STRUCTURAL OBSTRUCTION OF RECHARGE TO THE PALEOZOIC AQUIFER IN THE DENVER-JULESBURG BASIN ALONG THE LARAMIE RANGE, WYOMING

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CHAPTER 1

INTRODUCTION

PURPOSE

The purpose of this thesis is to examine the evidence for groundwater recharge to the Paleozoic aquifer along the east flank of the Laramie Range, Laramie County, Wyoming.

STATEMENT OF THE PROBLEM

The city of Cheyenne, in Laramie County, Wyoming, is anticipating a greater need for water in the near future due to the expansion of F. E. Warren Air Force Base. The Paleozoic aquifer has been identified as a potential water resource in Laramie County by several reconnaissance level studies including Eisen and others (1980), U.S. Forest Service (1981), and Western Water Consultants, Inc. (1982). Little has been done to examine, in detail, the production potential of this aquifer. This thesis attempts to further what is known about the Paleozoic aquifer by examining the evidence for recharge to it.

GEOLOGIC AND GEOGRAPHIC SETTING:

The Denver-Julesburg Basin, shown on Figure 1, is a structural basin which extends south to the Apishapa and Las Animas Arches in Colorado, and north to the Chadron-Cambridge Arch and the Hartville Uplift in Nebraska and Wyoming, respectively. The western perimeter of the basin in Wyoming is delimited by west dipping thrust faults which bound the Laramie Range (Huntoon,1985).

The project area, shown also on Figure 1, is located in the northwest part of the Denver-Julesburg Basin. It includes the western part of Laramie County from R66W to R70W and from T13N to T21N. A smaller area, shown on Figure 2, is defined within the project area for detailed mapping of tectonic structures along the east flank of the Laramie Range.

The Paleozoic aquifer is defined in this paper as the saturated and permeable parts of the Casper Formation (Richter, 1984). The Casper Formation crops out within the study area in the foot wall of the thrust faults which bound the Laramie Range and as imbricate slices within the thrust zone. Mesa and Table Mountains, located in the southern part of the mapping area, are the exceptions. The sections

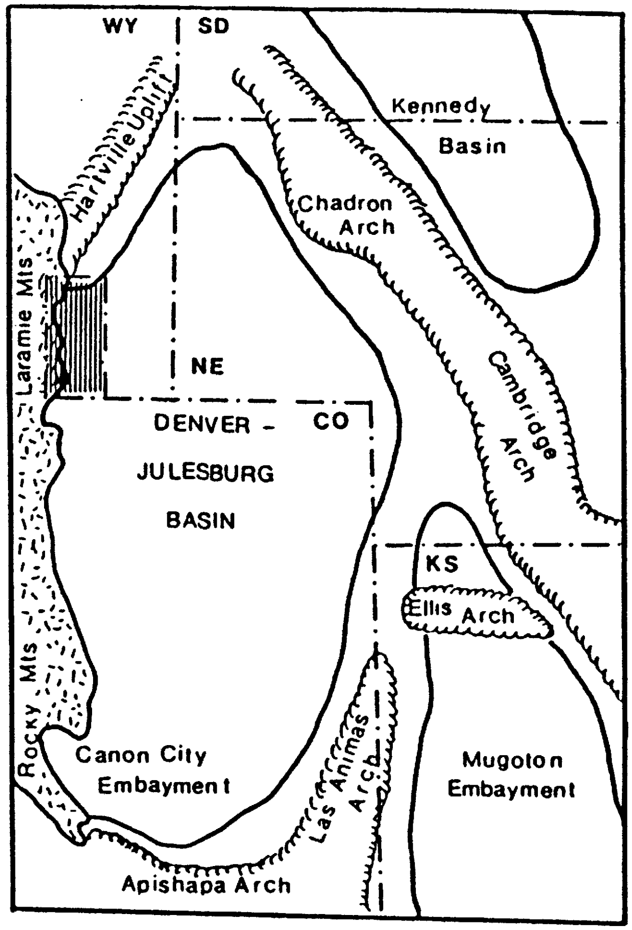

Figure 1. The Dever-Julesburg Basin in Wyoming, Nebraska, and Colorado. The location of the project area is shaded.

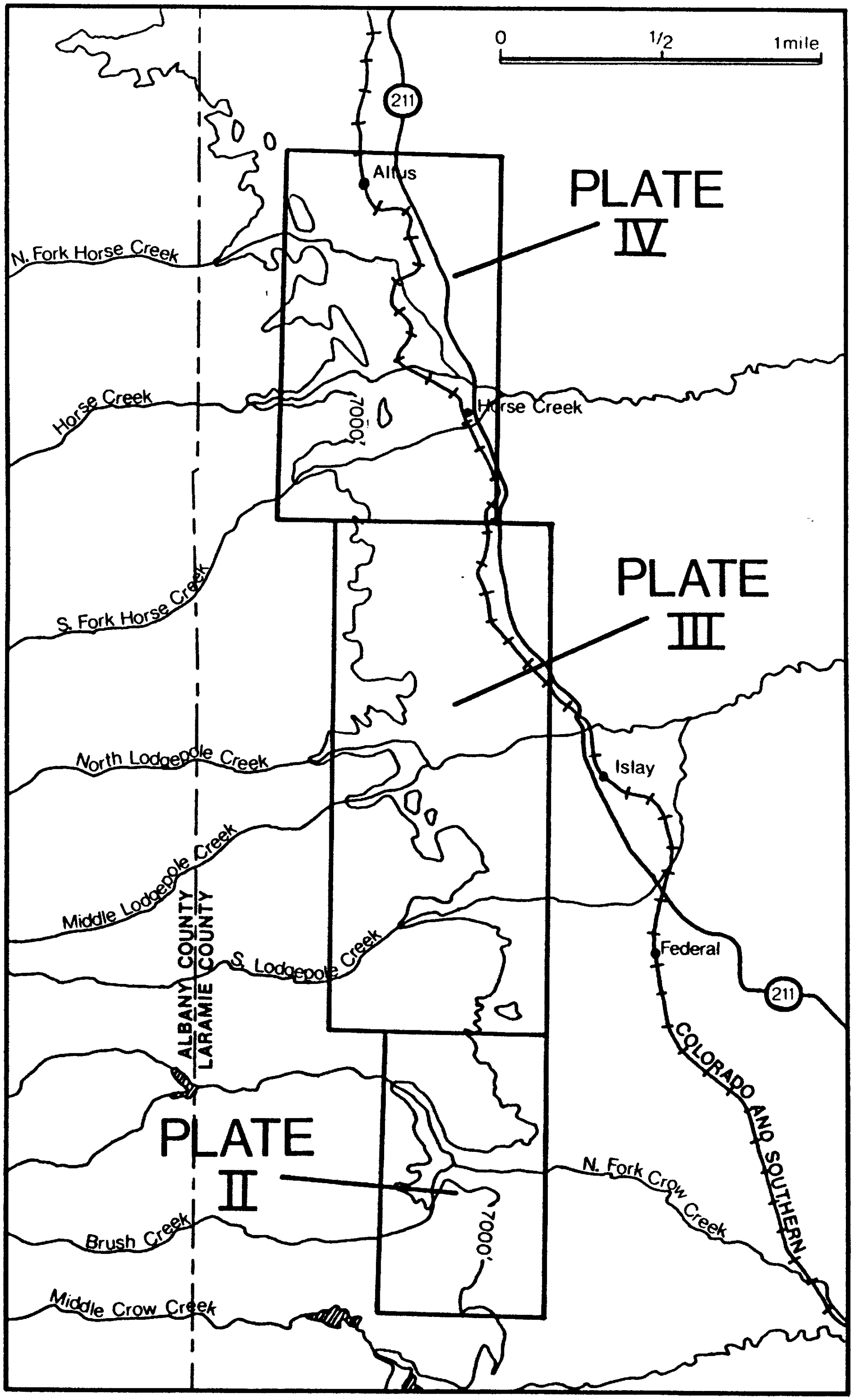

Figure 2. Locations of detailed tectonic maps (Plates II, III and IV) Laramie County, Wyoming.

of the Casper Formation capping these mountains are not saturated and are part of the hanging wall.

At its deepest in the region the aquifer lies approximately 10,000 feet below the land surface. This deepest part is located along the synclinal axis of the Denver-Julesburg Basin in the vicinity of Cheyenne, Wyoming. In contrast, several perennial and intermittent streams which flow from the Laramie Range cross exposures of the Casper Formation at the western edge of the basin. These streams are a potential source for recharge to the basin aquifers and the focus of this study.

PHILOSOPHY OF APPROACH:

Two questions must be addressed when examining evidence for recharge to an aquifer. First, how much water, if any, is entering outcrops of rocks which comprise the aquifer? Second, can water entering the outcrops circulate to the basin interior where production is to occur? Water which enters an outcrop and which is discharged before reaching the basin interior, for example along a fault, does not replace water withdrawn during production and should be excluded from recharge estimates.

A detailed water budget analysis was conducted on the North Fork of Horse Creek to address the first question. The water budget was used to quantify the amount of recharge entering Paleozoic rocks from the North Fork of Horse Creek which is one of several perennial streams in the area which flow across outcrops of the Paleozoic rocks. The amount of recharge to the Paleozoic section along this stream is considered representative of all streams along the east flank of the Laramie Range which cross Paleozoic rocks under similar circumstances, that is, similar tectonic settings.

An understanding of the patterns by which recharge circulates within, between and around the three major components of the groundwater system was obtained through the detailed examination of: 1. the geologic framework through which groundwater flows, and; 2. the shape of the potentiometric surface. The three major components include: the recharge area; the hydraulically interconnected parts of the aquifer; and, the hydraulically isolated compartments within the aquifer.

Examination of the geologic framework involved the identification of tectonic structures which deform the aquifer and an understanding of how these structures influence permeability. For example, an impermeable barrier will exist where motion along a thrust fault has completely juxtaposed aquifer strata against impermeable rocks. Conversely, extensional fractures in the axis of an anticline will act as highly permeable conduits in many environments. Examination of the geological framework also involves the identification of hydraulically isolated compartments within the aquifer. These compartments are sealed off from the rest of the aquifer by impermeable, or semipermeable boundaries which act as barriers around which groundwater must flow.

Further information concerning the patterns by which recharge circulates to the production area is obtained from the shape of the potentiometric surface. The slope of the potentiometric surface is the hydraulic gradient which drives groundwater flow. Circulation patterns are deduced by considering these gradients in conjunction with the permeability distribution.

CHAPTER 2

METHODOLOGY

WATER BUDGET ANALYSIS

The water budget analysis conducted on the North Fork of Horse Creek was an accounting of all inflow to and outflow from the reach which flows across outcrops of the Casper Formation. The water budget can be summarized as

$$Qin + P + GWin = Qout + E + ET + GWout \quad (1)$$

where:

Qin and Qout are stream flow into and out of the study reach, respectively,

P is the water gained by the study reach due to precipitation,

E and ET are water lost by evaporation from the stream and from evapotranspiration from the phreatophyte zone, respectively;

GWin and GWout are discharge from the aquifer to the stream and recharge to the aquifer form the stream, respectively.

For the purposes of this study, GWin and GWout were combined into a single term, net GW flux, for which equation (1) was then solved:

$$\text{net GW flux} = \text{Qin} + \text{P} - \text{Qout} - \text{E} - \text{ET}. \quad (2)$$

Net groundwater flux is positive if the aquifer is being recharged. The net groundwater flux was computed for each month based on estimates for the five remaining variables: Qin, Qout, P, E, ET.

Approximations of Qin and Qout were based on stream flow data collected from the east and west stream gauging stations, respectively. These two stations were established at each end of the study reach as shown on Figure 3. Continuous records of stream stage were obtained with a U.S. Geological Survey type bubble gage servo-manometer. The average stage for each day was estimated from these records.

Standard staff gages and Parshall flumes were used to obtain weekly paired observations of stage and discharge at the east and west stream gaging sites. These paired observations were used to develop a log-log regression between stage and discharge for each site. The regression was then used to convert daily average stage to daily average discharge. The total volume of stream flow which passed each gaging station was then computed on a daily basis and summed to obtain the monthly totals of inflow to and outflow from the study reach.

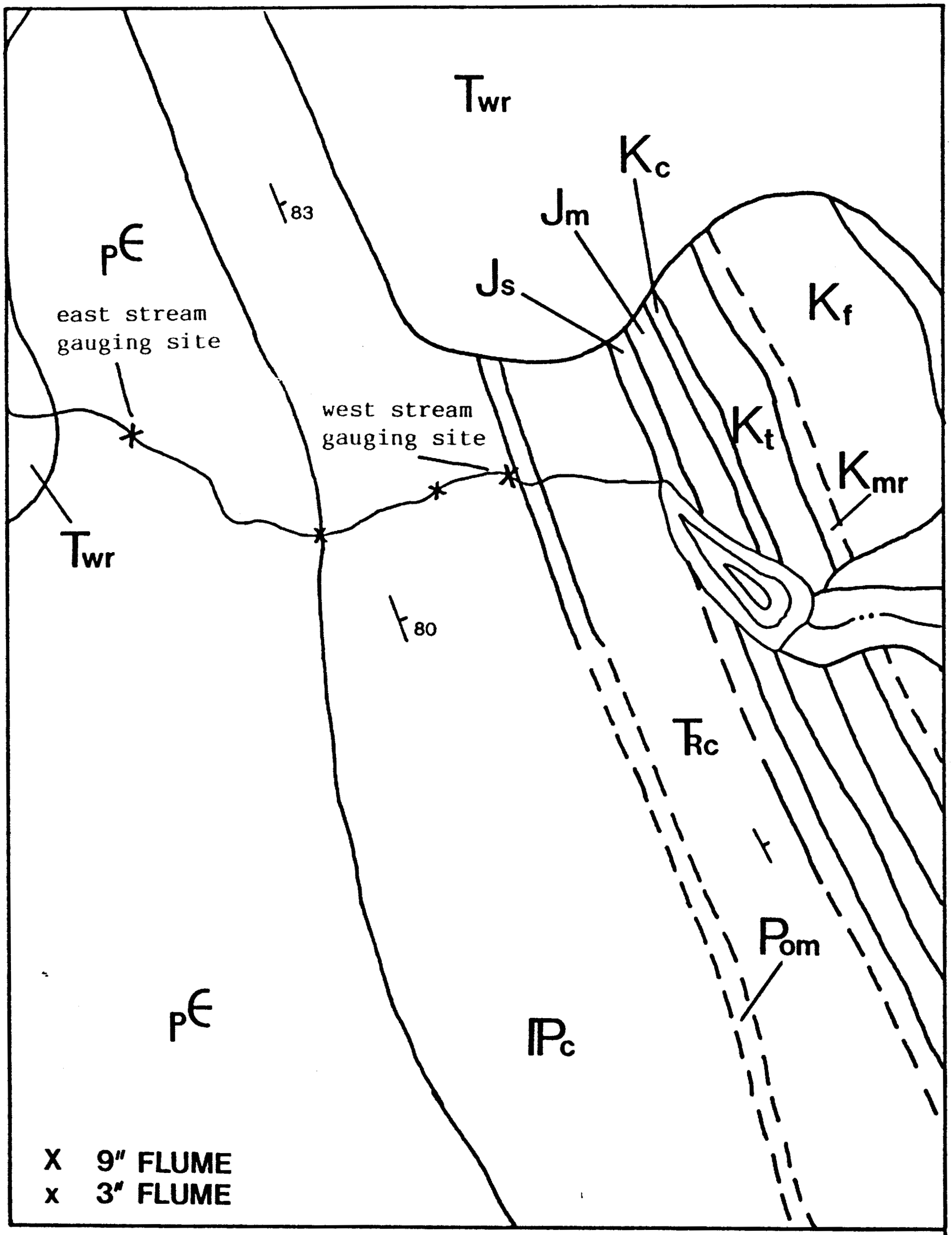

Figure 3. Location of stream gauging stations on the North Fork of Horse Creek, Laramie County, Wyoming.

P was estimated by applying the local monthly accumulation of precipitation over the surface area of the stream. Precipitation was measured by a Belfort, weighing-bucket type recording gage which was located on a hill near the east stream gaging station. The gage had an alter type windshield around the collector orifice.

Contributions to the gauged reach resulting from runoff associated with precipitation events were not considered for two reasons. First, no evidence of overland flow entering the stream was observed even during large precipitation or snowmelt events. Second, it was believed that any significant runoff reaching the phreatophyte zone would infiltrate and be accounted for by the groundwater flux term.

Estimates of E and ET rates for the North Platte River drainage basin were obtained from Lewis (1978) and Van Klaveren (1975), respectively, for each month. Volumes were computed by applying the evaporation rate over the surface area of the stream and by applying the evapotranspiration rate over the area of the phreatophyte zone along the stream. The rate of evapotranspiration is zero for the non growing season months of October through April.

In order to understand where the recharge and discharge is occurring and to further isolate the part of the gauged reach which flows over the limestones of the Casper Fm., the study reach was divided into three segments by two three-inch Parshall flumes. Stream flow losses for each of the three segments were calculated by subtracting the weekly flow rate at the downstream flume from the flow rate at the upstream flume. Precipitation, evaporation and evapotranspiration were considered negligible for this analysis.

Gauging of additional streams in the region, to verify that the results of the North Fork of Horse Creek study are applicable to all streams along the east flank of the Laramie Range, was considered unnecessary because these streams flow across outcrops of the Casper Formation which are hydraulically severed from the rest of the basin by thrust faults. These faults are impermeable boundaries which effectively prohibit any recharge occurring along these streams from reaching the basin interior. The two streams which do flow through parts of the recharge area which may be in hydraulic communication with the rest of the aquifer are the North Fork of Horse Creek and Mill Creek. The North Fork of Horse Creek was gaged in detail for the water budget analysis. Mill Creek, which is the next stream to the south of the North Fork of Horse Creek, flows over Paleozoic rocks which were heavily disrupted by the limestone mine on the adjacent hogback. Mining practices have altered the hydrologic characteristics of these rocks to such an extent as to render the results of any gauging of this stream unique to this one circumstance and therefore, of limited interest to this study.

EXAMINATION OF THE GEOLOGIC FRAMEWORK

The geologic framework through which recharge must flow was examined by identifying any variations in permeability which could impact groundwater circulation patterns. These features included tectonic structures which deform the aquifer and hydrologically isolated compartments which are isolated within the aquifer by zones of small permeability.

TECTONIC MAPS. Tectonic structures were identified on two different scales. A structure contour map of the Muddy Sandstone was prepared on a scale of 1:125,000 and is presented on Plate I. Tectonic structures along the east flank of the Laramie Range, where the Paleozoic and Mesozoic rocks crop out, were mapped on a 1:24,000 scale and are presented on Plates II, III and IV. Lithologic descriptions of the geologic units present in this area are listed in Table 1.

Table 1. Lithologic Descriptions of the Geologic Units Present Along the East Flank of the Laramie Range, Laramie County, Wyoming, (from Grey, 1947).

GEOLOGIC AGE	NAME OF UNIT	DESCRIPTION OF UNIT
Quaternary	Quaternary Alluvium	Floodplain alluvial deposite.
UNCONFORMITY		
Oligocene	White River Group	Brule Fm.: tough sandy clay, 200 ft.
		Chadron Fm.: Interbedded red and green sandy clay, with arkosic gravel and light brown, poorly cemented, arkosic conglomerates, 20 to 200 ft.
UNCONFORMITY		
Cretaceous	Fox Hills Fm.	light brown to grey sandstone, with tan and dark grey shales, 360 ft.
	Pierre Fm.	Succession of shales and sandstones, 3000 ft.
	Niobrara Fm.	Calcareous shales and sandstones, 420 ft.
	Frontier Fm.	Black sandy shales, with some sandstones, 165 ft.
	Mowry Shale	Black siliceous shales which weathers to silver-grey, 150 ft.
	Thermopolis Fm.	Upper: dark ferruginous shale, 50 to 60 ft.
		Muddy Sandstone: siliceous sandstone, 50 to 75 ft.
		Lower: black shale, 100 ft.
	Cloverly Group	Fall River Sandstone, 25 ft.
		Fuson Shale, 50 ft.
		Lakota Sandstone, 27' ft.
UNCONFORMITY		

Table 1, continued.

GEOLOGIC AGE	NAME OF UNIT	DESCRIPTION OF UNIT
Jurassic	Morrison Fm.	Variegated shales, 200 ft.
	Sundance Fm.	Grey to buff, fine to medium grained sandstone, with orange poorly indurated sandstones at the base, 100 to 165 ft.
UNCONFORMITY Triassic Permian	Chugwater Fm.	Red shales and sandy shales with, two thin limestones at the base, 600-700 ft.
	Opeche-Minnekahta Succession	Minnekahta Limestone: Pink to purple interbedded limestones and siltstones, 22 ft.
		Opeche Shale: Red shales and sandstones, 89 ft.
Pennsylvanian	Fountain-Casper	Casper Fm.: Upper: red shales and sandstones, 400 ft.
		Middle: interbedded shales limestones and sandstones, 660 ft.
		Lower: red, coarse-grained arkosic sandstones, 200 ft.
		Fountain Fm.: red coarse grained, arkosic sandstones and conglomerates, 30 ft.
UNCONFORMITY Precambrian	Sherman Granite	Pink, coarse grained, arkosic granite.

A structure contour map of the Muddy Sandstone, Plate I, was made by contouring depth-to-formation data obtained from library files which are open to the public at the Wyoming Oil and Gas Commission and from Petroleum Information Cards at the Wyoming Geological Survey. Depth-to-formation data were based on well logs including both mud logs and geophysical logs obtained during oil and gas exploration. Among the geophysical logs used were conductivity, resistivity, spontaneous potential and gamma ray logs. This map was then used to identify tectonic structures which could potentially enhance or inhibit groundwater flow in the basin. Depth to formation data is listed in Appendix B and the spacial distribution of these data points is shown on Plate V.

Tectonic structures which deform the Paleozoic and Mesozoic rocks along the east flank of the Laramie Range were identified and mapped using previously published maps by Gray (1946) and Brady (1949), stereo aerial photographs, and field observations, where access was permitted. The purpose of these maps was to identify any tectonic features which impede or enhance the flow of groundwater from the recharge area to the basin interior.

It was not possible to map the structure of the basin interior in as much detail as was possible along the east flank of the Laramie Range. Paleozoic rocks in the basin interior and the structures which deform them are unconformably buried by the Oligocene White River Group.

Use of the Muddy Sandstone. Although the Muddy Sandstone is not part of the Paleozoic aquifer, it was necessary to use it as the source of data for much of the analysis done for this thesis because there is virtually no data available for the Paleozoic aquifer in this area.

The Muddy Sandstone was chosen because the circulation patterns which describe groundwater flow through the Muddy Sandstone closely mimic the patterns which describe groundwater flow through the Paleozoic aquifer. This occurs because the basic geologic framework for both formations is the same including common basin boundaries, common tectonic deformation of the strata and common overall basin geometry. Copeland (1984), Gray (1946), Brady (1949) and I have shown through our mapping that all of the stratigraphic units from the Pennsylvanian Fountain Formation to the Late Cretaceous Fox Hills Formation are involved in the same major geologic structures. There are no angular unconformities in the stratigraphic sequence from the Pennsylvanian Fountain Formation to the Late-Cretaceous Fox Hills Formation that would indicate any deformation of the Paleozoic aquifer which did not also involve the Muddy Sandstone.

The premise that the groundwater circulation patterns will be the same in the Paleozoic aquifer as they are in the Muddy Sandstone, because the geologic framework is the same, is substantiated in work done by Belitz (1985). This work shows structure contour and potentiometric maps for several stratigraphic levels from pre-Cambrian to late Cretaceous in the Denver-Julesburg Basin. Comparison of these maps shows that the Middle Cretaceous units, including the Muddy Sandstone, and the Paleozoic units, including the Casper Formation have the same geologic framework and the same groundwater circulation patterns.

Unlike data for the Paleozoic aquifer, data for the Muddy Sandstone is readily available because, locally, it is a major target for petroleum exploration and development. In fact, there are two fields in the study area which are currently producing from the Muddy: the Horse Creek and the Borie fields.

Hydraulically Isolated Compartments. Hydrologically isolated compartments within the aquifer were identified by locating zones of anomalous fluid pressure within the basin. A zone has anomalous fluid pressure if the fluid level, or hydraulic head,in a well completed in that zone is not within a few hundred feet of the land surface (Belitz, 1985). Zones in which the hydraulic head is significantly below the land surface, that is, not within a few hundred feet, are under pressured. Zones in which the hydraulic head is significantly above the land surface are over pressured.

Zones of anomalous fluid pressure were located by plotting the greatest recorded shut-in pressure against depth of measurement for all of the drill stem test (DST) data available for the area. This plot is presented as Figure 4 and the DST data is listed in Appendix A. DST data was obtained from library files at the Wyoming Oil and Gas Commission and from Petroleum Information Cards at the Wyoming Geological Survey.

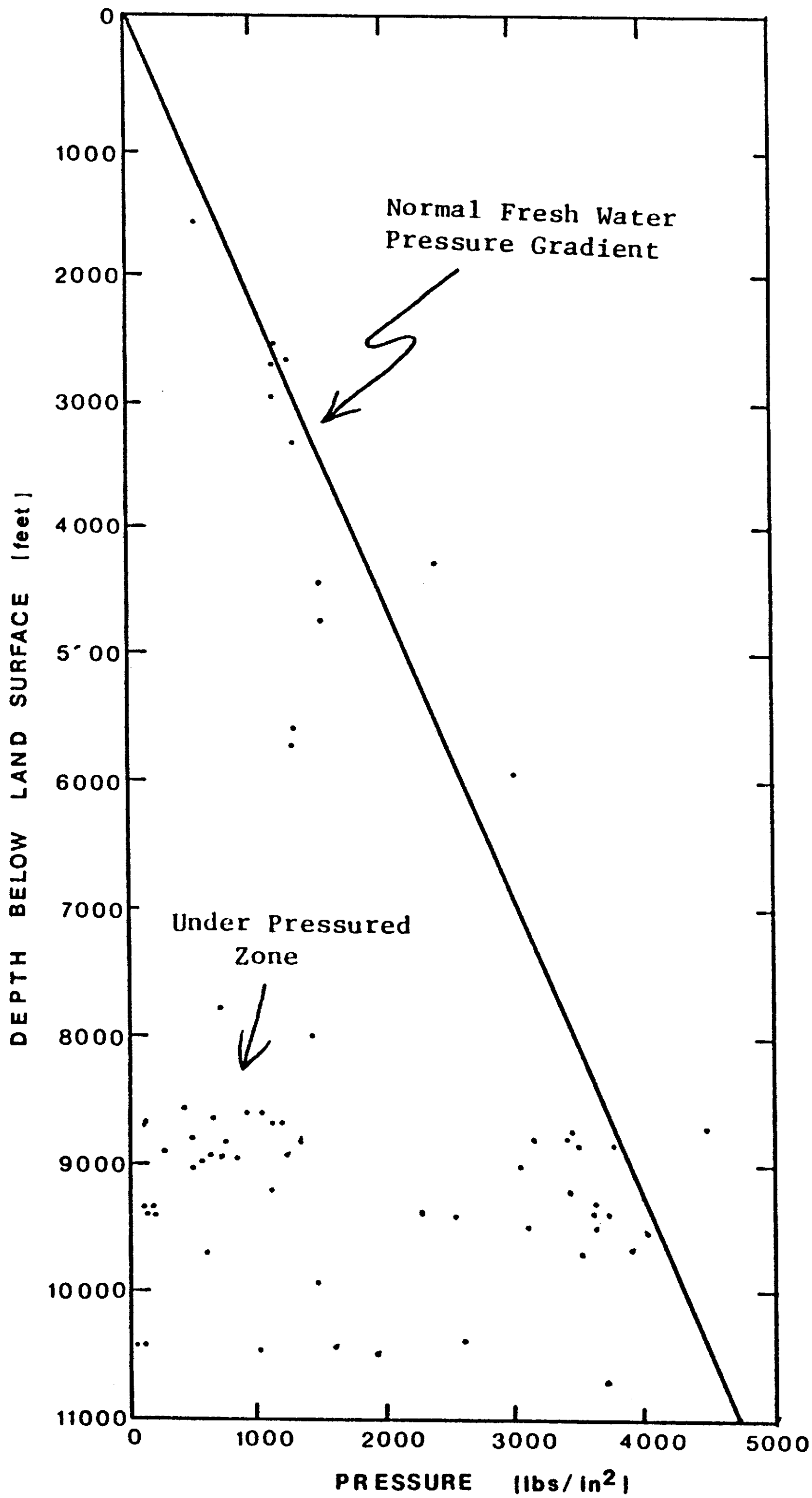

Figure 4. Pressure as a Function of Depth Below the Land Surface as Measured in Drill-sten Tests, Laramie County, Wyoming.

There is a linear increase of pressure with depth in hydraulically connected zones of an aquifer that follows the equation

$$P = gd, \qquad (3)$$

where:

P = pressure,

= density of formation fluids

g = gravitational acceleration, and

d = depth below the water in the saturated zone.

This relationship appears as a line on pressure-depth plots such as Figure 4, where the slope depends on the density of the fluid. Slopes are steeper for less dense fluids and, gentler for more dense fluids.

This line is called the normal pressure line for a fluid of a given density. The line shown on Figure 4 is the normal pressure line for fresh water. Abnormally pressured parts of the basin produce data points which plot significantly to the left (underpressured) or to the right (overpressured) of this line. Data from several depths within a given abnormally pressured zone produce clusters of points which fall on a line that lies roughly parallel to the normal pressure line.

Hydraulic head is expressed in the Bernoulli equation as

$$h = P/\ g + z, \tag{4}$$

where:

h = hydraulic head,

g = gravitational acceleration

= density of formation fluids

z = elevation of the point of measurement.

If equation (3) is substituted into equation (4),

$$h = d + z. \tag{5}$$

It follows that h is a constant for normally pressured parts of a basin which is fully saturated, and which has a reasonably flat land surface. Similarly, the heads within an abnormally pressured zone will also be a constant, but that value will be greater than (overpressured) or less than (underpressured) the value obtained for the normally pressured parts of the basin. Obviously, under- and overpressuring implies that the zone in question is not in good hydraulic connection with the normally pressured parts of the basin.

POTENTIOMETRIC SURFACE

The potentiometric surface was mapped by contouring hydraulic head data obtained from drill stem tests preformed by the petroleum industry throughout the basin. DST's are transient formation pressure tests which are used by the petroleum industry to evaluate the production potential of a specific stratigraphic interval (Jarvis, 1986). The test is performed by isolating a specific stratigraphic interval and allowing the fluids in that interval to flow into the well and then allowing pressure to build up. The changes in pressure are recorded for two or four alternating periods during which the well is either shut-in or open. The shut in periods are intended to allow the measured pressure to equilibrate with formation pressure as closely as possible (Bair and others, 1985).

Complete DST records include a continuous record of the fluid pressure changes during the entire test, the volume of fluid recovered during the shut-in periods, a chemical and thermal analysis of the fluids recovered, the reference elevation, and the gauge depth (Jarvis, 1986). The complete pressure record can be used to extrapolate the undisturbed formation pressure as demonstrated by Bredehoeft (1965). These calculations involve a curve matching technique for radial fluid flow to a producing well which was adopted from Theis (1935).

Complete DST records were not readily available for the project area because they are proprietary. Incomplete DST records are, however, routinely filed with state agencies such as the Wyoming Oil and Gas Commission. These incomplete records were used to compute the hydraulic head values listed in Appendix A and used to map the potentiometric surface on Plate I. The spatial distribution of these data points is shown on Plate V. The incomplete DST records most often included the reference elevation, the interval tested, the gauge depth, the volume and type of fluid recovered during the shut-in periods, discrete measurements of hydrostatic and shut-in pressures, and the length of time which elapsed during each shut in and flow period.

Numerous hydrogeologic studies have made use of incomplete DST data including: Miller (1976) in the Madison Group in Montana; Bair and others (1985) in the Palo Duro Basin of Texas and New Mexico; and Jarvis (1986) and Doremus (1986) in the Big Horn Basin of Wyoming.

Murphy (1965) developed the following equation to compute hydraulic head from DST data:

$$PE = RE - GD + (2.319 * Ps) \tag{6}$$

where:

PE = elevation of the potentiometric surface;

RE = reference elevation, usually derrick floor, rotary bushing, or ground level;

GD = gauge depth, as measured from RE;

Ps = extrapolated static pressure, highest shut-in pressure is often substituted for this value;

2.319 = constant for converting pounds per square inch to feet of head.

The assumptions built into this equation include: (1) the density of formation fluids is equal to that of fresh water, (2) the temperature of the fluid is approximately 35 degrees celsius, and (3) the shut-in period which is used to measure shut-in pressure (SIP) is long enough to closely approximate the stabilized formation pressure.

Extrapolated static pressure refers to approximation of the undisturbed formation pressure made from continuous pressure data recorded during a DST (Bredehoeft 1965). For this thesis, the greatest shut-in pressure reported in the incomplete DST record was used instead of the extrapolated static pressure because of the lack of complete DST data. Bair and others (1985) preformed an analysis of the differences which result from substituting greatest SIP for extrapolated formation pressure and concluded that computations using these two values should not be mapped together, because the use of SIP resulted in significantly lower head values than did the use of the extrapolated formation pressure. Bair and others further concluded that the consistency of this error allowed for reasonable accuracy in a potentiometric map which was constructed from SIP's exclusively. The value of the greater number of data points available if the SIP's are used was considered to outweigh the value of greater accuracy for a few points.

Inconsistencies in the quality of data reported by incomplete DST records prompted Jarvis (1986) to develop a data quality ranking system. This system ranked each calculated hydraulic head according to the number of data quality criteria met by the DST record. The data quality criteria include (1) 10%, or less, difference between the hydrostatic pressures measured at the beginning and at the end of the test, (2) 25%, or less, difference between the shut-in pressures measured at the beginning and at the end of the test, (3) one of the shut-in periods lasted 30 minutes or longer, and (4) two of the shut-in periods lasted 30 minutes or longer.

The hydraulic head data computed for this thesis was ranked accordng to this system and the potentiometric surface (Plate I) was then mapped by contouring all of the hydraulic head data, giving weight to the head values with higher data quality rank. The resulting potentiometric map was overlaid onto the structure contour map so that the direction of groundwater flow could be deduced assuming increases or decreases in permeability parallel to the strike of folds and faults.

CHAPTER 3

RECHARGE FROM THE NORTH FORK OF HORSE CREEK

The results of the water budget analysis, shown in Figure 5, indicate that both recharge and discharge occur along the North Fork of Horse Creek between the east and west stream gauging sites. Annual recharge estimates for the entire gauged reach were 5.3 and 0.2 million cubic feet per year for 1986 and 1987, respectively. These amounts are insignificant and only represent water lost from the gauged reach, not how much of that water actually reaches the basin interior. Estimates of recharge to the basin interior are even less. The conclusion must be drawn that streams which flow across outcrops of the Casper Formation do not contribute a significant amount of recharge to the Paleozoic aquifer.

The stream flow losses measured within each of the three subdivisions of the gauged stream reach are shown on Figure 6. The locations of these three subdivisions, called the upper, the middle and the lower segments of the gauged reach, are shown on Figure 3.

The upper segment of the stream shows consistent gains throughout the year. These gains are most likely the result

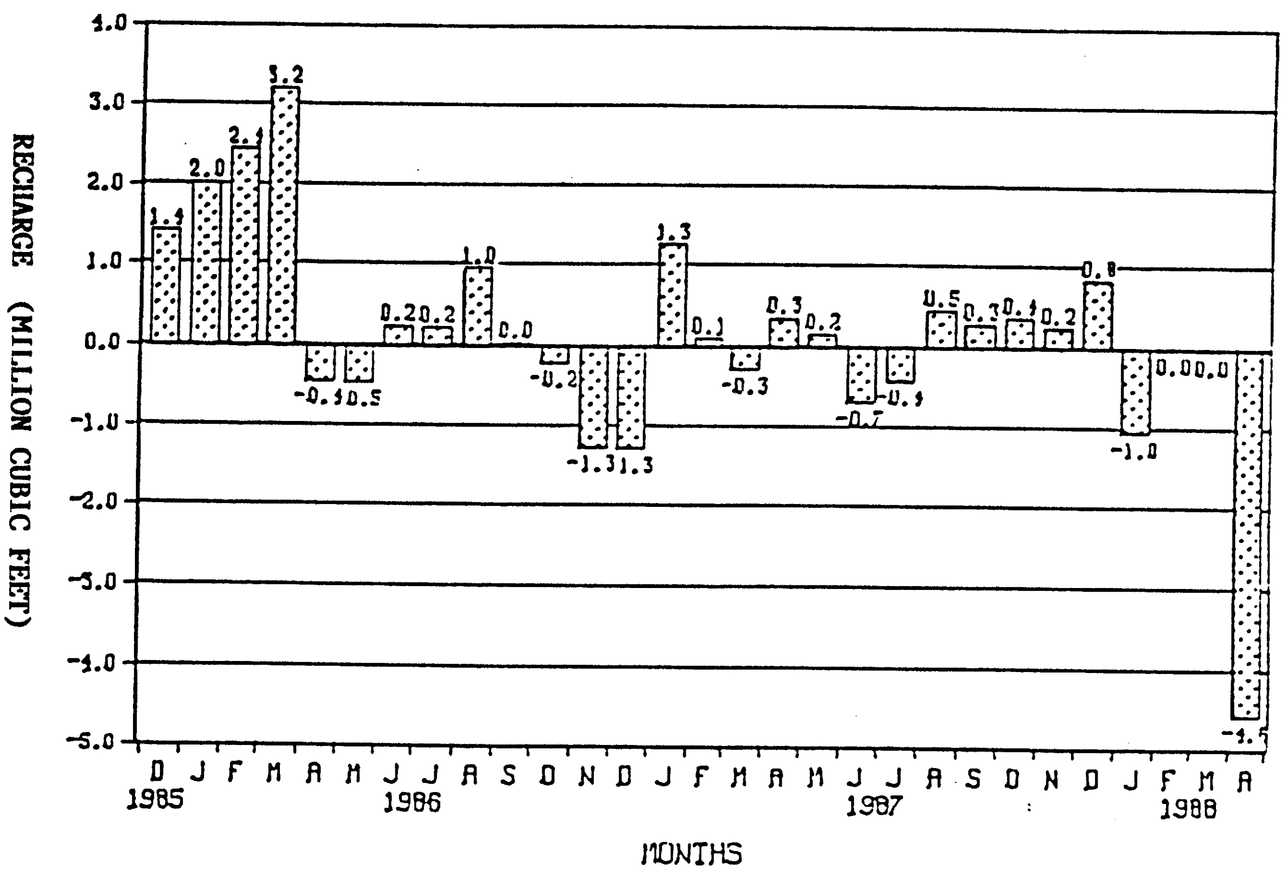

Figure 5. Net Groundwater Recharge for the period December 1985 - April, 1988 Along the North Fork of Horse Creek gauged Reach, Laramie County, Wyoming.

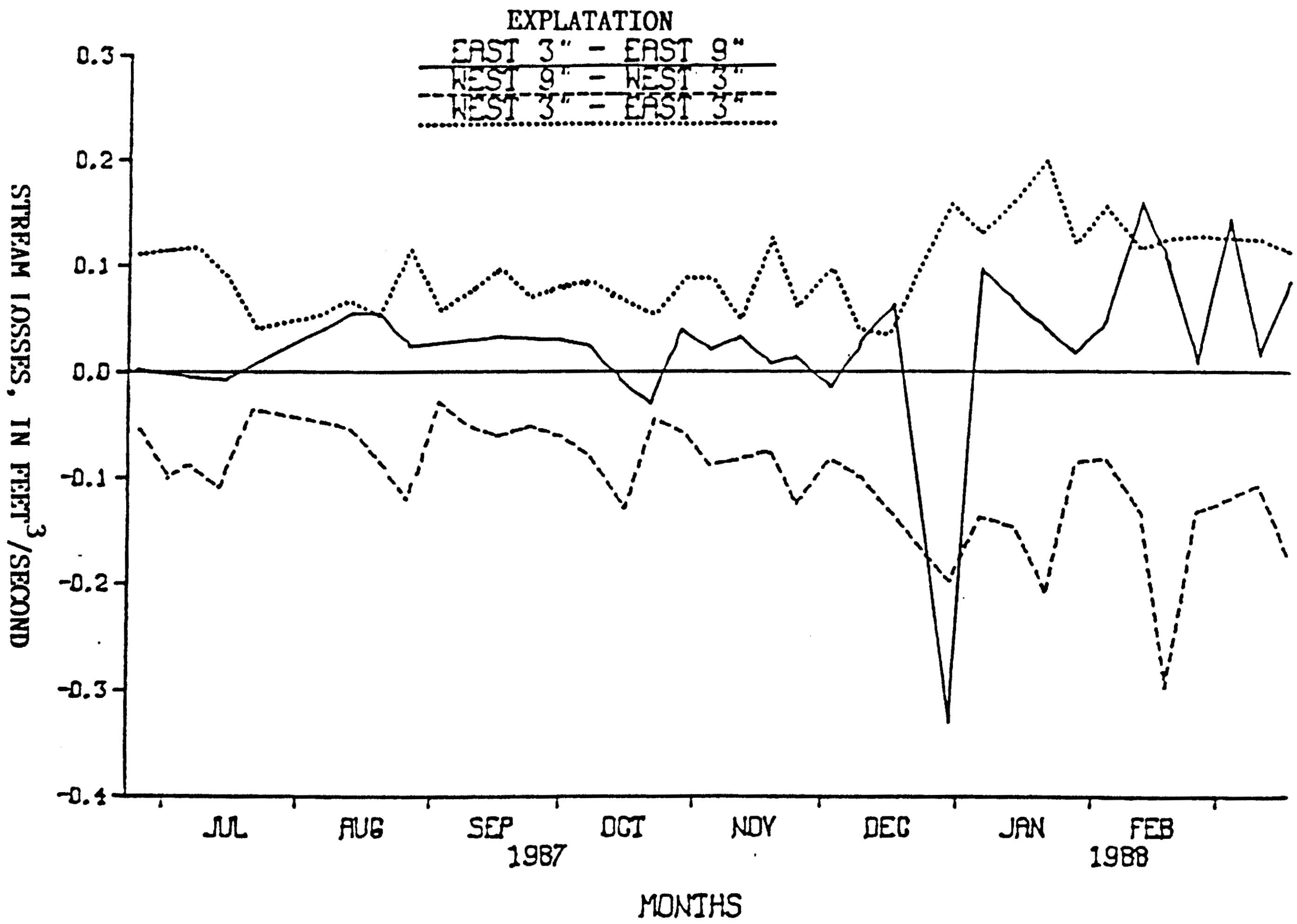

Figure 6. Stream Losses during 1987 and 1988 Along the Subdivisions of the gauged reach of the North Fork of Horse Creek, Laramie County, Wyoming.

of groundwater flowing from the Laramie Range through open fractures in the Sherman Granite. These fractures are intersected by a west dipping thrust fault in the vicinity of the upper segment of the gauged reach.

The middle segment of the gauged reach was located in order to isolate the segment of stream which flows over the Casper Formation. The data indicate that this segment of the gauged reach looses water consistently throughout the year. These losses must be either entering fractures in the Casper Formation or evaporating because there is very little alluvium in this part of the canyon. Of these possibilities, I favor loss by evaporation. I observed that negligible quantities of water are recharging through the limestone. Fractures in the Casper Formation which are open enough to transmit appreciable amounts of water are widely spaced and show little evidence of water flowing through them. Where fractures are exposed the walls are rough and angular, indicating that little dissolution has occurred along them. Groundwater staining of the rocks next to the exposed fractures is also limited. In addition, there is not enough water present in them to support much vegetation. Two paleokarst cavities were observed in the area. These are filled with sand and gravel and do not appear to be extensive. Neither the observed fractures nor the paleokarst cavities intersect the gauged reach of the stream.

The most likely explanation for these losses is the wind. The middle segment of the stream flows through a very narrow part of the canyon. Wind blasts through this part of the canyon at terrific speeds. Spray picked up by these gusts was regularly observed which accounts for the unusually high evaporation rates as well as wholesale transport of water droplets. I believe these processes are sufficient to account for the small but consistent losses along this segment of the gauged reach.

The lower segment of the gauged reach shows consistent stream flow losses throughout the year. These losses are best explained as recharge to the alluvium because this segment of the stream flows entirely over alluvial fill which is at least 40 feet thick at the east stream gauging site. Five wells were drilled in the vicinity, four of which were completed in the alluvium. Excellent hydraulic connection between the stream and the alluvium is demonstrated by immediate potentiometric response in the wells to stream flow fluctuations. Potentiometric levels measured in the four alluvial wells reveal flow from the stream to the alluvium consistently throughout the year.

CHAPTER 4

TECTONIC STRUCTURE

The structure of the east flank of the Laramie Range is characterized by varying degrees of crustal shortening brought about by generally east-west directed compressive stresses (Gries, 1983). It will be shown that Berg's (1962) fold-thrust style of Laramide deformation characterizes the tectonic structures found in the project area. Next, the impact of this type of structure on groundwater circulation will be discussed.

Berg's (1962) model, shown on Figure 7, is an asymmetric anticline-syncline pair cored by a thrust fault in the basement under the anticlinal hinge. Increasing displacement along the fault results in increased asymmetry within the overlying anticline as well as the development of a new reverse fault parallel to the original fault, but nearer to the synclinal hinge. The steep limb of the structure is increasingly rotated and tectonically thinned between the two faults until the entire folded section becomes severed and the hanging wall is thrust over the overturned, younger sediments (Brown, 1983).

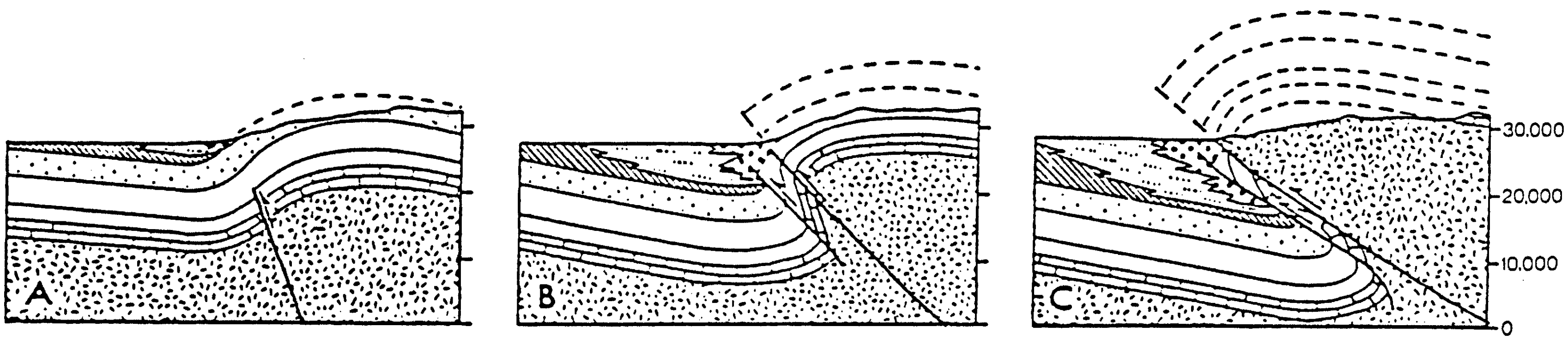

Figure 7. Stages in the Development of a typical Laramide Fold-Thrust Structure in Southeastern Wyoming (Brown, 1983). **A** - initial, **B** - intermediate, **C** - advanced.

Seven locations were chosen within the project area to demonstrate the applicability of Berg's model.

(1) The hogbacks on either side of the North Fork of Horse Creek, shown on Plate II and Figure 8, are in the initial-intermediate stages of Berg's fold-thrust development. There is a well developed anticlinal fault directly west of and parallel to the hogbacks. The units which form the hogbacks dip steeply eastward and are not overturned. The synclinal fault does not appear to be present.

(2) The hogback to the south of Mill Creek, shown on Plate II, where a limestone quarry was once located, is more advanced than those on either side of the North Fork of Horse Creek but is still in the intermediate stage of development. The anticlinal fault is mapped just west of, and parallel to, the hogback. A synclinal fault emerges from the south side of the hogback, just north of Horse Creek. Units in the footwall are overturned.

(3) The limestone ridges on either side of Fisher Canyon, shown on Plates II and III, are in the late stage of development. The anticlinal fault is located to the west of, and parallel to, the limestone ridge. The units which form these ridges are part of imbricate blocks which have been rotated to an overturned position. The synclinal fault, is located parallel to strike within the Chugwater Formation. The Chugwater shows marked loss of stratigraphic

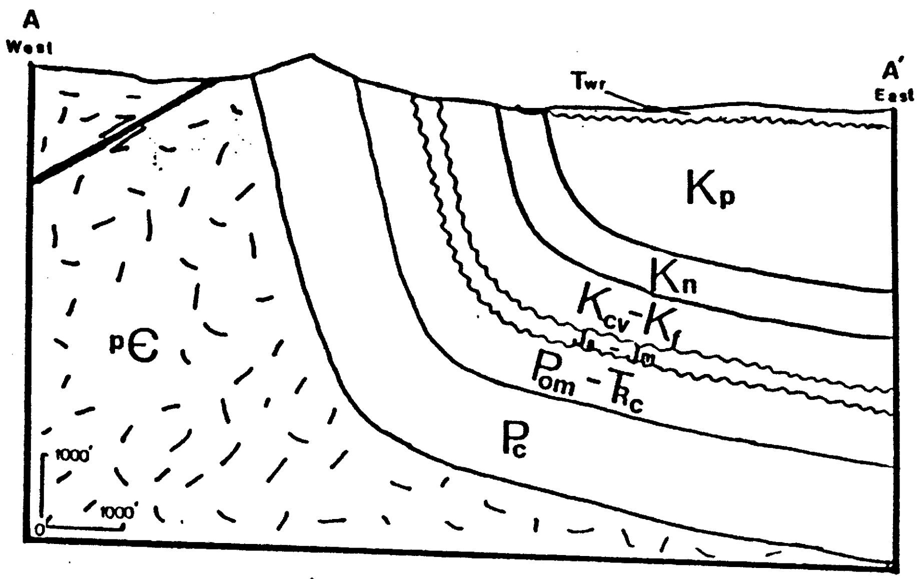

Figure 8. Cross-section A-A', Showing Thrust Fault and Stratigraphy in the Vicinity of the North Fork of Horse Creek, Laramie County, Wyoming. Section trends N.60°E. Its location is shown on Plate II. Geologic symbols are defined on Plate II.

thickness in this area and the younger units in the footwall are overturned. It is evident that dip slip along the synclinal fault is small because the Chugwater Formation is present on either side of the fault plane.

(4) The series of hogbacks south of Fisher Canyon, shown on PLate IV, are in the intermediate stage of development. The anticlinal fault is located west of the hogbacks. The hogbacks themselves are within an imbricate block. The beds of the hogback are nearly vertical at their base and curl to the west near the top of the hogback. This curl represents the crest of the anticline. The synclinal fault is believed to penetrate all the way through the Paleozoic section, however, the rotational distortion of the imbricate block is limited, leaving the block very much intact. The trace of the synclinal fault is located further to the east and is covered by the White River Group.

(5) The tight folds located north of Mesa Mountain, shown on Plate IV, are an anomaly in the pattern described thus far. This area appears to be in a very advanced stage of development. The crustal shortening which was elsewhere taken up almost entirely by thrust faulting, is, here, being accommodated by tight folding as well.

(6) Table and Mesa mountains, shown on PLates IV and V and Figure 9, are also in a very advanced stage of development. The units which crop out as Mesa and Table mountains form a gentle syncline in the hanging wall of the

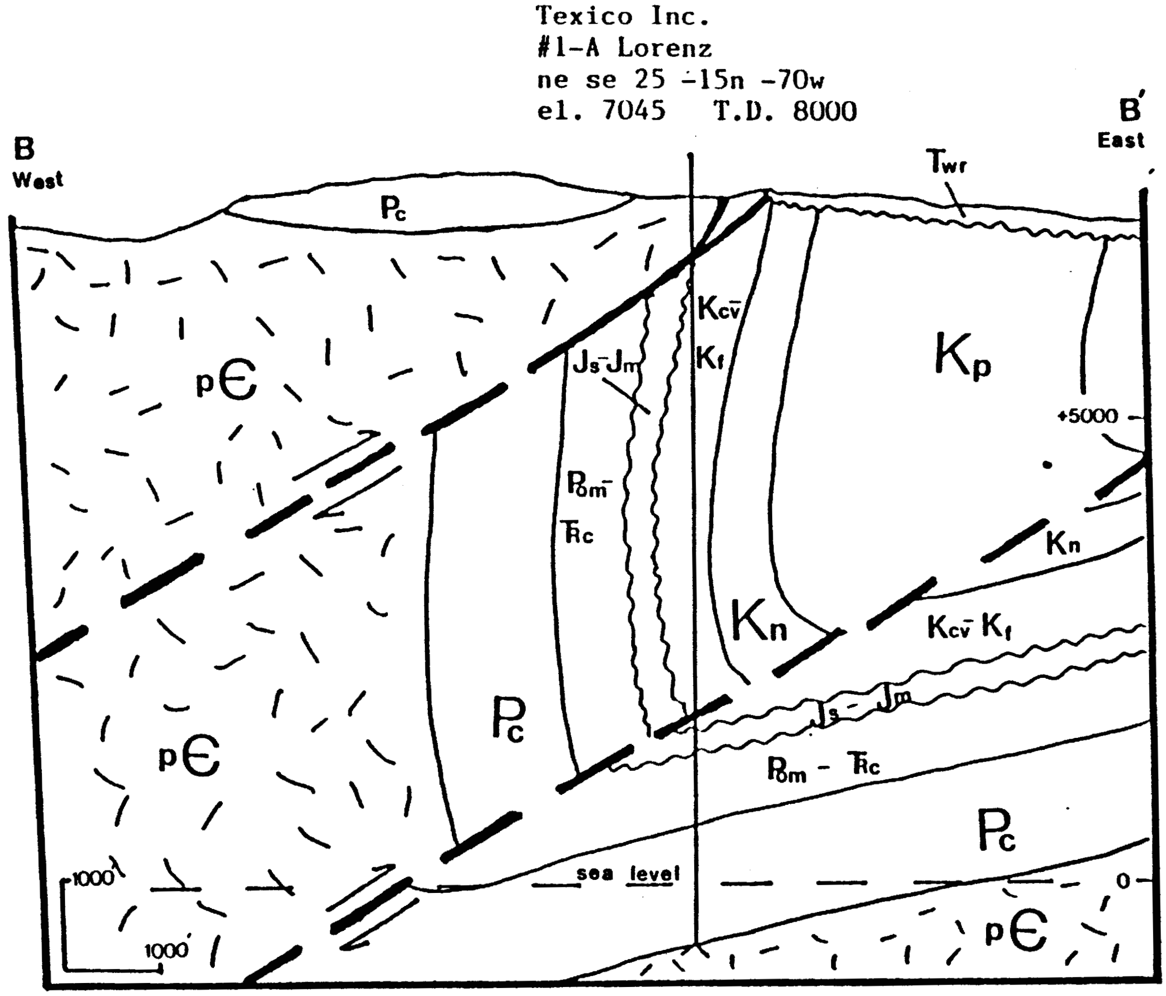

Figure 9. Cress-section B-B', Showing Thrust Faults and Stratigraphy in the Vicinity of Table and Mesa Mountains, Laramie County, Wyoming. Section trends N.60°E.. Its location is shown on Plate IV. Geologic symbols are defined on Plate IV.

thrust zone. An anticline and its associated anticlinal fault is traced through the Precambrian core located east of the two mountains. The synclinal thrust is located further east where it is covered by the White River Group. The trace of an imbricate of the anticlinal fault is delineated by a line of springs which parallels the mountain front. The imbricate slice is mostly covered by the White River Group, and is expected to be smeared out.

(7) The hogbacks south of Table Mountain and north of Happy Jack Road, shown on Plate V, are in the intermediate stage of development as were the curled hogbacks south of Fisher Canyon.

Most of the recharge area for the Paleozoic aquifer is hydrologically isolated from the rest of the basin by the thrust faults which delineate the eastern boundary of the Laramie Range. These thrust faults act as impermeable barriers to recharge. Water which reaches these fault planes is forced through joints and fractures in the overlying strata onto the surface. The springs along the trace of the eastern most thrust shown on Plate III, and the water gained by the reach of the North Fork of Horse Creek which flows over the fault located west of the hogbacks in Plate II are a result of these barriers.

The only place in the project area where the recharge area may not be isolated from the rest of the aquifer in the

Denver-Julesburg Basin is located north of Horse Creek where the Paleozoic rocks crop out to the west of the anticlinal fault and where there may not be a well developed synclinal fault. It is conceivable for recharge entering the Paleozoic rocks in this area to flow to the basin interior.

Extensional fractures were found along the axis of anticlines located in the series of tight folds north of Mesa and Table Mountains. These fractures do not provide high permeability pathways into the basin interior because they trend north-south.

CHAPTER 5

HYDROLOGICALLY ISOLATED COMPARTMENTS

Hydraulic communication is somehow limited between abnormally pressurized and normally pressurized parts of the Paleozoic aquifer because abnormally pressurized compartments have hydraulic heads which, by definition, differ from normally pressured zones by more than a few hundred feet. Such head differences should equilibrate with the rest of the system if good hydraulic communication exists.

Petroleum exploration geologists have observed a close association between natural gas zones and abnormally pressured compartments. The potential that this association has for petroleum exploration has motivated the development of many theories explaining the nature and origin of these compartments and whatever it is that isolates them from the rest of the aquifer. These theories are too numerous and too involved to be discussed adequately in this paper. However, Table 2 provides a summary of the literature pertaining to abnormally pressured reservoirs reviewed for this thesis.

Table 2. Trapping Theories for Abnormally Pressured Reservoirs.

I. DIAGENETIC TRAP
   A. Quartz overgrowthes
      *Law and Dickinson, 1985.
   B. Crushing of sedimentary rock fragments
      *Cant, 1983, SW Alberta.
   C. Cementation by carbonates and clay
      *Powley,

II. HYDRODYNAMIC TRAP
   A. Berg, 1985, NE Powder River Basin, WY.
   B. Moore, 1984, SW Powder River Basin, WY.
   C. Lin, 1981, Powder River Basin, WY.

III. WATER TRAP (water on top of gas)
   A. Gies, 1984, SW alberta, Canada.
   B. Davis, 1984.
   C. Masters, 1979, Deep Basin, Western Canada.

IV. EXPULSION OF INSITU NATURAL GAS
   A. Silver, 1968, San Juan Basin, NM and CO.

V. STRATIGRAPHIC TRAP
   A. Stone and Hoeger, 1973, Big Muddy - S. Glenrock area.

Under pressurized compartments existing along the axis of the Denver-Julesburg basin are documented by Belitz (1984) and Matuszczak (1973). The Wattenberg field, which produces natural gas from a large under pressured reservoir in the Muddy Sandstone, is located along the synclinal axis of the Denver-Julesburg basin northeast of Denver. There is a large area in the Wattenberg field which continues to produce gas with out producing water. This demonstrates the lack of hydraulic communication between the under pressured and the normally pressured parts of the Muddy Sandstone (Matuszczak,1973).

The mechanism which traps the gas in these compartments is, presumably, the same mechanism which keeps the water out. According to Matuszczak (1973), the trap on the south and west sides of the Wattenberg field is formed by the pinchout of the reservoir sandstone into a thin, tight siltstone and silty sandstone. On the northeast and east sides of the field the gas is trapped by a loss of permeability resulting from an increase in the presence of siliceous cement and clay (Matuszczak, 1973).

Petrographic work reported by Dickinson and Guatier (1983) indicates that the loss of permeability at the abnormally pressurized compartment boundary is caused by one or more of the following: (1) precipitation of calcite and/or silica cements early in the burial history, (2) grain deformation and compaction, and (3) filling and coating of primary and secondary pores with illite, chlorite, microcrystalline quartz or ferroan carbonates.

Figure 4 indicates the presence of one or more under pressured compartments in the Muddy Sandstone which extend the full length of the project area from north to south. Evidence for compartmentalization is revealed on the potentiometric map as an abnormally low potentiometric surface throughout the study area, especially on either side of the synclinal axis. Potentiometric contours were drawn through the low pressure compartments even though they are hydraulically isolated from the rest of the aquifer because there was not enough data to define their boundaries.

Evidence supporting the presence of under pressured compartments in the Paleozoic aquifer is limited by the complete lack of potentiometric data available for the Paleozoic aquifer in the interior of the basin. Hoeger (1968) reports, in a general discussion of the hydrostratigraphic units of the Denver-Julesburg basin, that the formations beneath the Permian Lyons Sandstone are under pressured, although to a lesser extent than the Lyons Sandstone, which is a stratigraphic equivalent to the Satanka Shale of southeast Wyoming. No potentiometric data could be found to either support or to disclaim this statement for my area.

If the Paleozoic aquifer does have under pressured compartments like the Muddy Sandstone then recharge is probably blocked from reaching the synclinal axis of the basin by these compartments. Without more conclusive evidence, however, it is impossible to say what influence hydrologically isolated compartments have on the circulation patterns in the Paleozoic aquifer.

CHAPTER 6

POTENTIOMETRIC SURFACE

Groundwater flow through a porus medium is governed by the Darcy Equation:

$$Q = -K * dh/dl * A \tag{7}$$

where:

Q = discharge L^3/T ,

K = hydraulic conductivity L/T ,

dh/dl = hydraulic gradient dimensionless ,

A = cross sectional area L^2 ,

l = length in the direction of flow L ,

h = hydraulic head L .

The hydraulic gradient is a measure of the slope of the potentiometric surface. Groundwater flows from a higher hydraulic head to a lower hydraulic head.

The potentiometric surface of the Muddy Sandstone slopes to the east-southeast in the Denver-Julesburg basin, as shown on Plate I. The general direction of groundwater flow is, therefore, to the east-southeast from the Laramie Range. If recharge does flow past the fault severed boundary along the flank of the range, then the potential does exist for that recharge to flow towards the basin interior.

The possibility that significant recharge flows past the fault severed boundary is remote because the fault plane is impermeable. Effects of the impermeable fault plane documented in the study area include stream flow gains along the upper segment of the gauged reach of the North Fork of Horse Creek and the line of springs along the eastern most thrust fault on Plate IV, located east of Table Mountain.

CHAPTER 7

SUMMARY AND CONCLUSIONS

This thesis has examined the evidence for recharge to the Paleozoic aquifer along the east flank of the Laramie Range in Laramie County, Wyoming.

The amount of water entering outcrops of rocks which comprise the Paleozoic aquifer was estimated by a water budget analysis conducted on the North Fork of Horse Creek. This study showed that no significant recharge to the Paleozoic rocks occurred during the two years of record. The results from this stream are considered representative of other streams which flow across outcrops of Paleozoic rocks in the area in a similar structural environment.

The geologic framework was examined in conjunction with the shape of the potentiometric surface in order to learn if recharge to the Paleozoic aquifer can circulate from the recharge area to the basin interior. The recharge area, from Horse Creek to the southern boarder of the study area is hydrologically isolated from the rest of the aquifer by an impermeable thrust zone. This thrust zone effectively prohibits recharge from circulating into the basin interior.

The recharge area to the north of Horse Creek does not appear to be separated from the rest of the aquifer. Conceivably, recharge could circulate to the basin interior under the influence of a east-southeast hydraulic gradient.

APPENDIX A. DRILL STEM TEST DATA.

LOCATION T	R	S	Q	Q	REF. ELEV.	INTERVAL FROM	TO	FM. TESTED	GAUGE DEPTH	SIP	P.S. ELEV.	RANK
13	66	33	NW	NW	6133	9850	10023	Kmd	9937	1468	-400	2
13	68	3	SE	SE	6612	9250	9450	Kmd	9350	3577	5557	2
13	68	3	SE	SE	6612	4740	4820	Kmd	4780	1473	5248	2
13	68	4	SW	NE	6633	9385	9447	Kmd	9416	2522	3060	3
13	68	4	NE	NE	6633	9378	9467	Kmd	9042	3580	3200	2
13	68	11	NW	SW	6570	8954	9131	Kmr-Ksc	9024	476	-1368	4
13	68	12	SW	SW	6482	8985	9064	Kmd	8589	2996	4405	0
13	68	13	SW	SW	6527	8577	8601	Kmd	8671	391	-1155	4
13	68	14	SE	SE	6578	8640	8702	Kmd	8694	1103	465	3
13	68	23	NE		6546	8663	8724	Kmd	8701	3420	5783	1
13	68	23	NE		6546	8632	8770	Kmd-Ksc	8697	4520	8327	1
13	68	23	SE		6562	8678	8716	Kmd	8778	100	-1903	0
13	68	23	SE		6562	8710	8773	Ksc	8945	3100		1
13	68	23	SE	SW	6508	8872	9018	Ksc	8858	1203		4
13	68	23	SE	SW	6508	8820	8896	Ksc	8589	676		2
13	68	24	SW	NW	6502	8575	8603	Kmd	8622	992	213	4
13	68	24	SW	NW	6502	8595	8650	Kmd	8764	913	-3	4
13	68	24	NE	SW	6537	8733	8796	Ksc	8809	3400	572	0
13	68	25	SW	NW	6415	8792	8825	Kmd	8828	1279	572	3
13	68	25	NW		6397	8758	8897	?	7808	3750	6265	0
13	68	25	NW	NW	6427	8680	8814	Kmd	8660	705		3
13	68	25	NW	NW	6427	7750	7865	Km	8965	1165		2
13	68	26	NW	SE	6531	8906	9024	Kmd	8835	780	-625	4
13	68	26	SE		6528	8810	8860	Kmd or up	8935	3430	5647	0
13	68	26	SE		6528	8910	8961	Kmd	9193	700	-784	0
13	68	35	NE	SW	6440	9138	9248	Kmd	1545	3413	5162	4
13	69	28	SE	SW	7194	1540	1550	Kd	9375	495		0
14	68	12	SW	SW	6860	9340	9410	Kms	10428	152		4
14	68	12	SW	SW	6860	10422	10434	Kmd	9373	22	-3517	3
14	68	13	NW	NW	6332	9340	9410	Km	9375	152		4
14	68	13	NW	NW	6332	10422	10434	Kmd	10428	41	-4248	4
14	68	14	NE	SE	6350	10375	10464	kmd	10420	2612	1987	4
14	68	14	NE	SE	6350	10464	10513	kmd	10488	1910	291	3
15	67	19	NW	NW	6490	10425	10517	Kmd	10471	1013		3
15	67	19	NW	NW	6490	10632	10746	Kd-Km	10689	3695	4588	4
16	67	29	NW	NW	6426	10413	10443	Kmd	10428	1604	-282	3
16	68	6	NW	NW	6786	5279	5370	above Kmd	5324	2340		4
17	66	23	SW	SW	5942	8841	9105	Km	8634	604		4
17	66	23	SW	SW	5942	8450	8819	Km	8973	586		3
17	66	23	SW	SW	5942	9640	9775	Kmd	9708	597	-2382	3
17	66	29	NW	NW	6094	8810	9150	Km	8980	539		3
17	67	9	NW	NE	6010	9757	9850	Kmv	4453	1458		3
17	67	9	NW	NE	6010	4446	4460	Kmd	9804	429	-2799	3
17	68	28	NW	SE	6519	5933	5979	Kmd	5956	2928	7353	2
17	68	31	SE	NE	6666	5520	5700	Kmd	5610	1269		4
17	68	31	SE	NE	6629	6216	6236	Kmd	6226	49	517	4
17	68	31	SE	NE	6651	8012	8007	pre-Miss	8009	1416		1
17	70	36	SW	NW	6568	2635	2653	Kmd	2644	1225	6765	3
17	70	36	SW	NW	6568	2656	2696	Kmd	2676	1110	6466	1
17	70	36	SW	NW	6568	2857	2875	Kl	2866	1100		1

APPENDIX A. DRILL STEM TEST DATA, continued.

LOCATION					REF.	INTERVAL		FM.	GAUGE		P.S.	
T	R	S	Q	Q	ELEV.	FROM	TO	TESTED	DEPTH	SIP	ELEV.	RANK
18	67	6	SE	SW	6010	9624	9654	Kmr	9639	3870	5346	4
18	69	4	SW	NE	6659	2920	3028	Kmd	2974	1075	6178	4
19	66	4	NW	SE	5610	8815	8954	Kcodell	8884	241		3
19	66	4	NW	SE	5610	9594	9769	Kmd	9682	3497	4038	3
19	67	3	SE	NW	5891	9358	9402	Kmd	9380	3681		4
19	67	36	SE	NW	5767	9580	9585	Kmd	9582	3081	3330	2
19	67	36	SE	NW	5767	9580	9585	Kmd	9582	3606	4537	4
19	68	7	NE	SW	6235	2555	2587	Kmd	2571	1088	6187	2
19	68	17	SE	NW	6206	2889	2960	Kmd	2924	1241	6160	4
19	69	29	NE	SW	6378	2812	2830	Pminn	2821	9		4
19	69	29	NE	SW	6378	3290	3309	Pminn	3300	1274		4
20	67	26	SW	SW	5725	5700	5846	KN or abo	5773	1250		0
20	67	26	SW	SW	5725	9210	9239	Kmd	9224	1116		1
20	67	34	SE	NW	5860	9337	9414	Kd	8351	102		4
20	67	34	SE	NW	5860	9545	9604	Kl	9574	3957		3
20	67	34	SE	NW	5860	8300	8420	Kn	9376	2246	1692	4

APPENDIX B. WELL CONTROLL FOR STRUCTURE CONTOUR MAP OF THE MUDDY SANDSTONE.

LOCATION					ELEVATION
T	R	S	C	C	TOP OF MUDDY
13	66	33	NW	NW	-3762
13	66	35	SW	SW	-3593
13	67	22	SW	SW	-4146
13	67	36	SW	SW	-3882
13	68	3	SE	SE	-2658
13	68	4	SW	NE	-2718
13	68	4	NE	NE	-2712
13	68	11	SW	NE	-2468
13	68	11	NW	NW	-2560
13	68	11	NW	SW	-2400
13	68	12		SW	-2458
13	68	13	NW	SW	-1975
13	68	13	SW	SW	-1971
13	68	13	SW	NW	-2017
13	68	14	SE	SE	-2038
13	68	22		SE	-2715
13	68	23	NE	NE	-2036
13	68	24	NW	NW	-2008
13	68	24	SW	NW	-2039
13	68	25	NW	NW	-2223
13	68	25	SW	NW	-2261
13	68	25	SE	NW	-2411
13	68	26	NW	SE	-2329
13	68	26		SE	-2367
13	68	35	NE	SW	-2628
13	69	28	SE	SW	5260
14	66	11	SW	SE	-3480
14	68	1	SW	SE	-4111
14	68	1	NW	SW	-4066
14	68	11	SE	SE	-4054
14	68	11	SW	NE	-4041
14	68	12	SW	SW	-4084
14	68	12	NE	SW	-4086
14	68	13		NW	-4084
14	68	14	NE	SE	-4084
14	68	34	NW	SW	-3152
15	66	11	SW	SW	-3529
15	66	23	SE	NW	-3521
15	67	19	NW	NW	-3927
16	66	9	SE	NE	-3790
16	66	13	NW	SW	-3641
16	66	13	NW	SW	-3595

LOCATION					ELEVATION
T	R	S	C	C	TOP OF MUDDY
16	66	14	NE	SE	-2750
16	66	15	SW	NE	-3696
16	66	15	SE	NE	-3672
16	66	23	NW	SE	-3651
16	68	29	NW	NW	-4022
16	68	5	NE	NW	1082
16	68	6	NE	NW	1244
16	68	6		NW	1292
16	68	6	NE	SE	1047
16	68	6	SE	SW	1105
16	68	6	NW	NW	1504
16	68	6	NE	NE	1490
16	68	6	SE	SE	1083
16	68	6	NE	SE	1221
16	68	7	NE	NE	975
16	68	7	NW	SE	663
16	68	19	NE	NE	-187
16	68	30	NE	NE	-781
17	66	23	SW	SW	-3690
17	66	29	NW	NW	-3996
17	67	4	SW	SE	-3710
17	67	9	NW	NE	-3754
17	67	26	SW	NW	-4039
17	68	21		SE	360
17	68	28	NW	SE	556
17	68	28		NW	1132
17	68	28		NW	888
17	68	28	SE	NW	1051
17	68	28	NW	SW	1059
17	68	29		SW	895
17	68	29		SE	1065
17	68	29	NE	SE	1228
17	68	29		SE	1249
17	68	31		SW	1156
17	68	31	SE	NE	1492
17	68	31		SE	1556
17	68	31	SE	NE	1547
17	68	31	NW	NE	439
17	68	32		NW	1352
17	68	32	SW	SW	1408
17	68	32		NW	1413
17	68	32		SW	1353

LOCATION					ELEVATION
T	R	S	C	C	TOP OF MU
17	68	32	SE	SW	1216
17	68	32	NW	NE	1360
17	68	32	SW	SE	999
17	68	32	NE	SE	887
17	68	32	SW	NW	1533
17	68	33	NW	NW	849
17	70	36	NE	NW	3929
18	67	6	SE	SW	-3620
18	68	18	NW	NW	794
18	68	25	NW	NW	-3336
18	69	4	SW	NE	3739
18	69	14	SW	SW	2340
18	69	18		SE	2824
18	69	36	NW	SE	1139
18	70	26	NW	NW	3266
18	70	35	NW	SE	1601
19	66	4	NW	SE	-3984
19	66	31	SW	SW	-3933
19	67	3	SE	NW	-3488
19	67	11	NW	SE	-3613
19	67	15	NE	SW	-3474
19	67	15	SW	SW	-3462
19	67	36	SE	SW	-3821
19	68	7	NE	SW	3657
19	68	8	NW	NW	4681
19	68	17	SE	SE	
19	68	17	SE	NW	3556
19	68	32	NW	NW	1374
19	69	24	SE	SW	2701
19	69	29	NE	SW	5024
20	67	26	SW	SW	-3474
20	67	34	SE	NW	-3488
21	68	12	SW	NE	2070

REFERENCES
(includes selected works not directly cited herein)

Babcock, H.M., and J.R. Rapp, 1952, Reconnaissance of the Geology and groundwater resources of the Horse Creek-Bear Creek area, Laramie and Goshen Counties, Wyoming: Circular No. 162, U.S. Geological Survey.

Babcock, H.M. and L.J. Bjorklund, 1956, Groundwater geology of parts of Laramie and Albany Counties, Wyoming and Weld County, Colorado: Water Supply Paper 1367, U.S. Geological Survey.

Bjorklund, L.J., 1959, Geology and Groundwater resources of the Upper Lodgepole Creek drainage basin, Wyoming: Water Supply Paper 1483, U.S. Geological Survey.

Bair, E.S., O'Donnel, T. P. and Picking, L. W., 1985, Potentiometric mapping from incomplete drill-stem test data, Palo Duro basin area, Texas and New Mexico: Groundwater, v. 23, pp. 198-211.

Belitz, Kenneth, 1985, Hydrodynamics of the Denver Basin: An explanation of subnormal fluid pressures, Ph.D. Thesis, Stanford University.

Berg, R.R., 1961, Laramide tectonics of the Wind River Mountains, in Symposium on Late Cretaceous rocks: Wyoming Geol. Assoc. 16th Ann. Field Conf. Guidebook, pp. 70-80.

Berg, R.R., Larberg, G. M., and Recker, L. D., 1985, Hydrodynamic flow in the lower Cretaceous Muddy Formation, Northeast Powder River Basin, Wyoming and Montana, IN Thirty-sixth annual field conference -- 1985, Wyoming Geological Association Guidebook.

Brady, R.T., 1949, Geology of the east flank of the Laramie Range in the vicinity of Federal and Hecla, Laramie County, Wyoming, M.S. Thesis, Dept. of Geology, University of Wyoming, Laramie, Wyoming.

Bredehoeft, J.D., 1965, The drill-stem test: The petroleum industry's deep-well pumping test: Groundwater, v. 3, pp. 31-36.

Brown, W.G., 1983, Sequential development of the fold-thrust model of foreland deformation, in Lowell, J.D., ed., Conference on Rocky Mountain foreland basins and uplifts: Rocky Mtn. Assoc. Geol. Guidebook, p. 57-64.

Cant, Douglas J., 1983, Spirit River Formation -- A Stratigraphic-Diagenetic Gas Trap in the Deep Basin of Alberta: The American Association of Petroleum Geologists Bulletin, v. 67, pp. 577-587.

Copeland, John R., 1984, Laramide Structural deformation at the interface between the Laramie Range and the Denver-Julesburg Basin Southeastern Wyoming, M. S. Thesis, Dept. of Geology, University of Wyoming, Laramie, Wyoming.

Dickinson, W.W., and D. L. Guatier, 1983, Diagenesis of nonmarine rocks and gas entrapment in northern Green River basin, Wyoming: AAPG Bulletin, v. 67, p. 450, abstract only.

Dockery, W.L., 1940, Underground water resources of Horse Creek and Bear Creek Valleys, Southeastern Wyoming: Bulletin No. 30, Geological Survey of Wyoming, University of Wyoming, Laramie, Wyoming.

Doremus, D.M., 1986, Groundwater circulation and water quality associated with the Madison aquifer, north-eastern Big Horn basin, Wyoming, M.S. Thesis: University of Wyoming, Laramie, Wyoming.

Eisen, C., K. Feathers, and C. Goodwin, 1980, Reconnaissance study of the water development potential of the lower Paleozoic aquifer, southeastern Wyoming, Water Resources Research Institute, University of Wyoming, Laramie, Wyoming.

Gatlin, C, 1960, Petroleum Engineering and Well Completions: Prentis Hall, Inc., Englewood Cliffs, New Jersey, p. 260-263.

Gray, L.O., 1947, Geology of the east flank of the LAramie Range in the vicinity of Horse Creek, Laramie county, Wyoming, M.S. Thesis, Department of Geology, University of Wyoming, Laramie, Wyoming.

Gies, Robert M., 1984, Case history for a major Alberta Deep Basin gas trap: The Cadomin Formation. IN Case Study of a Deep Basin gas field, John A. MAsters, ed.: American Association of Petroleum Geologists, Tulsa, Oklahoma, pp. 316.

Hoeger, R.L., 1968, Hydrodynamic study of the western Denver Basin, Colorado, in Hollister, J.C. and Weimer, R.S., eds., Geophysical and Geological studies of the relationships between the Denver earthquakes and the Rocky Mountain Arsenal well: Quarterly of the Colorado School of Mines, v. 63, no. 1, pp. 245-251.

Huntoon, P.W., 1985, Fault severed aquifers along the perimeters of Wyoming artesian basins: Groundwater, v. 23, pp. 176-181.

Jarvis, Todd W., 1986, Regional Hydrogeology of the Paleozoic aquifer system, southeastern Bighorn Basin, Wyoming with an impact analysis of Hot Springs State Park: M.S. Thesis, Department of Geology, University of Wyoming, Laramie, Wyoming.

Jenkins, P.T., 1938, The Geology of a Portion of the east side of the Laramie Range, Albany, Laramie and Platte Counties, Wyoming: M.S. Thesis, Dept. of Geology, University of Wyoming, Laramie, Wyoming.

Larberg, G.M. Byrd, 1981, Downward vertical fluid flow in subsurface: Implications at Kitty Field, Powder River Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 85, p. 947, abstract only.

Law, B.E., and W.W. Dickinson, 1985, Conceptual model for origin of abnormally pressured gas accumulations in low-permeability reservoirs: American Association of Petroleum Geologists Bulletin, v. 69, pp. 1295-1304.

Lewis, L.E., 1978, Development of an evaporation map for the state of Wyoming for purposes of estimating evaporation and evapotranspiration: M.S. Thesis, Dept. Civil Engineering, University of Wyoming, Laramie, Wyoming.

Libra, R.D., M. Collentine, and K.R. Feathers, 1981, Occurrence and Characteristics of groundwater in the Denver-Julesburg Basin, Wyoming: Water Resources Research Institute, University of Wyoming, Laramie, Wyoming.

Lin, Joseph T., 1981, Hydrodynamics flow in lower Cretaceous Muddy Sandstone Gas Draw Field, Powder River Basin, Wyoming: The Mountain Geologist, v. 18, pp. 78-87.

Loeffler, R.J., 1939, The stratigraphy of a portion of the east side of the Laramie Range, Laramie County, Wyoming, M.S. Thesis, Dept. of Geology, University of Wyoming, Laramie, Wyoming.

Lowery, M.E., and M.A. Crist, 1967, Geology and groundwater resources of Laramie County, Wyoming, Water-Supply Paper 425-B, U.S. Geological Survey.

McCurdy, H.R., 1941, Pennsylvanian and Permian stratigraphy along the eastern flank of the Laramie Range, southeastern Wyoming, M.S. Thesis, Dept. of Geology, University of Wyoming, Laramie, Wyoming.

Masters, John A., 1979, Deep Basin gas trap, Western Canada: The American Association of Geologists Bulletin, v. 63, pp. 152-181.

Matuszczak, R.A., 1973, Wattenberg Field Denver Basin, Colorado: Mountain Geologist, v. 10, pp. 99-105; AAPG Memoir 24, pp. 134-144.

Miller, W.R., 1976, Water in carbonates of the Madison group in southeastern Montana - A preliminary evaluation: U.S. Geol. Survey Water Supply Paper 2043, pp. 12-29.

Moore, Richard W., 1984, Hydrodynamic control on oil entrapment in channel sandstones of the Dakota Sandstone, South Cole Creek Field, Converse County, Wyoming: The Mountain Geologist, v. 21, pp. 105-113.

Murphy, W.C., 1965, The interpretation and calculation of formation characteristics from formation test data: Halliburton Services, Duncan, Oklahoma, 19 p.

Orr, E.D., and C.W. Kreitler, 1984, Interpretation of underpressuring using pressure-depth profiles, Palo Duro Basin, Texas: AAPG Bulletin, v. 68, p. 514, abstract only.

Richter, Henry R., 1982, Ground water resources in the part of Canyonlands National Park east of the Colorado River and contiguous Bureau of Land Management lands, Utah, M.S. Thesis, Dept. of Geology, University of Wyoming, Laramie, Wyoming.

Silver, Casewell, 1968, Principals of gas occurrence, San Juan Basin, IN Natural Gasses of North America: AAPG Memoir 9, pp. 946-960.

Stone, Donald S., and Roger L. Hoeger, 1973, Importance of hydrodynamic factors in formation of lower Cretaceous combination traps, Big Muddy--South Glenrock area, Wyoming: the AAPG Bulletin, v. 57, pp. 1714-1733.

Theis, C.V., 1935, The Relation between lowering the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, v. 16, pp. 519-524.

U.S. Forest Service, 1981, Cheyenne stage II water diversion proposal: Final Environmental Impact Statement: USDA Forest Service, Medicine Bow National Forest, Laramie, Wyoming.

Van Klaveren, R.W., 1975, Estimating Evapotranspiration in the North Platte Basin of Wyoming, M. S. Thesis, Dept. of Agricultural Engineering, University of Wyoming, Laramie, Wyoming.

Western Water Consultants, Inc., 1982, Ground-water development potential for the Paleozoic aquifer along the flanks of the Laramie Range and Hartville Uplift, Southeast Wyoming, Prepared for the Wyoming Water Development Commission, Cheyenne, By Western Water Consultants, Inc., Laramie, Wyoming.