FAULT SEVERING OF AQUIFERS AND OTHER GEOLOGICALLY CONTROLLED PERMEABILITY CONTRASTS IN THE BASIN-MOUNTAIN INTERFACE, AND THE IMPLICATIONS FOR GROUND WATER RECHARGE TO AND DEVELOPMENT FROM THE MAJOR ARTESIAN BASINS OF WYOMING

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CHAPTER I

Fault Severed Aquifers along the Perimeters of Wyoming Artesian Basins

ABSTRACT

The mountain uplifts which border the major artesian basins of Wyoming are asymmetric antiforms bounded on one flank by large displacement Laramide thrust faults. These thrusts sever the hydraulic continuity of the Paleozoic aquifers, thereby creating separate circulation systems in the Paleozoic rocks respectively in the hanging wall and foot wall blocks. Fault severing can be identified by (1) potentiometric discontinuities across the faults, (2) water quality contrasts across the faults, and (3) thermally heated waters in the foot wall blocks.

Isolated but active circulation systems develop in the hanging wall blocks in which good permeabilities and good quality water prevail. In contrast the foot walls are characterized by poor permeabilities and poor water qualities. The result is that exploration for large volume, good quality supplies is focused on the hanging wall blocks in fault severed environments. Fault severing of the Paleozoic aquifers in the Wyoming foreland province is significant because just under half of the basin perimeters are severed.

PURPOSE AND ACKNOWLEDGEMENTS

Large scale faulting parallel to the foreland uplifts in Wyoming precludes recharge to the Paleozoic aquifers in the adjacent artesian basins in cases where the Paleozoic rocks in the foot wall remain buried. This article will (1) describe the geologic environment in which fault severed aquifers are found, (2) reveal the extent of fault severing, and (4) discuss the implications of severing on recharge and development.

Many of the concepts outlined here were refined by the writer using project specific data from subcontracts through the following consulting firms: Western Water Consultants, Laramie, and Banner Associates, Laramie. Individuals who helped compile supporting data and develop the concepts include Henry Richter and Karen Tarr, Western Water Consultants; and Richard Johnson, Banner Associates. Larry Wester and Jack Kelly of Anderson and Kelly Consultants, Laramie and Boise, generously shared supporting data which verified findings reported herein for other areas in the region. Considerable site specific data is held by these firms under priority status for clients and is therefore unavailable for publication. The office of Water Research and Technology, U.S. Department of the Interior, supported the regional aspects of this project through the Wyoming Water Center under contract 14-35-0001, project A-034-WYO.

BASIN PERIMETERS

The perimeters of the foreland artesian basins in Wyoming fall into three broad classes based on the degree of hydraulic interconnection between the recharge areas and deep basins. The classes are from least to best connected: (1) fault severed, (2) continuous homoclines, and (3) obliquely faulted.

Fault severed boundaries - treated herein - encompass slightly less than half of the basin perimeters in the Wyoming foreland. They are characterized by faulting parallel to the basin perimeter wherein the rocks comprising the Paleozoic aquifers have been displaced entirely past each other. The aquifers in the foot wall are typically in fault contact against impermeable basement rocks, thus precluding lateral flow or recharge from the mountain uplift.

Basin perimeters comprised of continuous homoclines are as common as fault severed boundaries and contain rocks which dip unbroken from the recharge area into the deep parts of the basins (Huntoon, 1983). The obliquely faulted perimeter is the least common class. This class is characterized by tectonic structures - usually fault cored anticlines - which trend across the basin margins and extend deeply into the basins. Such structures, having created zones of greatly enhanced secondary fracture permeability, provide excellent hydraulic connection between the recharge areas and the interior parts of the basin.

FAULT SEVERED PERIMETERS

Fault severed perimeters are extremely important because as shown on Figure 1 they comprise just under half of the basin margins in the Wyoming foreland province. The principal faults which bound the mountain uplifts in Wyoming are Laramide thrusts with displacements ranging up to ten miles of dip slip. Vertical offsets associated with such faults can be as great as a few miles. The tectonic and geometric character of these faults has been documented by Berg (1962, 1981), Blackstone (1963), and Johnson and others (1978). The most complete summary article dealing with this class of thrust faults is that of Gries (1983).

As shown on Figure 2, the typical mountain range in the Wyoming foreland is a large asymmetric antiform 12 to 60 miles across that is bounded on one flank by a major thrust fault which dips beneath the range. The opposite flank is comprised of a broad gently dipping homocline. This structural style results in approximately equal percentages of fault severed and homoclinal basin perimeters within the province.

The hydrologic implications for the Paleozoic aquifers along fault severed boundaries is obvious from Figure 2. If the foot wall remains buried, there is no opportunity for recharge to the Paleozoic aquifers in the basin along the boundary. The result is that two completely separate circulation systems develop, one restricted to the Paleozoic rocks comprising the hanging wall block, and the other contained in the same rocks in the basin.

IDENTIFICATION

The identification of such fault severed boundaries would not appear to be difficult based on the large offsets involved. However it has taken the petroleum geologists decades to define the geometric form, magnitude of displacement, and placement of these structures through the use of sophisticated subsurface and geophysical techniques. The reasons for this difficulty lies in the fact that the traces of the faults generally occur basinward from the flanks of the ranges where they are buried by unfaulted Tertiary sediments. See Figure 2. Also the flanks of the ranges are characterized by folding of the leading edges of the thrust plates such that the basement-Paleozoic contacts are sharply downfolded toward the basins beneath the Tertiary cover. The folded exposures of Paleozoic rocks in the hanging wall along the flanks of the ranges give the false impression of structural continuity between the Paleozoic rocks in the mountains and those in the basins.

Fault severing of the rocks comprising the Paleozoic aquifers isolates the circulation systems in the hanging wall from those in the foot wall. Three criteria can be used to demonstrate that the systems are independent. (1) Head differences occur across the fault. (2) Water qualities are dramaticaly different such that fresh waters occupy the hanging wall blocks and, in the extreme, petroleum and brine occur in the foot wall blocks. (3) Thermally heated waters occur in the deeply buried foot wall blocks.

In addition, the permeabilities in the hanging walls are commonly orders of magnitude greater than those found in the foot walls. Permeability contrasts result from post-fault differences in diagenetic processes between the respective blocks. The dominent process in the hanging wall blocks involves the solutional removal of cements and matrix in clastics, or development of solution cavities in carbonates. In contrast, the processes of recrystallization, cementation, and compaction operate to destroy permeability in the deeply buried foot wall blocks. It must be noted that the presence of permeability contrasts does not uniquely identify fault severed basin margins. Permeability contrasts between basin subcrops and recharge outcrops also develop as a result of the same diagenetic processes within continuous homoclines (Huntoon, 1983).

LARAMIE RANGE TYPE EXAMPLE

The northern and eastern flanks of the Laramie range are bounded by thrust faults located as shown on Figure 3 which have as much as two miles or more of dip slip (Jenkins and Rea, 1978; Richter and Huntoon, 1982; Johnson and others, 1982). Figure 4 is an idealized composite cross section through the flank of the range prepared using the down plunge projection technique employed by Sales (1971). Notice that (1) the Paleozoic aquifers in the hanging and foot walls are isolated, and (2) there are several levels of exposure along the structure.

Profiles C and E on Figure 4 are very unusual for the Wyoming foreland because the Paleozoic rocks in the foot wall are exposed. In these cases, the exposed Paleozoic rocks in the basin form an unhindered recharge zone which assumes the hydrologic character of a homoclinal perimeter.

Profiles A and B represent the most common situation along the fault severed perimeters of Wyoming basins. This setting is characterized by the preservation of grand hogbacks of Paleozoic rocks on the hanging wall which dip toward the basin. Many of these structurally isolated hanging wall blocks have been falsely identified as recharge areas for the Paleozoic aquifers in the adjacent basins.

The fact is that the hanging wall blocks have self-contained ground water circulation systems. These drain to gaining reaches of streams which cross the blocks, to springs located in topographic low spots along the toes of the Paleozoic outcrops, or to Tertiary aquifers which bury the toes of the hanging wall block. Mancini (1976) has documented gains in stream flows from the Paleozoic outcrops which occur in the hanging wall blocks along the northern Laramie range. My observations along the Paleozoic Casper and Madison hogbacks south of Douglas (Figure 3) concur. The water which recharges the rocks in the hanging wall blocks typically moves along strike to springs or gaining streams which occupy topographic low points within the hogbacks. Consequently it is clear that the gradients within the hanging wall blocks are dominately paralled to the strike of the rocks, not down dip.

HYDROLOGIC TRAPS

The geologic structures in the Wyoming foreland province have set some traps for hydrologists steeped in the tradition of treating aquifers as laterally continuous. Problems in dealing with the fault severed western perimeter of the Powder River basin (Figure 1) demonstrate this point.

Potentiometric data are available from oil wells completed in the Paleozoic rocks in the foot wall block within a few miles of the flank of the Bighorn range. These heads are considerably lower than those for springs and streams in good hydraulic connection with the same rocks in the hanging wall. Careful scientists such as Swenson (1974) and Swenson and others (1976) have contoured these data as if the aquifer was continuous across the faulted perimeter of the basin. Their maps show unusually steep potentiometric gradients across the mountain-basin interface, and very gentle gradients within the interiors of the basins. A diametrically opposed fact is that permeabilities in the exposed hogbacks are very large implying that gradients across the perimeter should be gentle. Recharge estimates made using the Darcy equation and incorporating the steep phantom gradients to compute the flow across the basin perimeter produce huge numbers where in fact there is no recharge. See Huntoon (1976) for a good example of someone falling into that trap.

Konikow (1976) was forced to either seal or minimize recharge across the western perimeter of the Powder River basin in order to verify his digital model for the Madison aquifer in the Powder River basin. Blackstone (1981a, 1981b) later substantiated the validity of this treatment by demonstrating that a major fault buried under Tertiary sediments has severed the Madison aquifer along most of the eastern flank of the Bighorn range as shown on Figure 1.

DISCUSSION

Recharge to the principal Paleozoic aquifers is not taking place along the majority of the fault severed basin perimeters in the Wyoming foreland province. The implications for development of water from the foot wall blocks from the Madison, Tensleep, and Casper aquifers are two fold. (1) Replenishment rates are small which compounds the impacts of specific developments on regional water levels. (2) Water qualities are poor in the foot wall blocks even in areas adjacent to mountain uplifts. In addition, permeabilities within the foot wall blocks are commonly orders of magnitude less than in the adjacent hanging walls. For example, typical specific capacities for the Madison aquifer within the interior parts of the Powder River Basin range from 0.5 to 5 gal/min-ft (Feathers and others, 1981).

The consequence of these facts is that large volume, good quality users in fault-severed environments are forced to abandon hopes of obtaining supplies from the foot wall and basinward parts of the Paleozoic section. Rather they end up focusing their exploration and development efforts on the hanging wall blocks where qualities are good, permeabilities larger, and drilling depths shallower.

The problems facing developments in the hanging wall blocks are several. These blocks are the sources for major springs and encompass part of the headwaters for most perennial streams in Wyoming. These surface supplies are already fully appropriated. Consequently ground water developments in the hanging walls which have the potential of impacting the flows from either the springs or streams are jealously scrutinized by existing surface water appropriators and the State Engineer. In addition, the hanging wall plays are often located tens of miles from basin users, and the hanging wall locations are commonly in very rugged mountain flank terrain.

More important, potential users find that because of the hydrologic facts associated with fault severing, the area of exploration has shrunk from the large surface areas of the basins to narrow bands in the upland parts of the basin perimeters. As documented in Huntoon (1983), the situation is little better for developers looking for supplies on the homoclinal flanks because permeabilities along these flanks also decrease dramatically basinward from the outcrops. Aerially extensive aquifers such as the Madison have turned out to be very fickle targets indeed because of the general basinward deterioration of permeabilities.

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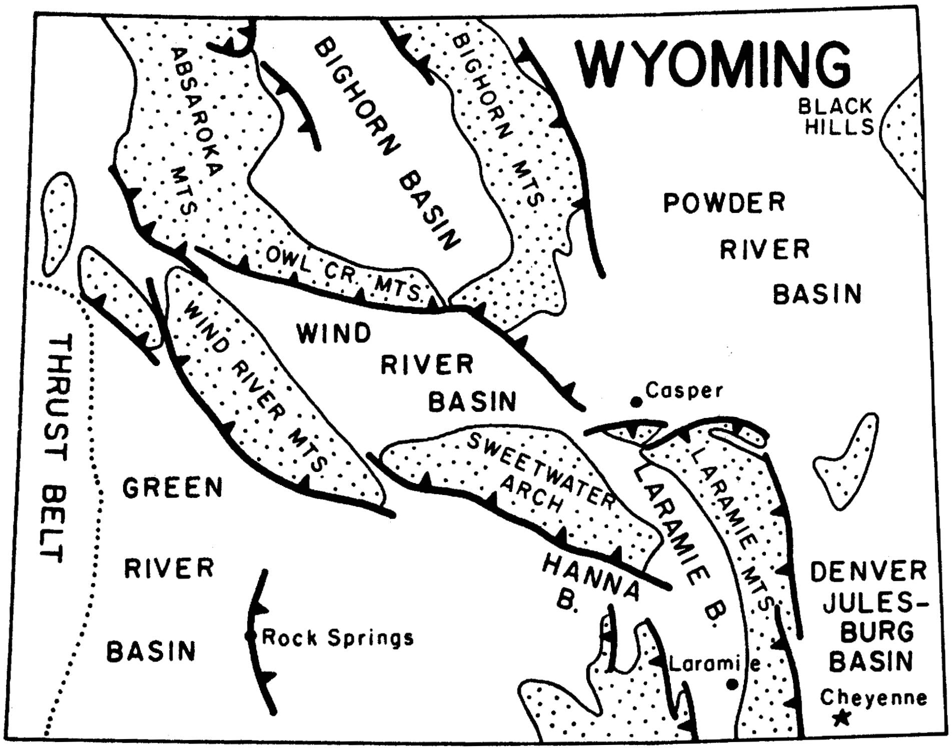
Figure 1. Principal artesian basins in Wyoming showing the locations of major thrust faults which sever the Paleozoic aquifers along the basin margins. Notice that approximately half the basin perimeters are fault severed. Data from Gries (1983), Blackstone (1981a), and Richter and Huntoon (1982).

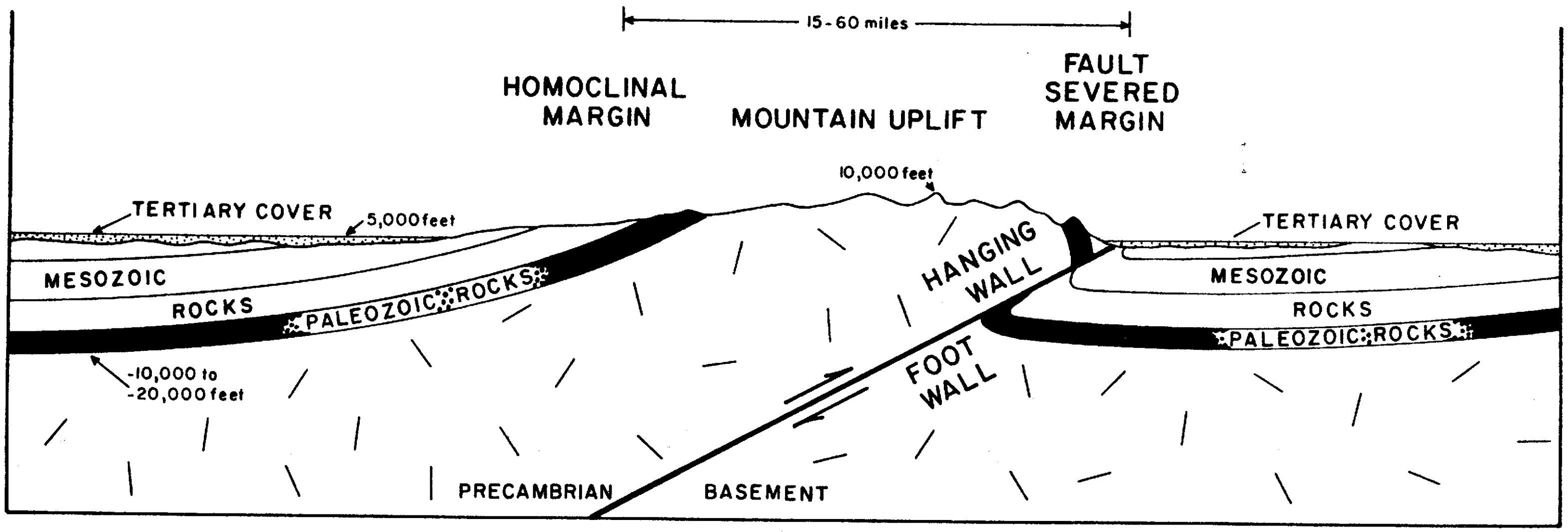
Figure 2. Schematic cross section through a typical Wyoming mountain uplift showing the style of deformation which results in approximately equal percentages of fault severed and homoclinal basin perimeters. Notice that the thrust fault subcrops basinward from the flank of the range where it is buried by Tertiary rocks.

Figure 3. Generalized tectonic map of the Laramie uplift, southeastern Wyoming, showing the locations of identified thrust faults on the eastern and northern flanks which sever the Paleozoic aquifers. The western flank of the range is a homoclinal margin. The lettered locations correspond to the locations of cross sections used to compile Figure 4.

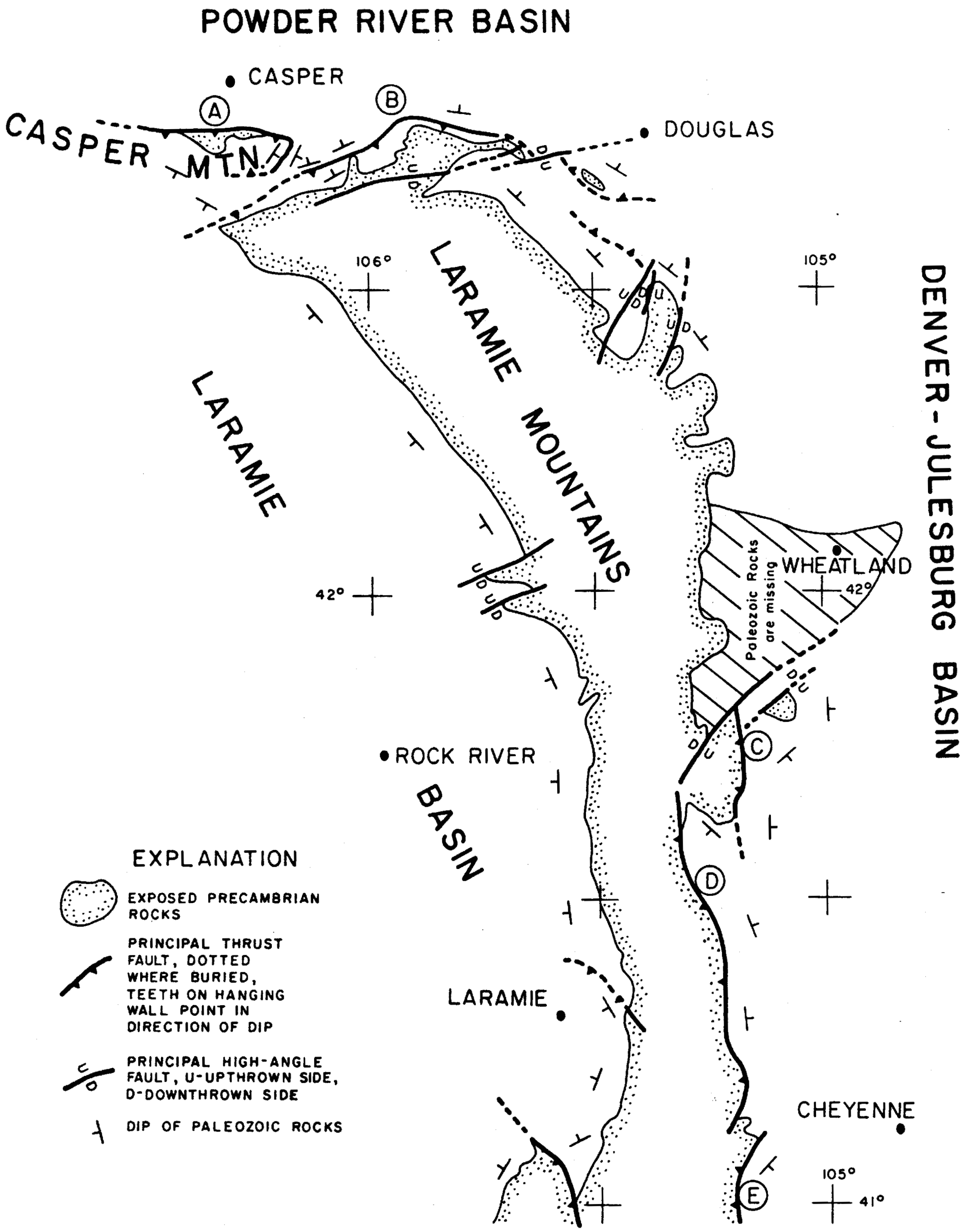
Figure 4. Generalized composite cross section through the eastern and northern flanks of the Laramie uplift, southeastern Wyoming, showing fault severing of the Paleozoic aquifers. The lettered profiles correspond to the positions of the land surface relative to the structure at the lettered locations on Figure 3. The elevations shown correspond to those at section B. Notice that the Paleozoic aquifers in the foot wall block on sections C and E are exposed.



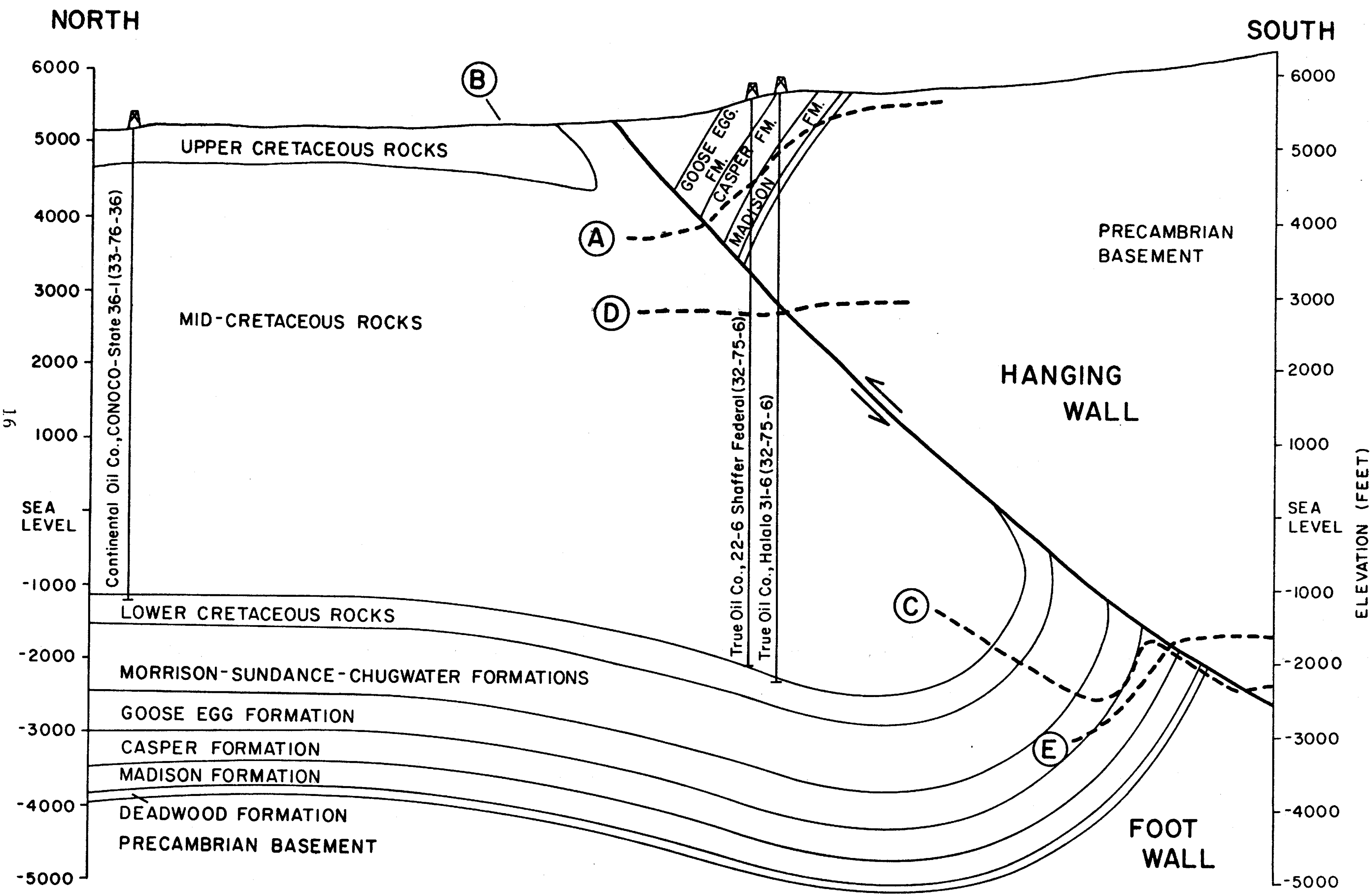
Huntoon - Faults - Figure 1



— Huntoon - Faults - Figure 2 —



— Huntoon - Faults - Figure 3 —



Huntoon - Faults - Figure 4

CHAPTER II

Rejection of Recharge Water from the Madison Aquifer along the Eastern Perimeter of the Bighorn Artesian Basin, Wyoming

ABSTRACT

Approximately half of the perimeters of Wyoming foreland artesian basins are characterized by structural continuity of the Paleozoic aquifers between the recharge areas and the interior parts of the artesian basins. A significant percentage of the ground water which circulates through such recharge areas is rejected through springs because there is a dramatic decrease in permeability basinward from the recharge area. The permeability contrast has developed since the recharge area became differentiated from the basin interior. Secondary enhancement of permeabilities is occurring in the recharge area through dissolution of the rock matrix and cement, and in some locations the rocks are tectonically fractured. In contrast the rates of dissolution within the basin interiors are substantially decreased, or processes of recrystalization, cementation, or compaction are operating to destroy permeability. The result is that in the case treated here, net recharge to the basin interior is a small fraction of measured stream losses in the headwaters of the recharge area.

SCOPE

The hydrologic phenomina treated here is that of natural rejection of ground water from the recharge area for the Madison aquifer along the edge of a typical foreland artesian basin in Wyoming. The issue treated is the need to carefully discriminate between net recharge to the artesian basins in this province and the "apparent" recharge obtained by summing the observed stream losses in the headwaters of the recharge areas. One irony that will arise in the following discussion is that more water is observed to discharge from the toe of the Trapper-Medicine Lodge recharge area than is observed to sink in its headwaters.

As shown on Figure 1, the Trapper-Medicine Lodge recharge area treated here lies on the eastern perimeter of the Bighorn Basin and is characterized by a homoclinal dip of the rocks comprising the Madison aquifer basinward from the recharge area into the basin interior. There is stratigraphic and therefore hydraulic continuity between the two parts of the system in this setting.

Rejection of recharge, defined by Mancini (1974), occurs because there is a dramatic decrease in permeabilities within the aquifer basinward from the recharge area. The permeability contrast has developed since the recharge area became differentiated as a hydrologic entity from the adjacent basin. Dissolution of carbonates is operating to enhance permeabilities in the recharge area whereas recrystallization, cementation, compaction or reduced rates of dissolution occur in the same rocks in the adjacent basin.

The Trapper-Medicine Lodge recharge area is typical of recharge areas for aquifers contained within the Paleozoic sections found along the perimeters of almost half of the foreland basins in Wyoming. The observations for this recharge area are very site specific and involve karst. However, the rejection mechanism can be generalized and usefully applied along the perimeters of other artesian basins in the foreland province of Wyoming and adjacent states.

HYDROGEOLOGIC SETTING

The perimeters of the Wyoming foreland artesian basins are coincident with large scale mountain uplifts. The structural character of the Paleozoic rocks at the basin-mountain interface fall into two broad catagories: (1) fault severed and (2) continuous homoclines. Each of these types is approximately equally represented in Wyoming.

The general form of a fault severed margin is one of large displacement faults - typically thrusts - which parallel the mountain front (Berg, 1962; Gries, 1983) and which sever the hydraulic continuity of the Paleozoic aquifers between the outcrops and deep-basin subcrops. Good examples of Wyoming basin margins of this type are the eastern and northern flanks of the Laramie range, southwestern flank of the Wind River range, and eastern flank of the Bighorn uplift.

Homoclinal margins - the type treated here - are typified by structural continuity of the Paleozoic aquifers between the outcrops in the recharge areas and deep basin subcrops. Examples of this type are found along the flanks of the Black Hills, west flank of the Laramie range, and parts of the west flank of the Bighorn uplift.

As shown on Figure 2 the rocks comprising the Madison aquifer crop out along a ten-mile wide band on a gently west dipping homocline. Figure 3 illustrates that the homocline is bounded on the east by a prominent north trending reverse fault in the basement which has produced a west dipping steep to vertical limbed faulted monocline in the overlying Paleozoic and younger rocks.

The exposed Precambrian core of the range is the headwaters for perennial flows in the Trapper and Medicine Lodge drainages. The White Creek drainage shown on the northern part of Figure 2 is wholely eroded within the homocline, and thus receives no surface drainage from the Precambrian highlands.

Originally, thousands of feet of Paleozoic and younger rocks covered the region including the present Precambrian core of the range. These rocks have been deeply eroded so that at the present time the White, Trapper, and Medicine Lodge drainages are incising through wide dip slopes which comprise the upper confining layer of the Madison aquifer. Trapper and Medicine Lodge canyons have cut almost through the rocks comprising the Madison aquifer for miles along their lengths.

The combination of the structural setting and geomorphic processes is the exposure of approximately 125 mi^2 of rocks comprising the Madison aquifer in this area. These outcrops are in intimate hydraulic connection with both the surface drainages and the basinward subcrops of the Madison aquifer.

The vertical relief between the highest Paleozoic outcrops around the perimeters of the Bighorn Basin and subcrops within the basin is on the order of six miles. Topographic elevations of the Paleozoic recharge areas in the Trapper-Medicine Lodge area range from 4,400 to 9,000 ft as compared to the maximum drillhole depths for the same rocks in the Bighorn Basin of -18,200 ft (Hunt Energy Co., 1982).

The fluids associated with these rocks range from high-quality fresh waters along the perimeters of the basin to progressively more saline and thermally heated waters toward the synclinal axis of the basin. Numerous petroleum accumulations occur in the Paleozoic rocks in the Bighorn Basin which are an integral part of the total hydraulic system treated here. In fact, ground water in the Bighorn artesian basin circulates under structural and hydrodynamic petroleum traps in the Paleozoic aquifers (Hubbert, 1953) before discharging from various springs in the interior of the basin.

MADISON AQUIFER DEFINITION

The Madison aquifer, identified on Table 1, is well defined in the area treated here. The Paleozoic units included within the aquifer are vertically connected by joints and solution enlarged fractures. The upper and lower surfaces of the aquifer are marked by confining shales which are demonstrably effective because they localize springs throughout the area. Additional evidence that the Madison aquifer is confined both from the overlying Tensleep and underlying Flathead aquifers are the substantial head differences between the aquifers. Data obtained from drill stem tests basinward from the Trapper-Medicine Lodge area which support this statement appear on Table 2. In contrast, tests within different intervals in the Madison aquifer have similar heads. Water quality data (not presented here) collected by the author from springs along the toe of the recharge area differ significantly in major ion concentrations between the Madison and Tensleep aquifers, but samples within the Madison aquifer have very similar concentrations.

On a regional scale, the definition for the Madison aquifer shown on Table 1 is valid only for the structurally unbroken homocline west of the Precambrian core of the Bighorn range. As the Madison aquifer is traced deeply into the Bighorn Basin, the character of the aquifer becomes very complex due to the presence of fault-cored anticlines which overlie basement faults. The fracturing associated with the anticlines has propagated upward through the Paleozoic section, thus destroying the hydraulic integrity of the confining layers shown on Table 1. Using head data and fluid chemistry, Stone (1967) has demonstrated that water and petroleum circulate vertically to overlying units along the anticlinal axes through zones of enhanced fracture permeability. The hydraulic intricacies resulting from these structures is incidental to this discussion because such zones lie to the west of the area under consideration.

CAVE CIRCULATION NETWORKS

Every surface stream shown on Figure 2 which originates on the Precambrian highlands south of Shell Canyon sinks in its entirety where it crosses the upturned hogbacks of Bighorn Dolomite. The flows lost from individual creeks range up to several tens of ft^3/sec during peak runoff periods. Such dramatic losses to the Madison aquifer nurtures a strong public perception that the upturned edges of the great Madison aquifer along the perimeters of the Wyoming basins are a source of tremendous quantities of recharge which moves through vast underground streams into the basins where it awaits exploitation. See Figure 4.

A fact rarely noticed is that considerably more water discharges from the Madison Limestone at the toes of the recharge areas through springs and gaining reaches of streams miles below the sinks. The resulting streams flow out to the surface of the basin perched above the confining layers that overlie the Madison aquifer.

MASS BALANCE

The mass balance equation for this recharge area has the form:

$$Q_{in} + Q_r = Q_{out} + Q_u$$

where

Q_{in} = surface inflows,

Q_r = recharge occurring as a result of precipitation on the recharge area,

Q_{out} = surface outflows, and

Q_u = subsurface flow out of the recharge area.

Q_r and Q_u are unmeasured, whereas at least for one point in time Q_{in} and Q_{out} are known from Table 3. Q_{in} at the time of the measurements listed in Table 3 was totally lost to the subsurface through swallow holes in the headwaters of the recharge area, and Q_{out} was the cummulative discharge of all the springs along the toe of the recharge area.

A maximum estimate for Q_u can be made for the Trapper-Medicine Lodge area by applying the Darcy equation to a cross section through the Madison aquifer which extends between the mouths of Trapper and Medicine Lodge canyons at a location basinward from the toe of the recharge area. The average head gradient basinward from the recharge area is 40 ft/mi based on contoured head data taken from Table 2. The length of the cross section between the canyons is 17 mi. The maximum Q_u is computed by using the maximum transmissivity (4.4×10^3 gal/day-ft) listed for the Madison aquifer in Table 2. Using these numbers, Q_u is found to be at most about 5 ft^3/sec. Providing that the values for

Q_{in} and Q_{out}, respectively 17.3 and 33 ft^3/sec, taken from Table 2, are remotely representive of averages, Q_u is clearly the smallest component in Equation 1.

The practical consequence of the small value for Q_u is that the net recharge to the Madison aquifer in the Bighorn Basin through this part of the recharge area is at the most 1/3 to 1/4 of the quantity of water observed to disappear down swallow holes in the headwaters of the recharge area. The actual recharge to the basin interior through this area is probably an order of magnitude less than the average losses to swallow holes in the headwaters.

The reported transmissivities in Table 2 which were used to compute Q_u are not of a magnitude associated with saturated cavern zones having the characteristics of the open caves such as shown on Figure 4 which have been explored in the Trapper-Medicine Lodge area. The fact is that the observed caves do not extend significant distances beyond the toe of the recharge area in this location. Consequently there is a marked reduction in permeabilities basinward from the recharge-basin interface. Neither the permeability reductions nor reduced rates of natural recharge are particularly good news for the development of water from the basin parts of the aquifer.

COUNTING WATER TWICE

A nuisance in gaging flows within a karst area is that of counting the same water twice. The only adequate protection against this risk in the area treated here was to gage the inflows from the Precambrian highlands at a point above the karst area, and to measure the outflows at a point located above the confining layers below the lowermost carbonates exposed at the toes of the recharge area. This type of well bounded karst area is unusual. An example of the problems associated with the measurement of flows internal to this karst area follows.

During the course of this study, the water observed to enter the Madison Limestone through the Taylor and Black Butte sinks (Table 3; Figure 3) was found to discharge two miles downstream from springs issuing from the Bighorn Dolomite on the walls of a canyon tributary to Dry Medicine Lodge Canyon. This water then sank in the floor of the canyon where it circulated to and joined water in the Tres Charros-Bad Medicine cave system (Figure 3) which lies beneath Dry Medicine Canyon. The combined flow discharges through the Dry Medicine Lodge springs shown on Figure 5.

The surface stream below the Dry Medicine Lodge springs gradually looses to the alluviated floor of Dry Medicine Lodge Canyon in the sink zone shown on Figure 5. The lost water does not flow downstream through the alluvium. Rather it reenters the Madison aquifer wherein as shown on Figure 5 it circulates under the topographic divide separating Dry Medicine Lodge and Medicine Lodge canyons. It then discharges from the same resurgences in the lower part of Medicine Lodge Canyon as does water circulating in the aquifer from Pbar Cave and the sinks in the upper reaches of Medicine Lodge Canyon.

Until the sub-divide circulation of the water was discovered, the discharge from the Dry Medicine Lodge springs and resurgences in Medicine Lodge Canyon were mistakenly cummulated to overestimate the yield from the aquifer.

MISSISSIPPIAN PALEOKARST

Regionally extensive paleokarst horizons exist throughout the Madison Limestone dating from Mississippian time (Roberts, 1966; Sando, 1974) which are well exposed in the walls of the canyon in the Trapper-Medicine Lodge area. The most prominent of these occupies the upper 200 feet of the Madison Limestone and is characterized by limestone-chert breccia zones, collapse features, and ancient caves and sinkholes filled with younger clastics. In addition small scale solution voids impart a permeable look to some exposures. Reexcavated paleokarst features result in numerous short but discontinuous caves in cliffed exposures of the Madison Limestone producing an impression of a highly caverous and permeable unit.

The Madison paleokarst is unimportant in contributing significantly to the permeability of the Madison aquifer in the area. The primary evidence for this conclusion is that no springs in the region discharge from the paleokarst. The residual cavities within the paleokarst are not interconnected. Close examination of partially reexcavated caves reveals that the clastic fills are commonly either fine grains silts and clays or well cemented breccias, neither of which imparts significant additional permeability to the Madison aquifer.

The location of the resurgences in the lower part of Medicine Lodge Canyon shown on Figure 5 coincides with the paleokarst zone in the upper part of the Madison Limestone. The paleokarst does not control the location of the springs but rather it is a passive lithologic relict. Several upstream springs between Sand and Medicine Lodge springs (Figure 5) lie below unsaturated exposures of the paleokarst further illustrating that there is no connection between the springs and the paleokarst.

REJECTED RECHARGE

Most of the water which circulates through the recharge area treated here is rejected through springs before entering the artesian basin. The identical situation has been documented by Rahn and Gries (1973) along the perimeter of the Black Hills. This occurs despite the fact that there is stratigraphic continuity and therefore hydraulic continuity between the recharge area and the basin. The primary reason for rejection of water from the toe of the recharge area is that the permeabilities within the aquifer decrease dramatically basinward. Also hydraulic gradients within the basin are substantially less than those found in the recharge area, 40 ft/mi compared to 400 ft/mi.

The carbonate rocks comprising the Madison aquifer in the Trapper-Medicine Lodge area are characterized by greatly enhanced localized zones of secondary permeability resulting from Cenozoic karstification. The cavernous zones do not extend significant distances beyond the toes of the recharge area. As a result, the permeability contrast is highly accentuated in this particular area.

Basinward decreases in permeability within the Paleozoic aquifers characterize the majority of foreland basin perimeters where stratigraphic continuity exists between the recharge areas and the basin interiors. The permeability contrast develops even in areas where karst is missing. Two lines of evidence support this statement. The toes of the outcrops of Paleozoic rocks which comprise the aquifers are typically the sites of large springs indicating that rejection of recharge is taking place. Transmissivities in the foreland province tend to decrease basinward from recharge areas (Bredehoeft, 1964; Head and Merkel, 1977) indicating that diagnetic processes affecting permeability have differed between the recharge areas and artesian basins since the mountains and basins were tectonically and geomorphically differentiated.

Secondary permeabilities in the recharge areas are imprinted through two processes: (1) solutional enlargement of pores, and (2) fracturing associated with uplifts of the range along the basin perimeters.

Solutional enhancement of permeabilities in recharge areas containing carbonates commonly involves the development of caves such as in the Trapper-Medicine Lodge Area. However the same process operates in clastic aquifers such as the Tensleep aquifer (Table 1) or the Casper aquifer in southeastern Wyoming. In such units, carbonate or other soluable cements and clasts are dissolved from the rock. Dissolution in recharge areas is facilitated by the good quality waters involved.

Most foreland recharge areas also coincide with the tectonic structures which produced the differential motion between the mountains and the basins. The tectonism has imprinted fracture permeabilities on the rocks ranging from subtile increases in joint densities to highly brecciated fault zones. Tectonically induced secondary permeabilities are locally very important in accentuating the permeability contrasts between the recharge areas and basin interiors provided the severity of deformation did not cause wholesale severing of the aquifers along faults parallel to the basin margins. Fracture permeability was not found to be particularly important in the Trapper-Medicine Lodge area, but it does become very significant in sharply folded Madison hogbacks north of Shell Canyon.

In contrast, the rates of dissolution are drastically reduced, or the diagenetic processes of recrystalization, cementation, and compaction are operating to destroy permeability in the aquifers in the interior parts of the basins. Under the best of circumstances, the rates of solutional enhancement are substantially reduced in the basins as compared to recharge areas. The rate difference results primarily from the reduced gradients basinward from the recharge areas. Todd (1963) has documented decreases in permeability in the Tensleep aquifer in the Bighorn aquifer resulting from reprecipitation of course dolomite in post-Laramide time. Mankiewicz and Steidtmann (1979) report that permeability is being lost through calcite pore filling, and anhydrite and silica fracture filling in the Tensleep aquifer.

RECHARGE EFFICIENCIES

The class of recharge area treated here is characterized by stratigraphic continuity between the outcrops and deep basin subcrops. This class embodies slightly less than half the basin perimeters found in the Wyoming foreland province. In terms of recharge efficiencies, this class ranks as intermediate in a diverse spectrum of available types.

The lease efficient setting is the fault-severed basin perimeter. About half of the mountain perimeters in the Wyoming foreland coincide with thrust faults which parallel the flanks of the ranges. Dip slip displacements along these faults range up to a few miles. The rocks comprising the aquifer in the basin blocks are commonly buried deeply and juxtaposed against impermeable basement rocks. Recharge to them from their severed counterparts in the mountain block is precluded. Fault severed margins will be the subject of a subsequent article.

The rare opposite end of the spectrum involves fault-fold zones with large fracture permeabilities which trend obliquely across the basin perimeters and which therefore hydraulically link the recharge and deep basin areas. These zones of greatly enhanced secondary permeability serve as important hydraulic conduits for recharge but account for only a small percentage of the foreland basin perimeters. Such zones are the focus of sophisticated exploration programs by well advised large volume users.

CONCLUSIONS

The thesis of this study is that large volumes of water are rejected from the Paleozoic aquifers before it can circulate beyond the toes of the recharge areas into foreland artesian basins. Although the rocks are the same, drastic contrasts in permeability occur between the recharge and deep basin domains. The consequences of these facts follow. Recharge cannot be measured by gaging the flows of streams which are lost to stream channels or disappear down shallow holes in the headwaters of recharge areas. Such losses can be thought of as "apparent recharge." Apparent recharge can be an order of magnitude greater than the net deep basin recharge because much if not most of the water is ultimately rejected through springs along the toes of the recharge areas. Great care must be taken to base development and management stratagies on net recharge and basin permeability characteristics, rather than on "apparent recharge" and the large permeabilities associated with the rocks in the recharge area. Rejection of recharge along the perimeters of the foreland basins helps explain why the Madison aquifer and other Paleozoic aquifers have proven to be far less productive than many of us had originally hoped.

ACKNOWLEDGEMENTS

Barbara Vietti sparked my interest in the Trapper-Medicine Lodge area through her MS thesis. Dale Doremus compiled Table 2 by conducting a thorough search of original and published sources for relevant data, and derived the values published here. Norm Pace provided cave photographs and cave maps. The Office of Water Research and Technology, U.S. Department of the Interior, supported this project through the Wyoming Water Center under contract 14-35-0001-2145, project A-034-WYO.

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Table 1. Lithologic and hydrologic character of the rocks in the Trapper-Medicine Lodge recharge area, Bighorn Basin, Wyoming. Data from Vietti (1977).

Age	Unit	Thickness (feet)	Lithology	Hydrologic Character
Permian	Phosphoria Fm.	200	shale, gypsum	confining layer
Pennsylvanian	Tensleep Ss.	150	sandstone	TENSLEEP AQUIFER
Pennsylvanian	Amsden Fm.	150	shale, siltstone, limestone	confining layer
Mississippian	Madison Ls.	800	limestone	MADISON AQUIFER
Denovian	Jefferson Ls.	20	limestone	MADISON AQUIFER
Ordovician	Bighorn Dol.	340	dolomite	MADISON AQUIFER
Cambrian	undivided Gallatin and Gros Ventre Fms.	650	shale, minor limestones	confining layer
Cambrian	Flathead Ss.	230	sandstone	FLATHEAD AQUIFER
Precambrian	Basement rocks	---	metamorphic rocks	confining layer

Table 2. Hydraulic heads and estimated transmissivities for the Paleozoic aquifers computed from data from water wells and petroleum tests in the Bighorn Basin in the area basinward from the Trapper-Medicine Lodge recharge area. Data from Lowry (1962) and Petroleum Information Corp. (misc.)

Well name	Location T-R-sec-¼-¼	Year of Test	Formation(s) Tested	Head in Test Interval	Transmissivity (gal/day-ft)	Test Method
Amoco Prod.	52-93-20 NE NW	1973	Madison	4255	1.5×10^3	drill stem test
1 Kruger			Madison	4250		
Florida Exploration, 1-2 Nupec-Lamb Fed.	51-93-2 SW SW	1982	Madison	4180	5.4×10^2	drill stem test
Florida Exploration, 1-12 Lamb Fed.	51-93-12 SE NE	1982	Madison	4240	3.2×10^3	drill stem test
Stuarco Oil,	51-93-14 SE NW	1967	Tensleep	2830	---------	drill stem test
1 Torchlight NW			Madison	4435	---------	drill stem test
Pan American, 10 Orchard Unit	51-93-24 SE NE	1962	Madison	4405	---------	drill stem test
Ameranda Petr.	51-92-2 NW NE	1955	Tensleep	4505	3.1×10^2	drill stem test
White Sheep Unit			Madison	4705	7.5×10^2	
Pan American Petr. 2 Lamb Gov't.	51-92-18 NW NW	1970	Madison	4425	2.0×10^1	drill stem test
Brunkerhoff Drilling	51-92-18 NW SW	1968	Tensleep	2830	1.1×10^2	drill stem test
1 Lamb Gov't.			Madison	4525	4.4×10^2	drill stem test
Stoltz and Co.,	51-92-29 SW NE	1970	Tensleep	4050	2.2×10^2	drill stem test
2-29 Barnett Serio			Madison	.4350	1.6×10^2	drill stem test
Stoltz and Co.,	51-92-29 SW NW	1970	Tensleep	4440	6.8×10^2	drill stem test
1-29 Barnett Serio			Madison	4380	---------	
Hanson Oil, 1 Lite Butte Fed.	50-92-2 NW NE	1981	Madison	4630	1.6×10^3	drill stem test

Table 2. Continued

Stanly Walters, Water well	50-90-14 NW NE	1953	Tensleep-Madison	4850+	4.5×10^2	Jacob recovery
Ameranda Petr. 1 Anderson	49-91-2 NE NW	1963	Jefferson	4890	4.4×10^3	drill stem test
Husky Oil, 10-12 Fed. Paintrock	49-91-12 SE NW	1979	Flathead	6370	2.3×10^2	drill stem test
Shell Oil, Unit 2	49-91-12 SE SE	1955	Tensleep Madison Bighorn	4495 4930 4905	1.8×10^2 --------- 2.0×10^3	drill stem test
Homer Renner water well	49-89-24 SE NW	1962	Tensleep-Bighorn	5040	5.0×10^3	Jacob recovery
Homer Renner water well	49-89-28 NW NE	1953	Madison	5085	5.4×10^2	Jacob recovery
Clarke Gapen water well	49-89-29 NE NW	1953	Madison	4980	8.9×10^2	Jacob recovery
Gulf Oil 1 Mills Fed.	48-89-31 NW SW	1952	Tensleep Madison	4225 4755	--------- 1.4×10^3	drill stem test

a. Transmisivities for drill stem tests are subject to substantial error. Permeabilities for the tested interval were computed from raw data using methods from Murphy (1965) and Miller (1976). Transmissivities were then estimated by multiplying by the thickness of the aquifer.

Table 2. Continued

Stanly Walters, Water well	50-90-14 NW NE	1953	Tensleep-Madison	4850+	4.5×10^2	Jacob recovery
Ameranda Petr. 1 Anderson	49-91-2 NE NW	1963	Jefferson	4890	4.4×10^3	drill stem test
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a. Transmisivities for drill stem tests are subject to substantial error. Permeabilities for the tested interval were computed from raw data using methods from Murphy (1965) and Miller (1976). Transmissivities were then estimated by multiplying by the thickness of the aquifer.

Table 3. Surface waters observed between July 25 and 27, 1981, to flow into and out of the Trapper-Medicine Lodge recharge area for the Madison aquifer, eastern perimeter, Bighorn Basin, Wyoming. All values in ft^3/sec.

Trapper Canyon Drainage		
Inflows to swallow holes:		
1.[a] Jack Creek sink	0.4	
2. Johnny Creek sink	1.0	
3. Great X cave	5.0	
4. South Trapper sink	0.1	
Sum of sinks	6.5	
Outflow at mouth of Trapper Canyon		13.0
Medicine Lodge Drainage		
Inflows to swallow holes:		
5. Mill Creek sink	0.5	
6. Trec Charros cave	5.0	
7. Taylor sink	0.1	
8. Black Butte sink	0.2	
9. Pbar cave	5.0	
10. Allen Draw and Deer Gulch sinks	neg.	
Sum of sinks	10.8	
Outflow at mouth of Medicine Lodge Canyon		20.0
Net Inflows (Q_{in})	17.3	
Net outflows (Q_{out})		33.0

a. Numbers correspond to numbered locations on Figure 3.

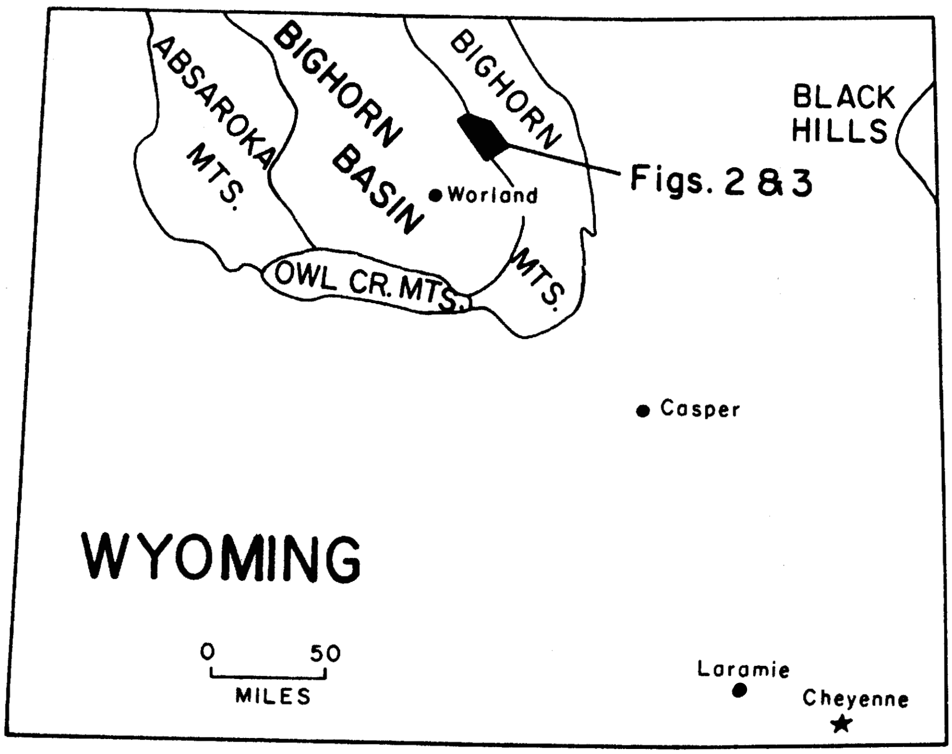
Figure 1. Location of the Trapper-Medicine Lodge recharge area on the eastern side of the Bighorn artesian basin of Wyoming.

Figure 2. Geologic map showing the outcrop pattern for the rocks comprising the Madison aquifer in the Trapper-Medicine Lodge area, Wyoming. Notice that the rocks dip basinward and become younger to the left.

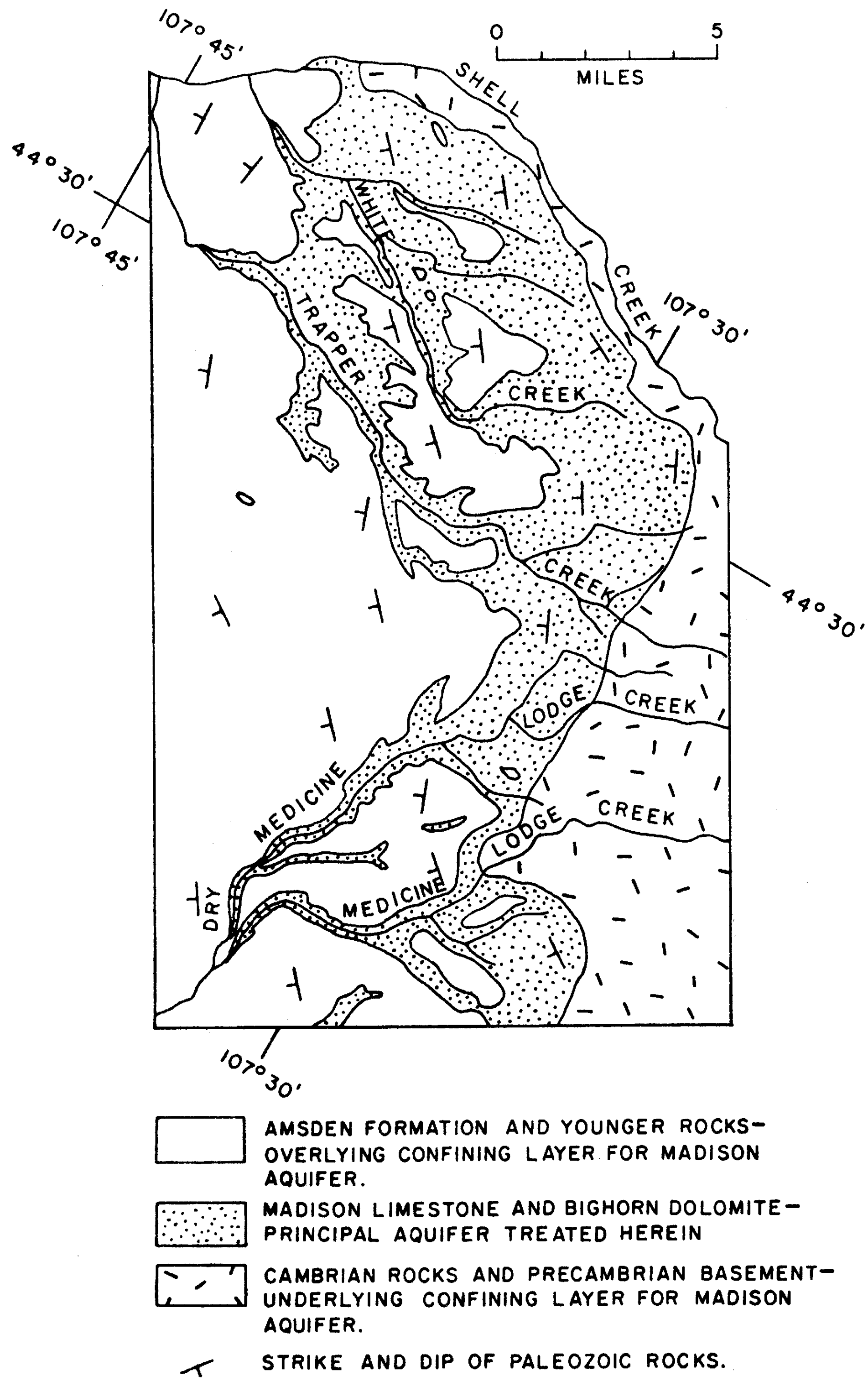
Figure 3. Location of sinks, resurgences, explored caves, subsurface waterways, and tectonic structures in the Trapper-Medicine Lodge area, Wyoming. The subsurface waterways are cave systems in the Madison aquifer which underlie the canyons in the area. Notice that their trends are independent of the dip of the rocks and strikes of the tectonic structures. Numbered location correspond to numbered swallow holes listed on Table 3.

Figure 4. Stream passage in Bad Medicine cave which is dissolved from the Bighorn Dolomite in the Trapper-Medicine Lodge area, Wyoming. These caves do not extend significant distances beyond the toes of recharge areas as demonstrated by small basinward permeabilities. Photo by Norm Pace.

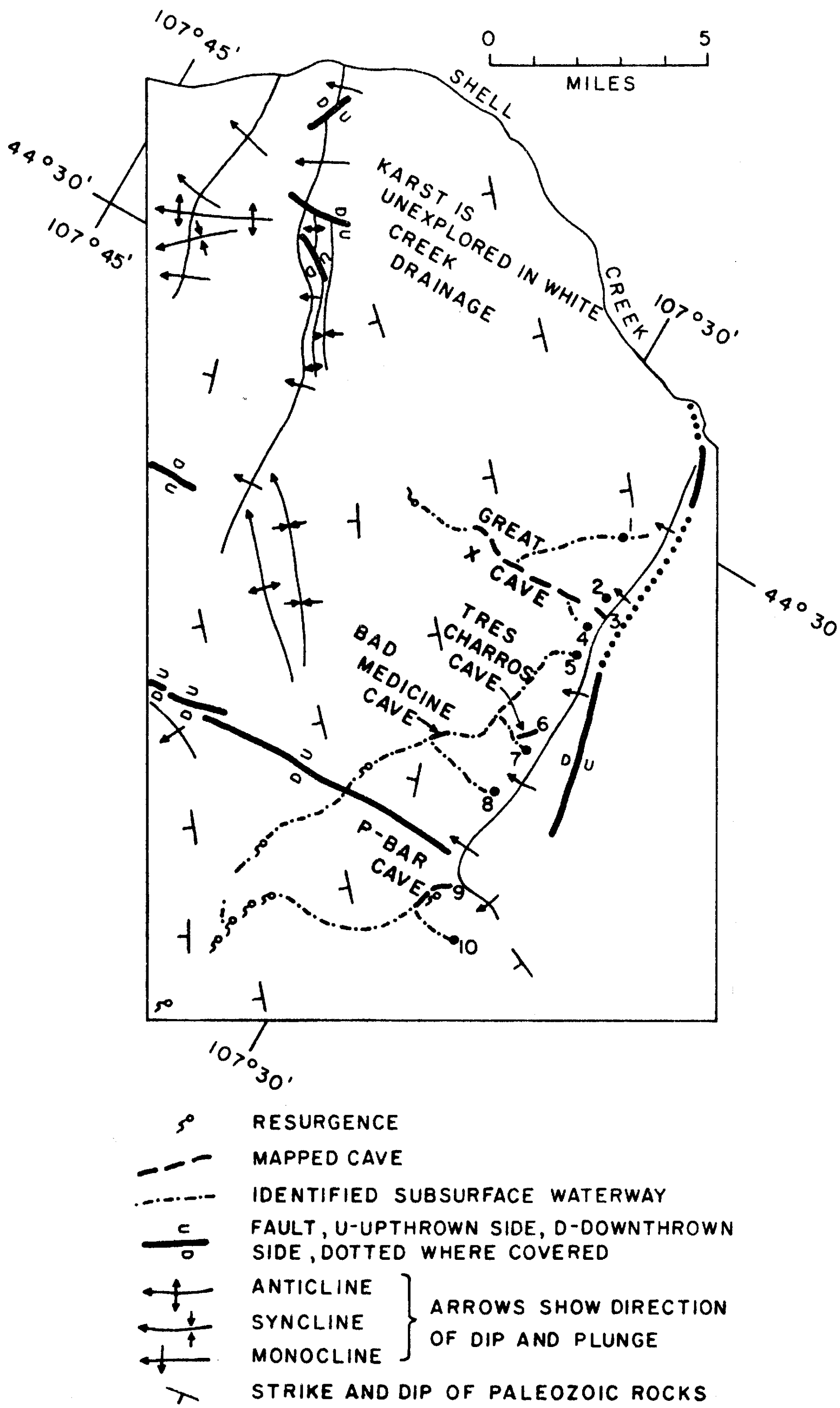
Figure 5. Detail map showing flow beneath the divide separating Dry Medicine Lodge (left) and Medicine Lodge (right) canyons, Trapper-Medicine Lodge area, Wyoming. Prior to discovery of this link, the discharges in both canyons were summed thus counting water from Dry Medicine Lodge spring twice in the total. Homestead spring discharges from the Tensleep aquifer, a circulation system independent from the Madison system which is the focus of this article.



Huntoon - Recharge - Figure 1

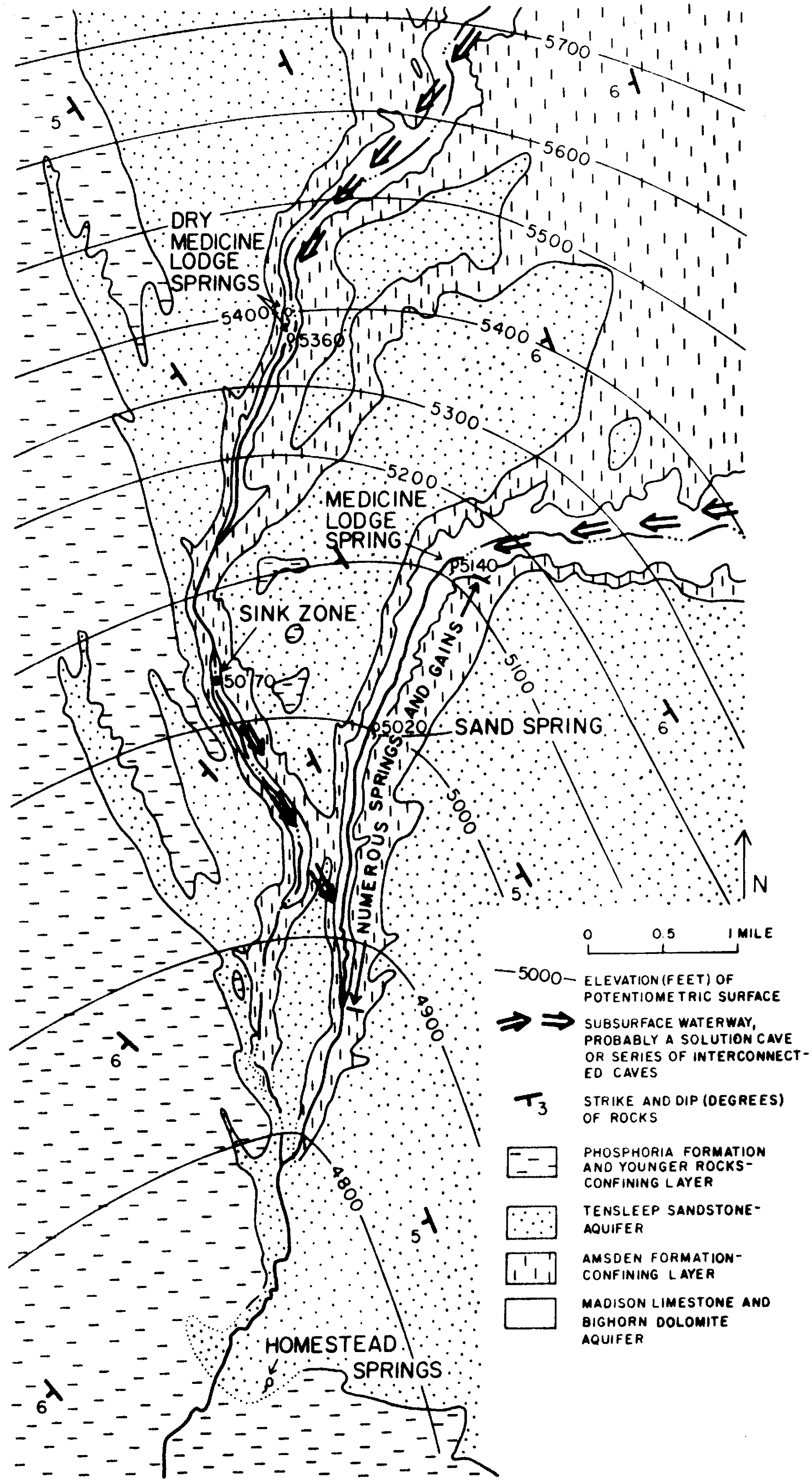


Huntoon - Recharge - Figure 2



— Huntoon - Recharge - Figure 3 —

— Huntoon - Recharge - Figure 4 —



Huntoon - Recharge - Figure 5

CHAPTER III

Gradient Controlled Caves, Trapper-Medicine Lodge Area,

Bighorn Basin, Wyoming

ABSTRACT

Extensive caves were found to have developed in the Trapper-Medicine Lodge recharge area in carbonate sequences where volumetric flow rates were maximized during Cenozoic time. The large flow rates resulted directly from the superposition of steep local gradients on the ground water circulation system as a consequence of the geomorphic evolution of the topography in the region. When the cave forming process in this area is boiled down to its essence, the development of the caves is a gradient controlled process, a conclusion that has possible applicability elsewhere.

PURPOSE AND PERSPECTIVE

The purpose of this article is to argue that hydraulic gradients controlled the locations of extensive caves found in the Trapper-Medicine

Lodge area along the eastern perimeter of the Bighorn artesian basin of Wyoming.

The development of a cave requires four factors: (1) a soluable host rock, (2) a solute, (3) an initial permeability to allow for circulation, and (4) an hydraulic gradient to cause the solute to circulate. Spelunkers have made hundreds of maps showing the planimetric distribution of caves, and the casual observer of such maps is commonly overwhelmed by the obvious rectilinear pattern of the passageways. It appears obvious that the caves are joint or fracture controlled so little more thought is given to the cave forming process. What has always intrigued this writer both from maps and experience underground is the large volumes of rocks which do not contain passable passageways. After all, the jointing of the carbonates is ubiquitous and the joints in the non-cavernous volumes of the rocks have equally good initial permeabilities to initiate the circulation of the aqueous solute. Why then didn't caves develop along these equally inviting joints? Are the caves in fact joint controlled? I will argue herein that the planimetric form of the caves in the Trapper-Medicine Lodge area are loalized on joints. However the selection of joints which ultimately evolved into caves is directly related to volumetric flow rates through the rocks. The flux is directly to the steepness of the local hydraulic gradient. Consequently the caves in this area are gradient controlled features.

REGIONAL HYDROGEOLOGY

As shown on Figure 1, the Trapper-Medicine Lodge area is situated on the eastern perimeter of the Bighorn artesian basin. Approximately 1150 ft of carbonates comprising the Madison aquifer crop out in this area as shown on Figure 2. Included in the Madison aquifer are the Ordovician Bighorn Dolomite, Devonian Jefferson Limestone, and Missisippian Madison Limestone.

These units are underlain by Cambrian confining beds comprised primarily of shales, and overlain by the Permian Amsden Shale which is the upper confining layer.

The Trapper-Medicine Lodge area is part of the recharge area for the Madison aquifer which underlies the Bighorn Basin. All surface streams which flow onto the rocks comprising the Madison aquifer in this area are lost to swallow holes which have developed in the first carbonate outcrops encountered by the streams in the headwaters of the recharge area. The canyons at the toe of the recharge area contain resurgences which actually discharge more water than is observed to enter the upstream swallow holes. The mass balance for this region, and the differentiation between "apparent recharge" - that water observed to go down swallow holes in the headwaters - and net basin recharge is treated elsewhere in this issue.

Extensive caves have developed in the Trapper-Medicine Lodge recharge area which conduct water between the swallow holes and downstream resurgences. See Figure 3 and 4. As shown on Figure 2, the trends of the caves mimic in the subsurface the trends of the overlying surface canyons. The respective discharges from the Trapper and Medicine Lodge systems during July, 1981, were 13 and 20 ft^3/sec. These flows were but fractions of spring flood runoffs through theses karst systems.

CAVE OBSERVATIONS

The mystery of the Trapper-Medicine Lodge sink-spring systems has been resolved through the exploration of the associated cave systems by numerous spelunkers within the past decade. The emerging perspective is one of highly localized but laterally extensive cave drainage systems which underlie and parallel the surface drainages in the recharge area.

The most important exploratory breakthrough occurred in Great X Cave (Figure 2) in 1980 when two cave explorers entered a cave at a location less than two miles upstream from a large resurgence in the floor of Trapper canyon. They began following a stream passage dissolved from the Bighorn Dolomite that at its worst was in places several hundred feet long, 18 inches high, and half filled with several ft^3/sec of rushing 39°F water. They emerged almost a day later from the principal shallow hole in Trapper Canyon some 1,400 ft in elevation above, and 3.6 air mi upstream from their entry point (Flurkey and others, 1981). For the first time, one of the active sink-spring networks in the area had been traversed virtually from end to end.

The hydrologic characteristics of the cave system observed by these explorers confirms earlier and subsequent uncontrolled dye tracings (Vietti, 1977; Norm Pace, personal communication) and numerous cave-specific observations by this writer in nearby karst networks. The general characteristics of the Trapper-Medicine Lodge caves are as follows. (1) The streams observed in the caves gain downstream as a result of inflowing tributary streams and vertical leakage from the overlying rocks. (2) The trends of passages in the caves mimic the orientations of the overlying surface drainages and are independent of cross-cutting tectonic structures, or regional or local dip. (3) The youngest generation of caves preferentially develop in the basal part of the Bighorn Dolomite but if the stratigraphic positions of the passages change, there is a tendancy for the cave to climb section into younger units toward the resurgence. (4) Large volumes of clastics derived from the Precambrian highlands wash through the cave systems along with the water. (5) The hydraulic gradients associated with the water in the caves is steep - gradients of 400 ft/mi are typical - and closely conform to the gradients of the overlying surface streams. (6) Hydraulic continuity with overlying surface drainages is good throughout the recharge area wherein some surface streams intermittantly gain and loose both spatially and seasonally along their courses. (7) Abandoned cave passages - those containing no flowing streams - are common and tend to parallel or overlie active passageways. (8) Intersections of tributary passageways, mazes of passages, and dome pits tend to develop under intersections of overlying surface canyons. (9) Passages develop primarily along favorably oriented joints and occasionally along fractures or fault planes which have favorable orientations. (10) Well indurated sandstones in the Bighorn Dolomite commonly floor passages for great lengths indicating that these interbeds are highly effective local confining layers which in some locations separate different levels comprising a given cavern networks.

The two sections that follow describe observations on ground water circulation and orientations of passageways from Pbar cave. Because the hydrologic and geologic character of this cave is typical for the area, these observations can be viewed as generalizations.

CIRCULATION THROUGH PBAR CAVE

Pbar cave (Figure 2) is one of the most revealing caves in the Trapper-Medicine Lodge area. The mouth of the cave is a broad cavern situated at the base of Bighorn Dolomite hogbacks. The outcrops are the first carbonates of the Madison aquifer which are encountered by Medicine Lodge creek. The creek originates on the Precambrian highlands and flows through an upstream valley which is choked to the mouth of the cave with glacial till.

The known part of the cave consists of an upper level of ephemeral floodways, and an active lower level which accepts the entire low flow of Medicine Lodge creek. Observed flows of up to 15 ft^3/sec only partially challange the capacity of the entrance. Flowing in with the water during large floods are granite boulders up to two feet in diameter and trees up to three feet in diameter.

The low flows take an impassable series of low level passageways to a resurgence ¼ mile downstream. From there, the water threads its way downstream back and forth between the surface channel and the karstified aquifer. Only flood flows enter the explored passageways in Pbar cave which have been followed for a distance of three to four miles parallel to the canyon. Wood and granite are strew throughout the known floodways. Some of these debris are jammed in cracks a few tens of feet above the floors of narrow but tall passages.

The ultimate resurgence for the water in Pbar cave and Medicine Lodge canyon is a series of springs and rises located five miles downstream from the cave (Figure 2). These springs discharge from the upper half of the Madison Limestone from solution widened fractures just upstream from the point where the Madison aquifer becomes buried by its overlying confining beds. A natural tracer proves that these waters are the same. Along with the water, many of these springs discharge micaceous and quartzitic sands which produce sand bars along the creek immediately below the springs. These clastics were derived from the granite boulders observed to enter Pbar cave and other sinkholes in the canyon floor. All motion of both the water and sand is down very steep hydraulic gradients averaging 400 ft/mi. Owing to the regional dip of the rocks, the water climbs about 1000 ft up section within the aquifer through openings at least large enough to pass sand.

FRACTURE CONTROLLED PASSAGEWAYS

The swallow hole entrance to Pbar cave is developed in the lower part of the Bighorn Dolomite in a deformed zone associated with the monocline shown on Figure 2. The outcrops at the entrance are characterized by closely spaced imbricated small displacement thrust faults, and slickensided vertical joints. Within 200 ft, these structural features disappear and the upper level floodways along interconnected joints continue through gently dipping undeformed beds. The floor is a well indurated sandstone which perches the cave above the stratigraphic base of the Bighorn Dolomite.

It is tempting to deduce that the cave is fault controlled at its mouth and joint controlled within. Such a conclusion is patently false from a process perspective. Flurkey (1981) has mapped two miles of passages and finds that the cave underlies the north wall of Dry Medicine Lodge Canyon. This parallelism with the canyon floor is independent of the dip of the rocks and the strikes of joints. The fractures that the cave happens to follow have a variety of orientations that when interconnected result in the overall trend parallel to the canyon. Obviously there is an overriding control operating which determines just which of the fractures ultimately develop into passageways. Clearly the cave is not joint controlled. The joints occur ubiquitously through the carbonate section but only a few selected joints in this environment are actually solution widened. I will argue that the overriding control is a local steepening of the hydraulic gradient related to the erosion of the canyon.

The floodways within Pbar cave are older than the partially flooded lower passages which capture the water at the entrance. Floodways and upper level dry passages are common in the cave systems in the area and represent parts of individual systems which have been dewatered as lower passages developed. As the surface canyons continue to erode, these higher level passages - like even higher level passages before them - are stripped away, leaving the hydraulic conveyance to newer and deeper channels. This interplay between evolving surface drainage and the underlying caves is central to understanding the development of the caves in this area. The gradient configuration favoring the development of pasages just below any specific base level is the convergence zone shown on Figure 5B.

LOCALIZATION OF CAVES

The development of caves in the Trapper-Medicine Lodge area coincides with erosion of canyon through the area. An appreciation of the cave forming process requires a brief discussion of the tectonic and geomorphic differentiation of this area from the basin interior.

In excess of 20,000 feet of sedimentary rocks were differentially uplifted and subsided as the Bighorn Basin and adjacent mountain ranges began to evolve as structural elements during late Mesozoic time. As the mountain building processes continued into Cenozoic time, the entire provence was uplifted thousands of feet so that erosion stripped rocks not only from the mountains but also from the surfaces of the basins. Owing to steep topographic gradients, rates of erosion were greatest in the mountain regions but thousands of feet of Cenozoic and Mesozoic rocks - principally confining layers - were stripped from all parts of the province. The evolving topography in the Trapper-Medicine Lodge area consisted of broad slopes subparallel to the dip of the rocks. The result was a time succession of broad, gently dipping surfaces comprising at any one moment of rocks of similar ages, a situation which still exists today.

Initially when the Paleozoic aquifers became exposed on the crest of the Bighorn range, there existed substantial topographic relief between these high exposures and the topographic surface of the Bighorn Basin. This produced a condition in which large head differences existed between ground water confined in the upturned Paleozoic aquifers and the streams which drained the basin. The confining layers between the two minimized circulation.

The confining layers on the flanks of the range were successively breached by several entrenching canyons as erosion of the basins and mountains progressed. Ultimately, the canyon floors provided line sinks in the aquifers which were oriented perpendicular to the mountain flanks. The result as shown schematically on Figure 5 was vigorous circulation of ground water within the Paleozoic aquifers stimulated by unusually steep hydraulic gradients toward the canyons. The circulation system was then as now supplied by both recharge directly on growing carbonate outcrops and surface drainage from the uplands. Gradients within the Madison aquifer were greatest in the zones under and adjacent to the canyon floors because of the convergence of flow toward the canyon floors. Today average gradients in the Trapper-Medicine Lodge are 400 ft/mi compared to 40 ft/mi in the adjacent parts of the Bighorn Basin.

The permeabilities of the Madison aquifer at the time of exposure were small and were similar to those now found in the unfaulted interior of the Bighorn Basin. However enhanced ground water circulation rates associated with canyon cutting produced a condition which favored solutional enlargement of fractures in the carbonates comprising the aquifer where gradients were steepest. The densities of solution conduits are proportional to the steepness of gradients, and therefore cave development became maximized under and adjacent to the entrenching canyon floors. This is exactly the condition that we find today, except the caves observed today are the youngest in the system because older upper level networks have been eroded away as the canyons have deepened.

Notice in this senerio that the caves develop along fractures having favorable orientations under the floors of the eroding canyons. The fractures are dominently joints because joints are abundant in the rocks. Only those fractures enlarge significantly which occupy the zone containing the steepest hydraulic gradients. Therefore the location of the caves are gradient controlled, not joint controlled.

Of extreme importance is the fact that the trends of the caves are independent of the dip of the strata or the orientations of tectonic structures. This fact can be observed from Figure 2.

The same gradient controlled cave forming process operates in the carbonates under tributary canyons. The cave passages under the intersections of canyons become multileveled complex mazes because of the complexities resulting from dual convergence of flow at the intersections.

Important is the fact that caves do not extend basinward for significant distances beyond the present toe of the recharge area. This follows because the canyons have not entrenched into the Madison aquifer in these locations and in so doing created gradient conditions favorable for cave development. Permeability data beyond the toe of the recharge area treated here is presented elsewhere in this issue and quantitatively demonstrates that there is a large reduction in permeabilities basinward. These data support the contention here that caves do not extend significant distances basinward beyond the carbonate outcrops.

DISCUSSION

The passageways of caves in the Trapper-Medicine Lodge area are planimetrically localized along favorably oriented joints and fractures. The specific fractures which enlarged in the vast volume of rock available were those upon which strong local hydraulic gradients were imposed. Imposition of strong local gradients allowed for highly localized increases in flow rates with attendant rapid rates of dissolution. The imposition of steep local gradients was accomplished in this region by incision of surface canyons through the overlying confining layers of the Madison aquifer. Consequently, the caves were gradient controlled and the steepest gradients within the volume of rock dictated just which fractures had "favorable" orientations.

The earliest caves developed high in the Madison section. As the canyons deepened, successively lower levels of caves developed downward through the carbonate section as upper levels were erosionally stripped away.

The cave forming mechanism proposed herein favors the development of caves under existing canyons. Their orientations are independent of the dips of the rocks or locations of tectonic structures. Important for the hydrologist is that (1) caves are not ubiquitous under the entire area, and (2) the caves do not extend basinward significant distances beyond the topographically lowest carbonate outcrops in the toes of the recharge area. As a result the caves enhance permeability contrasts between large values for the recharge area and typically small values in the basin interiors. If there is a lesson here, it is that hydrologists should not extrapolate permeabilities developed for recharge areas into deep basin domains. In this area, the difference in permeabilities between the recharge areas and basins is measured in orders of magnitude.

ACKNOWLEDGEMENTS

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Figure 1. Location of the Trapper-Medicine Lodge area on the eastern perimeter of the Bighorn Basin, Wyoming.

Figure 2. Outcrop pattern of the rocks comprising the Madison aquifer and locations of cave systems in the Trapper-Medicine Lodge area, Wyoming. Notice the correlation between cave alignments and canyon trends in this area. Also notice that the strikes of the caves are independent of the dip. Numbered canyons are: 1 - Trapper, 2 - Dry Medicine Lodge, and 3 - Medicine Lodge.

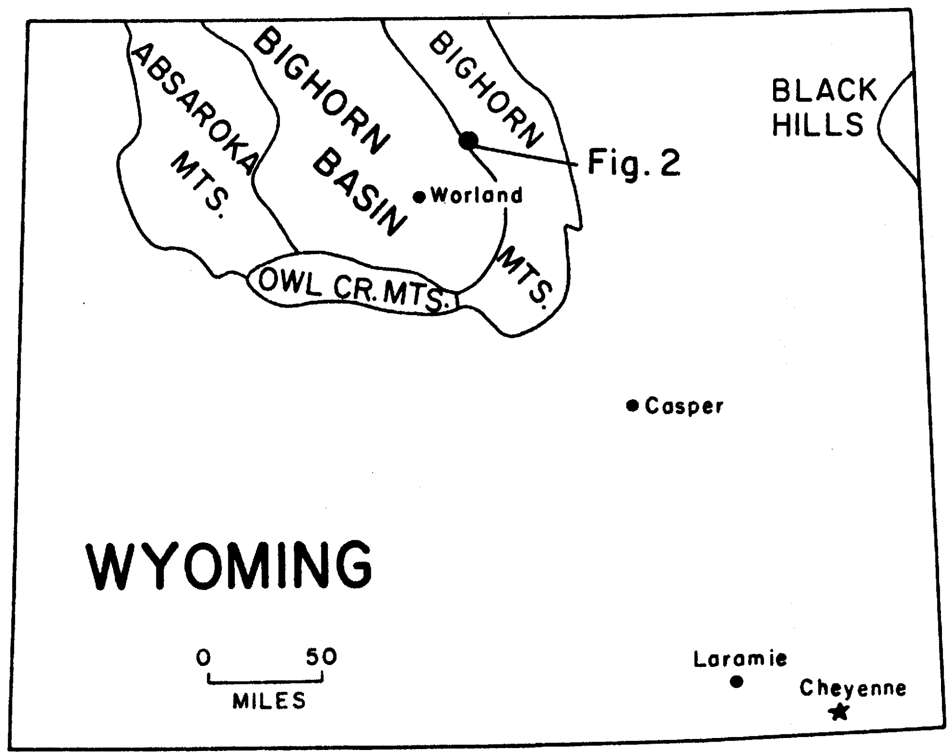
Figure 3. Stream passage in Great X cave dissolved from the Bighorn Dolomite, Trapper-Medicine Lodge area, Wyoming. Water is 39°F. The passages are dissolved along joints but the specific joints which develop into passages were located in regions containing steep hydraulic gradients. Photo by Norm Pace.

Figure 4. Stream passage in Bad Medicine cave, Trapper-Medicine Lodge area, Wyoming. The floors of such passages are commonly perched on insoluable clastic interbeds in the Bighorn Dolomite. Photo by Norm Pace.

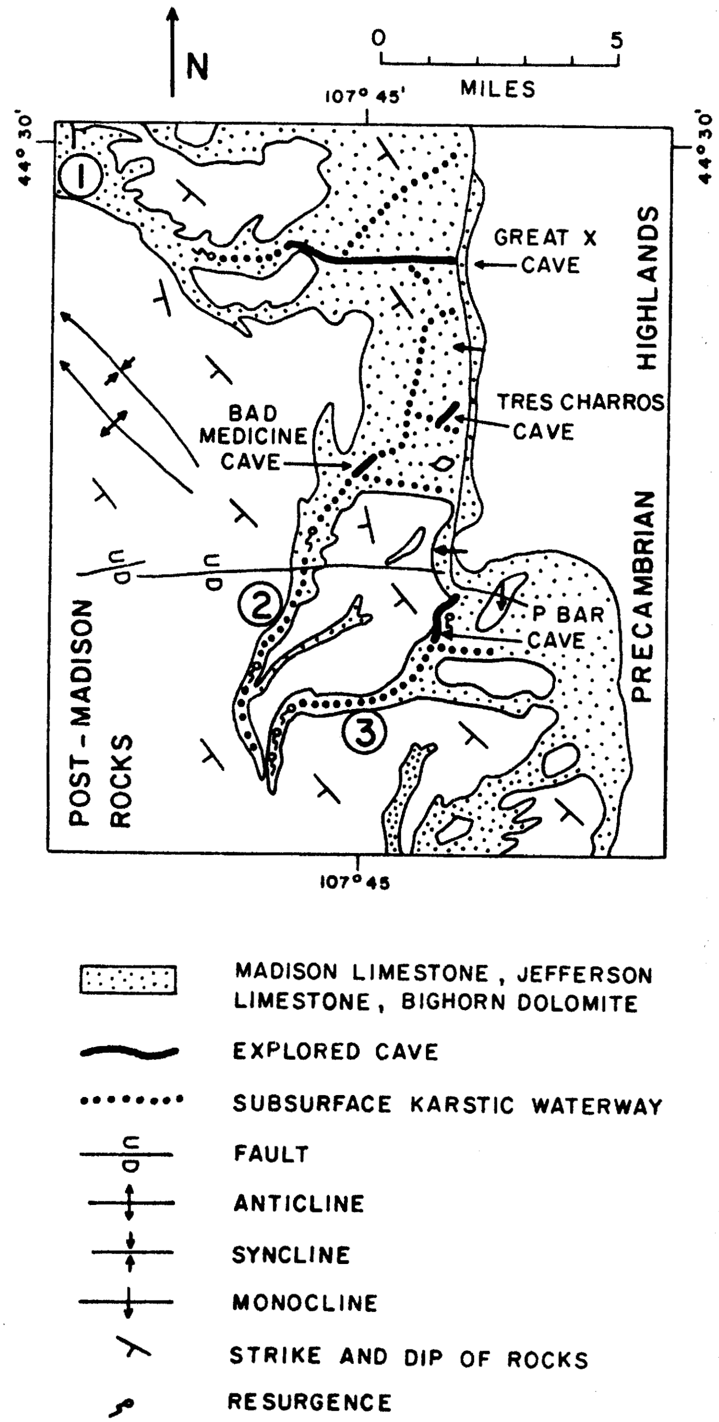
Figure 5. Diagramatic sketch illustrating the gradient configuration which concentrates ground water flow beneath the floors of canyons that have incised through the upper confining layer of the Madison aquifer in the Trapper-Medicine Lodge area, Wyoming. A - planimetric map; B - profile; heavy lines are potential lines; fine lines are flow lines. The sketch assumes that the permeabilities under the canyon become progressively more anisotropic as the caves evolve. The maximum principal permeability tensor under the canyon parallels the axis of the canyon and the degree of

Figure 5. Continued

anisotrophy decreases laterally away from the canyon toward inter-canyon divides where rates of dissolution are minimized in the recharge area.

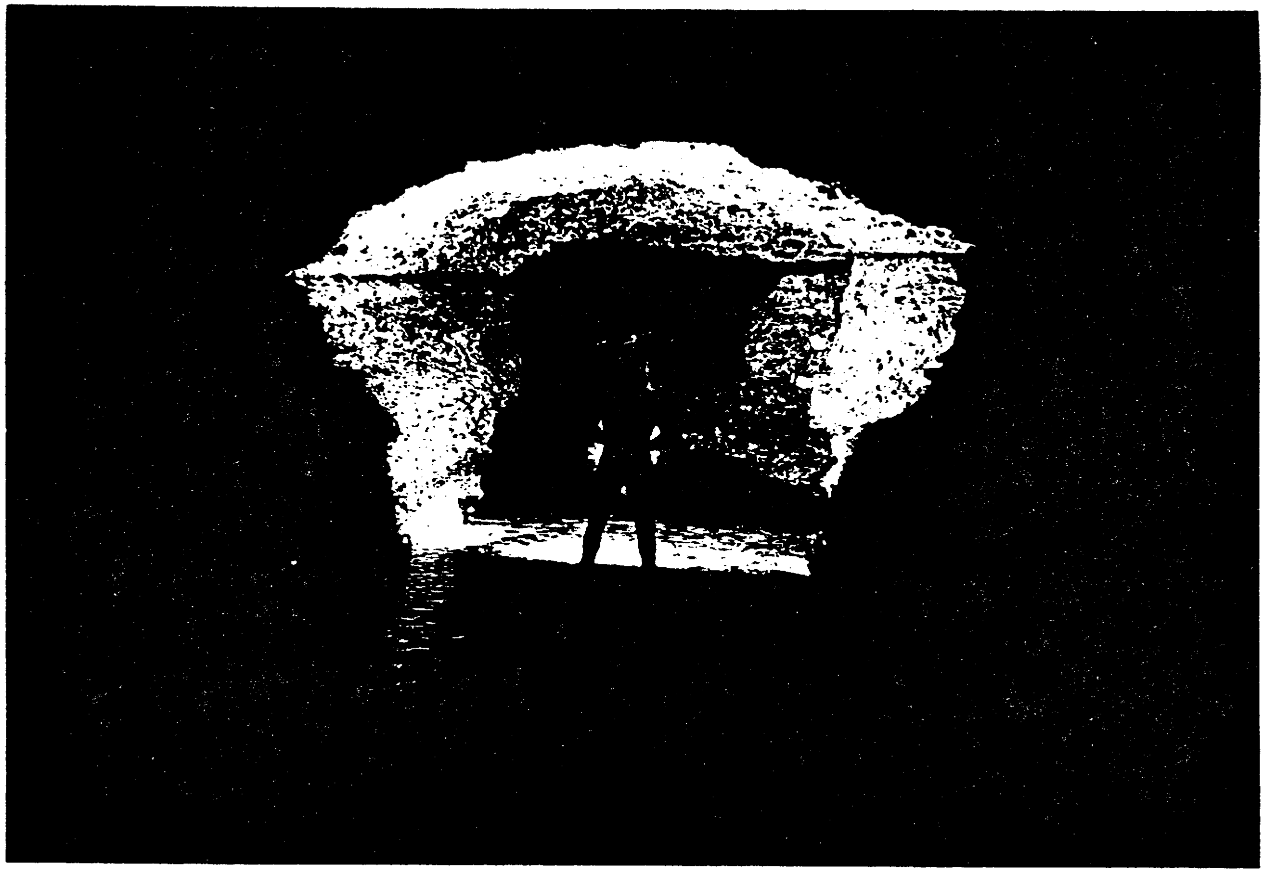


Huntoon - Caves - Figure 1

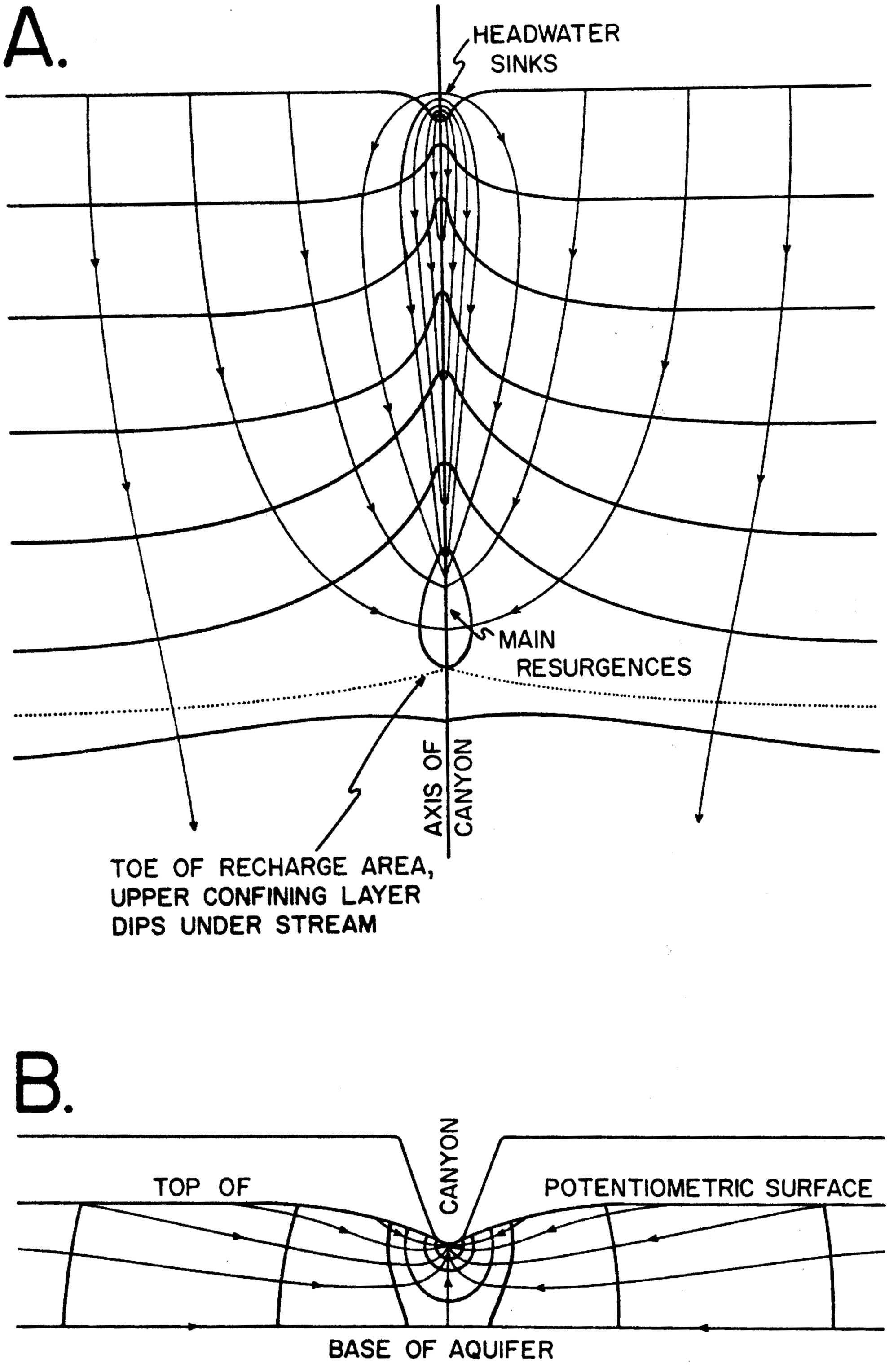


Huntoon - Caves - Figure 2

— Huntoon - Caves - Figure 3 —



— Huntoon - Caves - Figure 4 —



Huntoon - Caves - Figure 5