly, the Wind River basin is a broad, west-northwest trending, asymmetric syncline that contains approximately 18,000 feet of sedimentary rocks (Richter and Huntoon, 1981).

These two prominent intermontane basins are separated by the Casper arch, a broad, asymmetric, southwest-verging anticline cored by the Casper Arch thrust fault, as shown on Figure 1 (Ray and Berg, 1985). Stratigraphic displacements along this fault reach a maximum of 16,000 feet in the southwestern corner of T 37 N, R 86 W (Keefer, 1970), and diminish to the southeast as illustrated on Figure 2.

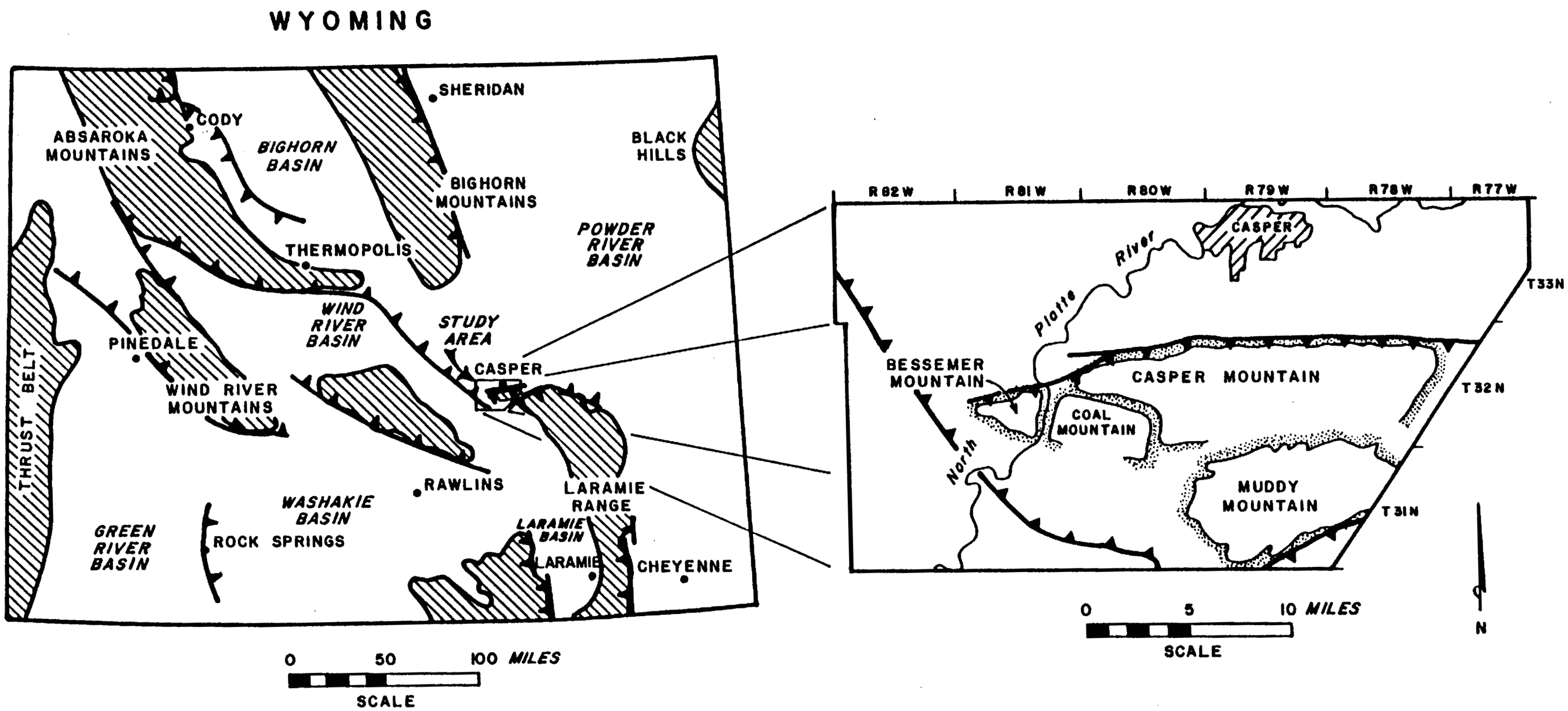


Figure 1. Location of the Casper Mountain area in Natrona County, Wyoming. Notice that roughly half of the basin margins along the mountain uplifts (diagonally striped on the state map) coincide with large displacement thrust faults (sawteeth on upthrown side) that sever the Paleozoic strata between the hanging and footwall blocks. Modified from Huntoon, 1993, Figure 2.

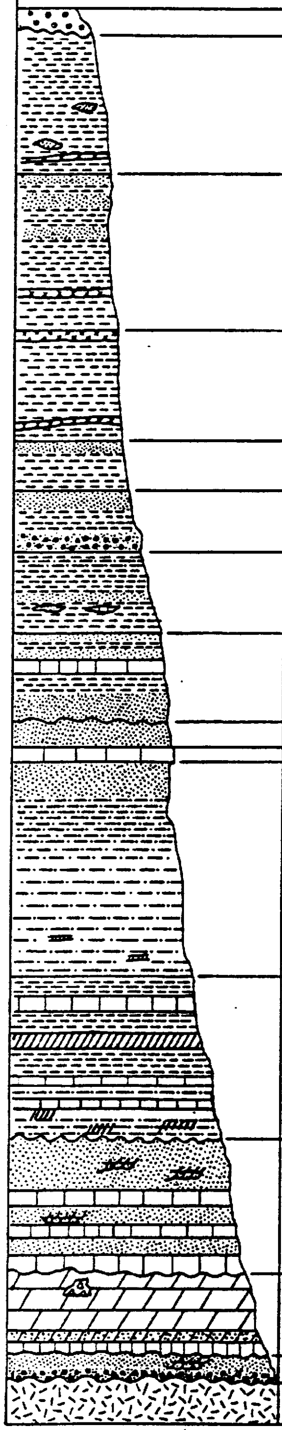
Casper Mountain is the largest in a series of doubly-plunging, asymmetric, fault-cored anticlines depicted on Figure 3 that trend parallel or subparallel to the crest of the Casper arch. This northeast-verging, Precambrian-cored anticline is cored by the Casper Mountain thrust fault. Stratigraphic displacements along this fault exceed 5,000 feet in section 3 of T 32 N, R 80 W (Sears and Sims, 1954).

The stratigraphy in this area is summarized on Figure 4. The Paleozoic Fremont Canyon, Madison, Casper, and Goose Egg formations are central to this investigation.

Statement of the Problem:

Many groundwater exploration attempts in Wyoming have failed because the hydrogeologic boundary conditions associated with the basin margins of the Wyoming foreland province have not always been correctly interpreted. For example, Swenson (1974), Swenson and others (1976), and Huntoon (1976) thought that the exposed, upturned permeable strata along the flanks of the foreland uplifts, in particular the eastern flank of the Bighorn Mountains, allowed for plentiful recharge to the artesian aquifers in the adjacent basins (Huntoon, 1993). Consequently, many groundwater exploration wells were drilled within the basins. However, commercial quantities of potable groundwater were often not found. Detailed analysis of the drillhole-controlled cross sections of Berg (1962; 1976) through Hamilton dome, the seismic line shot across the Wind River Mountains by Smithson and others (1979), seismic lines shot through numerous wells which were drilled along various mountain fronts into the footwalls of faults (Gries, 1983), and cores and geophysical logs of the Casper-equivalent Tensleep sandstone from the Bighorn basin (Bredehoeft, 1964) clearly revealed that these groundwater exploration attempts were unsuccessful for two reasons.

First, groundwater exploration attempts often failed because large displacement thrust faults along roughly half the basin margins in Wyoming form impermeable barriers



LITHOLOGY	THICKNESS (FEET)	AGE	UNIT	REFERENCE
		QUATERNARY	UNDIVIDED	
	3500-4000	CRETACEOUS	CODY SHALE	LUPTON (1916) THOMPSON (1949)
	680-1100	CRETACEOUS	FRONTIER FORMATION	KNIGHT (1902) HALE (1960)
	230-275	CRETACEOUS	MOWRY SHALE	DARTON (1904) DAVIS (1970)
	80-260	CRETACEOUS	THERMOPOLIS SHALE	LUPTON (1916) HOOPER (1962)
	100-115	CRETACEOUS	CLOVERLY FORMATION	DARTON (1904) HOOPER (1962)
	170-256	JURASSIC	MORRISON FORMATION	CROSS (1894) EMMONS & OTHERS (1896) LOVE (1958)
	325	JURASSIC	SUNDANCE FORMATION	DARTON (1899) PIPIRINGOS (1968)
	70-115	TRIASSIC	CHUGWATER GROUP: JELM FORMATION	KNIGHT (1917) PIPIRINGOS (1968)
	20	TRIASSIC	CHUGWATER GROUP: ALCOVA LIMESTONE	LEE (1927) BOWER (1964)
	625-700	TRIASSIC	CHUGWATER GROUP: RED PEAK FORMATION	LOVE (1939) HIGH & PICARD (1967)
	380-615	PERMIAN	GOOSE EGG FORMATION	BURK & THOMAS (1956) ORIEL & CRAIG (1960)
	505-550	PENNSYLVANIAN	CASPER FORMATION	DARTON (1908) KNIGHT (1929) MALLORY (1967)
	170-290	MISSISSIPPIAN	MADISON FORMATION	PEALE (1893) SANDO & OTHERS (1975)
	49-210	DEVONIAN	FREMONT CANYON SANDSTONE	MAUGHAN (1963) SANDO & SANDBERG (1987)
		PRECAMBRIAN	UNDIVIDED	GABLE & OTHERS (1988)

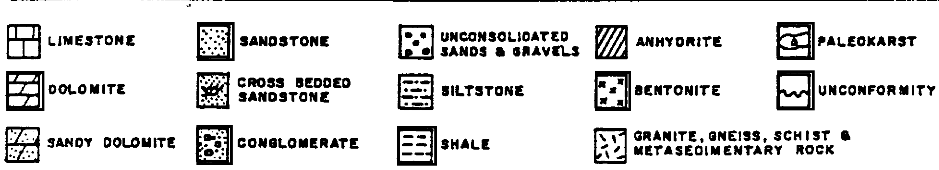


Figure 4. Stratigraphy exposed in the Casper Mountain area, Natrona County, Wyoming.

to groundwater circulation between the hanging and footwall blocks, as depicted on Figures 1 and 5. This results because displacements along these faults which range up to ten miles along dip and several miles vertically have placed permeable Paleozoic strata in the footwall in fault contact with impermeable Precambrian crystalline rocks in the hanging wall (Huntoon, 1985a). In addition, the permeability of the Paleozoic strata in the footwall blocks of these fault-cored folds, particularly in the Bighorn basin, has been diminished through the mechanical thinning of beds and tectonic compression along fracture surfaces (Jarvis, 1986).

Similarly, groundwater exploration attempts on the homoclinal flanks opposite the thrust faults often failed to produce commercial quantities of groundwater because of diagenetic processes that have destroyed aquifer permeability basinward from the recharge area. Huntoon (1985b) has documented cases on the western homoclinal flank of the Bighorn Mountains where the volume of water discharged through Madison springs near the toe of the recharge area exceeds the volume of water that apparently recharges the Madison aquifer through upgradient sinkholes and other solution features. Such rejection of recharge along the perimeter of the recharge area occurs either because hydraulic gradients diminish basinward or because permeabilities dramatically decrease basinward, regardless of rock type, as a result of compaction, cementation, and recrystallization (Bredehoeft, 1964; Head and Merkel, 1977; Huntoon, 1993).

Methodology:

In addition to the permeabilities of various geologic features, regional geologic structures, water quality distributions, and groundwater circulation patterns have been documented to ensure the success of future groundwater exploration attempts for the Madison aquifer in the study area. The locations of data points used in this investigation to document these structural and hydrogeologic components are shown on Figure 6.

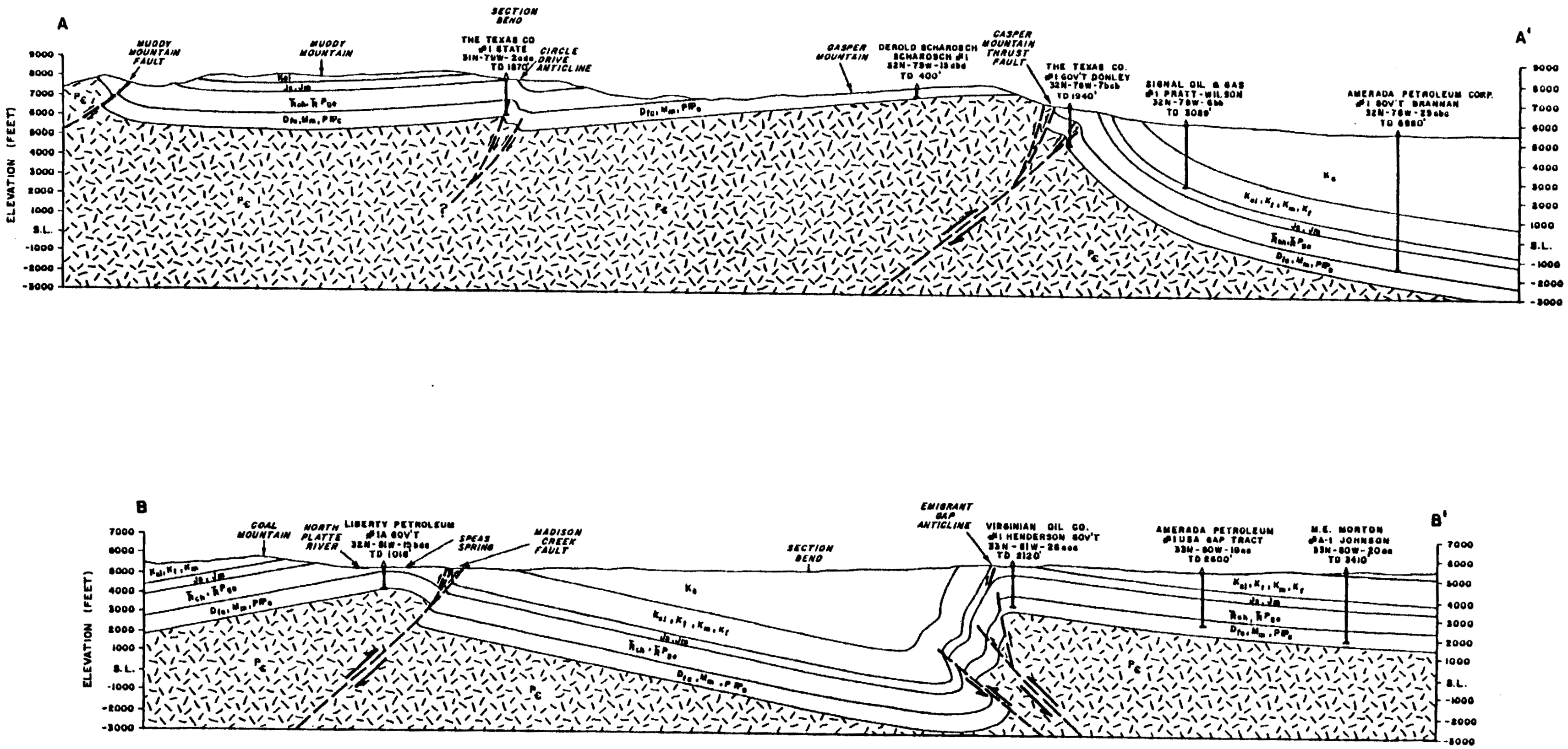


Figure 5. Cross sections A-A' and B-B' through typical foreland uplifts in the Casper Mountain area of Natrona County, Wyoming. Notice that displacements along the coring thrust faults have severed the Paleozoic rocks and juxtaposed permeable Paleozoic strata in the footwall and impermeable Precambrian crystalline rocks in hanging wall. Consequently, lateral circulation through the Paleozoic units across the fault is precluded. Explanation: Pc = Precambrian, Dfc = Fremont Canyon Sandstone, Mm = Madison Formation, PPc = Casper Formation, TrPge = Goose Egg Formation, Trch = Chugwater Group, Js = Sundance Formation, Jm = Morrison Formation, Kcl = Cloverly Formation, Kt = Thermopolis Shale, Km = Mowry Shale, Kf = Frontier Formation, Kc = Cody Shale. Arrows indicate relative movement along faults. Cross section locations shown on Figure 3.

Local geologic structures were closely examined to identify regional groundwater flow boundaries, and circulation pathways within the Madison aquifer. These local geologic structures were scrutinized because Huntoon (1985a; 1993) has demonstrated that groundwater moves parallel to faults which form barriers to groundwater flow where hydraulic head changes, water quality contrasts, and temperature differences delineate the faults. Furthermore, Huntoon (1985a) and Jarvis (1986) have also documented that faults or fault-cored folds which trend obliquely into the basin provide excellent hydraulic interconnection of the basin interiors and upland recharge areas, as revealed by good basinward water qualities along trend and by relatively cool, hanging wall water temperatures. Therefore, these structures were identified in two steps by first mapping the exposed folds and faults, shown on Figure 3, using aerial photographs and field observations, and then by structurally contouring the top of the Casper Formation, shown on Figure 2, using data obtained from well completion reports listed in Appendices C and D, geophysical logs, and published and unpublished geologic maps.

Geochemical data were analyzed using the geometrical plotting techniques devised by Piper (1944), Stiff (1951), and Mazor (1991) to identify aquifers, intracompartmental circulation pathways, and flow boundaries between hydraulically disconnected compartments of the Madison aquifer. Water qualities generally deteriorate along streamlines as a result of the basinward dissolution of matrix material and interstitial cements (Chebotarev, 1955). In contrast to this gradual deterioration, Huntoon (1985a) noted that water quality differences between the hanging and footwall blocks of fault-severed aquifers are dramatic, ranging in the extreme between potable waters in the hanging wall, and petroleum and brines in the footwall.

Regional groundwater circulation patterns for the Madison aquifer were documented through the preparation of a potentiometric map, shown on Figure 7. These patterns were identified for the purpose of delineating regional groundwater circulation systems that supply both Speas Spring and the Hat Six Warm Springs. This map was constructed using spring elevations, well pressure data, and reported water levels taken from well completion reports which are listed in Appendices B, D, and C, respectively.

The permeabilities of various geologic features in the study area were documented for the purpose of identifying potential groundwater exploration targets for the Madison aquifer. These locations were selected to provide water for future development in the area. Locations favored for groundwater development coincide with highly localized extensional fractures along anticlinal fold crests that have been enlarged through the dissolution of interstitial cements and matrix material.

The recharge rate to the Madison aquifer was calculated to provide a better estimate for recharge to karstified aquifers in the Wyoming foreland province. The Casper Mountain area is ideal for estimating recharge rates because (1) the recharge area on Casper Mountain is well defined and represents the only plausible source of recharge to the Madison aquifer, and (2) the amount of groundwater discharged from the Madison aquifer locally is well constrained. The recharge rate was calculated by summing the discharge of springs which emerge from the Madison aquifer and dividing by the recharge area, outlined on Figure 7. Spring discharges were calculated either by multiplying the cross sectional area of the stream by the surface water velocity, or by using a calibrated bucket and a stopwatch.

CHAPTER II

OVERVIEW OF THE MADISON AQUIFER WITHIN THE CASPER MOUNTAIN AREA

The Madison aquifer is locally composed of the saturated parts of the Casper, Madison, and Fremont Canyon formations. These Paleozoic units collectively contain sufficient, saturated permeable material, as defined by Lohman and others (1972), to yield significant quantities of water to wells and springs. Within the study area, the aquifer consists of up to 890 feet of saturated, permeable Paleozoic strata that are hydraulically interconnected through extensional fractures along the crests of anticlinal and monoclinal folds. The hydraulic properties of the Paleozoic strata are summarized on Figure 8.

The similarity of hydraulic heads and water qualities for the saturated parts of the Paleozoic units that locally compose the Madison aquifer reveals that these units are hydraulically interconnected. The similar hydraulic heads of springs shown on Figure 7 that emerge from saturated parts of the Casper and Madison formations along the hanging wall of the Hat Six fault in T 32 N, R 78 W, and of wells which produce water from the saturated Paleozoic units on Casper Mountain reveal that these saturated units are hydraulically interconnected. Hydraulic interconnection is further substantiated by the similar water qualities, depicted on Figure 9 and listed in Appendices E and F, of groundwater derived from saturated parts of the Paleozoic units within individual groundwater compartments. In fact, the only notable exception, listed in Appendix F, is the gross disparity between the concentrations of individual ions within water samples

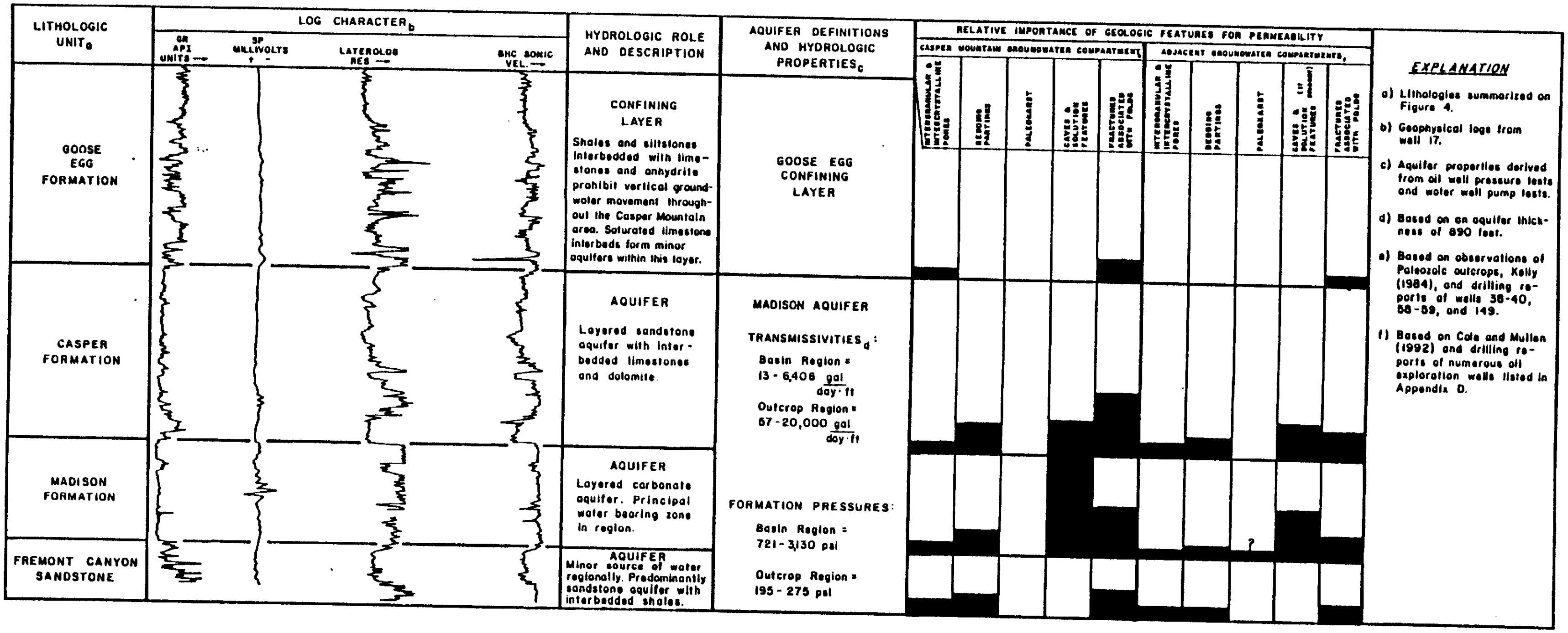


Figure 8. Hydraulic properties of the Paleozoic rocks within the Casper Mountain area, Natrona County, Wyoming.

obtained from saturated parts of the Casper and Madison formations in well 12 on Oil Mountain.

Regional Confinement:

With the exception of the Fremont Canyon, Madison, and Casper outcrops on Casper Mountain, the Madison aquifer is confined throughout the study area by the overlying Goose Egg Formation. The Goose Egg Formation is considered a regional confining layer for several reasons: (1) many springs, depicted on Figure 7, discharge from the Madison aquifer along the contact between the Casper and Goose Egg formations, (2) anhydrite beds within the Goose Egg Formation are still intact, (3) wells (39-40, 50, 53, and 149) drilled through the Goose Egg Formation into at least the upper part of the saturated Casper Formation encountered artesian conditions, and (4) the elevation of spring 41 which discharges groundwater from the Madison aquifer lies topographically above the North Platte River, the lowest potentiometric point for the hydrologic system in the study area.

Compartmentalization:

Faulting of the Paleozoic strata adjacent to local structural highs of the Casper Formation, shown on Figure 2, has locally severed the aquifer, as depicted on Figure 7. For example, aquifer-severing displacements along the south-dipping Casper Mountain thrust fault preclude groundwater circulation between the upland recharge area on Casper Mountain and the Powder River basin interior as shown on Figures 5 and 7. Circulation between the hanging and footwall blocks is precluded because the Paleozoic strata in the footwall lie in fault contact with less permeable Precambrian crystalline rocks in the hanging wall. Consequently, isolated circulation systems have developed within both the hanging and footwall blocks.

Faults that sever the aquifer and intersect at oblique angles have segmented the aquifer into five discrete groundwater compartments which are depicted on Figure 7. The five compartments are herein referred to as the Casper Mountain, Alcova, Wind River, Casper Arch, and Powder River groundwater compartments. These groundwater compartments are parts of the Madison aquifer that are bordered by aquifer-severing thrust faults wherein isolated active or inactive circulation systems have developed.

Active and inactive circulation systems are distinguished on the basis of the following criteria. Active circulation systems are characterized by (1) large volume, basinward discharge from springs and/or flowing wells, (2) good hydraulic connection between the recharge area and basinward discharge points, (3) relatively steep hydraulic gradients, and (4) ample groundwater circulation from the recharge area to the basinward discharge points. In contrast, inactive circulation systems are characterized by (1) little, if any, basinward discharge, (2) poor hydraulic connection between the recharge area and basinward discharge points, (3) negligible hydraulic gradients, and therefore, (4) relatively little groundwater circulation basinward from the recharge area.

Aquifer Productivity:

The potential for groundwater production from the Madison aquifer in the Casper Mountain groundwater compartment is good based on the production of several wells that penetrated at least the upper part of the saturated Casper Formation near the crests of local anticlines. In 1965 the Liberty Petroleum Corporation drilled wells 39 and 40 in section 15 of T 32 N, R 81 W, as shown on Figures 5 and 6. Summerford (1965a) reported that well 40 encountered "tremendous" flows of water once they had drilled several feet into the Casper Formation on Goose Egg dome. No discharge estimates were reported, but these flows "soon washed out the mud pits...toppled the rig over...(and) expanded (the drill hole) to approximately three feet wide, to a depth of approximately 70 feet."

The replacement well, #1A Government (well 39), was drilled only 50 feet to the south. Summerford (1965b) reported that this well "hit artesian waterflows" in the Casper Formation which increased with depth such that the "rams in (the) blowout preventor would not close (due to the) excessive waterflow." Less spectacular artesian flows were reportedly encountered in the underlying Madison Formation; and the Fremont Canyon Sandstone "appeared water wet" (Summerford, 1965b).

The Bodie Dome #1 groundwater exploration well (well 149) also developed water from the Madison aquifer. Wright Water Engineers (1984) noted that "significant increases in water production began after drilling into the upper part of the (saturated) Casper" Formation on Bodie dome at which time the water level in the well rose about 1,800 feet to within 380 feet of the land surface. Apparent increases in water production were encountered in two lower zones within the Madison aquifer, but "a precise determination of the water production from the hole could not be made" (Wright Water Engineers, 1984). Nevertheless, "it was evident (from a subsequent airlift test) that in excess of 200 gpm was being blown from the (Madison) aquifer..." (Wright Water Engineers, 1984).

Karstification of the Madison Formation:

Karst, as defined by Huntoon (in press), is a geologic environment containing soluble rocks wherein the network of permeable conduits which evolved as a consequence of the dissolution of the host rock is organized to facilitate fluid circulation downgradient.

The presence of an active karst developed in both the saturated and unsaturated parts of the Madison Formation is revealed by the following: (1) sinkholes, pictured on Figure 10, located along the strike of Madison outcrop in Beartrap Meadow, (2) a cavern developed beneath the drainage shown on Figure 10 into which a drill bit reportedly dropped about nine feet at a shallow depth (Hill and others, 1976), (3) passages within Casper Mountain Cave (Hill and others, 1976) that are more than seventy feet high and up

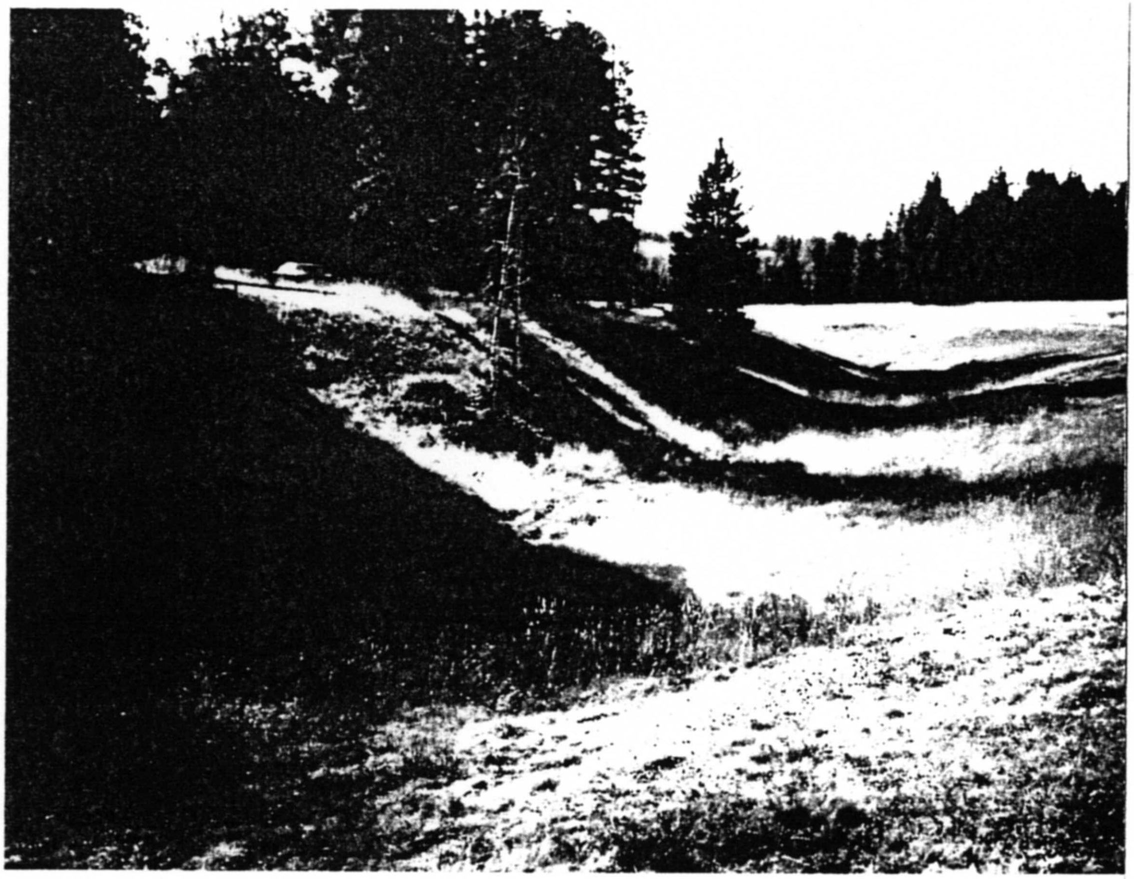


Figure 10. Infilled Madison sinkhole, located in the foreground, found within a blind valley in Beartrap Meadow on Casper Mountain. Hill and others (1976) report that a large cave entrance, visible on old aerial photographs, was once present at the sinking point. View is to the south looking upstream from the sinkhole.

to six feet wide, (4) several tributaries of Little Red Creek that disappear where these drainages cross Madison outcrop in section 19 of T 32 N, R 79 W, (5) caverns developed in saturated Madison and Casper carbonates that produced water in wells 39 and 149, respectively (Summerford, 1965b; Wright Water Engineers, 1984), (6) dissolution-enlarged fractures found within Madison outcrop in the hanging wall of the Hat Six fault, as shown on Figure 11, and (7) local depths to water in wells penetrating the Madison aquifer on Casper Mountain that range from 137 to 510 feet in T 32 N, R 79 W and qualitatively indicate the recharge area is well drained, and therefore, that permeabilities are very large.

Recharge:

The karstified Madison aquifer in the Casper Mountain groundwater compartment is recharged at the rate of 6.2 inches per year, or 22% of the annual precipitation recorded on Casper Mountain and illustrated on Figure 12, based on a steady-state water balance for the recharge area outlined on Figure 7. The recharge rate was calculated by dividing the discharge of springs listed in Appendix B (1.3×10^{12} in^3/year) by the recharge area (2.1×10^{11} in^2). However, the total volumetric discharge does not include the collective flow of several springs that discharge between 4 and 91 gpm from the Madison aquifer into streams which cross Casper outcrop downstream. In addition, the combined discharge of wells producing water from the Madison aquifer is considered negligible because most of these wells are located on Casper Mountain and are only used sparingly during the summer months for domestic purposes.

The Madison aquifer is recharged through approximately 36 mi^2 of Fremont Canyon, Madison, and Casper outcrops on Casper Mountain that lie south of a groundwater divide in the aquifer, as shown on Figure 7. Precipitation and runoff directly

Figure 11. Photograph of spring 117 which discharges groundwater from the Madison aquifer through a dissolution-enlarged longitudinal joint found in the hanging wall of the Hat Six fault near the base of Hat Six Canyon below the Harris Ranch Falls. View is to the south-southwest, parallel to the trend of the Hat Six fault.

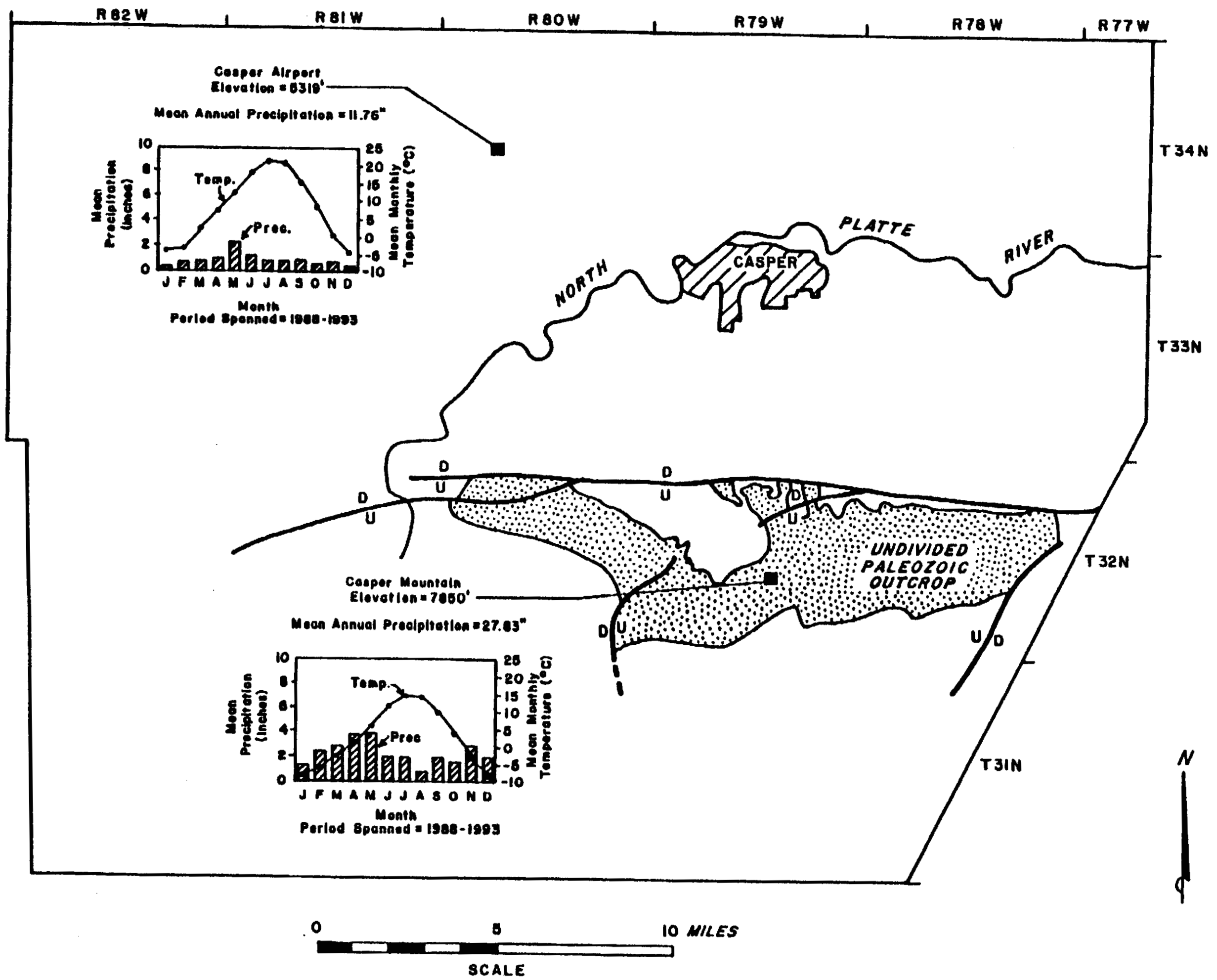


Figure 12. Recent climatic data for the Casper Mountain area of Natrona County, Wyoming. Notice that the mean annual precipitation falling on Casper Mountain is more than double the amount falling at the Casper Airport just north of the study area. Data obtained from Wyoming Water Resources Center data base.

recharge the Madison aquifer through fractures and intergranular pores in interdrainage areas on the flanks of Casper Mountain, and through sinkholes, fractures, and intergranular pores in drainages eroded into at least the upper part of the Casper Formation.

Recharge to the Madison aquifer is also derived from an additional 15 mi^2 area, depicted on Figure 7, that borders the Paleozoic outcrops on Casper Mountain and includes outcrops of both Precambrian crystalline rocks, and Mesozoic shales and limestones. Precipitation falling on the Mesozoic strata does not directly infiltrate the aquifer. However, inclusion of these additional outcrops within the recharge area is appropriate because (1) several streams that emerge from saturated Precambrian rocks as springs visibly lose water and disappear downstream over Paleozoic outcrops, and (2) several springs that emerge from saturated parts of the Goose Egg Formation on the northern flank of Muddy Mountain discharge water into drainages that cross Casper outcrop downstream near springs 76 and 77.

The Madison aquifer is not recharged through Paleozoic outcrops along the northwestern margin of the Laramie Range, shown on Figure 7, for two reasons. First, the potential recharge area consists of less than 4 mi^2 of steeply-dipping Fremont Canyon, Madison, and Casper outcrops; and secondly, displacements of as much as 800 feet along the Muddy Mountain fault in sections 25, 26, 34, and 35 of T 31 N, R 79 W which have placed the Casper Formation in fault contact with near vertical Red Peak strata (Schwarberg, 1959) have disturbed the hydraulic continuity of the Madison aquifer, as illustrated on Figure 5.

Most recharge occurs from mid-March through early June, corresponding to the spring snow melt. The fact that several of the highest monthly precipitation means fall within this timeframe, as illustrated on Figure 12, indicates that precipitation facilitates both snowmelt runoff, and recharge to the Madison aquifer.

Discharge:

Groundwater emerging from the Madison aquifer in the western part of the Casper Mountain groundwater compartment is discharged through several outlets. Speas Spring, also known as Goose Egg Spring (spring 41) and shown on Figures 5 and 6, is the most important discharge point in this part of the compartment because it discharges 7,630 gpm of potable water from the confined part of the Madison aquifer (Crist and Lowry, 1972). Springs 71 and 73, shown on Figure 6, are the only other discharge points located south of the Madison Creek fault in the western part of this compartment, but the collective discharge of these springs which represents rejected recharge as defined by Mancini (1974) is only 302 gpm. North of the Madison Creek fault, the combined discharge of several springs that emerge from the Madison aquifer in the Goose Egg Block, as shown on Figure 7, is about 154 gpm.

Groundwater in the eastern part of the Casper Mountain groundwater compartment is discharged from the Madison aquifer to springs and gaining streams located along either the contact between the Casper and Goose Egg formations, or the hanging wall of the Hat Six fault. Approximately 2,190 gpm discharge to the gaining reaches of the Clear and West Forks of Muddy Creek, and Beaver Creek; and several springs situated along the Hat Six hanging wall. Groundwater discharged to these springs and gaining streams represents rejected recharge from the Madison aquifer. No less significant, however, are the Hat Six Warm Springs (springs 108-109), located near the northern termination of the Hat Six fault, as shown on Figures 6 and 7. These springs discharge 81 gpm of 18°C water.

Groundwater discharge from the Madison aquifer at springs and flowing wells in other compartments in the study area is minimal. The most noteworthy discharge point is the Alcova Hot Springs that are submerged beneath the Alcova Reservoir southwest of the study area in sections 24 and 25 of T 30 N, R 83 W. These springs discharge on average 100 gpm of 54°C water from the lower part of the saturated Casper Formation in the

Alcova groundwater compartment (Breckenridge and Hinckley, 1978). The only other locally significant discharge point is the Mohawk Oil well (well 24) that, as of July, 1993, discharged 21 gpm of 20°C water from the Madison aquifer in the Powder River groundwater compartment.

CHAPTER III

WATER QUALITY OF SELECTED AQUIFERS IN THE CASPER MOUNTAIN AREA

This chapter is a brief overview of the distribution and derivation of the chemical constituents found within waters discharged from the Madison and other minor aquifers in the study area. Water quality data obtained for selected wells and springs are listed in Appendices E, F, and G. The geographic distribution of these data, shown on Figure 6, is biased because (1) many springs and wells that discharge groundwater from aquifers other than the Madison aquifer were neither located nor sampled for geochemical analysis, (2) oil exploration or producing wells drilled into the saturated Paleozoic rocks that compose the Madison aquifer are preferentially located along anticlines, and (3) springs that discharge from the Madison aquifer are generally situated along the perimeter of the recharge area.

Geochemical analysis of water quality data using the techniques of Piper (1944), Stiff (1951), and Mazor (1991) revealed that groundwater is derived from several aquifers in the study area. Groundwaters that emanate from the Madison, Cloverly, and minor aquifers in the Goose Egg and Chugwater confining layers were discriminated on the basis of differences in major ion compositions. Waters having intermediate compositions between end members of Madison, and minor aquifers in the Goose Egg and Chugwater confining layers were also distinguished. Cloverly waters were analyzed to confirm whether faulting of the Paleozoic and Mesozoic rocks had severed the Madison aquifer.

Water Quality of the Madison Aquifer:

The water quality of the Madison aquifer is highly variable and differs markedly between the Casper Mountain and adjacent groundwater compartments. The variability in water quality between compartments is due to unique diagenetic histories and differing groundwater circulation rates. Total dissolved solids concentrations of groundwater discharged or withdrawn from the Madison aquifer in the Casper Mountain groundwater compartment range from 97 mg/l in the recharge area to 298 mg/l where the aquifer is confined, as shown on Figure 9. The small total dissolved solids concentrations in combination with the predominance of Ca^{+2}, Mg^{+2}, and HCO_3^-, as depicted on Figure 13, reveal that groundwater circulation rates through the compartment are rapid. In contrast, the total dissolved solids concentrations in adjacent compartments range from 1,623 to 4,187 mg/l with Ca^{+2}, Na^+, SO_4^{-2}, and Cl^- being the predominant ions, indicating that groundwater movement in these compartments is relatively slow.

Figure 14 is a trilinear representation of the water quality of wells and springs that discharge water from the Madison aquifer. Calcium-bicarbonate type waters are characteristic of the Casper Mountain groundwater compartment, based on the method for identifying hydrochemical facies developed by Morgan and Winner (1962), and Back (1966) for use with the trilinear diagram of Piper (1944). In adjacent compartments, sodium-sulfate type waters are characteristic.

The relatively higher concentrations of Ca^{+2}, Na^+, Cl^-, and SO_4^{-2} in Madison water obtained from groundwater compartments adjacent to the Casper Mountain groundwater compartment are a result of the dissolution of interstitial anhydrite ($CaSO_4$) and halite ($NaCl$) from Casper sandstones where groundwater circulation has been negligible. The dissolution of anhydrite is considered extensive because (1) anhydrite occurs as an accessory mineral within Tensleep sandstones of the South Casper Creek Field in T 33 N,

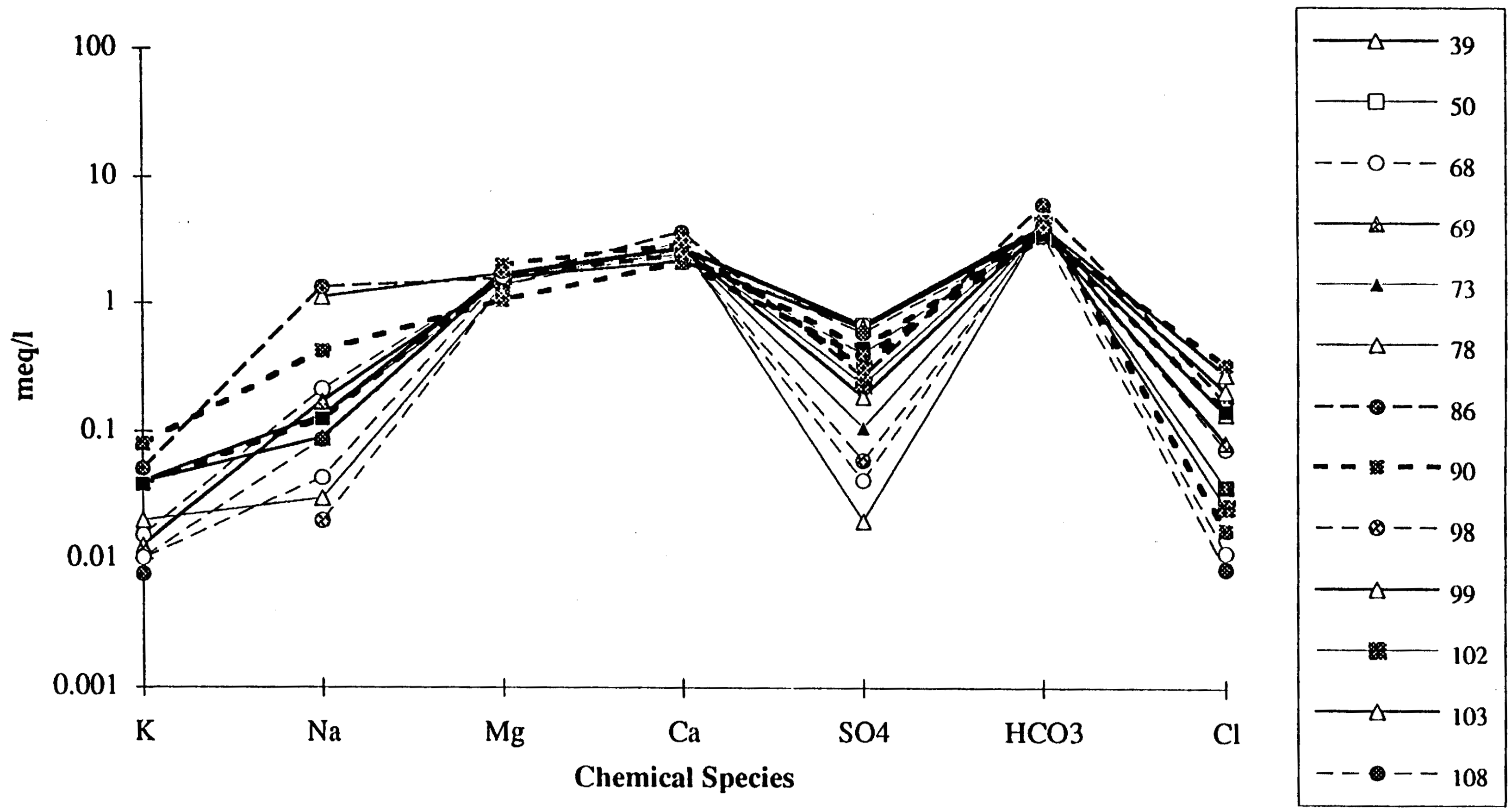


Figure 13. Fingerprint diagram showing the chemical composition of groundwater discharged from the Madison aquifer within the Casper Mountain groundwater compartment in the Casper Mountain area of Natrona County, Wyoming. Numbers correspond to locations shown on Figure 9 and to data listed in Appendices E and F. Plotting technique after Mazor (1991).

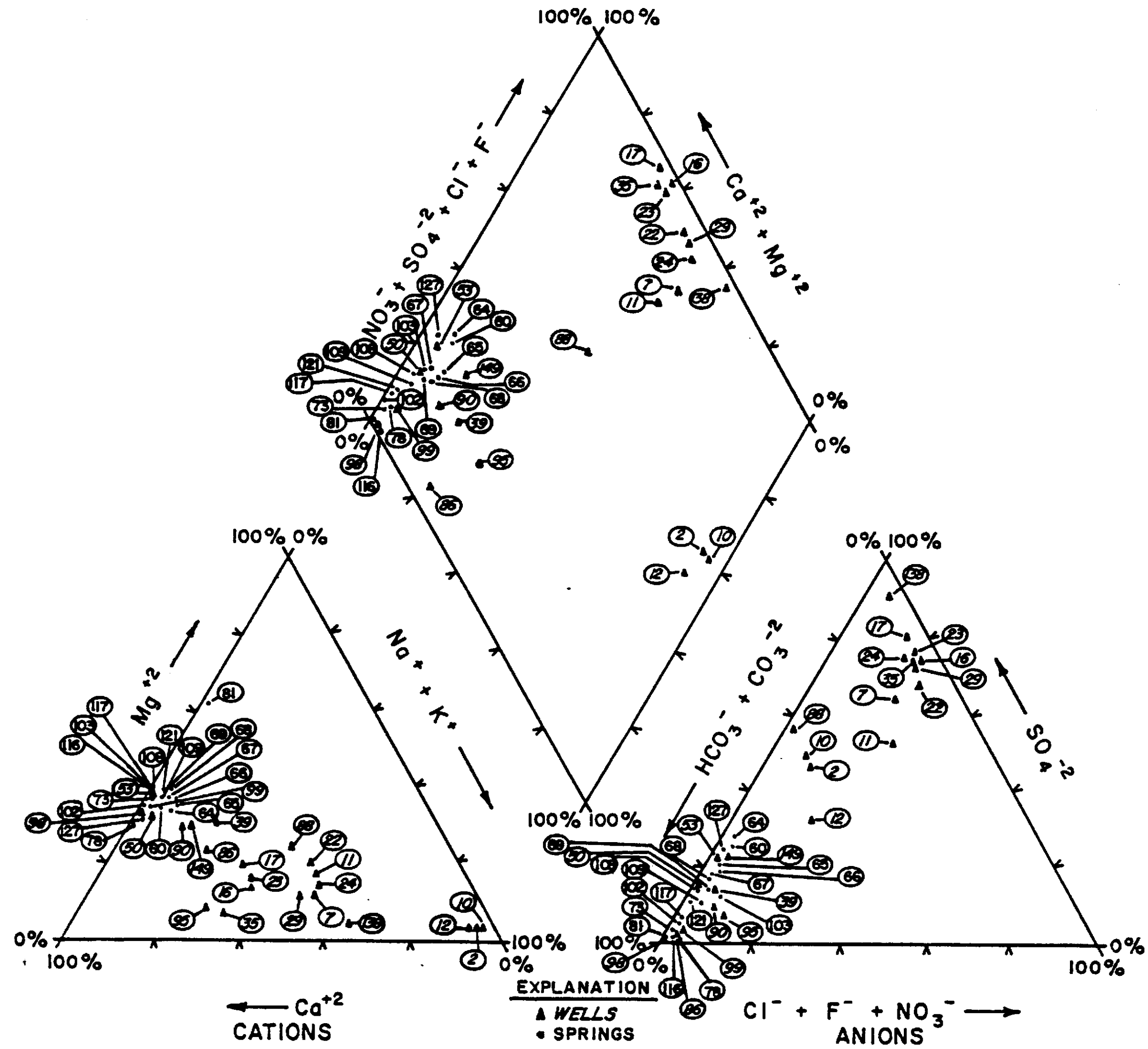


Figure 14. Trilinear diagram showing the chemical composition of groundwater discharged from the Madison aquifer within the Casper Mountain area of Natrona County, Wyoming. Numbers correspond to locations shown on Figures 6 and 9, and to data listed in Appendices E and F. Plotting technique after Piper (1944).

R 83 W (Cole and Mullen, 1992), and (2) the dissolution of anhydrite cements from the Casper-equivalent Minnelusa sandstones at Hawk Point Field has been pervasive (James, 1989). Although no halite has been observed locally, the higher concentrations of Na^+ and Cl^- in groundwater obtained from local oil exploration wells in these adjacent compartments, and relict halite crystal impressions in the Casper-equivalent Tensleep Formation in the Bighorn basin (Andrews and Higgins, 1984) strongly imply that minor amounts of halite are present where circulation has been minimal.

Water Quality of Minor Aquifers in the Goose Egg and Chugwater Confining Layers:

Although the Goose Egg and Chugwater formations constitute a regional confining layer, local aquifers exist where limestone interbeds are saturated. Groundwater obtained from these minor aquifers in the Goose Egg and Chugwater confining layers in the Casper Mountain groundwater compartment ranges in total dissolved solids from 1,027 to 2,886 mg/l. Ca^{+2}, Mg^{+2}, and SO_4^{-2} are the predominant ions, as illustrated on Figure 15.

Figure 16 is a trilinear representation of the water quality of wells and springs that produce water from these minor Goose Egg and Chugwater aquifers. Groundwater discharged from these limestone aquifers is predominantly of the calcium-sulfate type.

The dissolution of anhydrite from within the Goose Egg Formation accounts for most of the total dissolved solids. Burk and Thomas (1956) found numerous beds, thin partings, and lenses of gypsum within outcrops of the Goose Egg Formation. Furthermore, geophysical logs of wells drilled into at least the upper part of the Casper Formation within South Casper Creek Field reveal the presence of anhydrites near the base of the Goose Egg Formation, as shown on Figure 8 (Cole and Mullen, 1992).

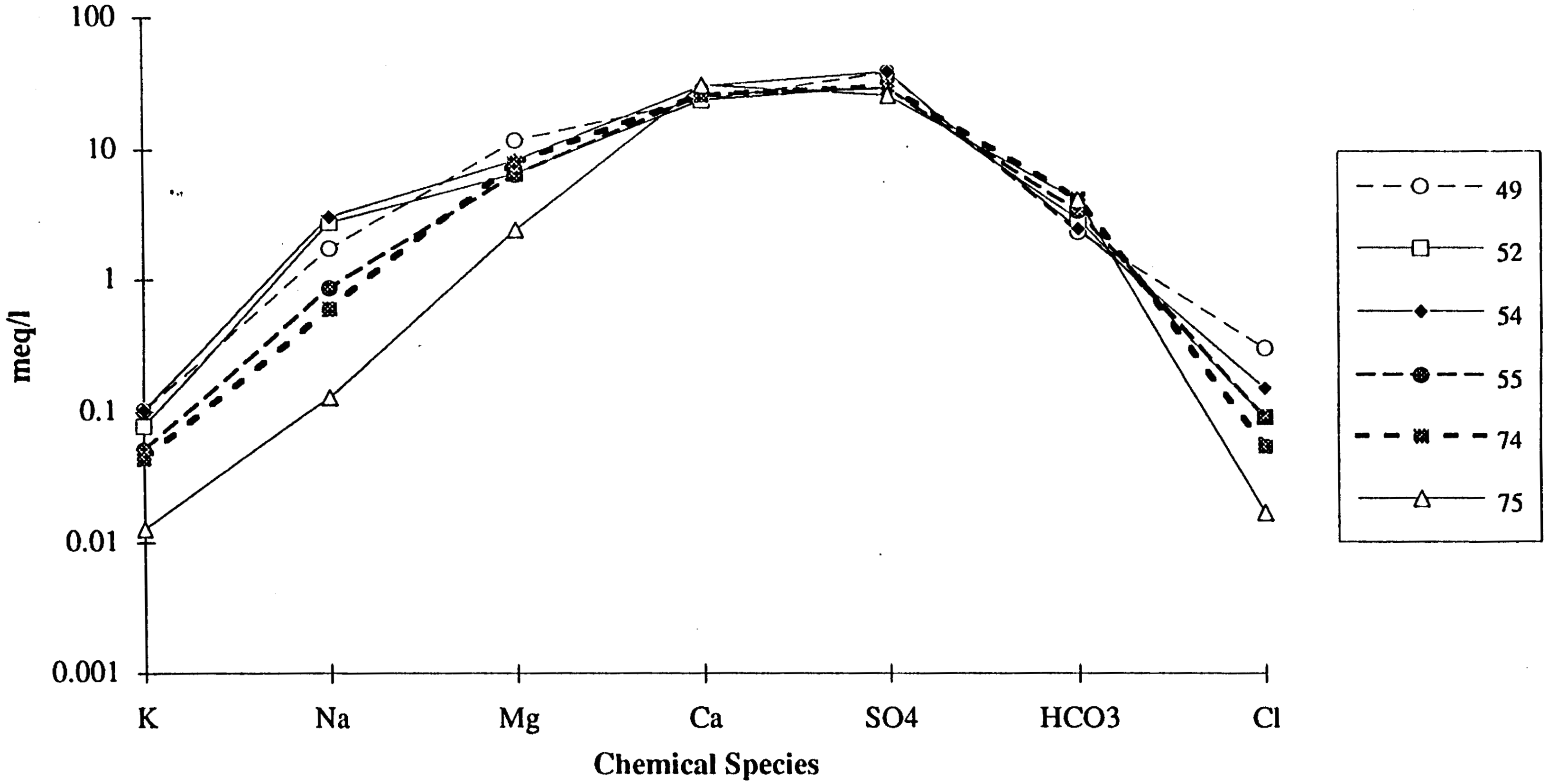


Figure 15. Fingerprint diagram showing the chemical composition of groundwater discharged from minor aquifers in the Goose Egg and Chugwater confining layers within the Casper Mountain groundwater compartment in Natrona County, Wyoming. Numbers correspond to locations shown on Figure 6 and to data listed in Appendices E and F. Plotting technique after Mazor (1991).

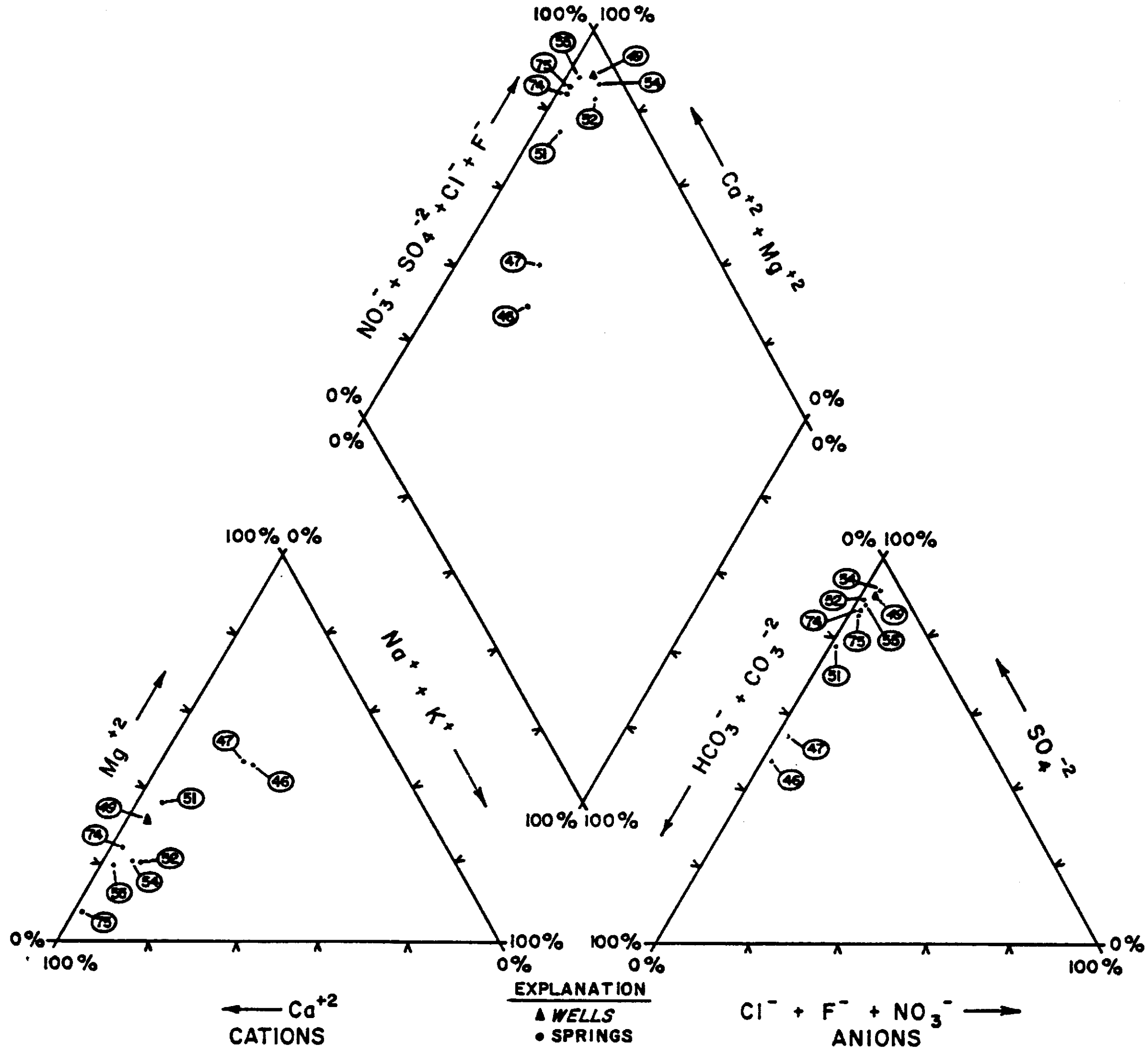


Figure 16. Trilinear diagram showing the chemical composition of groundwater discharged from minor aquifers in the Goose Egg and Chugwater confining layers in the Casper Mountain groundwater compartment in Natrona County, Wyoming. Numbers correspond to locations shown on Figures 6 and to data listed in Appendices E and F. Plotting technique after Piper (1944).

Water Quality of Groundwater Discharged from the Madison Aquifer through the Goose Egg Confining Layer:

Groundwaters discharged or produced from the Madison aquifer through fractures that breach the Goose Egg Formation along the perimeter of the recharge area have total dissolved solids concentrations that range between those for end members of the Madison, and minor aquifers in the Goose Egg and Chugwater confining layers. The total dissolved solids concentrations of groundwater discharged to springs and wells range from 446 to 1,030 mg/l, as shown on Figure 9. Ca^{+2}, SO_4^{-2}, and HCO_3^- are the predominant ions in groundwater obtained from these discharge points, as illustrated on Figure 17.

Figure 18 is a trilinear representation of the chemical composition of groundwater that originates from the Madison aquifer, and emerges through fractures that penetrate the Goose Egg Formation. The chemical composition of these waters ranges from calcium-bicarbonate to calcium-sulfate type.

Increases in the total dissolved solids concentration in groundwater discharged from the Madison aquifer at these springs and wells result from either the dissolving of anhydrite along fractured zones within the Goose Egg Formation, or the mixing of groundwaters from the Madison, and minor aquifers in the Goose Egg and Chugwater confining layers. Anhydrite dissolution or groundwater mixing is revealed by (1) concentrations of Ca^{+2} and SO_4^{-2} in groundwater discharged at well 39, shown on Figure 9, where the Goose Egg Formation had been cased off that are lower than the concentrations of these same ions at spring 41 where groundwater circulates through the lower part of the Goose Egg Formation along fractures before reaching the land surface, (2) the intermediate chemical composition of groundwater discharged at springs and wells located in structurally deformed areas, as shown on Figures 9 and 17, (3) the linear relationship between the concentrations of Ca^{+2}, SO_4^{-2}, and total dissolved ions, depicted on Figure 19, for

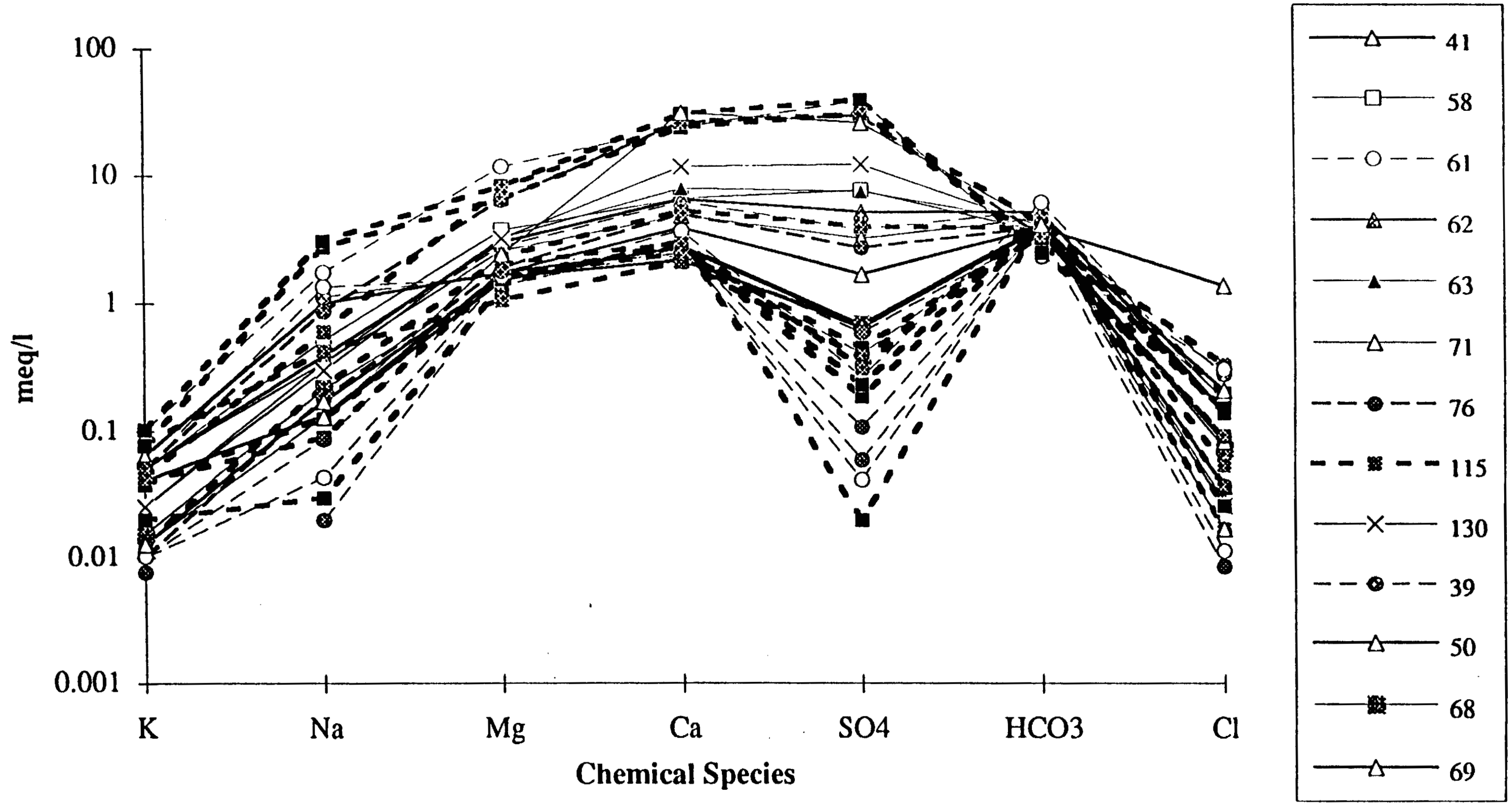


Figure 17. Fingerprint diagram showing the chemical composition of groundwater discharged from both the Madison and minor aquifers in the Goose Egg and Chugwater confining layers within the Casper Mountain groundwater compartment in Natrona County, Wyoming. Notice that the chemical compositions of groundwater discharged from the Madison through conduits that penetrate the Goose Egg confining layer plot between end member compositions for the Madison, and minor aquifers in the Goose Egg and Chugwater confining layers. Numbers correspond to locations shown on Figure 9 and to data listed in Appendices E and F. Plotting technique after Mazor (1991).

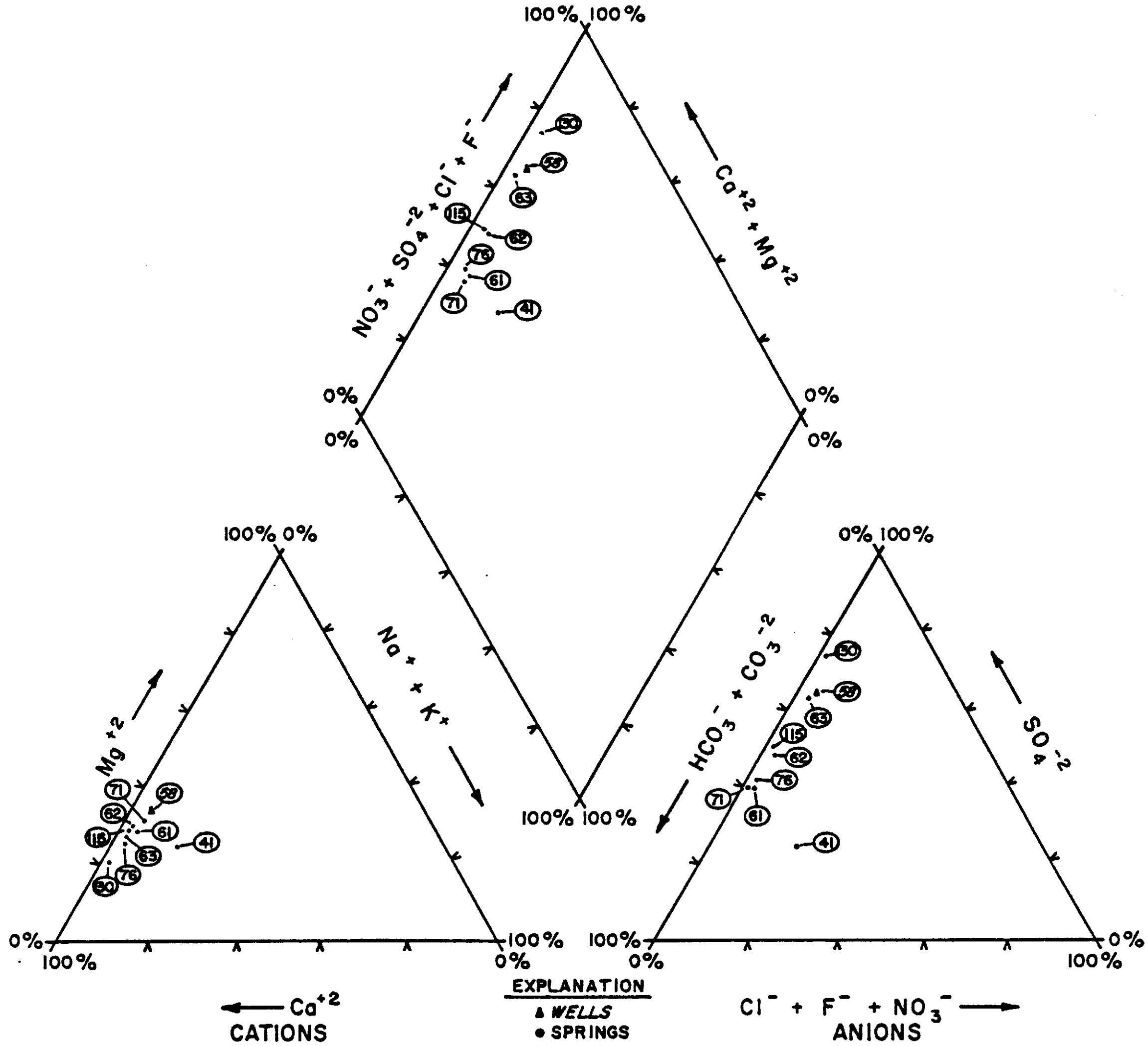


Figure 18. Trilinear diagram showing the chemical composition of groundwater discharged from the Madison aquifer through the overlying Goose Egg confining layer within the Casper Mountain groundwater compartment in Natrona County, Wyoming. Numbers correspond to locations shown on Figure 9 and to data listed in Appendices E and F. Plotting technique after Piper (1944).

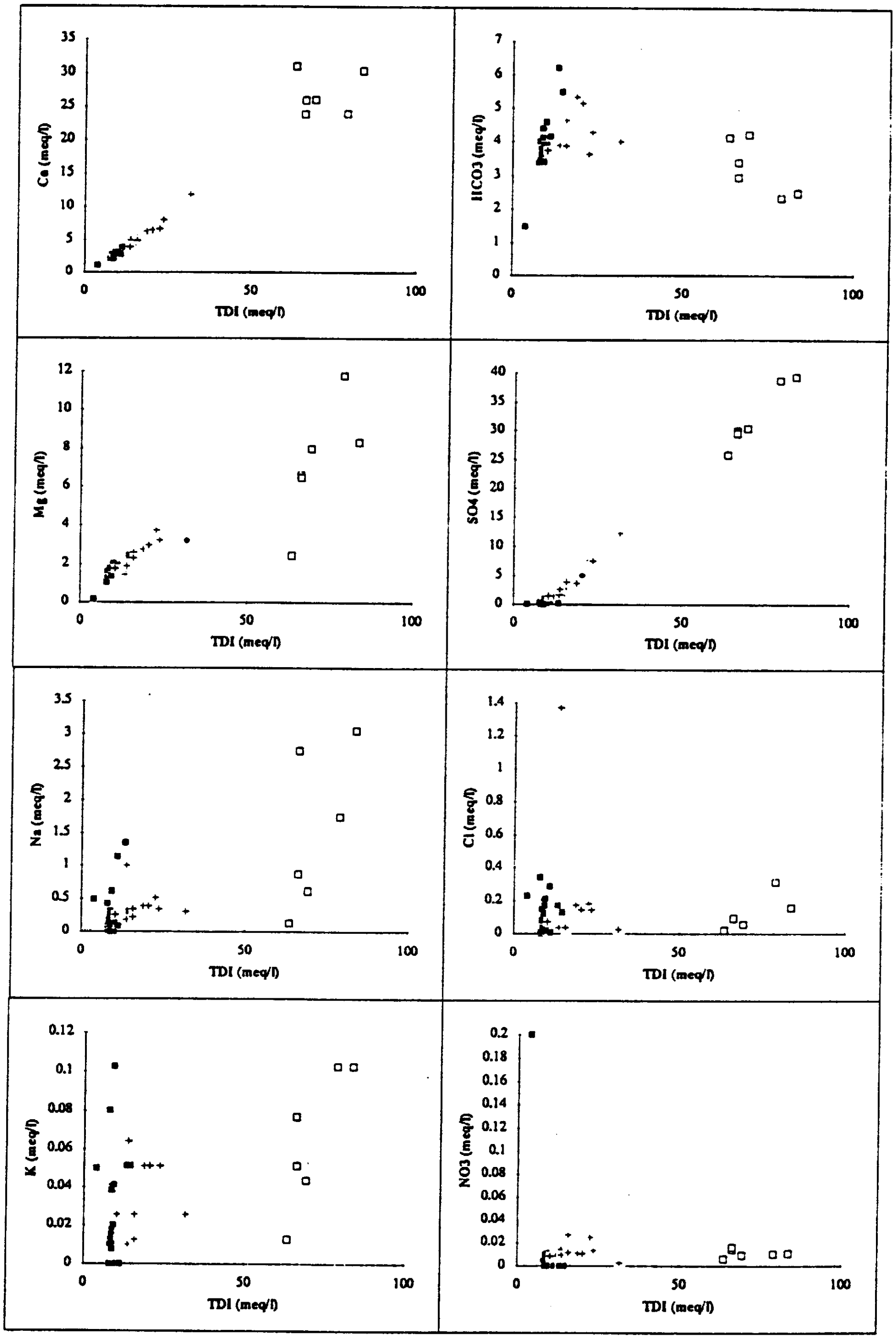


Figure 19. Water composition diagrams showing the chemical concentrations of major ions versus the concentration of total dissolved ions (TDI) for groundwater discharged from minor aquifers in the Goose Egg and Chugwater confining layers (open squares), directly from the Madison aquifer (solid squares), and from the Madison aquifer through the overlying Goose Egg confining layer (pluses) within the Casper Mountain area in Natrona County, Wyoming. Notice that only Ca^{+2}, Mg^{+2}, and SO_4^{-2} plot linearly versus TDI.

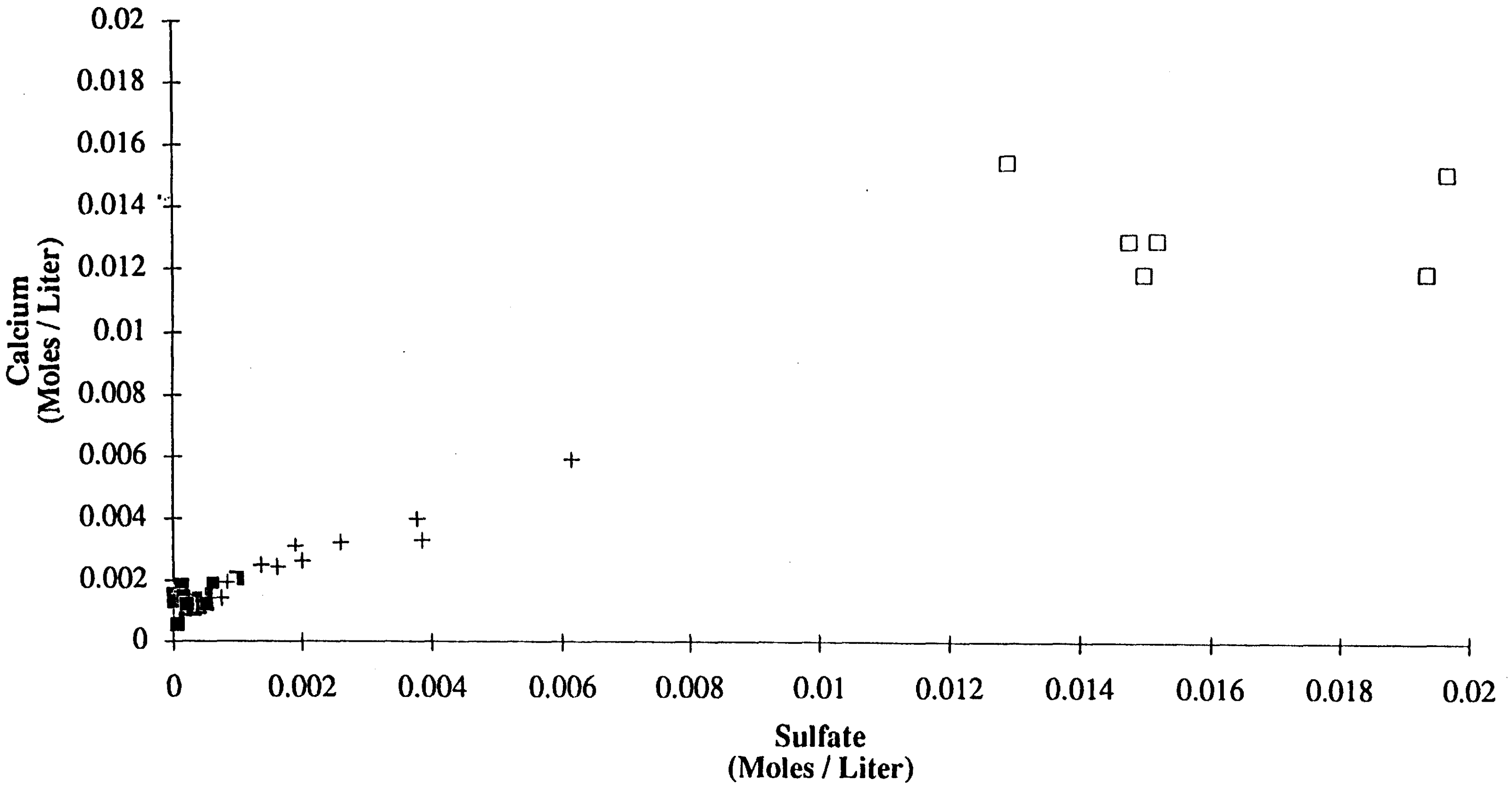


Figure 20. Water composition diagram showing the concentration of Ca^{+2} versus the concentration of SO_4^{-2} for groundwater discharged from minor aquifers in the Goose Egg and Chugwater confining layers (open squares), directly from the Madison aquifer (solid squares), and from the Madison aquifer through the overlying Goose Egg confining layer (pluses) within the Casper Mountain area of Natrona County, Wyoming. The linear stoichiometric relationship between these ions substantiates the hypothesis that anhydrite is being dissolved from the Goose Egg Formation along flowpaths.

groundwater discharged from the Madison, and minor aquifers in the Goose Egg and Chugwater confining layers, and (4) the linear, stoichiometric relationship between molar concentrations of Ca^{+2} and SO_4^{-2}, graphically illustrated on Figure 20, for water that emerges from the Madison, and minor Goose Egg and Chugwater aquifers.

Although anhydrite dissolution and groundwater mixing can both account for local increases in the concentrations of Ca^{+2} and SO_4^{-2}, mixing of water derived from the Madison, and minor aquifers in the Goose Egg and Chugwater confining layers is considered less likely based on the mixing criteria of Piper (1944) and the amount of water discharged from these minor Goose Egg and Chugwater aquifers locally. According to Piper (1944), the supposedly mixed water must (1) plot on a straight line between end member components on a trilinear diagram, and (2) satisfy the following equations:

$$V_a = \left(\frac{bE_b}{aE_a + bE_b}\right)100$$

$$E_m = \frac{E_a E_b\,(a + b)}{aE_a + bE_b}$$

$$C_m = C_a V_a + C_b V_b$$

Where:

V_a = percentage of component A in mixture

V_b = percentage of component B in mixture

E_a = concentration of total dissolved ions in component A of mixture in milliequivalents per liter (meq/l)

E_b = concentration of total dissolved ions in component B of mixture in milliequivalents per liter (meq/l)

E_m = concentration of total dissolved ions in mixture (meq/l)

C_a = concentration of particular ion in component A (meq/l)

C_b = concentration of particular ion in component B (meq/l)

C_m = concentration of particular ion in mixture (meq/l)

a = distance on Trilinear diagram between component A and mixture

b = distance on Trilinear diagram between component B and mixture

Examination of the trilinear diagrams shown on Figures 14, 16, and 18 indicates that the first criterion for mixing between the Madison, and minor Goose Egg and Chugwater aquifers is satisfied. Using the latter two equations, the calculated concentrations of total dissolved ions, calcium, and sulfate for springs 62, 63, 71, and 130 which on average differ only about 10% from the actual concentrations seem to further indicate that mixing is occurring. However, it is considered unlikely that mixing accounts for these ionic concentrations. Based on the first equation, 17% of the groundwater discharged at these four springs is on average derived from minor aquifers in the Goose Egg and Chugwater confining layers. Mixing of these waters with those of the Madison aquifer is implausible because the total discharge of springs that emerge from these minor aquifers in the western part of the Casper Mountain groundwater compartment is only about 240 gpm, an amount that is far less than the roughly 1,300 gpm needed to produce the ionic concentrations of Speas Spring through mixing.

Water Quality of the Cloverly Aquifer:

Groundwater discharged from the Cloverly aquifer in the Casper Arch and Casper Mountain groundwater compartments ranges in total dissolved solids from 402 to 905 mg/l. Na^+, HCO_3^-, and SO_4^{-2} are the predominant ions within water discharged or withdrawn from the aquifer in the footwall of the Madison Creek and Casper Mountain thrust faults. In the hanging wall, Ca^{+2}, Mg^{+2}, and HCO_3^- are the predominant ions.

Figure 21 is a trilinear representation of the chemical composition of groundwater discharged from the Cloverly aquifer. Water that emerges from the aquifer in the Casper Arch groundwater compartment is characteristically of the sodium-bicarbonate type.

The high concentration of HCO_3^- in water derived from the Cloverly aquifer in the Casper Arch groundwater compartment is attributed to the biochemical reduction of sulfate. Sulfate reduction is indicated by (1) sulfur springs and seeps (42-44, and 56-57) found along the trace of the Madison Creek fault, (2) grey-colored iron sulfides deposited in the drainages that lead away from these springs, and (3) small concentrations of Ca^{+2} and Mg^{+2} in groundwater discharged to these springs.

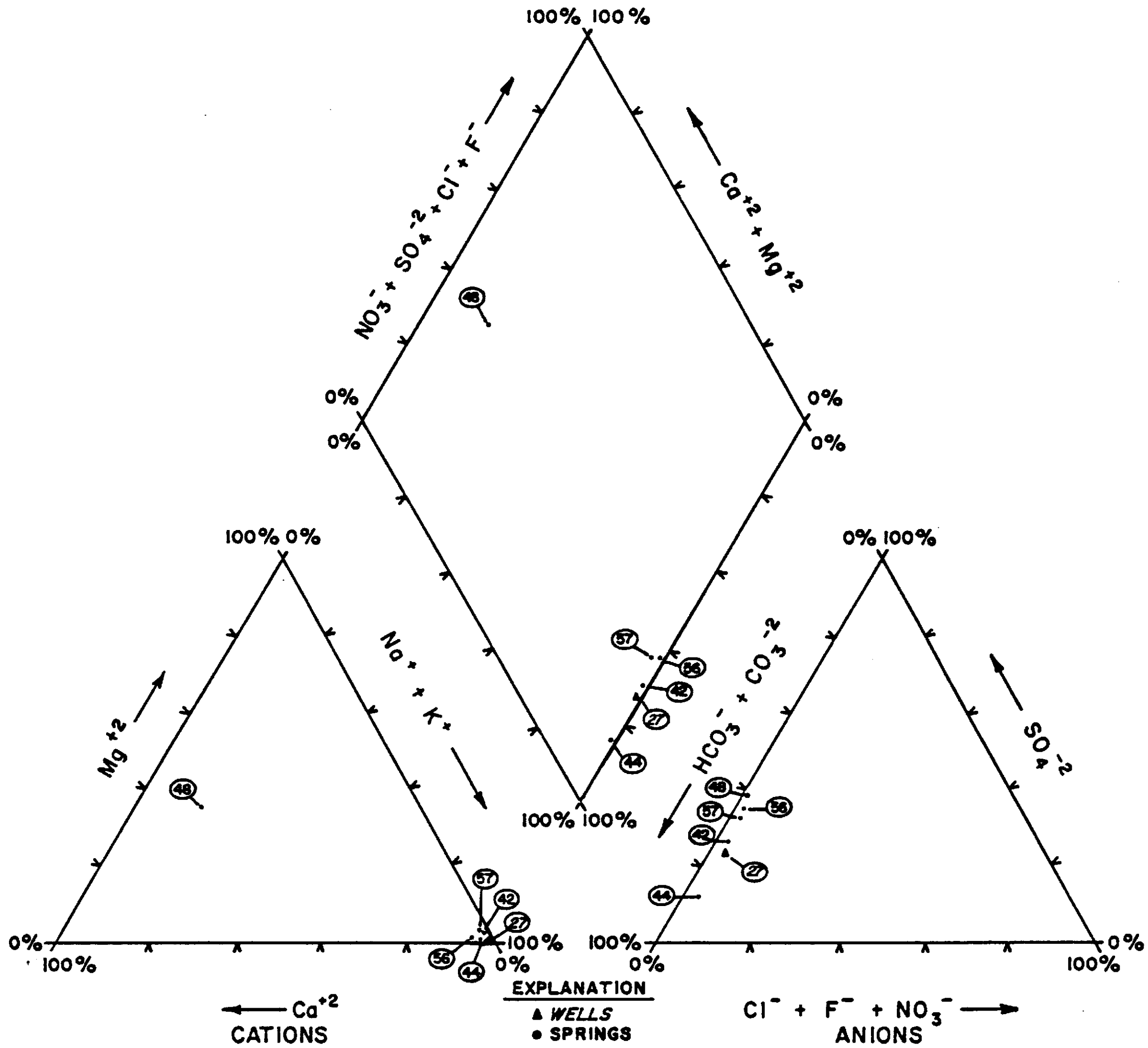


Figure 21. Trilinear diagram showing the chemical composition of groundwater discharged from the Cloverly aquifer within the Casper Arch and Casper Mountain groundwater compartments in the Casper Mountain area of Natrona County, Wyoming. Numbers correspond to locations shown on Figure 6 and to data listed in Appendices E and F. Plotting technique after Piper (1944).

CHAPTER IV
PERMEABILITY DISTRIBUTION IN THE PALEOZOIC ROCKS OF THE CASPER MOUNTAIN AREA

The objectives of this chapter are to document the permeability of various geologic features in the study area, and to delineate the network of permeable passages in the Madison aquifer. Interconnecting geologic features having bedding parallel and bedding perpendicular permeabilities form the network of permeable conduits that are organized to facilitate downgradient groundwater movement through the aquifer. Furthermore, specific geologic features within stratigraphic units and geologic structures form the principal conduits for groundwater circulation as a result of localized dissolution or structural deformation that has locally enhanced the permeabilities of these features.

Karst, fractures, intergranular pores, and paleokarst form the conduits for groundwater movement through the Madison aquifer. The contributions of these various geologic features to the whole-rock permeability of the Madison aquifer are summarized on Figure 8.

Intergranular Permeability:

Kelly (1984) and Cole and Mullen (1992) have shown that the sandstones of the Casper Formation are composed of eolian dune and interdune lithofacies that are cemented to varying degrees and have distinct permeabilities. The permeability of the intergranular pores within Casper sandstones differs between dune and interdune lithofacies within both outcrop and subcrop. In addition, the permeability of these pores also varies with the grain packing fabric and the degree of cementation. Though it has not been studied locally, the permeability of the cross-bedded sandstones that range up to two feet thick in the Fremont Canyon Sandstone (Sando and Sandberg, 1987) probably approaches that of the Casper sandstones.

The intergranular permeability of eolian dune sandstones in Casper outcrop on Casper Mountain is small and isotropic. Based on studies of fine grained dune sandstones of the Casper Formation exposed on Flat Top anticline near Medicine Bow, Wyoming, Kelly (1984) reports that these sandstones are well sorted and poorly cemented with anhydrite, calcite, and minor amounts of dolomite. However, dissolution of these cements, as well as silica, hematite, and limonite cements from the Fremont Canyon Sandstone (Sando and Sandberg, 1987), by water undersaturated with respect to these minerals has locally enhanced the permeability of the interconnected pores.

The intergranular permeability of interdune deposits within Casper outcrop in the study area is small and anisotropic based on interdune deposits exposed in the northern Laramie basin that are only moderately sorted and pervasively cemented with calcite and some dolomite. On average, the horizontal permeability component associated with these interdune sandstones is an order of magnitude greater than the vertical component based on permeameter tests conducted on samples of Casper sandstone that crop out on Flat Top anticline (Kelly, 1984).

The dissolution of interstitial cements from the Casper and Fremont Canyon formations does not in itself, however, render the units permeable in the recharge area. In fact, the relatively poor intergranular permeability associated with both the dune and interdune lithofacies of the Casper Formation is locally revealed by (1) ponded water on Casper sandstone outcrops depicted on Figure 22, (2) large drawdowns associated with several short pump tests of wells listed in Appendix C, and (3) seeps that discharge from

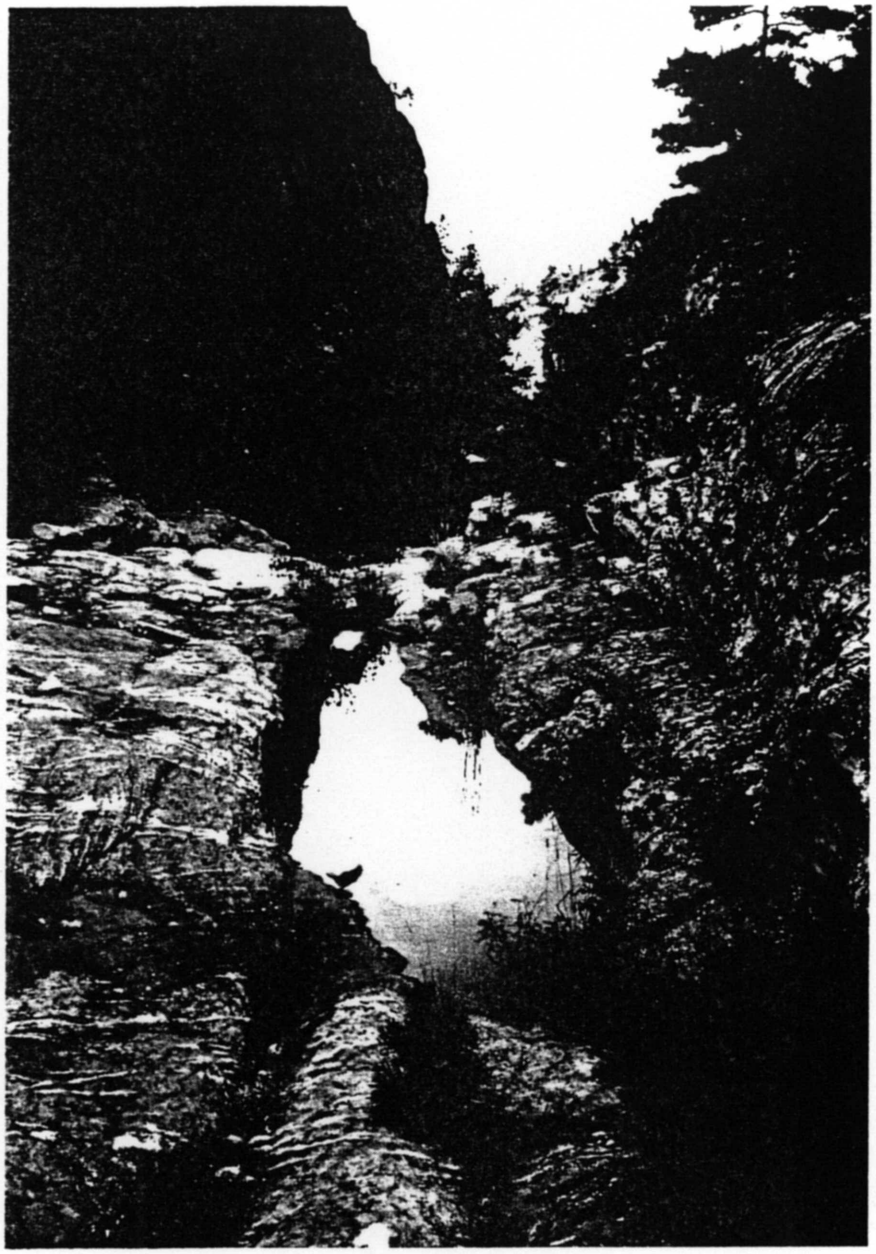


Figure 22. The permeability of fractures and intergranular pores within the Casper Formation is locally negligible as indicated by ponded water on Casper outcrop within Jackson Canyon in Natrona County, Wyoming. View is to the northeast.

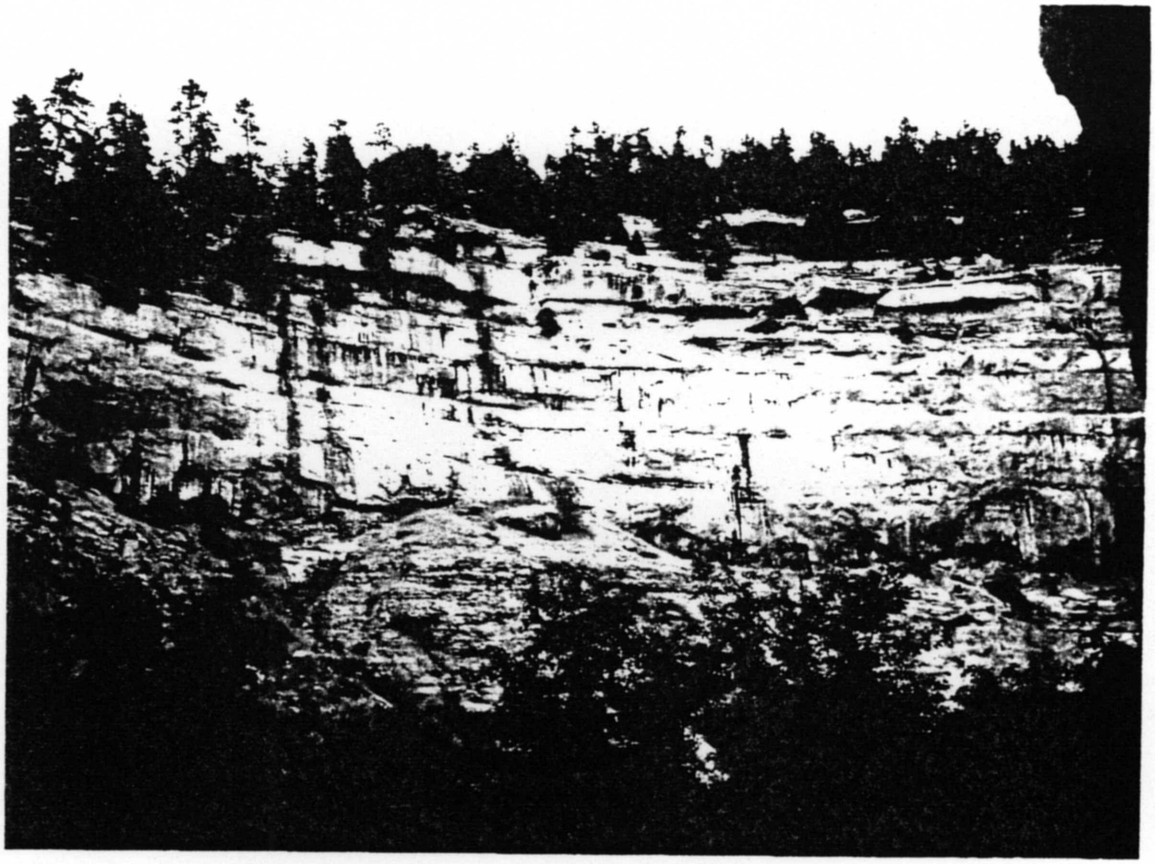


Figure 23. Partings along bedding within Casper and Madison outcrops in the north wall of Hat Six Canyon in Natrona County, Wyoming. The black streamers that descend from these partings are the result of algal growth where water has been discharged from the unsaturated zone through the cliff face.

the unsaturated Casper Formation through partings along bedding surfaces in Hat Six Canyon, as shown on Figure 23.

The intergranular permeability of dune and interdune lithofacies in Casper subcrop differs from that in outcrop of the Casper sandstones. The permeability of eolian sandstones within the South Casper Creek Field is more than three and a half times larger than that of the eolian sandstones cropping out at Flat Top anticline based on data reported by Kelly (1984) and Cole and Mullen (1992). In addition, the disparity between the horizontal and vertical permeability of the interdune lithofacies in Casper outcrop at Flat Top anticline has been minimized within subcrop at South Casper Creek Field even though the magnitude of the intergranular permeability remained virtually unchanged between these localities. Within Casper subcrop at South Casper Creek Field, Cole and Mullen (1992) also found that isotropic intergranular permeabilities associated with dune sandstones of the Tensleep Formation were more than five times larger than those of the interdune lithofacies.

Nevertheless, the intergranular permeability of the deeply buried subcrops of the Casper and Fremont Canyon sandstones is locally being destroyed through recrystallization and cementation where groundwaters are supersaturated with respect to various minerals. This conclusion is based on (1) the post-Laramide precipitation of coarse dolomite and calcite within pores of the Tensleep Formation in the Bighorn basin (Todd, 1963; Mankiewicz and Steidtmann, 1979), and (2) dolomite mineralization of the Minnelusa Formation in the Powder River basin (James, 1989).

Fracture Permeability:

The permeability of fractures located along fold crests and in the hanging walls of faults is largely dependent upon the kinematic origin of the fracture. Fractures developed as a result of extension are generally more permeable than fractures formed through compression. The following types of compressional and extensional fractures have been observed within the study area: (1) longitudinal joints, (2) cross and oblique joints, (3) vertical conjugate joint sets, (4) horizontal conjugate joint sets, (5) partings along bedding surfaces, (6) high-angle normal faults, (7) small-scale, low-angle thrust faults, and (8) large-scale thrust faults. Only the longitudinal joints, cross and oblique joints, and normal faults have significant permeabilities based on observations of these features in the study area.

The importance of fracture permeability in the study area has been documented through the following: (1) the lost circulation problems of wells 8, 20, 38, 133, and 150-151 which were drilled into Paleozoic rocks that core the Oil Mountain, Emigrant Gap, Bessemer Mountain, Bates Park, Circle Drive, and Freeland anticlines, (2) nearly instantaneous pressure recoveries in well 137 during a drill-stem test, (3) oil streaks and stains found on fracture surfaces, in addition to free oil located within open fractures, within the Casper Formation in wells 1, 2, 7, and 20 drilled on Poison Spider and Emigrant Gap anticlines, (4) the large volumetric discharge of Speas Spring (spring 41) from the confined Madison aquifer near the crest of Goose Egg dome, (5) variations in permeability measured at different tested intervals within the same formation in a given well (2, 16, and 20), (6) the dissolution of dolomite along fault and fracture zones in the South Casper Creek Field (Davis and others, 1992), and (7) the discharge of spring 69 from a fracture in Casper sandstone.

Longitudinal Joints

The significant permeability of longitudinal joints, pictured on Figure 24, is attributed to extension across the crestal parts of anticlinal and monoclinal folds. Dissolutional enlargement along a longitudinal joint found near the base of Madison outcrop in Hat Six Canyon has resulted in a three-inch-wide opening, shown on Figure 11. Similar dissolutional enlargements near the upper termini of longitudinal joints developed in

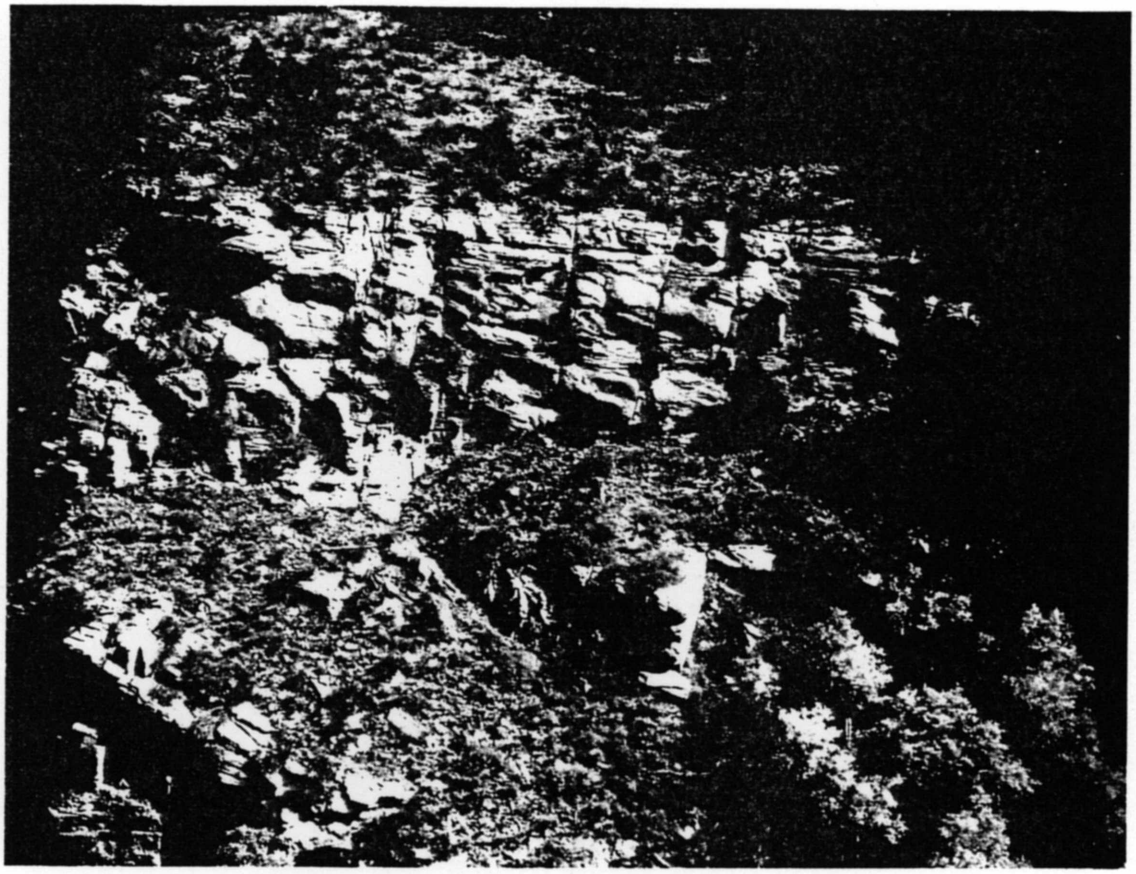


Figure 24. Longitudinal joints found within Casper sandstones on the south flank of Casper Mountain just north of spring 73 in Natrona County, Wyoming. View is to the east, roughly parallel to the trend of Casper Mountain anticline.

the Madison Formation of Sheep Mountain anticline have resulted in solution tubes that measure up to one and a half feet in diameter (Huntoon, 1993).

Longitudinal joints that extend up to hundreds of feet both horizontally and vertically form permeable conduits that vertically interconnect aquifers along the crestal parts of anticlines and monoclines. These conclusions are based on (1) rapid gas breakthroughs between a natural gas injection well and producing wells located along the strike of fractures in Little Buffalo Basin anticline (Emmett and others, 1971), and (2) the similar chemical composition of crude oils and formation water qualities, regardless of producing horizon, within anticlines of the Bighorn basin (Stone, 1967). These fractures typically attenuate upsection in the overlying shales and remain closed even where the thick, ductile Mesozoic section has been sharply folded over the Paleozoic rocks, based on the observations of Stone (1967) in the Bighorn basin.

Cross and Oblique Joints

The permeability of cross and oblique joints is attributed to extension that resulted in open separations along these fractures. The permeability of these fractures which resulted from the doubly-plunging geometries of anticlines (Hurley, 1990) is revealed by (1) a dissolution-enlarged cross joint, shown on Figures 25 and 26, that currently extends more than 200 feet into the Madison Formation from the entrance to Casper Mountain Cave, (2) sediments found within crevices in the walls of Casper Mountain Cave that indicate recent fluctuations in sediment levels, and (3) lines of pine needles found along the cave walls up to three and a half feet above the floor that reveal recent water levels in Casper Mountain Cave.

Permeable cross and oblique joints tend to be through-going. Cross and oblique joints, depicted on Figure 27, within Jackson Canyon crosscut several hundred feet of exposed Casper sandstones and limestones within Casper Mountain anticline. However,

Figure 25. Dissolution enlarged cross joint within Madison outcrop that forms the entrance to Casper Mountain Cave in Natrona County, Wyoming. Notice that the drainage leads directly to the entrance. View is to the south.

Figure 26. Dissolution enlarged cross joint near the entrance to Casper Mountain Cave in Natrona County, Wyoming. This joint forms a passage for groundwater circulation through the locally unsaturated Madison karst based on lines of pine needles found along the walls that reveal recent water levels in the cave and on sediment found in crevices in the cave walls indicating recent fluctuations in sediment levels within the cave. View is to the north toward the entrance to the cave.

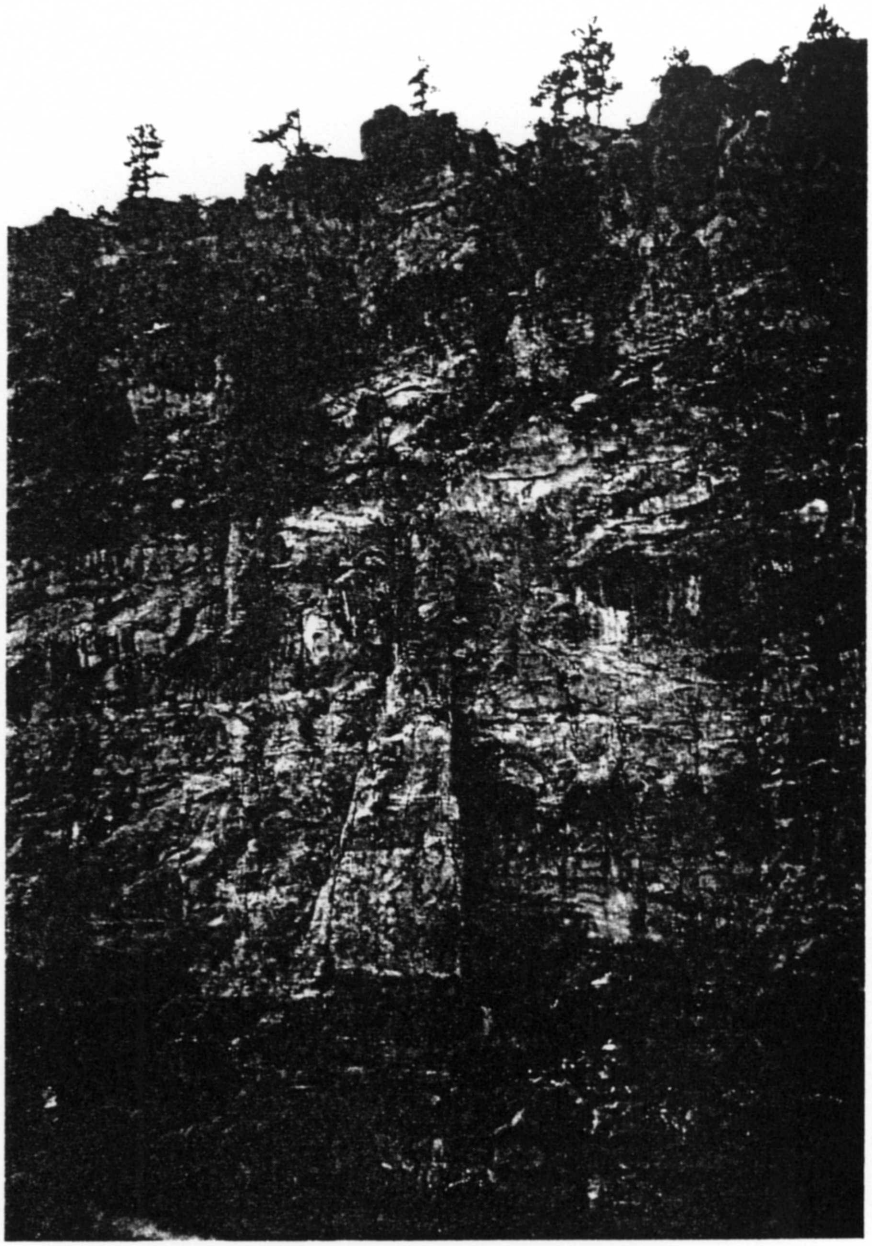


Figure 27. Cross and oblique joints found within Casper outcrop in the southwest wall of Jackson Canyon in Natrona County, Wyoming. Notice that these vertical fractures crosscut several hundred feet of Casper sandstones and limestones, and that some have minor offsets.

nowhere were these joints observed penetrating the overlying Goose Egg Formation, further substantiating Stone's (1967) observations in the Bighorn basin.

Vertical Conjugate Joint Sets

No direct evidence for the permeability of high-angle, conjugate joint sets developed along fold crests was found within the study area. Nevertheless, good examples of these joint sets, depicted on Figure 28, are found within Casper outcrop in the hanging wall of the Hat Six fault just north of Beaver Creek, and within Goose Egg outcrop in the hanging wall of the Madison Creek fault.

The development of large permeabilities along conjugate joint sets is, however, consistent with the extensional origin of these fractures. Together, the theoretical analyses of Hubbert (1951) and Dieterich (1970) indicate that the direction of applied maximum principal stress is oriented nearly vertical in a layer undergoing antiformal buckling, and that surfaces of shear failure should form 30° from the direction of this applied stress, as shown on Figure 28. Geometrical irregularities along these fracture surfaces in combination with minor displacements produce open separations that are permeable. In addition, Harris and others (1960), Bureau of Reclamation (1962), Cooley and Head (1979), and Allison (1984) found that these conjugate joint sets typically correspond to areas of greatest fracture density along the crestal parts of anticlinal and monoclinal folds located throughout the Bighorn basin.

Partings Along Bedding Surfaces

Partings along bedding surfaces in the Madison and Casper formations have been enlarged through dissolution by chemically undersaturated waters, and consequently, have enhanced permeabilities. The bedding parallel permeability of these features is indicated by (1) solution tubes formed along bedding surfaces shown on Figure 29, (2) black streamers,

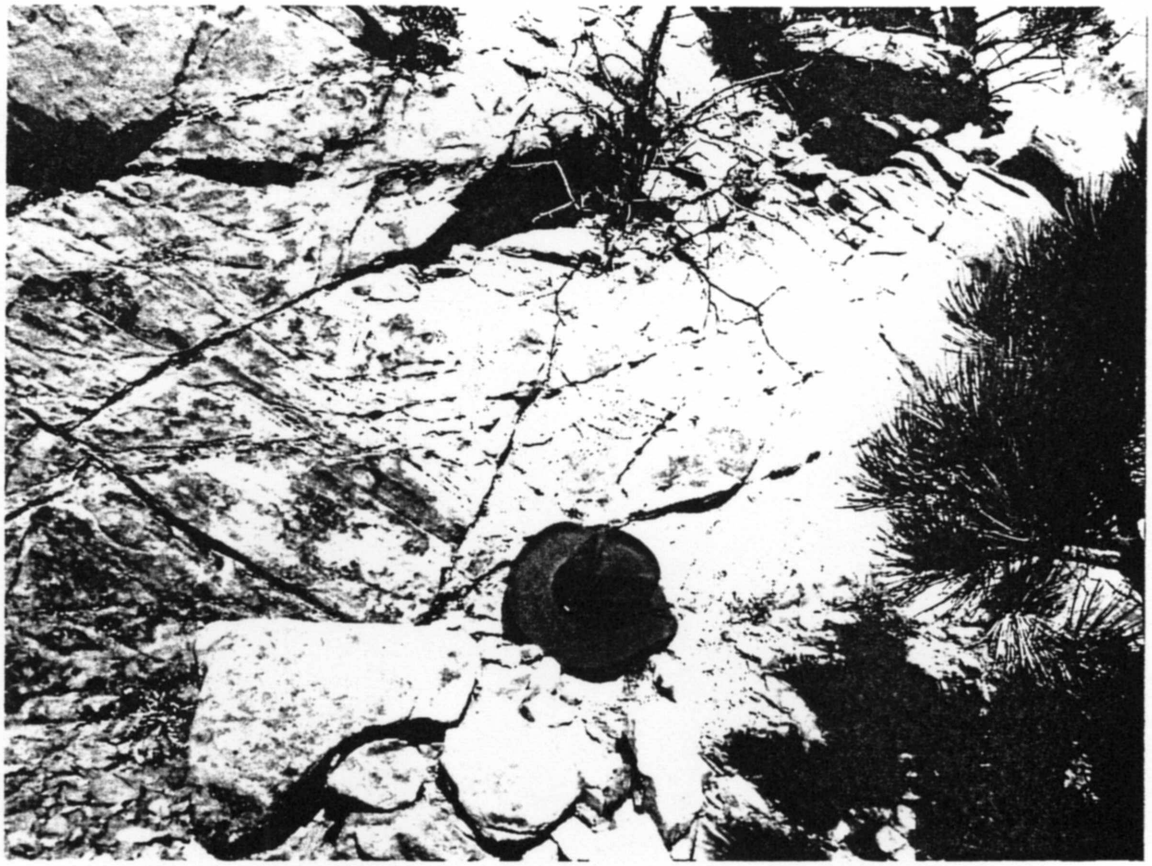


Figure 28. High-angle conjugate joint sets found within Casper outcrop in the hanging wall of the Hat Six fault just north of Beaver Creek in Natrona County, Wyoming. Notice that the acute angle formed by these joints is oriented vertical to bedding indicating that the maximum principal stress was oriented vertically during deformation and that these fractures resulted from extension. View is to the west.

Figure 29. Solution tubes developed along bedding partings in the Madison Formation in the hanging wall of the Hat Six fault in Natrona County, Wyoming. Narrow ends of white arrows indicate locations of solution tubes.

pictured on Figure 23, that descend from prominent partings along bedding in Casper and Madison outcrops in the hanging wall of the Hat Six fault, and (3) water seeps that emanate from unsaturated Casper and Madison rocks along bedding surfaces. Nevertheless, calcite deposits found on a bedding surface in a limestone unit within the Goose Egg Formation in section 12 of T 32 N, R 81 W reveal that the permeability of these fractures has locally been diminished.

Normal Faults

The enhanced permeability along normal faults within the study area is attributed to geometric irregularities along the fault surface which result in open separations. The bedding perpendicular permeability along these normal faults is revealed by springs 60, 63, and 64 which discharge nearly 70 gpm from the Madison aquifer through the overlying Goose Egg confining layer near the inconspicuous termini of several faults along the western plunge of Casper Mountain anticline.

The horizontal and vertical extent of these normal faults in the study area is limited. Vertical offsets along faults that crosscut Goose Egg and Chugwater strata are no more than several feet, as shown on Figure 30. Horizontally, these faults extend up to several hundred feet based on the distance between Casper outcrop and the locations of springs that discharge from the Madison aquifer in the overlying Goose Egg Formation.

Other Faults and Fractures

The permeability of various other fractures in the study area has generally been diminished as a result of mineralization following Laramide compression. For example, horizontal conjugate joint sets, depicted on Figure 31, within both Casper and Alcova outcrops have little permeability as a result of either calcite infilling or cementation following compression across the fracture surfaces. Similarly, variously oriented, small-

Figure 30. Normal fault slightly displacing a Goose Egg limestone within the western plunge of Casper Mountain anticline in Natrona County, Wyoming. Springs that discharge near the inconspicuous terminations of such faults indicate that these geologic features are permeable. Subhorizontal line (in the center of the photograph) indicates the trace of the fault. View is to the northwest.

Figure 31. Horizontal conjugate joint sets found within Casper outcrop in Gothberg Draw, Natrona County, Wyoming. The raised relief of these joints indicates that these fractures are more erosionally resistant as a result of cementation following compression across the fracture surfaces. This compressional event concurrently destroyed the permeability of these features.

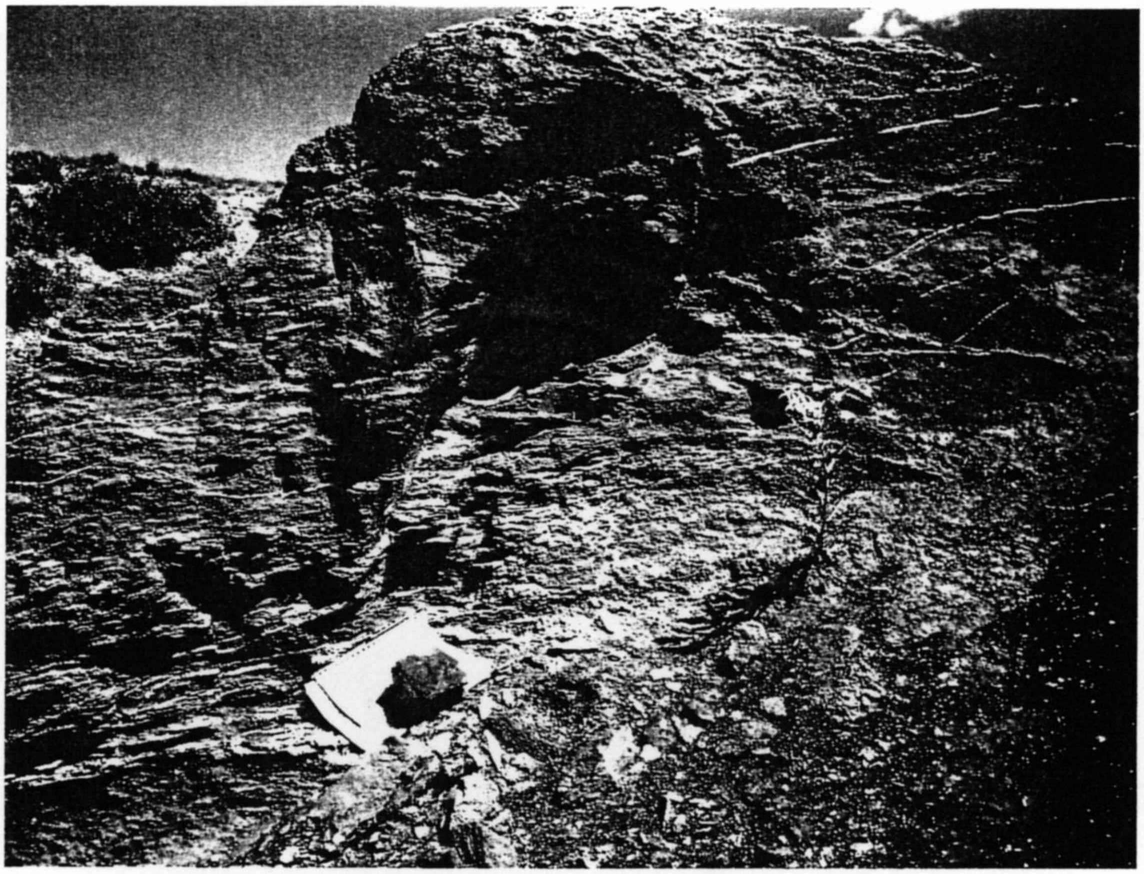


Figure 32. Variously oriented gypsum-filled fractures found within the Red Peak Formation near the crest of Bessemer Mountain anticline in the Casper Mountain area, Natrona County, Wyoming. Note that the permeability of these fractures has been destroyed as a result of the infilling.

Figure 33. Photograph of springs 42-43 that discharge groundwater along the trace of the Madison Creek fault from the Cloverly aquifer which lies in the footwall in the Casper Mountain area of Natrona County, Wyoming. The presence of these springs located on either side of the Alcova ridge which extends from the foreground to the knoll on the horizon indicates that the permeability within the Madison Creek fault has locally been enhanced. View is to the west.

scale fractures, pictured on Figure 32, infilled with gypsum in outcrop of the lower Chugwater Group along the crest of Bessemer Mountain anticline have no permeability. These findings are consistent with those of Emmett and others (1971) and Mankiewicz and Steidtmann (1979) for the Bighorn basin. Emmett and others (1971) realized that small, vertical closed fractures in Little Buffalo Basin anticline had no permeability, and that permeabilities normal to these healed fractures were diminished between 10 and 30%. Furthermore, Mankiewicz and Steidtmann (1979) reported that the permeabilities of fractures infilling with anhydrite and silica in the Bighorn basin are being reduced.

Permeabilities associated with various scales of thrust faults in the study area have generally been reduced, but there is evidence that the permeability of these structures has at least locally been enhanced. The permeability of a small-scale thrust fault found in outcrop of the Goose Egg Formation just south of the trace of the Madison Creek fault is considered negligible based on the small permeability of similar types of thrust faults found in Sheep Mountain anticline (Huntoon, 1993). In general, the permeability of these fractures is negligible owing to fault gouge. Nevertheless, the permeability of the large-scale, aquifer-severing Madison Creek fault has locally been enhanced. Groundwater discharge from the Cloverly aquifer which lies in the footwall to springs 42-44, pictured on Figure 33, which are located along the trace of the Madison Creek fault attests that the permeability of this fracture has locally been enhanced.

Karstic Permeability and Groundwater Storage in the Madison Aquifer:

Karstification of fractures developed in the Madison Formation of the Casper Mountain groundwater compartment accounts for a major part of the large, whole-rock permeability of the Madison aquifer. The large permeability of the Madison aquifer in the western part of the Casper Mountain groundwater compartment is evident based on the large, relatively constant flows from Speas Spring, shown graphically on Figure 34, in combination with the relatively small hydraulic gradient, depicted on Figure 7, between well 149 and spring 41. Quantitative analysis of the western part of the Casper Mountain groundwater compartment using the following form of the Darcy Equation confirms this:

$$K = \frac{Q}{\frac{\partial h}{\partial x} A}$$

Where:

$K \approx$ permeability of the Madison aquifer (gal/day-ft^2)

Q = the volumetric discharge of Speas Spring (7,630 gpm)

$\frac{\partial h}{\partial x}$ = the assumed average hydraulic gradient (43.8 ft/mi) between spring 41 and well 149, and

A = the cross-sectional area of the Madison aquifer (9.75 miles by 890 feet) measured along the 5,500 foot contour of Figure 7.

This analysis reveals that the average, whole-rock permeability of the Madison aquifer along the southwestern homoclinal flank of Casper Mountain approaches 29 gal/day-ft^2. However, the largest fracture permeability in the study area, calculated for well 59, is only about 22 gal/day-ft^2. Therefore, the large permeability of the aquifer is attributed to the development of a karst in the confined part of the saturated Madison Formation.

Karstification of the Madison Formation between the recharge area and basinward discharge outlets has resulted in the large storage capacity of the Madison aquifer. The storage capacity of the aquifer is considered enormous because (1) Speas Spring steadily discharges 7,630 gpm, indicating that recharge pulses are damped out before reaching the spring, and (2) the water temperature of the spring has remained between 15 and 17°C

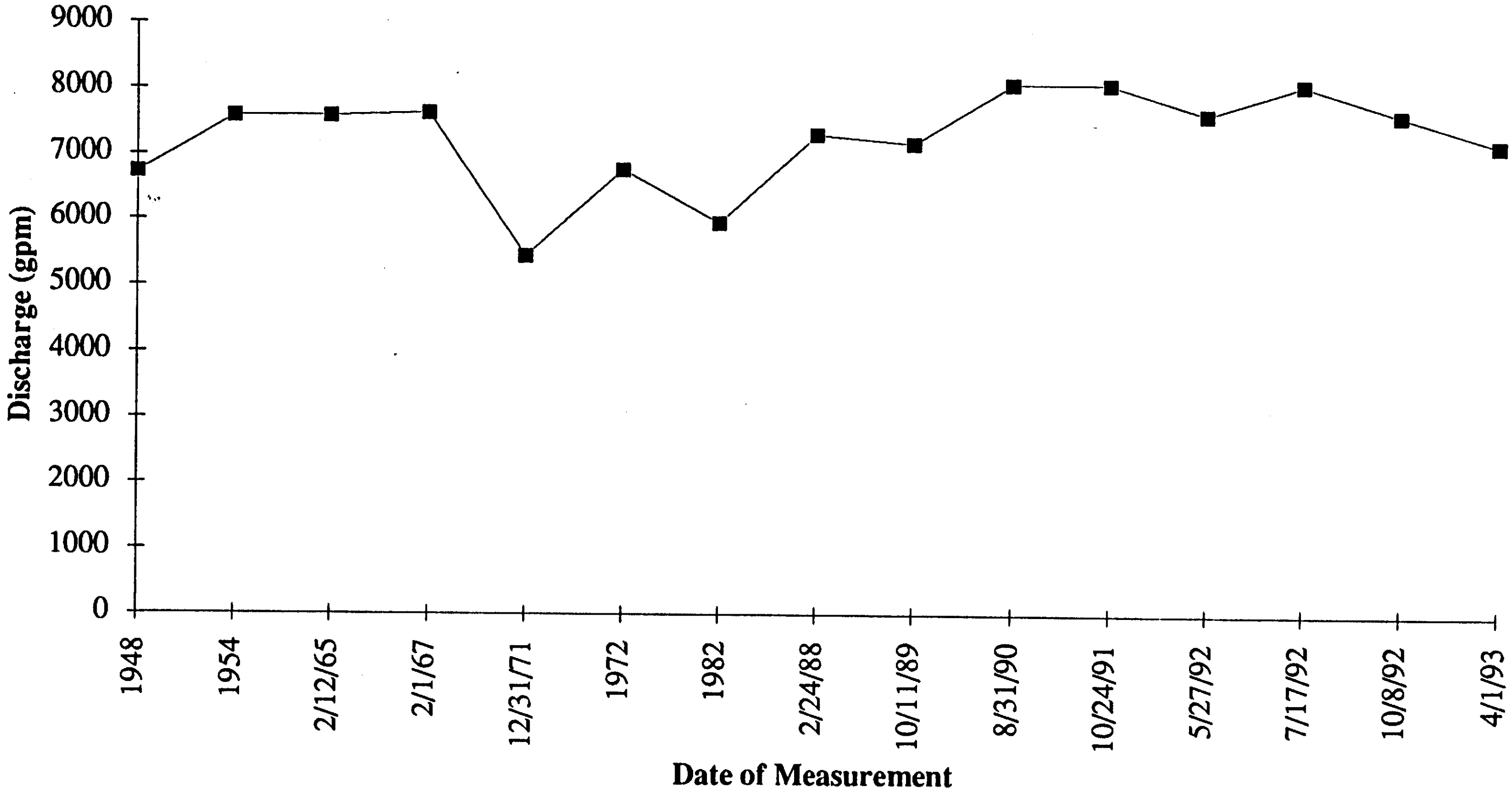


Figure 34. Graphic illustration of the large, relatively constant discharge of Speas Spring (41) from 1948-1993. Dots correspond to data listed in Appendices B and E.

since at least 1956. Consequently, the areas where the largest volumes of water are stored in the Madison aquifer correspond to the most highly transmissive zones in the study area.

Paleokarst Permeability:

At least two laterally extensive paleokarst zones developed in the upper third of the Madison Formation throughout Wyoming as a result of Mississippian dissolution followed by Pennsylvanian sedimentation (Sando, 1974). Within the study area, Madison paleokarst has been observed on the outcrop and in drill cuttings. Sando and Sandberg (1987) found that vertical and horizontal joints developed in the upper 15 feet of Madison outcrop on Casper Mountain had been infilled with sandstone. Similar sandstone-filled caverns that disrupt the horizontal continuity of bedding surfaces in the Madison were discovered in section 8 of T 32 N, R 79 W. In addition, Summerford (1965b) reported that well 39 encountered some "unconsolidated sandstone" about 100 feet into the Madison Formation. This sandstone represents one of the paleokarst horizons.

Huntoon (1993; in press) reported that paleokarst contributes little permeability to the Madison Formation in Wyoming because the network of permeable conduits associated with this inactive karst has been destroyed through burial, infilling, collapse, compaction, brecciation, cementation, or structural fragmentation. Within the study area, the meager permeability of these paleokarst zones is inferred on the basis of Summerford's (1965b) report on well 39. After encountering artesian flows in the upper part of the Madison aquifer, this well encountered a ten foot thick section of very fine to fine grained, calcareous sandstone at a depth of 740 feet in the Madison Formation. Summerford (1965b) concluded that these sediments were apparently derived from an infilled cave, but more importantly, did not record any flow of water from this sandstone. In contrast, Summerford (1965b) reported that within the next 120 feet of underlying Madison carbonates the well encountered another cave with "some sand (and an unspecified amount of)...water flowing" to the surface.

Network of Permeable Conduits that Localize Groundwater Circulation in the Madison Aquifer:

The network of permeable passages which transmit groundwater through the Madison aquifer from the recharge area to basinward discharge points within the Casper Mountain groundwater compartment is more elaborate than those networks found in adjacent compartments. This distinction results because cool, chemically undersaturated groundwater infiltrating the Madison aquifer of the Casper Mountain groundwater compartment is actively dissolving the interstitial cements and matrix material of the host aquifer, particularly within the Madison Formation, and concurrently enhancing aquifer permeability. In contrast, the permeability of the Madison aquifer in compartments adjacent to the Casper Mountain groundwater compartment is being destroyed through recrystallization, cementation, and compaction where groundwaters are supersaturated with respect to various minerals.

Network of Karstic Conduits and Fractures in the Casper Mountain Groundwater Compartment

The network of permeable conduits that facilitate groundwater circulation through the Madison aquifer in the Casper Mountain groundwater compartment differs between the saturated parts of the carbonate-rich Madison, and silica-rich Casper and Fremont Canyon formations. The morphologic and hydraulic differentiation of the Paleozoic strata results because rates of carbonate dissolution in the saturated parts of the Madison Formation exceed the rates of dissolution for the silica-rich clastic materials that compose the saturated parts of the Casper and Fremont Canyon formations. Dissolution of these soluble carbonates from the Madison Formation is facilitated by the rapid circulation of chemically undersaturated groundwater from the recharge area to basinward discharge points, particularly Speas Spring. This distinction is justified by the observations of Hill and others (1976) and Cradit (1982) who reported that Cave Creek Cave and Bad Medicine Cave, located in the Shirley and Bighorn Mountains, respectively, developed parallel to bedding surfaces between carbonate and clastic strata.

Dissolution enlarged cross and oblique joints which are typically oriented perpendicular to the trend of Casper Mountain anticline and mimic the orientations of overlying surface drainages form the principal conduits for groundwater circulation through the unsaturated karst of the Madison Formation in the recharge area. Sinkholes along the strike of Madison outcrop connect with solution-enlarged cross and oblique joints, such as Casper Mountain Cave, that closely resemble the orientations of the overlying surface drainages and trend parallel to the steepest hydraulic gradients in the recharge area. These caverns typically remain isolated in the recharge area because there are no interconnecting passages between conduits developed in adjacent drainages. Similarly, cave systems developed in the unconfined Madison aquifer along the western homoclinal flank of the Bighorn Mountains also copy the orientations of the overlying surface drainages and are independent of cross-cutting tectonic structures and regional or local dip (Huntoon, 1985c).

In contrast, uniform dissolution of soluble materials from the saturated, confined Madison Formation along rectilinear fracture networks and partings along bedding has resulted in a three dimensional network of cave passages located on the southwestern homoclinal flank of Casper Mountain between the recharge area and Speas Spring. Dissolutional enlargement or karstification of these fractures is inferred on the basis of (1) the turquoise color of groundwater discharged at Speas Spring, indicating that calcite is precipitating, (2) the large discharge of Speas Spring, and (3) the unsaturated karst developed in Madison outcrop in the recharge area. The probable configuration of this cavern system is analogous to that mapped by Scheltens (1984), Conn and Wiles (1986), and Bakalowicz and others (1987) for Wind and Jewel Caves. These authors found that carbonate dissolution along fractures in the formerly confined aquifer of the Madison-equivalent Pahasapa Limestone on the homoclinal flank of the Black Hills uplift had resulted in the development of extensive, three dimensional cavern networks. In fact, Bakalowicz and others (1987) noted that more than 70 miles of passages had been surveyed within less than a square mile in Jewel Cave.

Interconnected rectilinear fractures within the saturated Casper and Fremont Canyon formations form the principal conduits for groundwater circulation through these parts of the Madison aquifer. The importance of these fractures in diverting water from intergranular pores and transmitting it through these clastic formations is evident from (1) the large permeabilities of wells 58 and 59 which range up to two orders of magnitude larger than those measured in other wells within the Casper Mountain groundwater compartment, and (2) accumulations of Casper silt within the drainage leading away from spring 68, indicating that flow velocities through fractures are sufficient to pluck grains from fracture surfaces.

Network of Fractures in Adjacent Groundwater Compartments

The network of permeable passages that facilitates circulation through the Madison aquifer within compartments adjacent to the Casper Mountain groundwater compartment is conceptually simple. Karstic development of the Madison Formation in these parts of the study area is rare, and therefore, extensional fractures along the crestal parts of anticlines within these compartments generally account for most of the permeable passages in the aquifer. Emmett and others (1971) conclusively demonstrated the predominance of these fracture permeabilities in the Tensleep Formation at Little Buffalo Basin anticline. Open vertical fractures which facilitated the production of water even where analysis of the rock matrix indicated that it should have produced oil prompted the premature watering-out of wells. This resulted because the permeability of the open fractures far exceeded that of the intergranular pores.

CHAPTER V

GROUNDWATER CIRCULATION SYSTEMS AND EXPLORATION TARGETS FOR THE MADISON AQUIFER WITHIN THE CASPER MOUNTAIN AREA

The purpose of this chapter is to document groundwater circulation systems for the Madison aquifer that supply Speas Springs and the Hat Six Warm Springs, and to demonstrate that favorable targets for groundwater exploration exist in the Casper Mountain area. In general, groundwater circulation through the aquifer is constrained by numerous aquifer-severing, Laramide faults. These faults have hydraulically disconnected groundwater compartments having active or inactive circulation systems. The Wind River groundwater compartment is not considered at length because no data exists in the study area.

Active Circulation Systems:

Two active circulation systems are found within the Madison aquifer of the Casper Mountain groundwater compartment. The circulation system in the western Casper Mountain groundwater compartment is considered active because it is characterized by relatively steep hydraulic gradients, and a large volume basinward discharge point, Speas Spring. It is separated from the circulation system of the eastern part of the compartment by a central groundwater divide on Casper Mountain, shown on Figure 7. The circulation system in the eastern part of the compartment is considered marginally active because even though hydraulic gradients are relatively steep, the Hat Six Warm Springs only discharge minimal amounts of good quality, geothermally heated waters.

Groundwater Circulation in the
Western Casper Mountain Groundwater Compartment

Groundwater circulation within the Madison aquifer in the western Casper Mountain groundwater compartment is restricted as a result of faulting along the perimeter of the compartment. Structural displacements locally in excess of 5,000 feet along the Casper Mountain thrust fault (Sims, 1948), about 1,200 feet along the Madison Creek fault in section 10 of T 32 N, R 81 W (Faulkner, 1950), 3,000 feet between wells 138 and 139 along the Casper Arch thrust fault, and 800 feet along the Muddy Mountain fault (Schwarberg, 1959) have severed the Madison aquifer.

As a result of faulting, groundwater circulation systems within the Madison aquifer of the western Casper Mountain groundwater compartment remain hydraulically isolated from those in adjacent compartments, including those in the northwestern end of the Laramie Range. Hydraulic disconnection of the aquifer between these compartments is indicated by water quality contrasts between wells 22-24, 35, 39, 138, and 149 shown on Figure 9; hydraulic head changes between spring 41, and wells 22-24, 34-35, 137, and 149, as depicted on Figure 7; and differences in water temperatures, listed in Appendices B and D, between spring 41, and wells 24, 35, 133, and 149. In addition, water quality contrasts between Cloverly springs 42, 44, and 48 further confirm that faulting of the Paleozoic and Mesozoic strata has severed the Madison aquifer.

Contrasts in the tritium concentrations of groundwater discharged from the Madison aquifer in the Casper Mountain and Powder River groundwater compartments further reveal the hydraulic isolation of groundwater circulation systems between these compartments. Large quantities of tritium, a naturally occurring radioactive isotope of hydrogen, were added to the atmosphere during the 1950's and 1960's as a result of above ground nuclear testing. Even though tritium concentrations have diminished considerably since that time, tritium still provides a natural tracer for precipitation over the last 40 years. The tritium concentration of groundwater discharged from the Madison aquifer at Speas Spring (10.96 TU, sampled on 7/17/92; Ritz and Bruce, 1993) in the Casper Mountain compartment reveals that this water is a mixture of pre- and post-1952 water, based on the groundwater dating scheme of Mazor (1991). In contrast, the tritium concentration of groundwater discharged from the Madison aquifer in the Powder River groundwater compartment through well 24 (.04 TU, sampled on 7/28/93) reveals that the age of this water exceeds 40 years.

Groundwater discharged from the Madison aquifer within the western Casper Mountain groundwater compartment moves downgradient from the recharge area to Speas Spring along both sides of the Little Red Creek fault, as illustrated on Figure 7. This results because displacements of up to 1,000 feet along this fault, depicted on Figure 2, have locally disrupted the hydraulic continuity of the Madison aquifer. Consequently, groundwater west of the Little Red Creek fault and south of the northern groundwater divide moves downgradient parallel to bedding toward Speas Spring. On the upthrown side of the Little Red Creek fault, groundwater south of the northern groundwater divide moves southwestward, parallel to the fault, before reaching the fault termination where the hydraulic continuity of the Madison aquifer is restored.

Speas Spring

Speas Spring, depicted on Figures 35 and 36, is the lowest potentiometric point for the Madison aquifer in the western Casper Mountain groundwater compartment. With the exception of 302 gpm that discharge from springs 71 and 73, all water infiltrating the aquifer west of the central groundwater divide is discharged at Speas Spring.

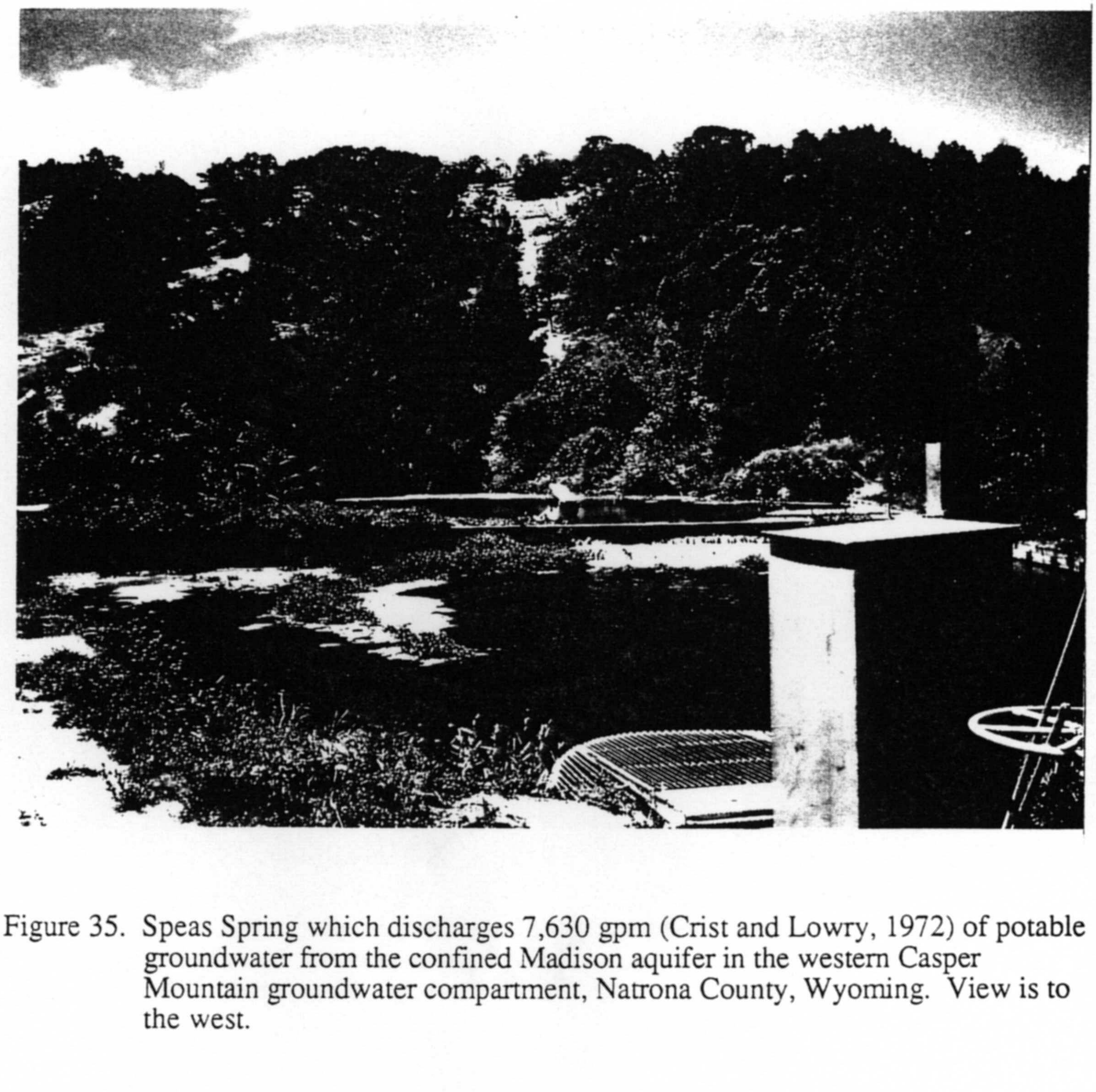


Figure 35. Speas Spring which discharges 7,630 gpm (Crist and Lowry, 1972) of potable groundwater from the confined Madison aquifer in the western Casper Mountain groundwater compartment, Natrona County, Wyoming. View is to the west.

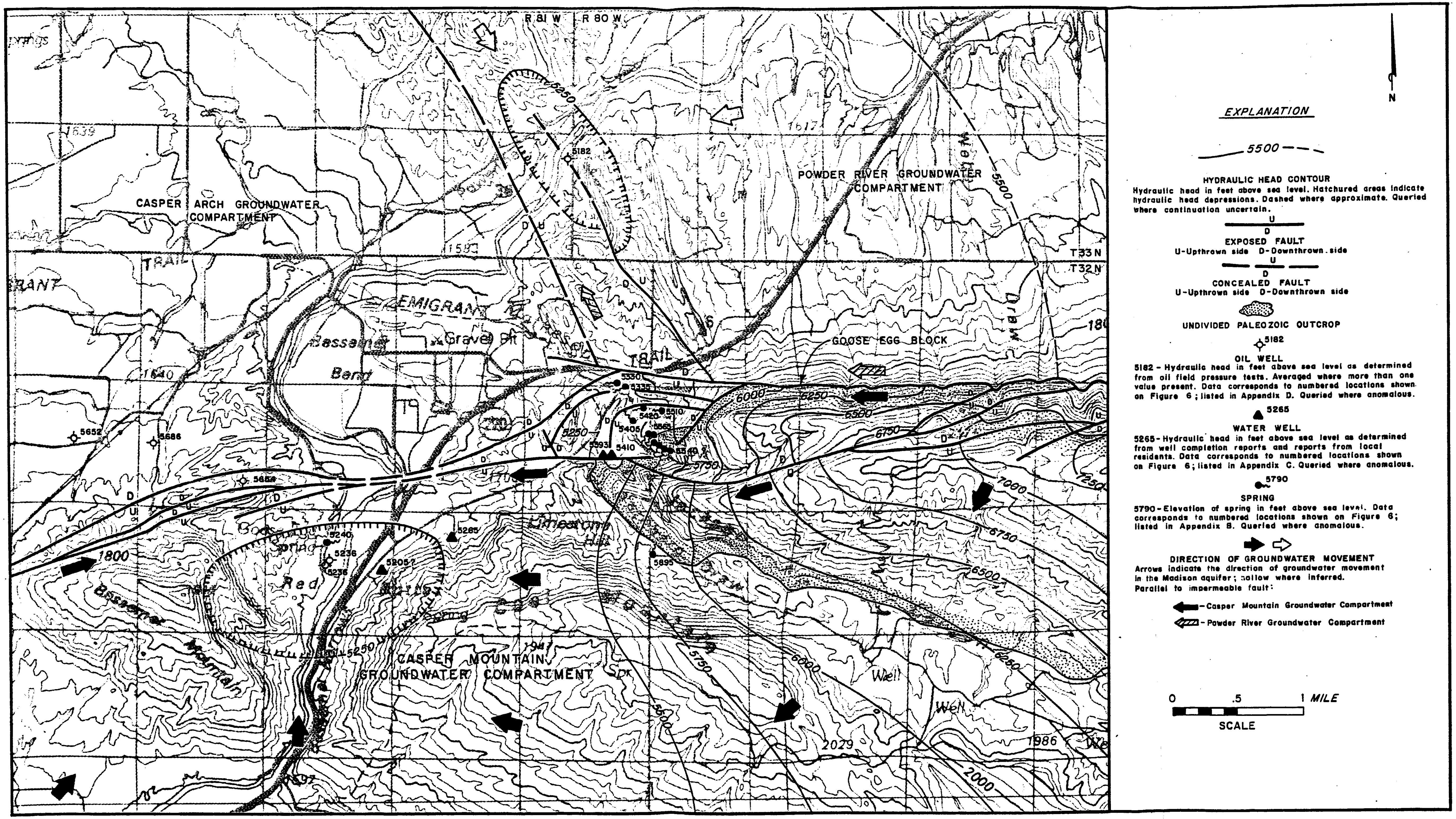


Figure 36. Hydraulic heads and groundwater flow directions associated with the Madison aquifer in the area around Goose Egg dome, Natrona County, Wyoming.

Speas Spring drains the Madison aquifer in the western Casper Mountain groundwater compartment as a result of local fracturing. Laramide uplift of Goose Egg dome along the Madison Creek fault and subsequent erosion of the Triassic and younger strata raised the Casper Formation to within 175 feet of the land surface (Summerford, 1965a), and more importantly, radially extended the Paleozoic strata across the crest of the dome. This localized extension resulted in the formation of prominent, through-going vertical joint sets, as well as longitudinal, cross, and oblique joints, that breached the overlying Goose Egg Formation. Interconnections between these joints and karst developed in the Madison Formation along the crest of Goose Egg dome form the network of permeable conduits that permit groundwater from the Madison aquifer to circulate upsection, but downgradient to the spring.

Tritium concentrations and water temperature data reveal that the discharge of Speas Spring is a mixture of pre- and post-1952 waters which circulate to depths of up to 3,000 feet within the western Casper Mountain groundwater compartment before discharging. Differences in the tritium concentrations of groundwaters discharged from the Madison aquifer in the eastern part of the recharge area at spring 112 (23.3 TU, sampled in 1989; James M. Montgomery, 1990), Speas Spring (10.96 TU, sampled on 7/17/92; Ritz and Bruce, 1993), and well 24 (.04 TU, sampled on 7/28/93) in the Powder River groundwater compartment qualitatively reveal that the discharge of Speas Spring is a mixture of pre- and post-1952 water, based on the groundwater dating scheme of Mazor (1991). Furthermore, the water temperature of Speas Spring (15.5°C) which lies between those measured for spring 73 (7°C) along the perimeter of the recharge area and well 149 (32.8°C) in the basin indicates that groundwater circulating to the spring is heated at the rate of 7.7°C per 1,000 feet (Buelow and others, 1986) before it emerges at the spring. Based on the difference between the structural elevation of the Casper Formation, shown on Figure 2, and the topographic surface, water within the Madison aquifer lies at depths in excess of 3,000 feet that are sufficient for such geothermal heating to occur.

Groundwater Circulation in the Goose Egg Block

The Goose Egg Block is a subcompartment of the Casper Mountain groundwater compartment because it remains hydraulically disconnected from the remainder of the Casper Mountain, Powder River, and Casper Arch groundwater compartments as a result of faulting. Aquifer-severing displacements of up to 1,500 feet along the Madison Creek fault and 3,000 feet along the Casper Mountain thrust fault, as shown on Figure 2, have severed the Madison aquifer and consequently disrupted the hydraulic continuity of the aquifer between the Goose Egg Block, and the Casper Arch and Powder River groundwater compartments.

Spring elevations, water quality contrasts, and temperature differences across these aquifer-severing faults indicate that the Madison aquifer within the Goose Egg Block is hydraulically disconnected from parts of the aquifer in adjacent compartments. Springs within the block, shown on Figure 36, which discharge from higher elevations than both Speas Spring and dry stream channels in Jackson Canyon and Gothberg Draw indicate that the Madison aquifer is not hydraulically connected between these parts of the Casper Mountain groundwater compartment. Furthermore, water quality contrasts, illustrated on Figure 9, between wells 24 and 35, and spring 64, in addition to temperature differences between wells 24-25 (20-28°C) and 35 (37°C), and springs 60-61 (11-15°C), indicate there is no hydraulic communication between the Goose Egg Block, and the adjoining Casper Arch and Powder River groundwater compartments.

Groundwater in the Madison aquifer of the Goose Egg Block circulates westward downgradient to springs that discharge near the toe of the recharge area, as shown on Figure 36. Springs that discharge as rejected recharge from the Madison aquifer near the termini of several normal faults, and the large transmissivity of wells 58 and 59 reveal that extensional faults and fractures form the principal conduits for groundwater circulation. The locations of these springs further indicate that either permeabilities or hydraulic gradients associated with the aquifer decrease basinward.

Groundwater Circulation in the
Eastern Casper Mountain Groundwater Compartment

Several faults that border the eastern part of the Casper Mountain groundwater compartment have hydraulically disconnected the Madison aquifer. Aquifer-severing displacements of up to 2,400 feet along the Casper Mountain thrust fault which extends at least three miles beyond the eastern limit of Casper Mountain (Bergstrom, 1950), and 1,000 feet along the Muddy Mountain fault (Sears, 1949) have hydraulically isolated circulation systems of the Madison aquifer in this compartment from those both in the northwestern end of the Laramie Range and in the Powder River groundwater compartment. Water quality contrasts, illustrated on Figure 9, between well 29 and springs 102 and 103, and differences in water temperatures between wells 28 and 29 (54-55°C) and springs 102-112 (7.5-18°C) further reveal that there is no hydraulic communication between the eastern Casper Mountain and adjacent compartments.

Within the eastern Casper Mountain groundwater compartment, water discharged from the Madison aquifer to springs and gaining streams in the Hat Six hanging wall is in places derived from both blocks of the Hat Six fault as shown on Figure 37. This results because stratigraphic displacements of up to 800 feet along the Hat Six fault (Sears, 1949) have locally disrupted the hydraulic continuity of the Madison aquifer within the compartment. Groundwater discharge from springs and gaining reaches of the Clear and West Forks of Muddy Creek and Beaver Creek in the Hat Six hanging wall does not contain water derived from the Madison aquifer in the footwall of the Hat Six fault. In contrast, groundwater discharged from the aquifer to springs located along the eastern

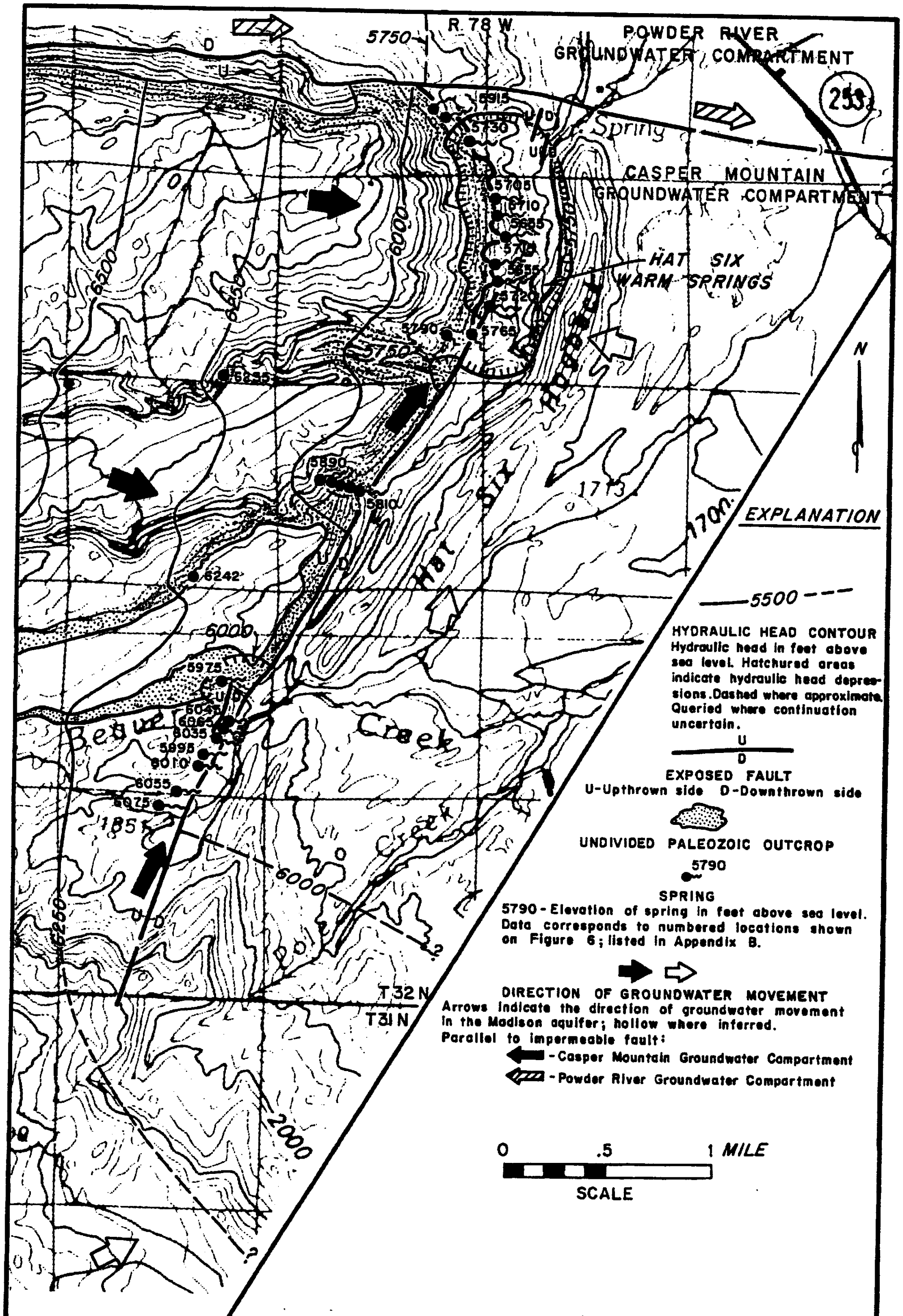


Figure 37. Hydraulic heads and groundwater flow directions associated with the Madison aquifer in the Hat Six area, Natrona County, Wyoming.

plunge of Casper Mountain anticline near the northeastern termination of the Hat Six fault is a mixture of hanging and footwall water. This results because the hydraulic continuity of the Madison aquifer is restored where the fault terminates. Consequently, groundwater that moves southeastward around the southwestern termination of the Hat Six fault circulates downgradient into the footwall of the fault toward the Hat Six Warm Springs, as shown on Figure 37.

Hat Six Warm Springs

Groundwater discharged from the Madison aquifer at the Hat Six Warm Springs, depicted on Figure 37, is a mixture of water derived from both the recharge area and the Hat Six footwall based on temperature and tritium data. The 18°C temperatures of these warm springs result from cooler recharge waters (7.5°C) mixing with waters discharged from the footwall of the Hat Six fault that are geothermally heated at the rate of 10°C per 1,000 feet (Buelow and others, 1986). Based on the contoured elevations of the top of the Casper Formation, shown on Figure 2, water lies at depths in excess of 2,000 feet in the footwall of the Hat Six fault. These depths are sufficient to allow significant geothermal heating of water within the Madison aquifer. In addition, the contrast between tritium concentrations for the warm spring 109 (8.73 TU, sampled in 1989) and cooler recharge waters discharged at spring 112 (23.3 TU, sampled in 1989) indicates that the discharge of the warm springs is a mixture of pre- and post-1952 waters.

Inactive Circulation Systems:

Groundwater circulation systems within the Madison aquifer in the Powder River, Casper Arch, and Alcova groundwater compartments are considered inactive because (1) these compartments are structurally isolated, and (2) hydraulic gradients associated with the aquifer in each of these compartments are negligible. These factors in combination with the minimal combined discharge of 120 gpm from the Alcova Hot Springs and well 24 qualitatively reveal that little groundwater is circulating through these compartments.

Groundwater Circulation in the Powder River Groundwater Compartment

The Powder River groundwater compartment is hydraulically disconnected from the adjoining Casper Mountain and Casper Arch groundwater compartments as a result of faulting. Aquifer-severing displacements, shown on Figure 2, of several thousand feet along the Casper Mountain thrust fault, and up to 4,000 feet along the fault which cores Emigrant Gap anticline have isolated groundwater circulation systems within these adjacent compartments. Differences in tritium concentrations across the Madison Creek fault between well 24 (.04 TU) and spring 41 (10.96 TU); in water quality between wells 24 and 39, and spring 41, shown on Figure 9; and in water temperature between well 24 (20-27°C) and spring 41 (15.5°C) further substantiate that these groundwater compartments are hydraulically isolated.

The Powder River groundwater compartment forms the southernmost extension of the Madison aquifer in the Powder River basin wherein groundwater predominantly moves downgradient to the east (Swenson and others, 1976). Within the study area, however, groundwater circulates to a local potentiometric depression, shown on Figure 36, that has developed around well 24 as a result of uncontrolled flow from the well since 1931. Circulation systems that supply well 24 are differentiated from other circulation systems within the compartment by hydraulic head and temperature contrasts between wells 19-25 (19-28°C) and 28-29 (54-55°C) that are located on either side of a groundwater divide shown on Figure 7.

Civil Engineering Professionals (1993) reported that flows from well 24 are ephemeral. Plausible explanations for this phenomena include (1) fluctuations in barometric pressure, and (2) pumping on nearby oil fields that extract fluids from the saturated Paleozoic rocks which compose the Madison aquifer.

Groundwater Circulation in the Casper Arch Groundwater Compartment

Groundwater circulation systems within the Madison aquifer of the Casper Arch groundwater compartment are hydraulically isolated from those in the Wind River, Casper Mountain, and Powder River groundwater compartments. Displacements of several thousand feet along both the Casper Arch thrust fault and the coring reverse fault of Emigrant Gap anticline coupled with approximately 2,000 feet of throw along the Madison Creek fault near Goose Egg dome have effectively severed the Madison aquifer. Water temperature differences between wells 33-35 (37-43°C) and spring 41 (15.5°C), and water quality contrasts between spring 41 and wells 35 and 39, shown graphically on Figure 9, reveal that displacements along these thrust faults preclude circulation through the aquifer.

The Casper Arch groundwater compartment is, however, only a small part of the larger Powder River groundwater compartment based on the location where the fault that cores Emigrant Gap anticline terminates, and on similar water quality and temperature data measured on either side of this fault. Regional structure maps of the Cloverly Formation by Barlow and Haun (1988) indicate the coring reverse fault of Emigrant Gap anticline terminates northwest of the study area in T 35 N, R 83 W. In addition, the similar water quality of wells 16-17, 22-24, and 35 illustrated on Figure 9, and comparable water temperatures of wells 1-16 (18-31°C) and 19-25 (19-28°C) in the adjacent Powder River groundwater compartment further reveal that the hydraulic continuity of the Madison aquifer is restored near the northwestern termination of the fault.

As shown on Figure 7, groundwater within the Madison aquifer of the Casper Arch groundwater compartment circulates southeastward downgradient toward Oil Mountain where the potentiometric surface has been altered due to oil production from Casper Formation reservoirs since 1945.

Groundwater Circulation in the Alcova Groundwater Compartment

Groundwater circulation systems within the Madison aquifer in the Alcova groundwater compartment are hydraulically isolated from those in the adjacent Casper Mountain and Wind River groundwater compartments. Differences in the total dissolved solids concentrations between wells 138 and 149, shown on Figure 9, and the Alcova Hot Springs (1,260-1,381 mg/l; Knight, 1900; Bradley, 1935) reveal that lateral circulation between these three compartments has been precluded as a result of aquifer-severing displacements along the bordering thrust faults. Contrasts in water temperature between well 149 (32.8°C), and wells 133-134 and 142 (52-64°C) further reveal that there is no hydraulic communication between the Casper Mountain and Alcova groundwater compartments.

Groundwater within the Madison aquifer of the Alcova groundwater compartment moves downgradient to the Alcova Hot Springs from the southwestern margin of the Laramie Range and northeastern flank of the Granite Mountains. The four main springs which discharge from the lower part of the saturated Casper Formation along the banks of the North Platte River lie 5,340 feet above sea level, but are submerged 160 feet beneath the surface of the Alcova Reservoir (Breckenridge and Hinckley, 1978). Nevertheless, these springs are located downgradient from wells 133 and 137 shown on Figure 7, and from Paleozoic outcrops along the Laramie Range and Granite Mountains. Similar water temperatures of the hot springs (54°C; Bradley, 1935) and wells 133-134 and 142 (52-64°C; Appendix D) confirm that these potentiometric points lie within the same compartment, and furthermore, imply that these springs represent the lowest potentiometric point for the aquifer in the Alcova groundwater compartment.

Selected Groundwater Exploration Targets for the Madison Aquifer:

The potential for groundwater development from the Madison aquifer within the Casper Mountain groundwater compartment is good based on (1) the large discharge of springs found along the perimeter of the recharge area on Casper Mountain and near the crest of Goose Egg dome, (2) the storage capacity of the Madison aquifer, (3) the transmissivity of the saturated Paleozoic rocks which compose the aquifer, and (4) the good quality of groundwater discharged from the aquifer at local springs.

Five locations were selected for groundwater exploration in the Madison aquifer. Nevertheless, 22 different locations, summarized by James M. Montgomery (1990), have been targeted for exploration previously by various consulting firms. The locations selected in this report represent, in the author's opinion, the five best drilling targets in the area. The five potential locations for exploration are shown and prioritized on Figure 38.

Groundwater Development Prospects on the Southwestern Homoclinal Flank of Casper Mountain

Three locations in addition to the obvious Goose Egg dome prospect have been selected for exploration within the western Casper Mountain groundwater compartment. These targets, shown on Figure 38, are the Freeland-Clark anticlinal prospect, the Holin Creek anticlinal prospect, and the Bates Creek prospect.

The Freeland-Clark, Goose Egg dome, and Holin Creek prospects were selected on the basis of: (1) the drilling reports of numerous unsuccessful oil exploration wells, listed in Appendix D, that produced water from the Madison aquifer after penetrating at least the upper part of the saturated Casper Formation on Goose Egg dome or along the Freeland-

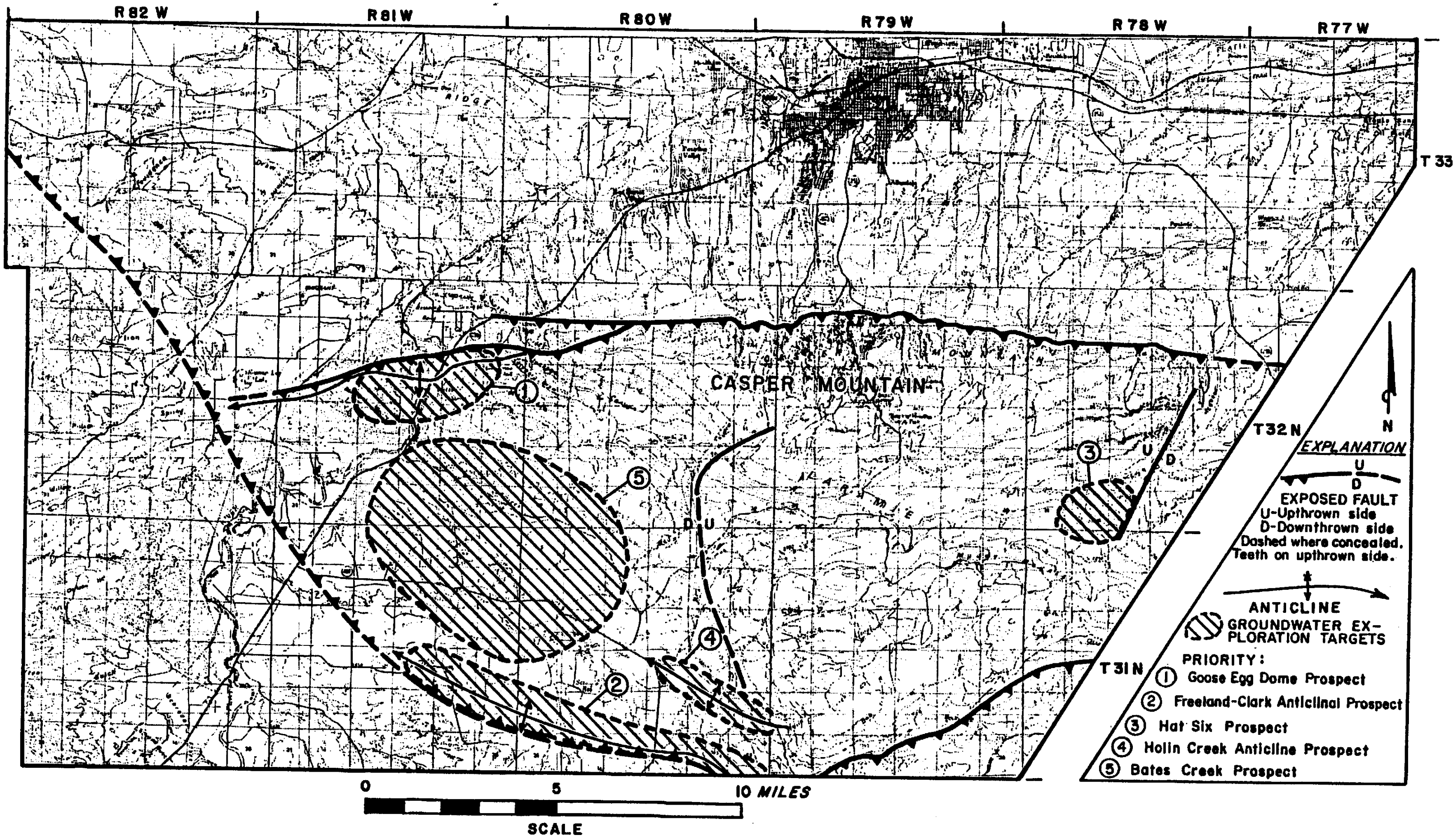


Figure 38. Locations of groundwater exploration targets for the Madison aquifer within the Casper Mountain area of Natrona County, Wyoming. Notice that the higher priority targets are located along the trends of anticlines and in the hanging walls of faults. These targets represent, in the author's opinion, the five best locations for exploration in the area.

Clark anticlinal trend, (2) the large permeability and storage capacity of the Madison aquifer within the western Casper Mountain groundwater compartment, and (3) the karstification of the Madison Formation.

Unsaturated cavern systems developed in the Madison Formation within the exposed cores of Sheep and Little Sheep Mountain anticlines in the northeastern Bighorn basin form the analog for karst developed within the anticlines selected as targets for groundwater exploration. Hill and others (1976) found that the Upper and Lower Kane Caves and Spence Cave extend up to 2,300 feet into Madison outcrop in the cores of Sheep and Little Sheep Mountain anticlines, and concluded that these caves formed under phreatic conditions parallel to the structural axes of the folds. In fact, the similar water qualities of groundwater discharged from the Madison aquifer through well 149 and several springs located in the cores of these folds (Doremus, 1986) imply that conditions within the study area are favorable for cavern development in the Madison aquifer along trend.

The Bates Creek prospect was selected on the basis of (1) the large permeability and storage capacity of the Madison aquifer in the western Casper Mountain groundwater compartment, indicated by the large, steady discharge of Speas Spring, and (2) the small hydraulic gradients in the area.

Groundwater Development Prospect on the Southeastern Homoclinal Flank of Casper Mountain

The Hat Six prospect, shown on Figure 38, is the only location selected for groundwater exploration in the eastern part of the Casper Mountain groundwater compartment. This location was selected for the following reasons: (1) groundwater discharged from the Madison aquifer to springs and gaining streams along the perimeter of the recharge area represents rejected recharge from the aquifer which in combination with the minimal discharge of the Hat Six Warm Springs indicates that basinward permeabilities have been diminished, and (2) dissolution-enlarged extensional fractures developed in the hanging wall of the Hat Six fault indicate that the permeability of the aquifer has locally been enhanced.

CHAPTER VI

DISCUSSION AND CONCLUSIONS

The large, basinward discharge of Speas Spring reveals that the groundwater development potential for the karstified Madison aquifer on the southwestern homoclinal flank of Casper Mountain is good. In contrast to adjacent compartments where the permeability of the aquifer is locally being destroyed through recrystallization, cementation, and compaction, the permeability of the confined Madison aquifer within the western Casper Mountain groundwater compartment continues to be enhanced predominantly through the dissolution of Madison carbonates along rectilinear fractures on the homoclinal flank of Casper Mountain. This dissolution has resulted in the large permeability and storage capacity of the aquifer. The implication for groundwater exploration is that large quantities of groundwater can be withdrawn from storage in the Madison aquifer throughout the southwestern homoclinal flank of Casper Mountain.

Conclusions:

- Aquifer-severing displacements along Laramide faults adjacent to local structural highs of the Casper Formation have disrupted the hydraulic continuity of the Madison aquifer and segmented the aquifer into five discrete groundwater compartments.

- The large permeability and storage capacity of the Madison aquifer are attributed to a Madison karst that has formed through the dissolution of interstitial cements and matrix material along streamlines which converge on Speas Spring.

- The karstified Madison aquifer of the Casper Mountain groundwater compartment is recharged at the rate of 6.2 inches per year, or 22% of the annual precipitation recorded over the recharge area on Casper Mountain.

- Speas Spring represents the lowest potentiometric point for the Madison aquifer in the western Casper Mountain groundwater compartment. Interconnections between Madison karst and local extensional fractures that propagate upward through the Goose Egg Formation permit the discharge of groundwater circulating from the recharge area to the spring through both the hanging and footwall blocks of the Little Red Creek fault.

- The Hat Six Warm Springs which discharge groundwater from the Madison aquifer result from the mixing of cooler recharge waters and geothermally heated groundwaters which circulate to the warm springs through the footwall of the Hat Six fault. Most groundwater discharged from the aquifer in the eastern Casper Mountain groundwater compartment, however, moves southeastward toward both the gaining reaches of the Clear and West Forks of Muddy Creek, and Beaver Creek; and various springs that discharge along the Hat Six hanging wall.

ırculation in the Madison aquifer of the Powder River, Casper Arch, ındwater compartments is negligible. The Alcova Hot Springs ly discharge outlet for the aquifer in the Alcova groundwater d discharge 100 gpm on average from four main springs that are ath the Alcova Reservoir. In addition, the Mohawk Oil well (well l potentiometric depression for the Madison aquifer in the Powder ter compartment as a result of uncontrolled flow from the well since

of groundwater can be withdrawn from storage in the Madison out the southwestern homoclinal flank of Casper Mountain.

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Wyoming Oil and Gas Conservation Commission, various, Data maintained in files in Casper, Wyoming.

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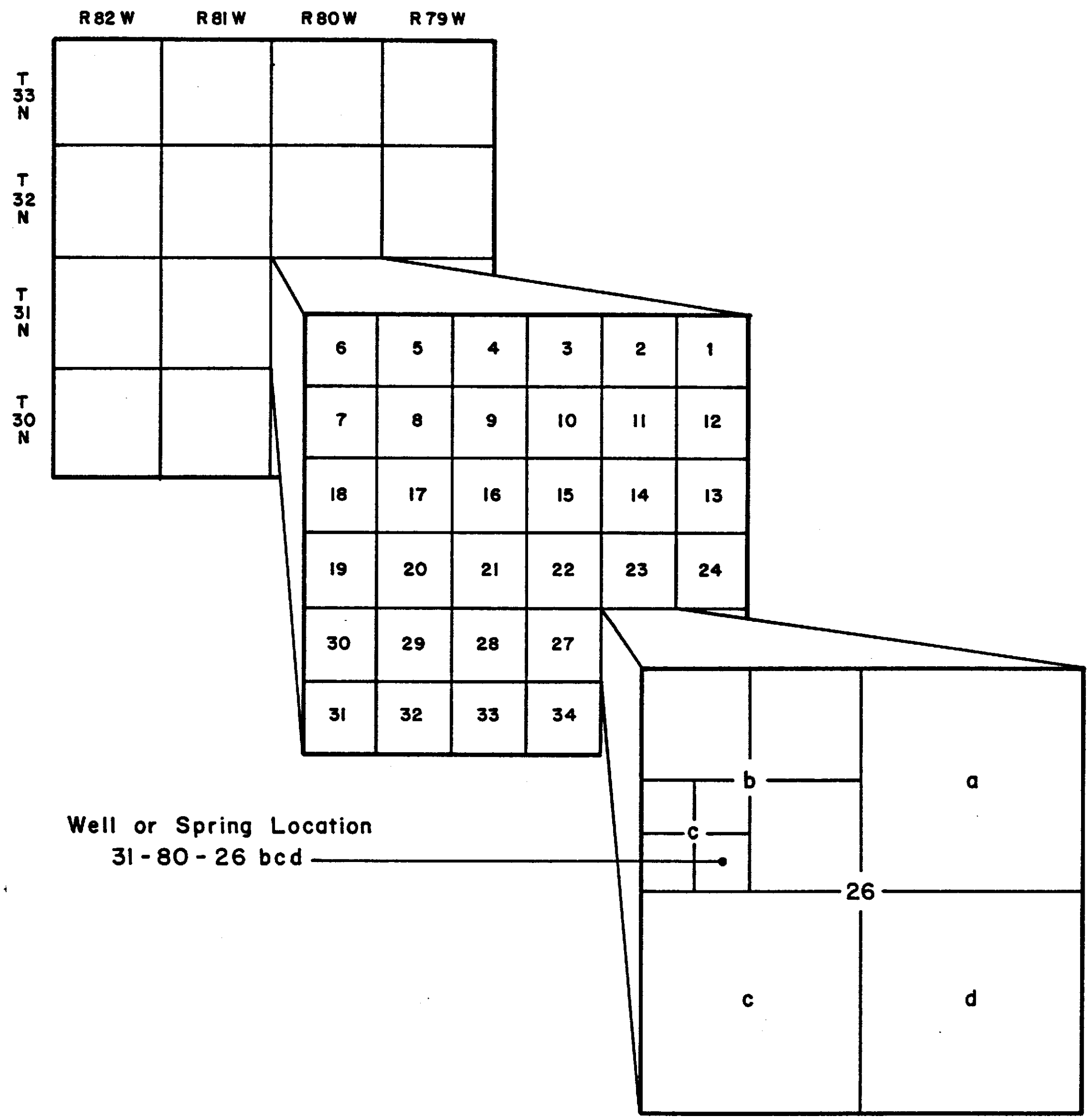
APPENDICES

APPENDIX A

UNITED STATES GEOLOGICAL SURVEY WELL AND SPRING LOCATION SYSTEM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APPENDIX B

INVENTORY OF SPRINGS LOCATED IN THE CASPER MOUNTAIN AREA, NATRONA COUNTY, WYOMING

APPENDIX B

Inventory of springs located in the Casper Mountain area, Natrona County, Wyoming.

#(a)	Location(b)	Spring Name	Producing Formation(c)	Elevation(d)	Discharge (gpm)(e)	Temp. °C	Water Analysis(f)	Remarks	Source(g)
36	32-81-9ddb	Mississippi River Fuels Spring	Kc	5375	2	13	No	Discharges near the base of a Cloverly Formation ridge just north of a Madison Creek fault splay.	6
41	32-81-15bad	Speas Spring	Pc, Mm(?)	5235	7630	15.5	Yes	Historic discharges of 6732, 7584, 7585, 5444, 6768, 5951, and 7316 gpm have also been recorded by Sims (1948), Flaccus (1982), and Wyoming Game and Fish (1954-55, 1965, 1971, 1988).	4
42	32-81-10cdb	Storey's Spring #1	Kc	5280	8	14	Yes	Storey's Spring's #1-3 are located along the trace of the Madison Creek fault. Several seeps are visible to the west.	6
43	32-81-10cdb	Storey's Spring #2	Kc	5310	3-5	16	No		6
44	32-81-10cdb	Storey's Spring #3	Kc	5255	31	13	Yes		6
45	32-81-15ddb	Hollywood Spring #1	Tc	5350	2		No	Springs 1, 2, and 3 discharge from the Alcova Formation.	6
46	32-81-15ddb	Hollywood Spring #2	Tc	5400	8		Yes		4,6
47	32-81-15ddb	Hollywood Spring #3	Tc	5390	<1		Yes		6
48	32-81-14cca	Hollywood Hills Spring	Kc	5965	270	10	Yes	Spring discharges through the Morrison Formation on the western slope of Coal Mountain. Cloverly sandstone fragments are scattered throughout the drainage.	6
51	32-81-14bad	Kamon's Spring	Tc	5470	1	14	Yes		6
52	32-81-14aba	Bicek Spring	Tc	5455	<1	11	Yes		6
54	32-81-12ccd	Burris' Spring	Tc	5516	2	20	Yes	Located south of the crest of Bessemer Mountain anticline. Numerous local fractures in the Chugwater Group are infilled with gypsum.	6
55	32-81-12cbd	Gillingham's Spring	Tc	5465	150	14	Yes	Located along the crest of Bessemer Mountain anticline.	6
56	32-81-11dbb	Whitney's Spring #1	Kc	5318	47	16	Yes	Spring is located along the trace of the Madison Creek fault.	6
57	32-81-11dbb	Whitney's Spring #2	Kc	5318	100(?)	13	Yes	Discharge is the approximate sum of three springs, two of which do not perceptibly flow.	6
60	32-81-12aad	Randall's Spring	Pc	5405	5	15	Yes	Spring discharge is diverted to the Randall's residence.	4,6
61	32-81-1ddc	Logan's Spring	Pc	5330	2-5	11	Yes	Discharges near the termination of an inconspicuous fault surface in the Madison Creek drainage.	6
62	32-81-12aab	Blue Spring	Pc	5335	22	12	Yes	Headwaters of Madison Creek. Rises from alluvium along an inconspicuous east-west trending fault.	6
63	32-81-12aaa	Shirk's Spring	Pc	5420	56	13	Yes	Water discharges along an inconspicuous fault surface.	6
64	32-80-7bbc	Garman's Spring	Pc	5510	7		Yes	Currently diverted to Garman's residence.	5,6
65	32-81-12ada	Canyon Village Spring #1	Pc	5565	2*	16	Yes	Bill Young (owner) recorded a discharge of 1.5 gpm during the summer of 1988.	6

#(a)	Location(b)	Spring Name	Producing Formation(c)	Elevation(d)	Discharge (gpm)(e)	Temp. °C	Water Analysis(f)	Remarks	Source(g)
66	32-80-7bcb	Canyon Village Spring #2	Pc	5570	31*	14	Yes	Bill Young (owner) recorded discharges of 25 gpm during July, 1983, and 30 gpm during September, 1982.	5,6
67	32-80-7bcb	Canyon Village Spring #3	Pc	5550	10*	13	Yes	Bill Young (owner) recorded a discharge of 20 gpm on 7/23/88.	5,6
68	32-80-7bcc	Canyon Village Spring #4	Pc	5560	15*	13	Yes		5,6
69	32-80-7bcc	Canyon Village Spring #5	Pc	5540	1*	15	Yes	Spring discharges through fracture in Casper sandstone. Bill Young (owner) recorded a discharge of 1.5 gpm on 10/17/73.	5,6
70	32-80-7bcc	Canyon Village Spring #6	Pc	5575	3	12	No		6
71	32-80-18bcb	Gothberg Draw Spring	Pc	5895	4*	11	Yes		6
73	32-80-26abc	Big Little Red Creek Spring	Pc	6540	298	7	Yes	Water rises from saturated Casper alluvium in north fork of Little Red Creek.	6
74	32-80-35cca	Little Red Creek Spring	Pge	6055	22	11	Yes	Water rises from alluvium in the south fork of Little Red Creek.	6
75	32-79-32ccc	Big Red Creek Spring	Pge	6890	56	7	Yes	Headwaters of Red Creek.	6
76	32-79-25ddd	Backside Spring	Pc	6835	35	7	Yes	Discharges along with Ahah Spring just above the West Fork of Muddy Creek.	6
77	32-79-25ddd	Ahah Spring	Pc	6835	6	7	No		6
78	32-79-10ccd	Mills Camp Spring	Dfc	7560		6	Yes		2
81	32-79-19abc	Sacajawea Spring	Prc	7855	26	6	Yes	Numerous Precambrian springs discharge nearby. Headwaters of Little Red Creek. All water lost downstream to the Fremont Canyon and Madison Formations before emerging from saturated alluvium at Big Little Red Creek Spring.	2,6
102	32-78-10dad	Chaput Spring	Pc	5915	38	8.9	Yes	Discharge is the sum of two springs.	3,6
103	32-78-10dda	Health Spring	Pc	5730	13	10.5	Yes		3
104	32-78-14bbb	Spring 'I'	Pc	5705	1-5		No	James M. Montgomery (1990) recorded no flow in this boggy drainage.	3
105	32-78-14bbc	Spring 'H'	Pc	5710	1-5	10.5	No	James M. Montgomery (1990) reported that water drips from a vegetated wall.	3
106	32-78-14bcb	Spring 'G'	Pc	5655	5	11.5	No		3
107	32-78-14bcc	Spring 'F'	Pc	5715	8	12	No		3
108	32-78-14cbb	Spring 'E'	Pc	5655	55	18	Yes	Associated radioactivity analysis presented in Appendix G.	3
109	32-78-14cbc	Spring 'D'	Pc	5720	26	18	Yes	Associated radioactivity and tritium analyses are presented in Appendix G.	2,3
110	32-78-15dda	Spring 'B'	Pc	5765	3-5	13	No		3
111	32-78-15dda	Spring 'C'	Pc	5790	1-2	13.5	No	Spring rises from saturated alluvium (James M. Montgomery, 1990).	3
112	32-78-15ccc	Spring 'A'	Pc	6235	436	7.5	No	Spring initially discharges from an outcrop in 15ccc (James M. Montgomery, 1990). Associated gaining stream discharges at the mouth of Hat Six Canyon. Radioactivity and tritium analyses are presented in Appendix G.	3
113	32-78-30cbd	Bashful Spring	Pc	6775	7	7	No	Discharge combines with that of Humble Spring before flowing into the West Fork of Muddy Creek.	6

#(a)	Location(b)	Spring Name	Producing Formation(c)	Elevation(d)	Discharge (gpm)(e)	Temp. °C	Water Analysis(f)	Remarks	Source(g)
114	32-78-30cca	Humble Spring	Pc	6780	84	7	No		6
115	32-78-29cbd	Crooked Road Spring	Pc	6565	20*	7	Yes	Natural headwaters of Beaver Creek. Water currently diverted into a reservoir, leaving the drainage dry downstream from the dam.	6
116	32-78-21dcd	Mostellar Spring	Pc	6242	91	9.2	Yes		2
117	32-78-22bcd	Harris Ranch Falls Spring	Mm	5890	75	10	Yes	Spring discharges below the falls through a solution enlarged, vertical fracture in the Madison Formation.	6
118	32-78-22bdd	Laughing Water Spring	Mm	5810	359	11	No	Spring discharges from the base of the Madison Formation above Muddy Creek.	3
119	32-78-22bdd	Stovepipe Spring	Mm	5810	3	11	No	Water discharges from the base of Madison outcrop. James M. Montgomery (1990) recorded a discharge of 4 gpm during November, 1989.	3,6
120	32-78-22caa	Stovepipe East Spring	Mm	5810	19	11	No		6
121	32-78-22caa	Bathtub Spring	Mm	5810	3	14	Yes	Water is piped to a bathtub on Harris' Ranch. James M. Montgomery (1990) recorded a discharge of 10 gpm during November, 1989.	3,6
122	32-78-28acd	Beaver Creek Spring	Pc	5975	598(?)	9	No	Water rises from alluvium in Beaver Creek drainage.	6
123	32-78-28dac	Spring 'Z'	Pc	6045	17	10	No	Springs 'Z-X' discharge from the hanging wall along the trace of the Hat Six fault.	6
124	32-78-28dac	Spring 'W'	Pc	6065	20	11	No		6
125	32-78-28dac	Spring 'Y'	Pc	6065	56	9	No		6
126	32-78-28dac	Spring 'X'	Pc	6065	50(?)	11	No	Discharge is approximate sum of three local springs.	6
127	32-78-28ddb	Yahoo Spring	Pc	6035	299	10	Yes	Crist and Lowry (1972) estimated a discharge of 600 gpm for a spring located in sec. 28dab.	1,6
128	32-78-28ddb	Rolling Spring	Pc	5995	202	10	No	Discharges along Hat Six fault trace along with Bubbling Spring.	6
129	32-78-28ddb	Bubbling Spring	Pc	6010	30	12	No		6
130	32-78-28dcd	Quiet Spring	Pc	6055	200	11	Yes	Discharges near attenuation of Hat Six fault.	6
131	32-78-33abb	Roaring Spring	Pc	6075	168	12	No		6

a.) Number corresponds to numbered location shown on Figure 6.

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

c.) Kc = Cloverly Formation
Tc = Chugwater Group
Pge = Goose Egg Formation
Pc = Casper Formation
Mm = Madison Formation
Dfc = Fremont Canyon Sandstone
Prc = Precambrian

d.) Elevation in feet above sea level.

e.) Estimated for this study using the following equation:
Discharge = Cross Sectional Area * Surface Water Velocity
* Discharge estimated using calibrated bucket and stopwatch.

f.) Water analyses listed in Appendix E.

g.) Sources of data:
1.) Crist and Lowry (1972)
2.) Gable and others (1988)
3.) James M. Montgomery (1990)
4.) Ritz and Bruce (1993)
5.) Wyoming State Engineer (various)
6.) This study

APPENDIX C

INVENTORY OF SELECTED WATER WELLS LOCATED IN THE CASPER MOUNTAIN AREA, NATRONA COUNTY, WYOMING

APPENDIX C

Inventory of selected water wells located in the Casper Mountain area, Natrona County, Wyoming.

#(a)	Location(b)	Well Owner Well Name	Permit #(c)	Year Drilled	Well Depth	Elevation of Casper Formation Top(d)	Ground Elevation(e)	Producing Formation(f)	Depth to Water(g)	Hydraulic Head(h)	Testing Date	Production Rate (gpm)(i)	Est. Permeability (gal/day-ft^2)(j)	Est. Transmissivity (gal/day-ft)(k)	Water Quality Analysis(l)	Remarks	Source(m)
27	33-79-24acc	Casper Country Club Country Club #1	UW98	1959	5101		5380	Kc	flowing	5380					Yes	Well initially produced 42 barrels of water per day. Rw (at 20°C) measured to be 20.82.	3,5
49	32-81-15daa	Albert Allen Allen #1	P14188W		700		5340	Pgo	150	5190					Yes	Temperature of 17°C measured at spigot.	5,6
50	32-81-15add	Gilbert Glynn Glynn #1	P12002W	1958	804	4570	5305	Pc	100	5205					Yes	Temperature of 18°C measured at spigot.	5,6
53	32-81-14bad	Robert Kamon Kamon #1			950	4815	5385	Pc	120	5265					Yes		6
58	32-81-12dab	Susan Cole Well #2	P53518W	1965	200		5460	Pc, Pge	50	5410		11.1	14.6*	13059	Yes	Temperature of 16°C measured at spigot. Pump test produced 1.7' of drawdown in 1.5 hours.	4,5,6
59	32-81-12dab	Susan Cole Well #3	P91744W	1993	135		5455	Pc, Pge	62	5393	7/21/93	25	22.5*	20000	No	Pump test resulted in 2.5' of drawdown in 4.5 hours.	4,5
72	32-80-13acb	Eddie Schwerdtfeger Schwerdt #1	P53521W	1983	135		7810	Dfc, Prc(?)	64	7746					No		5
79	32-79-10ccc	Wyoming Conference Association of 7th Day Adventists WYOSDA #1	P43964W	1979	160		7820	Mm, Dfc(?)	137	7683					No		1,5
80	32-79-19bba	B.G. Rock Rock #1	P34620W	1976	40		7840	Dfc, Mm(?)	15	7825					No		5
82	32-79-19dcc	Barbara Kaiser Kaiser #1	P35290W	1976	48		7960	Mm	16	7944					No		5
83	32-79-21cab	Starwallow Water District Starwallow #3	P6426W	1972	72	7970	7970	Pc(?)	17	7953		14	1.05	933	No	Pump test produced 30' of drawdown after 6 hours.	1,5
84	32-79-21bdd	Natrona Co. Board of Trustees Beartrap Meadow Well #1	P2542W	1961	95		7975	Dfc	70	7905	9/1/61	8	.72	640	No	Pump test resulted in 15' of drawdown in 2 hours.	1,5
85	32-79-21adc	O.L. Pierce Pierce #1	P38315W	1979	300	8060	8060	Pc	290	7770					No	"Well runs dry after 2 minutes. 7 days to recover to 8 gallons."	1,5
86	32-79-21caa	Leon Winkes Winkes #1	P6127W	1971	81	7925(?)	7925	Prc, Dfc(?)	30	7895		40		2000	Yes	Pump test produced 40' of drawdown in 15 minutes.	1,5

#(a)	Location(b)	Well Owner Well Name	Permit #(c)	Year Drilled	Well Depth	Elevation of Casper Formation Top(d)	Ground Elevation(e)	Producing Formation(f)	Depth to Water(g)	Hydraulic Head(h)	Testing Date	Production Rate (gpm)(i)	Est. Permeability (gal/day-ft^2)(j)	Est. Transmissivity (gal/day-ft)(k)	Water Quality Analysis(l)	Remarks	Source(m)
87	32-79-21cac	Starwallow Water District Starwallow #2	P6425W	1972	42	7905	7905	Pc(?)	20	7885		10		1333	No	Pump test resulted in 15' of drawdown in 3 hours.	1,5
88	32-79-21cac	L.J.W. Brouillette Brouillette #2	P3992W	1969	46	7920	7920	Pc	20	7900					Yes	Pumped 40 gpm for one hour, drawdown unknown.	1,5
89	32-79-21cbd	James Hallenburg Hallenburg #1	P6457W	1971	45	7960	7960	Pc	15	7945					No	Pumped 10 gpm for one hour, drawdown unknown.	1,5
90	32-79-21bdd	Jerry Stephenson Stephenson #1	P45024W	1979	35		7935	Mm	26	7909					Yes		1,5
91	32-79-21dcd	John Carrier Carrier #1	P57884W	1982	483	7920	7920									Well never produced water. Reportedly encountered a cavern in lower Casper Formation.	5
92	32-79-22ccb	David Huwe Huwe #1	P33589W	1977	625	7870	7870	Dfc, Mm, Pc(?)	510	7360	?/77	2	.49	57	No	Pump test resulted in 70' of drawdown in 4 hours.	5
93	32-79-22dbd	Gerald Rieck Rieck #1	P3317W	1970	575	7805	7805	Mm(?)	435	7370		6	1.71	240	Yes	Pump test produced 50' of drawdown in 1 hour.	1,5
94	32-79-22dbb	Samuel Roberts Roberts #1	P26185W	1976	580	7855	7855	Mm	500	7355					No	Pumped 7 gallons per hour for 5 hours, drawdown unknown.	1,5
95	32-79-23bab	Ruth Jones Tickbite #1	P84301W	1983	8	7890	7890	Pc	8	7882					Yes	Dry September through April.	5
96	32-79-14cad	Dennis Sheldon Sheldon #1	P61202W	1983	501	7985	7985	Mm	400	7585					No	"Trace of water at 240' but lost it, 1.5 gpm at 436', 3 gpm at 500."	5
97	32-79-14aca	Bill Webber Webber #1	P61164W	1983	500	7890	7890	Pc	305	7585					No		5
98	32-79-14ada	Donald Dockter D & G #1	P62015W	1982	565	7955	7955	Mm, Dfc	480	7475					Yes		5
99	32-79-13dbd	Derold Scharosch Scharosch #1	P61930W	1986	400	7610	7610	Dfc, Mm, Pc	265	7345	?/86	7-8	1.03	139	Yes	Pump test produced 115' of drawdown in 1 hour.	5
149	31-80-33bdd	Casper Board of Public Utilities Bodie Dome #1	P65578W	1984	3235	3769	5904	Prc, Dfc, Mm, Pc	204	5700	1/26/84	182	.86*	764	Yes	Transmissivity of 800 gal/day-ft calculated using Jacob Method (Wright Water Engineers, 1984). Transmissivity of 1000 gal/day-ft calculated on basis of recovery data. Water sample analyzed for radioactivity; listed in Appendix G.	2,5

#(a)	Location(b)	Well Owner Well Name	Permit #(c)	Year Drilled	Well Depth	Elevation of Casper Formation Top(d)	Ground Elevation(e)	Producing Formation(f)	Depth to Water(g)	Hydraulic Head(h)	Testing Date	Production Rate (gpm)(i)	Est. Permeability (gal/day-ft^2)(j)	Est. Transmissivity (gal/day-ft)(k)	Water Quality Analysis(l)	Remarks	Source(m)

a.) Number corresponds to numbered locations shown on Figure 6.

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

c.) Numbers correspond to groundwater permits on file with the Wyoming State Engineers Office in Cheyenne, Wyoming.

d.) Elevation in feet above sea level.

e.) Elevation in feet above sea level.

f.) Pge = Goose Egg Formation
Pc = Casper Formation
Mm = Madison Formation
Dfc = Fremont Canyon Sandstone
Prc = Precambrian

g.) Depth reported in feet below land surface.

h.) Elevation in feet above sea level.

i.) Production rate during reported pump test.

j.) Calculated using the following equation:
*Estimated Permeability = Estimated Transmissivity / Maximum Aquifer Thickness
Otherwise Estimated Permeability = Estimated Transmissivity / Height of water column above the base of the well

k.) Calculated using the following equation:
Estimated Transmissivity = 2000 * Production rate (gpm) / drawdown in the well (ft)

l.) Water quality analyses listed in Appendix F.

m.) Sources of data:
1.) Wright Water Engineers (1982)
2.) Wright Water Engineers (1984)
3.) Cardinal (1984)
4.) Moser (1993)
5.) Wyoming State Engineer (various)
6.) This study

APPENDIX D

INVENTORY OF SELECTED COMMERCIAL WELLS YIELDING STRATIGRAPHIC AND POTENTIOMETRIC DATA IN THE CASPER MOUNTAIN AREA, NATRONA COUNTY, WYOMING

APPENDIX D

Inventory of selected commercial wells yielding stratigraphic and potentiometric data in the Casper Mountain area, Natrona County, Wyoming.

#(a)	Location(b)	Operator Well Name	Year Drilled	Casper Formation Top Elevation(c)	Temp. °C(d)	Testing Date	Formation Tested(e)	Reference Elevation(f)	Interval Tested(g)	Shut-in Pressure (lbs/in^2)	Hydraulic Head(h)	Avg. Productivity of Tested Interval (gpm)(i)	Est. Permeability of Tested Interval (gal/day-ft^2)(j)	Est. Transmissivity of Aquifer Thickness (gal/day-ft)(k)	Water Analysis(l)	Remarks	Source(m)
1	33-82-5cda	M.D. Carroll / M&J Oil Co. #24-5 Federal	1983	1934	28			5521							No	Good porosity and permeability reported in Casper Formation. Dead oil stains found on fracture surfaces in Casper. Average penetration rate ranged from 7-28 min/ft.	4
2	33-82-7bdd	Argo Oil Co. #1 Jacobs	1956	2927		9/56	Pc	5880	2951-2973 2996-3006	1230 1200	5770 5662	20.9 55.0	.64 5.1	569.6 4539.0	Yes	Oil streaks in Casper Formation found on vertical fracture surfaces and parallel to bedding. Spotty oil saturated zones lack cement material. Recovered 903' of mud cut sulphur water from first Casper DST, and 2373' mud cut water from second test.	4
3	33-82-18adc	Pan American Petroleum Co. #1 Pan Am Government	1957	2847	25	3/57	Pc	5669	2821-2849	1295	5837	46.4	1.45	1290.5	No	Recovered 2000' of fresh water.	4,5
4	33-82-18ddb	Marathon Oil Co. #1 Taylor	1913	2752(?)				5592			5592				No	Artesian Casper well. Initially produced 263 gpm; currently plugged.	4
5	33-82-20dbd	True Oil Co. #1 Erickson	1957	2422				5579							No	Drilled through three faults (718', 1487', 2269'). Casper Formation found "bleeding droplets of brown oil."	4
6	33-82-21bad	Kirkwood Oil & Gas Co. #21-21 Federal	1981	2470		11/81	Pc	5624							No	Black liquid oil found in upper Casper Formation pores. "Large volume of water present in the (Casper) sand below."	4
7	33-82-21bda	Par West Oil Co. #1 Morton Government	1954	2478		12/54	Pc	5643kb	3155-3191	1400	5717	46.6			Yes	Recovered 2010' of fresh water. Good to excellent porosity reported in Casper Formation. Free oil found in upper Casper Formation fractures.	4

#(a)	Location(b)	Operator Well Name	Year Drilled	Casper Formation Top Elevation(c)	Temp. °C(d)	Testing Date	Formation Tested(e)	Reference Elevation(f)	Interval Tested(g)	Shut-in Pressure (lbs/in^2)	Hydraulic Head(h)	Avg. Productivity of Tested Interval (gpm)(i)	Est. Permeability of Tested Interval (gal/day-ft^2)(j)	Est. Transmissivity of Aquifer Thickness (gal/day-ft)(k)	Water Analysis(l)	Remarks	Source(m)
8	33-82-28bdc	Mobil Producing Co. #1 Clevidence	1958	1656				5578							No	Lost circulation in Goose Egg (3826', 3840', and 3869' (for 12.5 hrs)). Drilling time dropped to 2 min/ft at 3838'. Cored Goose Egg and Casper Formations without returns (3894' -3965'). Cored through Goose Egg cavity from 3902-3905'.	4,5
9	33-82-34aaa	Texaco, Inc. #1 Government Wallway	1965	2806		1/21/65	Pc	5846	3034-3069	1286	5777	52.4	1.36	1210.4	No	Recovered 2450' of oil speckled water. Drilled through two reverse faults (330', 2443').	4
10	33-82-35bdc	Summit Resources #3 Speas	1961	3044	31			5812							Yes	Drilled through fault 1992' below the land surface. Initially produced 9.5 gpm of water and oil.	4
11	33-82-35cac	Summit Resources #4 Speas	1964	3170		3/19/64	Pc	5711	2538-2556 2532-2576	985 1107	5448 5724	1.8 3.15	.07 .05	62.3 44.5	Yes	Recovered 124' of drilling mud during first Casper test. Recovered 40' of oil and 198' of muddy water during second test.	4
12	33-82-35caa	Summit Resources #1 Speas	1945	3155				5772							Yes		4
13	33-82-35cac	Summit Resources #1A Speas	1974	3187	18			5711							No	Found water in Casper Formation.	4
14	33-82-35bdd	Texaco, Inc. #2 Government Clark	1961	2969	23	5/1/61	Pc, Pge(?)	5926	2935-2998	1188	5714	59.4	1.23	1094.7	No	Recovered 630' of mud cut water and 1930' of slightly mud cut water.	4
15	33-82-35dbc	Summit Resources #2A Speas	1979	3135				5757							No		4
16	33-82-35dcb	Summit Resources #1 Government	1956	3126	26	3/56	Pc	5802	2675-2735 2686-2818	900 1060	5184 5508	12.8 8.3	.2 .06	178.0 53.4	Yes	Recovered 1100' of oil cut mud from first Casper DST. Recovered 1440' of oil cut mud from second Casper test.	4
17	33-82-36ccd	Amerada Hess Co. #1-36 State	1982	1937				5555							Yes		4
18	33-81-9cbd	R. Allen #9-12 Emigrant Gap Federal	1986	-154				5441							No		4
19	33-81-23aba	Lysite Ventures #23-1 Government	1957	3930	24	6/57	Pc	5850	2014-2041	756	5576	5.1	.18	160.2	No	Recovered 330' of oil and mud cut water.	4

#(a)	Location(b)	Operator Well Name	Year Drilled	Casper Formation Top Elevation(c)	Temp. °C(d)	Testing Date	Formation Tested(e)	Reference Elevation(f)	Interval Tested(g)	Shut-in Pressure (lbs/in^2)	Hydraulic Head(h)	Avg. Productivity of Tested Interval (gpm)(i)	Est. Permeability of Tested Interval (gal/day-ft^2)(j)	Est. Transmissivity of Aquifer Thickness (gal/day-ft)(k)	Water Analysis(l)	Remarks	Source(m)
20	33-81-23dba	Aztec Oil & Gas Co. #1 Government Roush	1961	4101	19	1/61	Pc	5943	1834-1857 1949-1984	721 732	5769 5674	65.1 6.1	6.3 .16	5607.0 142.4	No	Lost circulation at 1983' while drilling in Casper Formation. Dead oil stains found on fracture surfaces in otherwise "hard and tite" Casper sandstones. Recovered 1638' of fresh water from first Casper test; 265' of mud cut water during second test.	4,5
21	33-81-23daa	Ferguson & Bosworth #1 Government Woodward	1965	4023	23			5803							No		4
22	33-81-24dbb	Lysite Ventures #1 Government	1957	3557		1/57	Pc	5500	2088-2125 2125-2222	1040	5807	46.4	.69	614.1	Yes	Recovered 2000' of fresh water during first Casper DST and 97' of water during second. No pressures recorded for second Casper test. Recorded Rw of 2.70 for each tested interval in the Casper.	2,4,5
23	33-81-26aaa	Virginian Oil Co. #1 Henderson Government	1918	4110			Pc	5510			5510				Yes	Though not currently producing, this well initially produced 233 gpm from the Casper Formation 1400'-1882' below the land surface.	3,5
24	33-81-36aad	Mohawk Oil Co. #1 State	1931	3667(?)	20		Pc	5182			5182				Yes	Encountered water between 2710'-2730' in Casper Formation. Artesian well currently producing 21 gpm. Well flows ephemerally (Civil Engineering Professionals, 1993). Water sample analyzed for radioactivity and tritium; presented in Appendix G.	4,5
25	33-80-19ac	Amerada Petroleum Co. #1 U.S.A. Gap Tract	1965	2988	28			5281							No	Porosity in Casper Formation interval (2470-2520') ranged between 13-22%.	4
26	33-80-20aa	M.E. Morton #A-1 Johnson	1948	2540				5362							No		4
28	33-78-29abc	Amerada Petroleum Co. #1 Government Brannan	1953	-1332	54	8/16/53	Pc, Pge	5523	6836-6970	3130	5878	107.1	.52	462.8	No	Recovered 1660' muddy water, 5220' fresh water.	4,5
29	33-77-15bcb	Amax Petroleum Co. N-17-WS	1966	-1529	55			5175			5627				Yes	Well initially produced 47 gpm from Madison Formation from 7415'-7440' interval.	1,4

#(a)	Location(b)	Operator Well Name	Year Drilled	Casper Formation Top Elevation(c)	Temp. °C(d)	Testing Date	Formation Tested(e)	Reference Elevation(f)	Interval Tested(g)	Shut-in Pressure (lbs/in^2)	Hydraulic Head(h)	Avg. Productivity of Tested Interval (gpm)(i)	Est. Permeability of Tested Interval (gal/day-ft^2)(j)	Est. Transmissivity of Aquifer Thickness (gal/day-ft)(k)	Water Analysis(l)	Remarks	Source(m)
30	32-82-10adc	Humble Oil and Refining Co. #1 Iron Creek	1962	984				5506							No	Drilled through three faults which thicken and repeat the uppermost Paleozoic units.	4
31	32-82-11bcd	The Texas Co. #1 Johnson Government	1944	2068				5460							No		5
32	32-82-16dc	Michael Halbouty #16-1 State	1968	-4458				5610							No		4
33	32-82-14bac	Coastal Oil and Gas Co. #1-14-32-82 Federal	1987	602	43			5504							No	Drilled through fault 5525' below land surface. Casper Formation porosity ranged between 11-17%. Madison Formation porosity ranged between 12-13%.	4
34	32-81-8ac	The Texas Co. #1 Government Sprague	1957	2365		4/57	Pc, Pgc	5447	3077-3090	1418	5652	32	2.1	1869	No	Recovered 2760' of brackish water.	4
35	32-81-9cbb	General American Oil Co. #1-9 Federal	1976	2413	37	10/15/76	Pc, Pgc	5493	3075-3090	1414	5686	24.3	.9	801	Yes	Recovered 725' of muddy water and 60' of fresh water.	4
37	32-81-9dda	Mississippi River Fuels Inc. #1 Goose Egg Government	1955	2636		10/55	Pc	5400	2778-2790	1310	5654				No	Casper Formation core (2767'-2791') was wet and had both "good porosity and permeability, (and a) trace of black tarry oil."	4,5
38	32-81-16aca	Kemmerer and Kemmerer #1 State	1952	4985				5404							No	Lost circulation from 580'-635' and from 685'-755' in the Casper Formation.	4,5
39	32-81-15bda	Liberty Petroleum #1A Government	1965	5065				5236			5236				Yes	Artesian water flow encountered in Casper at 210'; increased with depth from 260'-295'. Blowout preventor would not close. Minor artesian flows encountered in the lower Casper (490'-510') and in the Madison (750'-870'). Fremont Canyon wet.	4

#(a)	Location(b)	Operator Well Name	Year Drilled	Casper Formation Top Elevation(c)	Temp. °C(d)	Testing Date	Formation Tested(e)	Reference Elevation(f)	Interval Tested(g)	Shut-in Pressure (lbs/in^2)	Hydraulic Head(h)	Avg. Productivity of Tested Interval (gpm)(i)	Est. Permeability of Tested Interval (gal/day-ft^2)(j)	Est. Transmissivity of Aquifer Thickness (gal/day-ft)(k)	Water Analysis(l)	Remarks	Source(m)
40	32-81-15bda	Liberty Petroleum #1 Government	1965	5065				5236			5236				No	Artesian flow encountered 210' subsurface. "The flow soon washed to a depth of fifteen feet over rectangular area approximately 20' by 50'. The drill hole expanded to approximately 3' wide, to a depth of approximately 70'."	4
100	32-78-7bcb	The Texas Co. #1 Government Donley	1955	6120				6707							No	Drilled through reverse faults 1042' and 1530' below the land surface. Reportedly produced enormous quantities of fresh water especially from the Madison Formation.	4,5
101	32-78-5acd	Southland Royalty Co. #1 Pratt Ranch	1965	1371	43	11/65	Pc	5931	4579-4591	1938	5840	131.9	7.2	6408	Yes	Recovered 100' of water cut mud, 4165' of fresh water.	4,5
132	31-82-19bcb	Skinner Corp. #1-19 Government	1966	-417				5944kb							No		3
133	31-82-27cdc	John McClure #1-27 Watson	1968	623	64	5/11/68	Pc(?)	5397	4776-4846	2141	5584	54.1	2.56	2278.4	Yes	Artesian water flow from Casper Formation dolomite 4786' below the land surface. DST conducted just below this point. Recovered 4600' of water and 64' of mud and lost circulation material.	4
134	31-82-26cbc	Ferguson and Bosworth #3-26 Government	1964	887	52			5402							No		4
135	31-82-26bad	S & J Operating Co. #1 Miles Federal	1989	959				5407							No		4
136	31-82-26cca	Earl Malette #1 Gov't-Gassman-Childers	1955	892				5367	4135-4215						No	No pressure data reported for Casper DST.	3
137	31-82-25bda	Ladd Petroleum #2 Schrader Flats	1976	892	28	7/26/76	Pc	5279	4403-4453	2023	5584	60.5	.63	560.7	Yes	Recovered 610' of muddy water, 2000' of fresh water.	4
138	31-81-6cdd	Tenneco Oil Co. #1-6 Clark State	1986	-1725				5347							Yes	Drilled through fault 6855' below the land surface. Found water in Casper Formation.	4
139	31-81-8dba	True and Brown Oil Co. #1 Klein State	1954	1446				5380							No	Found Casper Formation "porous, fractured, and wet."	4
140	31-81-30dba	Tenneco Oil Co. #1-30 Britz Federal	1988	778				5477							No		4

#(a)	Location(b)	Operator Well Name	Year Drilled	Casper Formation Top Elevation(c)	Temp. °C(d)	Testing Date	Formation Tested(e)	Reference Elevation(f)	Interval Tested(g)	Shut-in Pressure (lbs/in^2)	Hydraulic Head(h)	Avg. Productivity of Tested Interval (gpm)(i)	Est. Permeability of Tested Interval (gal/day-ft^2)(j)	Est. Transmissivity of Aquifer Thickness (gal/day-ft)(k)	Water Analysis(l)	Remarks	Source(m)
141	31-81-29dba	Trend Resources #1-29 EMC Federal	1979	1734				5448							No		4
142	31-81-33bdb	Mule Creek Oil Co. #1 Government	1962	1486	59	7/62	Pc	5479	4099-4149 4204-4220	1709	5318	1.86	.014	12.7	No	Casper Formation (4004'-4150') very "hard and tight." Averaged 20.6 min/ft from 4161'-4185'. First Casper DST recovered 40' of slightly water cut mud. Second Casper DST recovered 216' of water cut mud, 465' of muddy water, 2315' of salty water.	4
143	31-81-22bdc	R.M. Burke #1 Government	1952	1859				5509							No	Cored from 3710'-3727' in Casper Formation, recovering 17' of sand and water.	4
144	31-81-24cac	Pacific Western Oil Co. #1 Oborne	1944	2093(?)				5576							No	Found water in Dakota (1500'), Casper, and Madison Formations.	3,4
145	31-81-25bac	John Reeves #1-25 TwoBar Government	1968	2175				5608							No	Located water in Casper Formation from 3442'-3590' below land surface.	4
146	31-80-16add	Roy Farrel #2 Red Creek	1966	3137				5737							No		4
147	31-80-30ddd	Kinney Coastal #2 Kinney	1925	2755(?)				5690							No	Water present from 2935'-2942' below land surface in Casper(?).	4
148	31-80-33bdb	Producers and Refiners #1 Government	1923	3739				5904							No	Produced water from Casper Formation.	4
150	31-80-35cca	Miracle and Pifer #1 State	1958	4635				6415rt							No	Lost circulation 2004' below the land surface in Casper Formation.	4
151	31-79-2adc	Texas Co. #1 State	1955	6870				7928							No	Good porosity and permeability in Casper Formation. Complete and perceptible losses of drilling fluids in Casper. Reportedly encountered no oil, gas, or water.	4,5

#(a)	Location(b)	Operator Well Name	Year Drilled	Casper Formation Top Elevation(c)	Temp. °C(d)	Testing Date	Formation Tested(e)	Reference Elevation(f)	Interval Tested(g)	Shut-in Pressure (lbs/in^2)	Hydraulic Head(h)	Avg. Productivity of Tested Interval (gpm)(i)	Est. Permeability of Tested Interval (gal/day-ft^2)(j)	Est. Transmissivity of Aquifer Thickness (gal/day-ft)(k)	Water Analysis(l)	Remarks	Source(m)

a.) Number corresponds to numbered location shown on Figure 6.

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

c.) Elevation in feet above sea level. Queried where approximate.

d.) Approximate temperature near the top of the Casper Formation based on bottom hole temperatures.

e.) Pge = Goose Egg Formation
Pc = Casper Formation

f.) Elevation in feet above sea level, except when followed by:
rt= elevation of rotary table in feet above sea level
kb= elevation of kelly bushing in feet above sea level.

g.) Specific depth interval tested during the drill stem test; measured in feet. The midpoint of this interval was considered the gauge depth unless a gauge depth was specified.

h.) Elevation in feet above sea level at 35°C. Calculated using the following equation:
Potentiometric Surface = Reference Elevation - Gauge Depth + 2.319 * (Shut-in Pressure)
Method after Murphy (1965).

i.) Calculated using the following equation:
Average Productivity = Total Recovered Fluid Volume / flow duration
Method after Murphy (1965).

j.) Calculated using the following equation:
Est. Permeability = Effective Transmissivity of Tested Interval / Test Interval Thickness
where:
Effective Transmissivity = 624 * Avg. Productivity / Effective Pressure Differential
Effective Pressure Differential = Final Shut-in Pressure - (Initial Flow Pressure + Final Flow Pressure)/2
Method after Miller (1976) and Gatlin (1960).

k.) Calculated using the following equation:
Est. Transmissivity = Est. Permeability of Tested Interval * Aquifer Thickness
Aquifer thickness is here considered 890 feet.
Method after Miller (1976), Bredehoeft (1965), and Gatlin (1960).

l.) Water analyses listed in Appendix F.

m.) Sources of data:
1.) Swenson and others (1976)
2.) Cardinal (1984)
3.) Wyoming Geological Survey Files (various)
4.) Wyoming Oil and Gas Conservation Commission Files (various)
5.) Petroleum Information (various)

APPENDIX E

MAJOR IONIC COMPOSITIONS OF SPRING WATER SAMPLES TAKEN IN THE CASPER MOUNTAIN AREA, NATRONA COUNTY, WYOMING

APPENDIX E

Major ionic compositions of spring water samples taken in the Casper Mountain area, Natrona County, Wyoming

#(a)	Location(b)	Spring Name	Date of Collection	Water Yielding Unit(c)	Ca+2 mg/l (meq/l)	Mg+2 mg/l (meq/l)	K+ mg/l (meq/l)	Na+ mg/l (meq/l)	Cl- mg/l (meq/l)	HCO3- mg/l (meq/l)	CO3-2 mg/l (meq/l)	SO4-2 mg/l (meq/l)	F- mg/l (meq/l)	NO3- mg/l (meq/l)	SiO2 mg/l	Fe (total) mg/l	Calculated % Charge Imbalance(d)	Total Dissolved Solids at 180°C	Lab pH	Alkalinity as CaCO3 (mg/l)	Specific Conductance (umho/cm at 25°C)	Remarks	Source(e)
41	32-81-15bad	Speas Spring	4/1/93	Pc, Mm	77.0 (3.84)	22.0 (1.81)	2.50 (.06)	24.0 (1.04)	45 (1.27)			79 (1.65)	.30 (.02)		12	.003			7.8		650	Temperature = 15.0°C, Discharge = 7180 gpm	5
			10/8/92	Pc, Mm	72.0 (3.59)	20.0 (1.65)	2.40 (.06)	23.0 (1.0)	43 (1.21)			73 (1.52)	.30 (.02)		11	<.003			7.7		641	Temperature = 15.0°C, Discharge = 7629 gpm	5
			7/17/92	Pc, Mm	78 (3.90)	21 (1.73)	2.5 (.06)	23 (1.00)	48 (1.37)	236 (3.87)	0 (.00)	81 (1.69)	.2 (.01)	.45 (.00)	12	<.003			7.8	197	654	Analysis used to construct Stiff diagram for Figure 10. Temperature = 15.5°C, Discharge = 8078 gpm.	4
			5/27/92	Pc, Mm	77 (3.84)	21 (1.73)	2.4 (.06)	24 (1.04)	47 (1.33)	242 (3.97)	0 (.00)	78 (1.62)	.3 (.02)	.49 (.00)	13	.008			7.8	194	644	Temperature = 15.5°C, Discharge = 7629 gpm.	4
			10/24/91	Pc, Mm	79 (3.94)	21 (1.73)	2.4 (.06)	24 (1.04)	42 (1.18)			75 (1.56)	.2 (.01)	.40 (.00)	12	.023			7.7	190	636	Temperature = 15.5°C, Discharge = 8078 gpm.	4
			8/31/90	Pc, Mm	77 (3.84)	22 (1.81)	2.5 (.06)	23 (1.0)	46 (1.30)			84 (1.75)	.3 (.02)	.20 (.00)	12	.01			7.8	170	620	Temperature = 15.5°C, Discharge = 8078 gpm.	4
			10/11/89	Pc, Mm	77 (3.84)	22 (1.81)	1.8 (.05)	27 (1.17)	41 (1.16)			73 (1.52)	.3 (.02)	.4 (.00)	13	.005			7.8	180	578	Temperature = 15.5°C, Discharge = 7180 gpm.	4
			10/18/84	Pc, Mm	73 (3.65)	23.6 (1.94)	2.2 (.06)	25.5 (1.11)	35.5 (1.00)			70.2 (1.46)		.46 (.01)				452	7.9	223		Temperature = 15.0°C.	6
			9/29/82	Pc, Mm	82 (4.09)	22 (1.81)	4 (.10)	20 (.87)	54 (1.52)	244 (3.99)	0 (.00)	64 (1.33)						366	7.6		430		2
			2/1/67	Pc, Mm	88 (4.39)	20 (1.65)	2.8 (.07)	28 (1.22)	47 (1.33)	236 (3.87)	0 (.00)	92 (1.92)	.1 (.00)	.9 (.01)	13	.05		422	7.8		684	Temperature = 16°C, B= .04 mg/L.	1,5
			2/10/65	Pc, Mm	77 (3.85)	25 (2.06)		44 (1.92)	62 (1.75)	248 (4.07)	0 (.00)	96 (2.0)						466	7.6			Grab sample taken for comparison with water flowing from well 39. Sodium and Potassium reported together.	6
			1/17/56	Pc, Mm	78.4 (3.92)	24.7 (2.03)	2.3 (.06)	17.8 (.77)	42.5 (1.20)			92.4 (1.92)				0		387	7.2	199	662	Temperature = 17°C	6
42	32-81-10cdb	Storey's Spring #1	8/5/93	Kc	3.0 (.15)	.7 (.06)	<.1 (.00)	331 (14.39)	14.7 (.42)	609 (9.99)	15.3 (.51)	185 (3.85)	1.80 (.09)	<.1 (.00)	16.3	.22	-.53	884	8.7	520	1432		7
44	32-81-10cdb	Storey's Spring #3	8/5/93	Kc	2.0 (.10)	.3 (.02)	<.1 (.00)	282 (12.26)	9.6 (.27)	615 (10.09)	25.1 (.84)	72.2 (1.50)	2.10 (.11)	<.1 (.00)	12.6	.09	-1.11	697	8.9	539	1184		7
46	32-81-15ddb	Hollywood Spring #2	8/5/93	Tc	68 (3.40)	60.1 (4.95)	5.7 (.15)	49.0 (2.13)	2.6 (.07)	322 (5.28)	0 (.00)	242 (5.04)	.45 (.02)	.29 (.00)	16.7	<.05	1.18	628	8	264	944		7
47	32-81-15ddb	Hollywood Spring #3	8/5/93	Tc	71 (3.55)	61.0 (5.02)	5.6 (.14)	45.0 (1.96)	4.1 (.12)	298 (4.89)	0 (.00)	279 (5.81)	.45 (.02)	.29 (.00)	16	<.05	-.54	648	7.8	244	963		7
48	32-81-14cca	Hollywood Hills Spring	8/4/93	Kc	71 (3.55)	31.4 (2.58)	6.0 (.15)	24.0 (1.04)	.6 (.02)	276 (4.53)	0 (.00)	143 (2.98)	.31 (.02)	.47 (.01)	11.7	<.05	-1.33	419	8	226	614		7
51	32-81-14bad	Kamon's Spring	8/4/93	Tc	190 (9.50)	69.8 (5.74)	4.0 (.10)	26.0 (1.13)	3.2 (.09)	221 (3.63)	0 (.00)	620 (12.92)	.31 (.02)	.47 (.01)	16.3	<.05	-.37	1027	7.8	181	1237		7
52	32-81-14aba	Bicek Spring	8/4/93	Tc	476 (23.80)	80.0 (6.58)	3.0 (.08)	63.0 (2.74)	3.2 (.09)	179 (2.94)	0 (.00)	1438 (29.96)	.33 (.02)	.87 (.01)	20.5	<.05	.33	2166	7.7	147	2716		7

#(a)	Location(b)	Spring Name	Date of Collection	Water Yielding Unit(c)	Ca+2 mg/l (meq/l)	Mg+2 mg/l (meq/l)	K+ mg/l (meq/l)	Na+ mg/l (meq/l)	Cl- mg/l (meq/l)	HCO3- mg/l (meq/l)	CO3-2 mg/l (meq/l)	SO4-2 mg/l (meq/l)	F- mg/l (meq/l)	NO3- mg/l (meq/l)	SiO2 mg/l	Fe (total) mg/l	Calculated % Charge Imbalance(d)	Total Dissolved Solids at 180°C	Lab pH	Alkalinity as CaCO3 (mg/l)	Specific Conductance (umho/cm at 25°C)	Remarks	Source(e)
54	32-81-12ccd	Burris' Spring	8/4/93	Tc	606 (30.30)	101 (8.31)	4.0 (.10)	70 (3.04)	5.4 (.15)	151 (2.48)	0 (.00)	1888 (39.33)	.48 (.03)	.66 (.01)	15	<.05	-.21	2886	7.7	124	2949		7
55	32-81-12cbd	Gillingham's Spring	8/4/93	Tc	518 (25.90)	78.4 (6.45)	2.0 (.05)	20.0 (.87)	3.2 (.09)	206 (3.38)	0 (.00)	1416 (29.50)	.90 (.05)	1.00 (.02)	22.3	<.05	.40	2090	7.5	169	2239		7
56	32-81-11dbb	Whitney's Spring #1	8/5/93	Kc	1.0 (.05)	.3 (.02)	<.1 (.00)	322 (14.00)	8.0 (.23)	517 (8.48)	24.2 (.81)	236 (4.92)	1.25 (.07)	<.1 (.00)	16.3	<.05	-.97	881	8.9	457	1379		7
57	32-81-11dbb	Whitney's Spring #2	8/5/93	Kc	3.0 (.15)	2.7 (.22)	<.1 (.00)	343 (14.91)	13.7 (.39)	585 (9.59)	13.4 (.45)	239 (4.98)	1.90 (.10)	<.1 (.00)	12.4	<.05	-.45	905	8.6	498	1505		7
60	32-81-12aad	Randall's Spring	8/4/93	Pc	83 (4.15)	29.6 (2.44)	2.0 (.05)	7.0 (.30)	4.5 (.13)	334 (5.47)	0 (.00)	95 (1.98)	.54 (.03)	<.1 (.00)	17.8	<.05	-4.43	433	7.7	274	660		7
61	32-81-1ddc	Logan's Spring	8/4/93	Pc	125 (6.25)	33.7 (2.77)	2.0 (.05)	9.0 (.39)	6.1 (.17)	325 (5.33)	0 (.00)	182 (3.79)	.57 (.03)	.69 (.01)	18	<.05	.75	548	7.4	266	802		7
62	32-81-12aab	Blue Spring	8/4/93	Pc	130 (6.50)	36.4 (3.00)	2.0 (.05)	9.0 (.39)	5.1 (.15)	314 (5.15)	0 (.00)	250 (5.21)	.60 (.03)	.65 (.01)	16.9	<.05	-2.88	591	7.6	257	844		7
63	32-81-12aaa	Shirk's Spring	8/4/93	Pc	160 (8.00)	39.5 (3.25)	2.0 (.05)	8.0 (.35)	5.1 (.15)	261 (4.28)	0 (.00)	363 (7.56)	.70 (.04)	.83 (.01)	17.9	<.05	-1.64	751	7.7	214	971		7
64	32-80-7bbc	Garman's Spring	8/4/93	Pc	58 (2.90)	21.4 (1.76)	1.0 (.03)	6.0 (.26)	2.6 (.07)	229 (3.76)	0 (.00)	71.5 (1.49)	.33 (.02)	.52 (.01)	15.7	<.05	-3.91	309	7.6	188	490		7
65	32-81-12ada	Canyon Village Spring #1	7/30/93	Pc	48.0 (2.40)	19.4 (1.60)	1.5 (.04)	7.0 (.30)	3.80 (.11)	229 (3.76)	0 (.00)	39.9 (.83)	.31 (.02)	<.1 (.00)	14.9	<.05	-3.96	242	8	188	450		7
66	32-80-7bcb	Canyon Village Spring #2	7/30/93	Pc	46.0 (2.30)	19.2 (1.58)	.7 (.02)	7.0 (.30)	3.8 (.11)	228 (3.74)	0 (.00)	39.5 (.82)	.30 (.02)	.28 (.00)	14.5	<.05	-5.38	224	8.1	187	439		7
67	32-80-7bcb	Canyon Village Spring #3	7/30/93	Pc	45.0 (2.25)	19.3 (1.59)	.7 (.02)	6.0 (.26)	2.2 (.06)	229 (3.76)	0 (.00)	38.1 (.79)	.22 (.01)	.31 (.01)	14.5	<.05	-5.80	235	8.1	188	435		7
68	32-80-7bcc	Canyon Village Spring #4	7/30/93	Pc	45.0 (2.25)	19.0 (1.56)	.6 (.02)	5.0 (.22)	2.6 (.07)	228 (3.74)	0 (.00)	33.3 (.69)	.28 (.01)	.28 (.00)	14.7	<.05	-5.49	221	8.1	187	415		7
69	32-80-7bcc	Canyon Village Spring #5	7/30/93	Pc	43.0 (2.15)	19.3 (1.59)	.5 (.01)	4.0 (.17)	2.9 (.08)	231 (3.79)	0 (.00)	31.3 (.65)	.25 (.01)	.20 (.00)	14.3	<.05	-6.99	207	8.1	189	417		7
71	32-80-18bcb	Gothberg Draw Spring	8/4/93	Pc	98 (4.90)	31.4 (2.58)	1.0 (.03)	8.0 (.35)	1.0 (.03)	282 (4.63)	0 (.00)	155 (3.23)	.49 (.03)	1.67 (.03)	18.8	<.05	-.81	474	7.8	231	696		7
73	32-80-26abc	Big Little Red Creek Spring	10/2/93	Pc	56.0 (2.80)	19.9 (1.64)	<.1 (0.0)	<1.0 (0.0)	.9 (.03)	251 (4.12)	0 (.00)	5.2 (.11)	.12 (.01)	.17 (.00)	11.3	<.05	2.68	219	7.7	206	383		7
74	32-80-35cca	Little Red Creek Spring	10/2/93	Pge	519.0 (25.95)	96.9 (7.98)	1.7 (.04)	14.0 (.61)	1.9 (.05)	257 (4.22)	0 (.00)	1458 (30.38)	.60 (.03)	.57 (.01)	15.8	<.05	-.06	2350	7.5	211	2559		7
75	32-79-32ccc	Big Red Creek Spring	10/16/93	Pge	620 (31.00)	29.5 (2.43)	.5 (.01)	3.0 (.13)	.6 (.02)	251 (4.12)	0 (.00)	1239 (25.81)	.28 (.01)	.36 (.01)	14.4	<.05	5.68	2097	7.90	206	2208		7
76	32-79-25ddd	Backside Spring	10/16/93	Pc	100 (5.00)	23 (1.89)	.4 (.01)	4.2 (.18)	1.3 (.04)	238 (3.90)	0 (.00)	131 (2.73)	.24 (.01)	.60 (.01)	11.2	<.05	2.87	391	7.9	195	616		7

#(a)	Location(b)	Spring Name	Date of Collection	Water Yielding Unit(c)	Ca+2 mg/l (meq/l)	Mg+2 mg/l (meq/l)	K+ mg/l (meq/l)	Na+ mg/l (meq/l)	Cl- mg/l (meq/l)	HCO3- mg/l (meq/l)	CO3-2 mg/l (meq/l)	SO4-2 mg/l (meq/l)	F- mg/l (meq/l)	NO3- mg/l (meq/l)	SiO2 mg/l	Fe (total) mg/l	Calculated % Charge Imbalance(d)	Total Dissolved Solids at 180°C	Lab pH	Alkalinity as CaCO3 (mg/l)	Specific Conductance (umho/cm at 25°C)	Remarks	Source(e)
78	32-79-10ccd	Mills Camp Spring	?/79	Dfc	62 (3.10)	17 (1.40)	.7 (.02)	.8 (.03)	6.9 (.20)	269 (4.41)	0 (.00)	1 (.02)	.09 (.00)			<.01			7.7		387		3
81	32-79-19abc	Sacajawea Spring	10/17/93	Prc	25.3 (1.27)	26.7 (2.20)	<.1 (.00)	.9 (.04)	.6 (.02)	217 (3.56)	0 (.00)	2.5 (.05)	.16 (.01)	.34 (.01)	31.4	<.05	-1.77	179	7.8	178	335		7
102	32-78-10dad	Chaput Spring	10/4/93	Pc	58.0 (2.90)	18.9 (1.56)	<.1 (.00)	<1.0 (.00)	.9 (.03)	268 (4.4)	0 (.00)	11.3 (.24)	.18 (.01)	.3 (.00)	7.2	<.05	-1.82	237	7.6	220	432		3,7
103	32-78-10dda	Health Spring	?/79	Pc	54 (2.70)	21.0 (1.73)	1.6 (.04)	3.1 (.13)	7.4 (.21)	238 (3.90)	0 (.00)	32.0 (.67)	.18 (.01)			.01			7.30		448		3
108	32-78-14cbb	Spring 'E'	10/4/93	Pc	47.0 (2.35)	19.7 (1.62)	.4 (.01)	2.0 (.09)	.3 (.01)	211 (3.46)	0 (.00)	29.0 (.60)	.23 (.01)	.27 (.00)	10.6	<.05	-.15	204	7.9	173	416		7
109	32-78-14cbc	Spring 'D'	?/79	Pc	49 (2.45)	20 (1.65)	1.5 (.04)	2.9 (.13)	5.2 (.15)	222 (3.64)	0 (.00)	22 (.46)	.16 (.01)			<.01			7.50		408		3
115	32-78-29cbd	Crooked Road Spring	10/16/93	Pc	106.0 (5.30)	28.0 (2.30)	.5 (.01)	5.2 (.23)	1.3 (.04)	237 (3.89)	0 (.00)	192.0 (4.00)	.30 (.02)	.74 (.01)	12.1	<.05	-.70	446	7.9	194	738		7
116	32-78-21dcd	Mostellar Spring	?/79	Pc	53 (2.65)	20 (1.65)	.4 (.01)	1.0 (.04)	.4 (.01)	268 (4.40)	0 (.00)	2 (.04)	.12 (.01)			<.01			7.6		412		3
117	32-78-22bcd	Harris Ranch Falls Spring	10/4/93	Mm	59.0 (2.95)	24.5 (2.02)	<.1 (.00)	<1.0 (.00)	0.6 (.02)	279 (4.58)	0 (.00)	15.3 (.32)	.16 (.01)	.51 (.01)	6.8	<.05	.80	257	7.8	229	434		7
121	32-78-22caa	Bathtub Spring	10/4/93	Mm	49.0 (2.45)	21.5 (1.77)	.3 (.01)	<1.0 (.00)	1.3 (.04)	251 (4.11)	0 (.00)	19.6 (.41)	.17 (.01)	.58 (.01)	8.9	<.05	-3.59	231	7.8	206	417		7
127	32-78-28ddb	Yahoo Spring	10/4/93	Pc	75.0 (3.75)	22.9 (1.88)	<.1 (.00)	2.0 (.09)	.3 (.01)	253 (4.15)	0 (.00)	61.4 (1.28)	.18 (.01)	.59 (.01)	7.6	<.05	2.42	303	7.7	207	502		7
130	32-78-28dcd	Quiet Spring	10/4/93	Pge, Pc(?)	237 (11.85)	39.4 (3.24)	1.0 (.03)	7.0 (.30)	.9 (.03)	244 (4.00)	0 (.00)	592 (12.38)	.26 (.01)	.16 (.00)	13.7	<.05	-2.88	1030	7.8	200	1302		7

a.) Number corresponds to numbered location shown on Figure 6.

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

c.) Kc = Cloverly Formation
Tc = Chugwater Formation
Pge = Goose Egg Formation
Pc = Casper Formation
Mm = Madison Formation
Dfc = Fremont Canyon Sandstone
Prc = Precambrian
Queried where uncertain.

d.) Negative numbers indicate a calculated excess of anions.
Positive numbers indicate a calculated excess of cations.

e.) Sources of data:
1.) Crist and Lowry (1972)
2.) Flaccus (1982)
3.) Gable and others (1988)
4.) Ritz and Bruce (1993)
5.) Wyoming Water Resources Center (various)
6.) Wyoming Game and Fish Commission (various)
7.) This study

APPENDIX F

MAJOR IONIC COMPOSITIONS OF WATER SAMPLES TAKEN FROM SELECTED WELLS IN THE CASPER MOUNTAIN AREA, NATRONA COUNTY, WYOMING

APPENDIX F

Major ionic compositions of water samples taken from selected wells in the Casper Mountain area, Natrona County, Wyoming.

#(a)	Location(b)	Owner / Operator Well Name	Date of Collection	Water Yielding Unit(c)	Ca+2 mg/l (meq/l)	Mg+2 mg/l (meq/l)	K+ mg/l (meq/l)	Na+ mg/l (meq/l)	Cl- mg/l (meq/l)	HCO3- mg/l (meq/l)	CO3-2 mg/l (meq/l)	SO4-2 mg/l (meq/l)	F- mg/l (meq/l)	NO3- mg/l (meq/l)	SiO2 mg/l	Fe (total) mg/l	Calculated % Charge Imbalance(d)	Total Dissolved Solids at 180°C	Lab ph	Alkalinity as CaCO3 (mg/l)	Specific Conductance (umho/cm at 25°C)	Remarks	Source(e)
2	33-82-7bdd	Argo Oil Co. #1 Jacobs	9/56	Pc	20 (.99)	11 (.90)		719 (31.26)	120 (3.38)	855 (14.02)	0 (.00)	757 (15.75)						2048	7.9			Sample derived from Casper DST. Sodium and potassium reported together as sodium.	7
7	33-82-21bda	Far West Oil Co. #1 Morton Government	12/54	Pc	326 (16.27)	68 (5.59)		553 (24.05)	348 (9.81)	366 (6.00)	12 (.40)	1428 (29.70)						2858	8.3			Sample derived from Casper DST. Sodium and potassium reported together as sodium.	7
10	33-82-35bdc	Summit Resources #3 Speas	10/16/64	Pc	7 (.35)	11 (.90)	13 (.33)	562 (24.43)	72 (2.03)	659 (10.81)	0 (.00)	633 (13.17)						1623	8			Sample taken from the wellhead.	7
11	33-82-35cac	Summit Resources #4 Speas	8/20/64	Pc	183 (9.13)	59 (4.85)	37 (.95)	306 (13.29)	260 (7.33)	354 (5.81)	0 (.00)	725 (15.08)						1744	7.8			Production water sample.	7
12	33-82-35caa	Summit Resources #1 Speas	10/16/64	Pc	31 (1.55)	14 (1.15)	61 (1.56)	716 (31.14)	200 (5.64)	915 (15.01)	60 (2.00)	613 (12.75)						2146	8.6			Sample taken from wellhead.	7
			2/45	Pc	103 (5.14)	248 (20.39)		116 (5.02)	190 (5.36)	425 (7.70)	trace	840 (17.49)						1955				Sample obtained using a Halliburton Tester. Sodium and potassium reported together as sodium.	7
			2/45	Mm	20 (1.0)	20 (1.64)		553 (24.06)	171 (4.79)	905 (14.83)	146 (4.87)	106 (2.21)						1536				Sample obtained using a Halliburton Tester. Sodium and potassium reported together as sodium.	7
16	33-82-35dcb	Summit Resources #1 Government	2/56	Pc	526 (26.25)	89 (7.32)		451 (19.62)	400 (11.28)	100 (1.64)	0 (.00)	1936 (40.27)						3800	7.5			Production water sample. Sodium and potassium reported together as sodium.	7
17	33-82-36ccd	Amerada Hess Co. #1-36 State	1/26/82	Pc	596 (29.74)	148 (12.17)	24 (.61)	437 (19.02)	350 (9.87)	107 (1.75)	0 (.00)	2400 (49.92)						4008	7			Sample obtained from DST sampler.	7
22	33-81-24dbb	Lysite Ventures #1 Government	1/57	Pc	279 (13.92)	105 (8.63)		441 (19.16)	384 (10.83)	145 (2.38)	0 (.00)	1370 (28.50)						3218	7.5			Well flowed 100 barrels of water per hour. Water rich in organic material. Sodium and potassium reported together as sodium.	7
23	33-81-26aaa	Virginian Oil Co. #1 Henderson Government	pre-1940	Pc	541 (27.05)	116 (9.55)		471 (20.48)	400 (11.43)	105 (1.72)	0 (.00)	2112 (44.00)						3692				Sodium and Potassium reported together as sodium.	1

#(a)	Location(b)	Owner / Operator Well Name	Date of Collection	Water Yielding Unit(c)	Ca+2 mg/l (meq/l)	Mg+2 mg/l (meq/l)	K+ mg/l (meq/l)	Na+ mg/l (meq/l)	Cl- mg/l (meq/l)	HCO3- mg/l (meq/l)	CO3-2 mg/l (meq/l)	SO4-2 mg/l (meq/l)	F- mg/l (meq/l)	NO3- mg/l (meq/l)	SiO2 mg/l	Fe (total) mg/l	Calculated % Charge Imbalance(d)	Total Dissolved Solids at 180°C	Lab ph	Alkalinity as CaCO3 (mg/l)	Specific Conductance (umho/cm at 25°C)	Remarks	Source(e)
24	33-81-36aad	Mohawk Oil Co. #1 State	10/3/93	Pc	355 (17.75)	92.2 (7.59)	17.0 (.44)	635 (27.61)	291 (8.31)	251 (4.12)	0 (.00)	1894 (39.46)	3.80 (.20)	<.1 (.00)	8.8	.18	1.43	3573	7.90	206	4475	Temperature = 20°C	12
			6/26/79	Pc	510 (25.5)	120 (9.87)	23 (.59)	160 (6.96)	56 (1.58)			2000 (41.76)	3.00 (.16)	.1 (.00)	11			2930	7.8	89	4400	Se = <.001 mg/l, Temperature = 27.0°C, PO4 = .003 mg/l	10
27	33-79-24acc	Casper Country Club Country Club #1	3/23/67	Kc	1.0 (.05)	0 (.00)	.3 (.01)	149 (6.48)	6.7 (.19)	278 (4.56)	0 (.00)	74 (1.54)	.7 (.04)	0 (.00)	27	.05		402	8	228	538	B = .07 mg/l Temperature = 31.0°C	3
29	33-77-15bcb	Amax Petroleum Co. N-17-WS	5/3/75	Mm	360 (18.0)	55.0 (4.52)	58.00 (1.48)	560.0 (24.36)	580 (16.36)	1310 (21.47)	0 (.00)	1400 (29.15)	4.0 (.21)	0 (.00)	37			3390	8.6	8050(?)	3720	Temperature = 16.0°C	10
			7/23/68	Mm	393 (19.61)	55 (4.52)	64 (1.64	582 (25.32)	560 (15.79)	159 (2.61)	0 (.00)	1572 (32.69)				.00		3304	7.1			"Sampled as known Madison water (from production)."	7
			4/18/64	Mm	338 (16.90)	55 (4.53)	58 (1.49)	452 (19.65)	322 (9.20)	124 (2.03)	0 (.00)	1560 (32.50)	5.0 (.26)	1.1 (.02)	40	4.8		3040	7.4	102	3660	B= .71 mg/l	2,10
35	32-81-9cbb	General American Oil Co. #1-9 Federal	10/76	Pc	682 (34.03)	50 (4.11)	33 (.84)	454 (19.74)	420 (11.84)	195 (3.20)	0 (.00)	2100 (43.68)						3835	7.6			Sample taken from DST sampler.	7
39	32-81-15bda	Liberty Petroleum #1A Government	2/4/65	Pc	56 (2.80)	21 (1.73)		26 (1.13)	10 (.29)	254 (4.17)		33 (.69)						298	7.6			Sodium and Potassium reported together as sodium.	8
49	32-81-15daa	Albert Allen Allen #1	8/4/93	Pge	478 (23.90)	143 (11.77)	4.0 (.10)	40.0 (1.74)	10.9 (.31)	142 (2.33)	0 (.00)	1857 (38.69)	1.80 (.09)	.63 (.01)	18.8	<.05	-4.79	2769	7.84	116	2843		12
50	32-81-15add	Gilbert Glynn Glynn #1	8/4/93	Pc	56.0 (2.80)	18.2 (1.50)	<1.0 (.00)	3.0 (.13)	1.3 (.04)	242 (3.97)	0 (.00)	33.3 (.69)	.22 (.01)	.66 (.01)	12.3	<.05	-2.97	249	8.17	198	434		12
53	32-81-14bad	Robert Kamon Kamon #1	8/4/93	Pc	62.0 (3.10)	19.9 (1.64)	<1.0 (.00)	4.0 (.17)	2.2 (.06)	238 (3.90)	0 (.00)	58.3 (1.21)	.23 (.01)	<.10 (.00)	11.3	<.05	-2.32	287	8.05	195	471		12
58	32-81-12dab	Susan Cole Cole #2	8/4/93	Pc, Pge	133 (6.65)	45.7 (3.76)	2.0 (.05)	12.0 (.52)	6.4 (.18)	222 (3.64)	0 (.00)	370 (7.71)	1.10 (.06)	1.55 (.03)	21.5	<.05	-2.92	739	8.03	182	961		12
			9/3/75	Pc, Pge	100.0 (5.00)	43.0 (3.54)	1.9 (.05)	10.0 (.44)	5.2 (.15)	221 (3.62)		260 (2.71)	1.1 (.06)	1.5 (.03)	23	.06		554	7.7		950	Temperature = 10.0°C	10
86	32-79-21caa	Leon Winkes Winkes #1	12/6/72	Pxc, Dfc(?)	74 (3.69)	19 (1.56)	2 (.05)	31 (1.34)	6 (.17)	378 (6.20)	0 (.00)	13 (.27)				<.05		331	8.0	263			9
88	32-79-21cac	L.J.W. Brouillete Brouillette #2	4/29/69	Pc	126 (6.29)	50 (4.11)	6 (.15)	160 (6.98)	8 (.23)	451 (7.40)	0 (.00)	476 (9.90)				<.05		1048	7.5			Well reportedly penetrates various shales overlying the Casper Formation.	9
90	32-79-21bdd	Jerry Stephenson Stephenson #1	7/3/79	Mm	42 (2.1)	13 (1.07)	3 (.08)	10 (.43)	12 (.34)	207 (3.39)	0 (.00)	18 (.38)					5.5	200	8.18		395		9
93	32-79-22dbd	Gerald Rieck Rieck #1	11/20/70	Mm(?)								8.2 (.17)		0 (.00)				190		237			9
95	32-79-23bab	Ruth Jones Tickbite #1	7/17/84	Pc	23 (1.15)	2 (.16)	2 (.05)	11 (.49)	8 (.23)	90 (1.48)	0 (0.0)	7 (.14)		.20 (.00)				97	6.91	66	144		9

#(a)	Location(b)	Owner / Operator Well Name	Date of Collection	Water Yielding Unit(c)	Ca+2 mg/l (meq/l)	Mg+2 mg/l (meq/l)	K+ mg/l (meq/l)	Na+ mg/l (meq/l)	Cl- mg/l (meq/l)	HCO3- mg/l (meq/l)	CO3-2 mg/l (meq/l)	SO4-2 mg/l (meq/l)	F- mg/l (meq/l)	NO3- mg/l (meq/l)	SiO2 mg/l	Fe (total) mg/l	Calculated % Charge Imbalance(d)	Total Dissolved Solids at 180°C	Lab ph	Alkalinity as CaCO3 (mg/l)	Specific Conductance (umho/cm at 25°C)	Remarks	Source(e)
98	32-79-14ada	Donald Dockter D & G #1	10/29/82	Mm, Dfc	53 (2.64)	17 (1.40)	0 (.00)	1 (.02)	0 (.00)	244 (4.00)	0 (.00)	3 (.06)						194	7.5	202			9
99	32-79-13dbd	Derold Scharosch Scharosch #1	9/10/85	Prc, Dfc, Mm, Pc(?)	55 (2.75)	20 (1.65)	1 (.04)	2 (.09)	5 (.14)	244 (4.0)	5 (.17)	9 (.19)		.17 (.00)				217	8.23	219	360		9
101	32-78-5acd	Southland Royalty Co. #1 Pratt Ranch	11/65	Pc					400 (11.28)														11
133	31-82-27cdc	John McClure #1-27 Watson	5/11/68	Pc					250 (7.05)														11
137	31-82-25bda	Ladd Petroleum #2 Schrader Flats	7/26/76	Pc					470 (13.25)														11
138	31-81-6cdd	Tenneco Oil Co. #1-6 Clark State	6/18/86	Pc	390 (19.46)	29 (2.38)	35 (.90)	902 (39.24)	99 (2.79)	85.4 (1.40)	<1 (.00)	2660 (55.33)	3.8 (.20)	7.8 (.13)		6.5	2	4187	8.2				7
149	31-80-33bdd	Casper Board of Public Utilities Bodie Dome #1	2/3/84	Prc, Dfc, Mm, Pc	50 (2.50)	17 (1.04)	4 (.10)	14 (.61)	6 (.17)	207 (3.40)	0 (.00)	50 (1.04)	.33 (.02)	<.1 (.00)	15.2		.8	284	7.4	170	394		5

a.) Number corresponds to numbered location shown on Figure 6.

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

c.) Kc = Cloverly Formation
Pge = Goose Egg Formation
Pc = Casper Formation
Mm = Madison Formation
Dfc = Fremont Canyon Sandstone
Prc = Precambrian
Queried where uncertain.

d.) Negative numbers indicate a calculated excess of anions.
Positive numbers indicate a calculated excess of cations.

e.) Sources of data:
1.) Crawford (1940)
2.) Hodson (1971)
3.) Crist and Lowry (1972)
4.) Wright Water Engineers (1982)
5.) Wright Water Engineers (1984)
6.) Moser (1993)
7.) Proprietary (various)
8.) Wyoming Game and Fish Commission (various)
9.) Wyoming State Engineer (various)
10.) Wyoming Water Resources Center (various)
11.) Wyoming Oil and Gas Conservation Commission (various)
12.) This study

APPENDIX G

TRACE ION COMPOSITIONS OF SELECTED SPRINGS AND WELLS IN THE CASPER MOUNTAIN AREA, NATRONA COUNTY, WYOMING

APPENDIX G

Trace ion compositions of selected springs and wells in the Casper Mountain area, Natrona County, Wyoming.

#(a)	Location(b)	Operator Spring / Well Name	Date of Collection	Water Yielding Unit(c)	Al mg/l	As mg/l	Ba mg/l	Be mg/l	B mg/l	Cd mg/l	Cr mg/l	Co mg/l	Cu mg/l	Fe mg/l	Pb mg/l	Li mg/l	Mn mg/l	Hg mg/l	Mo mg/l	PO4 mg/l	Se mg/l	Ag mg/l	Sr mg/l	Zn mg/l	Gross Alpha pCi/l (d)	Gross Beta pCi/l (e)	Uranium (U3O8) mg/l	Ra 226 pCi/l	Ra 228 pCi/l	Tritium TU(f)	Remarks	Source(g)
24	33-81-36aad	Mohawk Oil Co. #1 State	7/28/93	Pc(?)	<.1	<.001	<.1	<.005	.94	<.01	<.05	<.01	<.01	.25	<.05	.36	.01	<.001				<.05	7.02	<.01	7.7±2.8	81.8±19.7				.04±.09		8
29	33-77-15bcb	Amax Petroleum Co. N-17-WS	5/3/75	Mm	.01	.018	<.1	<.01	1.1	<.002	<.001	<.001	<.002		.002	<.01	.20	<.0005	.002	.02	<.001	<.001	10.0	<.001								6
41	32-81-15bad	Speas Spring	4/1/93	Pc, Mm(?)	.03	.0004	.071	<.0005	.05	<.001	<.001	<.003	.002	.003	<.001	.037	<.001	<.0001		<.03	.001	<.001	.78	.006	14.0±3.95* 18.0±5.19**	5.7±1.44* 4.2±1.08**	.0063	1.2				6
			10/8/92	Pc, Mm(?)	<.01	.003	.063	<.0005	.04	<.001	<.001	<.003	.001	<.003	<.001	.035	<.001	<.0001		<.03	<.001	<.001	.76	.004								4
			7/17/92	Pc, Mm(?)	<.01	.03	.062	<.0005	.05	<.001	<.001	<.003	.005	<.003	.001	.033	<.001	.0005		.01	.001	<.001	.8	.014						10.96		4
			5/27/92	Pc, Mm(?)	.02	.03	.063	<.0005	.05	<.001	.004	<.003	.002	.008	<.001	.036	<.001	.0002		.03	<.001	<.001	.8	.003								4
			10/24/91	Pc, Mm(?)	<.01	.003	.062	<.0005	.05	<.001	<.001	<.003	.005	<.003	.001	.033	<.001	.0005		.01	.001	<.001	.8	.014	14.0±4.7**	6.4±1.6* 4.8±1.2**	.0058	1.1±.18				4
			8/31/90	Pc, Mm(?)	<.01	.03	<.1	<.0005	.04	<.001	<.001		.002	.01	<.001		<.01	<.0001		<.03	<.001	<.001		.01	13±4.3**	4.0±1.2* 3.1±.9**	.0066	1.2±.17				4
			10/11/89	Pc, Mm(?)		.03	.067	<.0005	.04	<.001	.001		.002	.005	<.001		<.001	.0002		<.03	<.001	.001		<.003								4
			10/18/84	Pc, Mm(?)	<.05	<.005				<.001	<.003			.02	<.01		<.002	.001	<.02	.004	<.005			.012								5
58	32-81-12dab	Susan Cole Well #2	9/3/75	Pc, Pge	.04	.011		.01	.05	.01	.01		.01	.06	.1	.03	.01	.00	.04	.01	.004			.26							Ni= .05 mg/l	6
102	32-78-10dad	Chaput Spring	?/79	Pc									<.003				<.01							<.01								2
103	32-78-10dda	Health Spring	?/79	Pc									<.003				<.01							<.01								2
108	32-78-14cbb	Spring 'E'	?/89	Pc																					17±4.4	8.5±2.0	.0174				Springs 108-109 compose the Hat Six Warm Springs.	3
109	32-78-14cbc	Spring 'D'	?/79 ?/89	Pc									<.003	<.01			<.01							<.01	21±4.8	9.7±2.1	.0174	1.0±.5		8.73±.28		2,3
112	32-78-15ccc	Spring 'A'	?/89	Pc																					10±3.9	8.7±2.1	0	1.0±.6		23.31±.7		3
116	32-78-21dcd	Mosteller Spring	?/79	Pc									<.003				<.01							<.01								2
138	31-81-6cdd	Tenneco Oil Co. #1-6 Clark State	6/18/86	Pc			.26		<1					6.5		<1	.13			<.1			5.5									7
149	31-80-33bdd	Casper Board of Public Utilities Bodie Dome #1	2/3/84	Pc, Mm, Dfc, Pre		.01	<.5		<.1	<.01	<.05		<.02	.62	<.05		.01	<.0004	.14	<.01	<.01	<.02		<.01	239±20	91±7	.052	47±2	2.9±2.5			1

#(a)	Location(b)	Operator Spring / Well Name	Date of Collection	Water Yielding Unit(c)	Al mg/l	As mg/l	Ba mg/l	Be mg/l	B mg/l	Cd mg/l	Cr mg/l	Co mg/l	Cu mg/l	Fe mg/l	Pb mg/l	Li mg/l	Mn mg/l	Hg mg/l	Mo mg/l	PO4 mg/l	Se mg/l	Ag mg/l	Sr mg/l	Zn mg/l	Gross Alpha pCi/l (d)	Gross Beta pCi/l (e)	Uranium (U3O8) mg/l	Ra 226 pCi/l	Ra 228 pCi/l	Tritium TU(f)	Remarks	Source(g)

a.) Number corresponds to numbered location shown on Figure 6.

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

c.) Pge = Goose Egg Formation
Pc = Casper Formation
Mm = Madison Formation
Dfc = Fremont Canyon Sandstone
Prc = Precambrian
Queried where uncertain.

d.) Gross Alpha reported using EPA method 900.0, unless:
*pCi/l as TH-230 (dissolved) **micrograms/l as U-natural (dissolved)

e.) Gross Beta reported using EPA method 900.0, unless:
*pCi/l as CS-137 (dissolved) **pCi/l as Sr/Yt-90 (dissolved)

f.) Measurements taken prior to 1993 were recalculated using the following equation:
Old TU Value X Correction Factor (f) where: f = 1.0368 + (year - 1990) X .0008
to correspond to the better half-life value of 12.43 years.

g.) Sources of data:
1.) Wright Water Engineers (1984)
2.) Geble and others (1988)
3.) James M. Montgomery (1990)
4.) Ritz and Bruce (1993)
5.) Wyoming Game and Fish Commission (various)
6.) Wyoming Water Resources Center (various)
7.) Proprietary
8.) This study