Hydrogeology of the Armstrong and Nelson Springs, Park County, Montana
by William D Clarke III

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University


Abstract:
Armstrong and Nelson Springs, Park County, Montana, are nationally recognized trout fishing areas. The hydrogeology of the springs, however, has never been formally investigated. The stratigraphic and structural characteristics of the spring area suggest the springs may issue from any one of three aquifers present in the spring area and may be fault, stratigraphically, and/or topographically controlled. A hydrogeologic study was conducted to determine the source aquifer(s) of the springs, the controls on spring formation, and related groundwater flow systems.

Spring discharges and temperatures were periodically measured throughout the field study. The positions of individual springs were identified and mapped. Local domestic-water wells were inventoried, measured, and tested. Previously published geologic maps of the area were field checked and modified as necessary. Finally, groundwater samples were collected from springs and water wells for field and laboratory analysis.

Three aquifers are present in the study area: the Cenozoic Yellowstone and alluvial fan aquifers, and the Mississippian Madison Group aquifer. The three aquifers discharge chemically distinct water. Armstrong and Nelson Springs are made up of individual spring areas which peak in discharge at different times of the year and are positioned at different elevations with respect to the Yellowstone River. Some spring temperatures are seasonally dependent and some are seasonally independent. Each sampled Armstrong and Nelson Spring discharges chemically similar water which is equivalent to the chemical quality of the Yellowstone aquifer.

The Yellowstone aquifer is interpreted to be the source aquifer of Armstrong and Nelson Springs. The Yellowstone aquifer is a wedge-shaped alluvial body which thins from approximately 820 m in thickness south of the study area to 15.5 m in thickness immediately north of the study area. Chemical characteristics, groundwater flow patterns, and groundwater temperature patterns indicate the alluvial fan aquifer and the Madison Group aquifer are not source aquifers for the springs. Armstrong and Nelson Springs are topographically controlled and form in response to the thinning of the Yellowstone aquifer. Groundwater is forced to the surface to form the springs. Spring discharges, temperatures, and positions indicate both local and regional groundwater flow systems discharge in the area.

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**APPROVAL**

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William D. Clarke III

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Chairperson, Graduate Committee

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Date August 16, 1991

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## ABSTRACT

Armstrong and Nelson Springs, Park County, Montana, are nationally recognized trout fishing areas. The hydrogeology of the springs, however, has never been formally investigated. The stratigraphic and structural characteristics of the spring area suggest the springs may issue from any one of three aquifers present in the spring area and may be fault, stratigraphically, and/or topographically controlled. A hydrogeologic study was conducted to determine the source aquifer(s) of the springs, the controls on spring formation, and related groundwater flow systems.

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Three aquifers are present in the study area: the Cenozoic Yellowstone and alluvial fan aquifers, and the Mississippian Madison Group aquifer. The three aquifers discharge chemically distinct water. Armstrong and Nelson Springs are made up of individual spring areas which peak in discharge at different times of the year and are positioned at different elevations with respect to the Yellowstone River. Some spring temperatures are seasonally dependent and some are seasonally independent. Each sampled Armstrong and Nelson Spring discharges chemically similar water which is equivalent to the chemical quality of the Yellowstone aquifer.

The Yellowstone aquifer is interpreted to be the source aquifer of Armstrong and Nelson Springs. The Yellowstone aquifer is a wedge-shaped alluvial body which thins from approximately 820 m in thickness south of the study area to 15.5 m in thickness immediately north of the study area. Chemical characteristics, groundwater flow patterns, and groundwater temperature patterns indicate the alluvial fan aquifer and the Madison Group aquifer are not source aquifers for the springs. Armstrong and Nelson Springs are topographically controlled and form in response to the thinning of the Yellowstone aquifer. Groundwater is forced to the surface to form the springs. Spring discharges, temperatures, and positions indicate both local and regional groundwater flow systems discharge in the area.

# INTRODUCTION

Armstrong and Nelson Springs in Park County, Montana (Figure 1), are nationally recognized for their prime trout habitats, spawning areas, and superb fishing challenges (Decker-Hess, 1986). The springs represent a natural resource which may become threatened by the increased residential expansion in the spring creek area. Paradise Valley is a richly scenic area of southwestern Montana and as such the valley is an attractive location for people to live. According to water-well-drilling records obtained from the Montana Department of Natural Resources and Conservation, Montana Bureau of Mines and Geology, and the Park County Courthouse, the number of domestic groundwater wells in the study area has increased from 22 in 1970 to 115 in 1987, a 523 % increase (Figure 1). There is concern that increased groundwater withdrawal may affect the springs. Additionally, with the increase of residential expansion into the area is an increase in associated septic system effluent which could potentially degrade the quality of groundwater discharged from Armstrong and Nelson Springs. Despite the obvious importance of the springs as a natural groundwater and surface water resource and concern regarding continued groundwater development of the area, no detailed hydrogeologic investigation of the origin of the springs has been conducted.

Armstrong and Nelson Springs issue from Cenozoic valley-fill deposits which overlie Paleozoic and Mesozoic rocks including faulted Mississippian Madison Group limestone. Cenozoic valley fill, including both Tertiary and Quaternary deposits, and the Paleozoic Madison Group represent major aquifers throughout much of Montana (Hackett and others, 1960; Groff, 1962a, 1962b, 1965; McMurtrey, Konizeski, and Brietkrietz, 1965; Zimmerman, 1966, 1967; Feltis, 1973, 1977; Sondregger and others, 1982; Wilke, 1983; Donovan, 1985; Downey, 1986; Levings, 1986). The valley-fill and Madison Group aquifers are also often associated with spring development.

The Madison Group often forms springs or discharges water to overlaying alluvium, especially where the Madison Group is significantly fractured and faulted (Feltis, 1973; Huntoon 1976a, 1976b, 1985a, 1985b, 1985c; Krothe and Bergeron, 1981; Wilke, 1983; Wyatt, 1984). Faults and fractures in the Madison Group as well as in other limestone aquifers provide a zone of higher permeability as compared to the primary permeability in the aquifer and so, often serve as a preferrential path of groundwater migration (Huntoon, 1976a, 1981, 1985c; Wilke, 1983; Huntoon and Coogan, 1987). With time, groundwater flow through the trace of faults and fractures may increase as the limestone wall rock dissolves to form well developed solution channels which can eventually carry a large volume of groundwater flow and therefore support a large spring network (Huntoon 1976a, 1981, 1985c; Wilke, 1983; Huntoon and Coogan, 1987). Armstrong and Nelson Springs originate in the immediate vicinity of

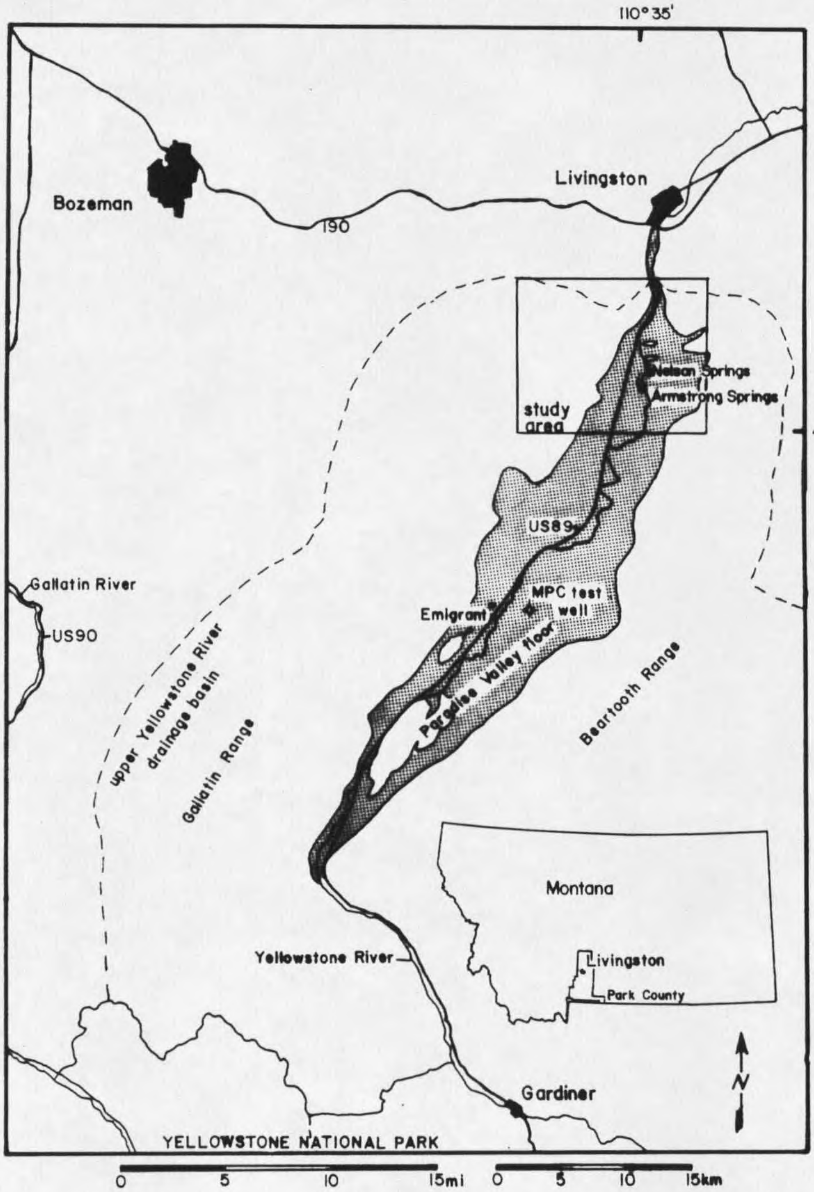


Figure 1. Paradise Valley and the study area. Dotted line denotes the regional Yellowstone River drainage basin. Stippled pattern denotes the distribution of Cenozoic alluvium within the valley floor.

faulted Madison Group rocks which suggests a possible hydrologic connection between Armstrong and Nelson Springs and the Madison Group. In other studies in Montana and Wyoming, leakage to springs and overlaying formations from the Madison Group at depth has been identified based upon groundwater chemical compositions, anomalous groundwater temperature patterns, groundwater gradient patterns, and inference based upon geographic, stratigraphic, and structural relationships between springs and the Madison Group (Feltis, 1973; Huntoon, 1976a, 1976b, 1976c, 1985a, 1985b; Downey, 1986; Sondregger and others, 1982; Wilke, 1983; Wyatt, 1984; Huntoon and Coogan, 1987).

Alternatively, the springs may not be related to the Madison Group. The springs may be stratigraphically controlled, formed at a zone of lesser hydraulic conductivity within the Cenozoic valley fill. Faults which cut the Cenozoic valley fill may influence development of the springs. Also, the springs may simply issue from topographic depressions in the Cenozoic valley fill or where the valley fill is thin due to local subsurface bedrock patterns. Cenozoic valley fill has been determined to yield significant volumes of groundwater to wells and springs. Cenozoic valley-fill groundwater has been identified by the location of wells and springs with respect to geographic, stratigraphic and structural relationships, chemical composition of groundwater, groundwater temperatures, and groundwater gradients (Hackett and others, 1960; Groff, 1962a, 1962b; McMurtrey, Konizeski, and Brietkrietz, 1965; Feltis, 1973; Sondregger and others, 1982; Wilke, 1983; Donovan, 1985; Levings, 1986).

## Purpose

A study was undertaken to determine the hydrogeology of Armstrong and Nelson Springs using conventional methods. More specifically, the study addresses the following questions:

(1) Are the springs controlled structurally, stratigraphically, or topographically or do they reflect some combination of these controls?

(2) Which aquifer(s) is (are) the probable source aquifer(s) for Armstrong and Nelson Springs?

(3) Do the springs originate from a single or multiple groundwater flow system?

## General Setting

The study area is approximately 16 km south of Livingston, Montana, near the northern terminus of the Paradise Valley (Yellowstone Valley) (Figures 1 and 2). Springs occur on both sides of the Yellowstone River, which flows north through the valley. The study area lies within Townships 3 and 4 South and Ranges 9 and 10 East, and includes all springs known to discharge to the spring creeks (Figure 2). Field investigations were confined to the valley floor.

The Beartooth and Gallatin mountain ranges respectively form the eastern and western margins of the study area. A narrow canyon at the northern terminus of Paradise Valley forms the northern boundary. The

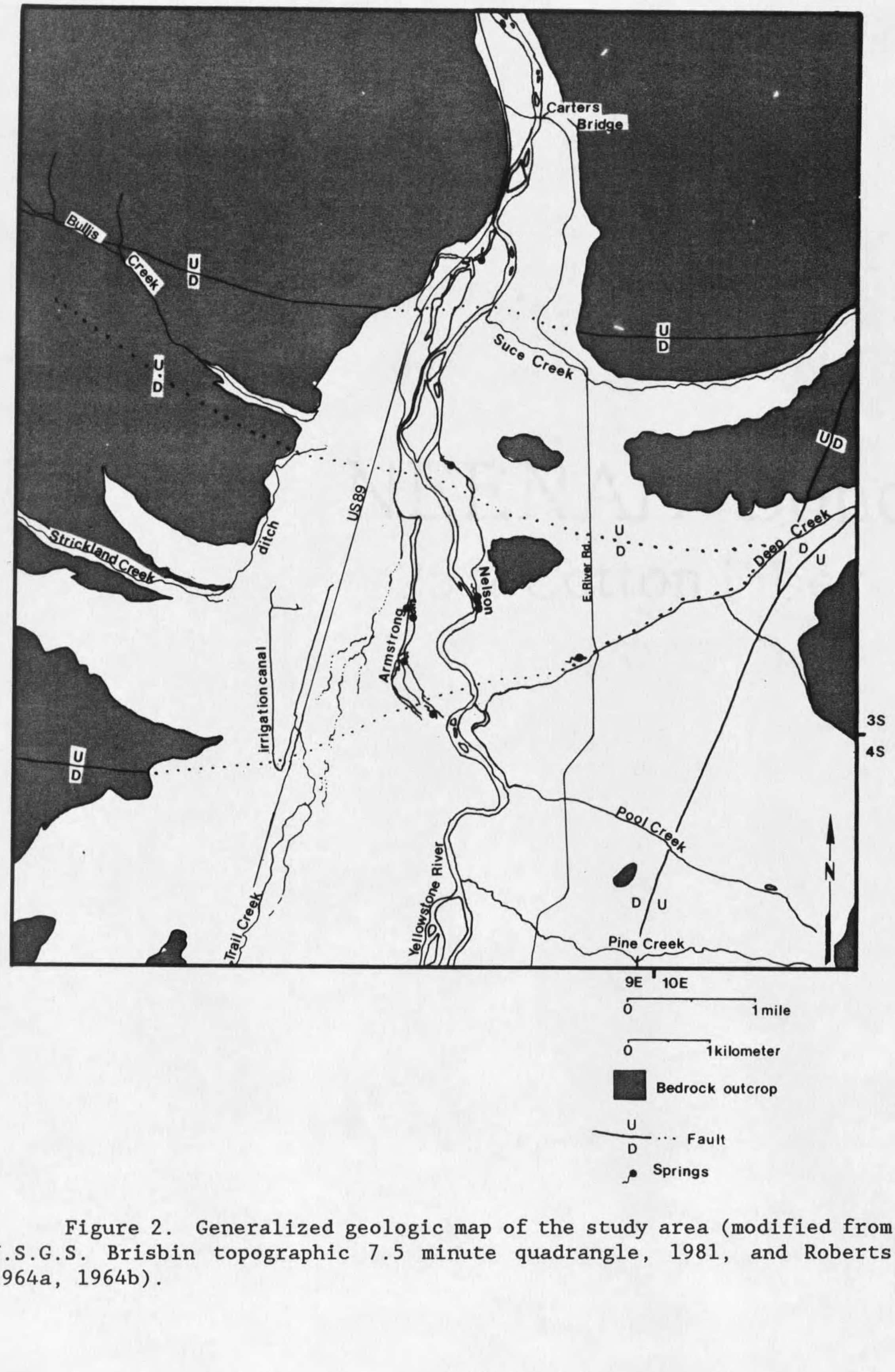


Figure 2. Generalized geologic map of the study area (modified from U.S.G.S. Brisbin topographic 7.5 minute quadrangle, 1981, and Roberts 1964a, 1964b).

southern boundary was arbitrarily drawn upstream of the spring creeks at the approximate position of Pine Creek (Figure 2).

Paradise Valley is a wide, linear fault-block basin which trends northeast for approximately 55 km (Figure 1) (Bonini and others, 1972). The valley is terminated at the north and south ends by narrow canyons cut through bedrock by the Yellowstone River. The valley varies from 0.5 to 10 km in width. Within the study area, the valley ranges from 0.5 to 8 km in width. Topography within the valley floor dips gently to the north dropping from an elevation of 1,520 m above sea level at the southern terminus to 1,390 m above sea level near the northern terminus. The local relief between the bordering mountain ranges and valley floor is approximately 1,500 m. Seven peaks within the Beartooth and Gallatin Ranges border the valley and exceed 2,900 m above sea level.

Mean monthly temperatures for the Paradise Valley area range from a maximum of 13.5°C to a minimum of 1.6°C. The mean annual temperature is 7°C (Ruffner, 1985). The valley floor receives between 36 and 51 cm of precipitation (rain and snow) annually (United States Department of Agriculture, 1971). The surrounding peaks receive between 102 and 127 cm of annual precipitation (United States Department of Agriculture, 1971).

## Drainage Systems

The Yellowstone River is the master stream for the region (Figure 1). The river receives water from the many perennial streams which drain the Gallatin and Beartooth highlands and the Yellowstone Plateau. The average discharge for the Yellowstone River based on a 60 year record measured near Livingston is 107 $m^3/s$ (United States Department of the

Interior, 1985). Over this period the river discharge ranged between 1,030 and 17 $m^3/s$ (United States Department of the Interior, 1985). Between October 1986 and February 1988 the Yellowstone River flow varied between 156 and 28 $m^3/s$ (M. White, United States Geological Survey, written communication, 1988).

Four streams in the study area flow from the east and are confluent with the Yellowstone River (Figure 2). In contrast, the flow from only one of three stream channels on the west side of the valley in the study area continues to the Yellowstone River (Figure 2). Strickland and Bullis Creeks lose their entire flow to the alluvial groundwater system prior to reaching the Yellowstone River. Strickland Creek is partially diverted for irrigation purposes, but the lack of any abandoned stream channels on aerial photos or topographic maps indicates the stream has not reached the Yellowstone River in post-glacial time. Trail Creek is the only creek which flows from the west that discharges into the Yellowstone River. Trail Creek is diverted twice for irrigation. Below the second diversion, flow is ephemeral, but the channel is clearly defined on aerial photographs and the topographic map of the area. Thus, flow in the western tributaries is commonly lost to the groundwater system before reaching the Yellowstone River, whereas the eastern tributaries flow directly into the river.

## Stratigraphic Setting

The rocks are the framework in which groundwater occurs and moves. In the study area, Precambrian through Tertiary-age bedrock is exposed

(Roberts, 1964a, 1964b) (Table 1, Plate 1). The Paleozoic section is composed primarily of carbonate rocks with some fine grained clastic units (Table 1). The Mesozoic section consists of fine to coarse grained clastic rocks (Table 1). Tertiary volcanic rocks are exposed in outcrop in the southwestern portion of the study area, but no Tertiary-age basin-fill deposits have been formally recognized in outcrop or in the subsurface in the study area (Roberts, 1964a, 1964b). Only a thin veneer (approximately 16 m in thickness) of Quaternary deposits and possibly some Tertiary deposits are present in the central portion of the study area (Bonini and others, 1972).

This thesis focuses on large-discharge springs; therefore, aquifers which characteristically are capable of producing such springs must be identified. Due to the dearth of hydrogeologic information pertaining to the area, the general hydrogeologic properties of the stratigraphic units in the area are inferred from other studies in the region (Table 1). This data will be supplemented later in the thesis with data from the field study. In general, rocks in the study area older than the Madison Group have not been recognized to yield large quantities of groundwater or produce large springs (Groff 1962a, 1962b, 1965; Roberts 1964a, 1964b, 1966; Zimmerman 1967; Konizeski, Brietkrietz, and McMurtrey, 1968; Swenson, 1968; Feltis, 1977; Head and Merkel 1977; Taylor 1978; Miller 1979; Downey 1982, 1986).

Table 1. Generalized stratigraphic section and water-bearing properties of rocks found in the study area. (After Groff, 1962a, 1962b, 1965; Roberts, 1964a, 1964b, 1966; Zimmerman, 1966, 1967; Konizeski, Brietkrietz, and McMurtrey, 1968; Swenson, 1968; Feltis, 1977; Head and Merkel, 1977; Taylor, 1978; Miller, 1979; Downey, 1982, 1986; Wyatt, 1984).

| Series | Formation | Maximum Thickness (m) | General Character | Water-Bearing Properties |
|---|---|---|---|---|
| | Recent Alluvium | 16+ | Modern stream and river deposits of silt, sand, and gravel. | Principal aquifer. Can yield adequate water for small to large irrigation wells. |
| Quaternary | Alluvium and Colluvium | 42+ | Unconsolidated alluvial fan and slope wash deposits of silt, sand, and gravel. | Yields enough to meet domestic and stock needs. |
| | Glacial Outwash | 22+ | Unconsolidated sands and gravels. | Yields appreciable domestic supplies. |
| | Till and Pediment Veneer | ? | Unconsolidated and semiconsolidated clay, silt, sand, and gravel. | Too thin and/or localized to be a significant aquifer. Possible small local yield. |
| ---UNCONFORMITY--- | | | | |
| Tertiary | Volcanic | 1220 | Andesite and basalt flows, breccias, tuffs, conglomerates, sandstones. | May yield small to moderate water quantities where extensively fractured. |
| ------------- | | | | |
| Upper Cretaceous | Cody Shale and Frontier Formations | 159 | Dark shale with some arkosic sands. | Not an aquifer. |
| ------------- | | | | |
| Lower Cretaceous | Mowry and Thermopolis Shale | 354 | Dark gray shale and sandstones. | Yield some water to local wells. |

Table 1. Generalized stratigraphic section and water-bearing properties of rocks found in the study area-Continued.

| Series | Formation | Maximum Thickness (m) | General Character | Water-Bearing Properties |
|---|---|---|---|---|
| Lower Cretaceous | Kootenai Formation | 85 | Sandstone, mudstone, fossil bearing limestone. | Probably not an important aquifer here due to limited presence. Yields water to some minor springs. |
| ---UNCONFORMITY--- | | | | |
| | Morrison Formation | 137 | Varicolored shale, siltstone, mudstone, and limestone. | Yields water to some small springs. Not generally an aquifer. |
| Upper Jurassic | Swift Formation | 31 | Calcareous glauconitic oyster bearing sandstone. | May yield small amounts of water. Not an important aquifer. |
| | Rierdon Formation | 29 | Olive gray shale to bluish limestone. | Generally not an aquifer. |
| | Piper Formation | 104 | Olive gray shale to argillaceous limestone. | Generally not an aquifer. |
| ---UNCONFORMITY--- | | | | |
| Pennsylvanian | Quadrant Formation | 88 | Quartzite to well sorted sandstone and dolomite. | Yields water to some small springs. Not an important water source. |
| ------------- | Amsden Formation | 46 | Dolomite, calcareous sandstone, siltstone, and limestone. | Yields some water to local wells. Poor quality water here. |
| ---UNCONFORMITY--- | | | | |

Table 1. Generalized stratigraphic section and water-bearing properties of rocks found in the study area-Continued.

| Series | Formation | Maximum Thickness (m) | General Character | Water-Bearing Properties |
|---|---|---|---|---|
| Upper Mississippian | Mission Canyon Limestone | 61 | Massive gray limestone and dolomite. | Yields 1.3 x $10^{-3}m^3/s$ to a well in the area. Generally considered to have appreciable aquifer potential. |
| Lower Mississippian | Lodgepole Limestone | 146 | Well bedded chert bearing limestone and dolomite. | |
| | Three Forks Shale | 15 | Dark fossiliferous shale with basal chert. | Not an aquifer. |
| Upper Devonian | Jefferson Dolomite | 107 | Massive gray limestone and dolomite. | Possibly yields small quantities to local wells. |
| ---UNCONFORMITY--- | | | | |
| Ordovician | Bighorn Dolomite | 27 | Massive mottled gray and yellow dolomite. | Not an important water source. |
| Upper Cambrian | Grove Creek and Snowy Range Formations | 70 | Limestone and shale with limestone pebbles. | Not an important water source. |
| | Pilgrim Limestone | 40 | Massive magnesian and dolomitic limestone with flat pebble conglomerates. | May yield small amounts of water if fractured. |
| Middle Cambrian | Park Shale | 67 | Multicolored shale and argillaceous limestone, siltstone, and mudstone. | Not water bearing. |

Table 1. Generalized stratigraphic section and water-bearing properties of rocks found in the study area-Continued.

| Series | Formation | Maximum Thickness (m) | General Character | Water-Bearing Properties |
|---|---|---|---|---|
| | Meagher Limestone | 40 | Thin bedded medium gray limestone and yellow gray dolomite. | Not an important aquifer. |
| Middle Cambrian | Wolsey Shale | 85 | Green gray calcareous shale and mudstone. | Not water bearing. |
| | Flathead Formation | 30 | Gray to red quartz sandstone and quartzite. | Yields small water amounts from fractures. |
| ---UNCONFORMITY--- | | | | |
| Archaen | Undiff. | | Gneiss, schist and granite. Pegmatite dikes locally. | Yields small amounts of water if fractured. |

Mississippian Madison Group Aquifer

The Madison Group is considered to be an important aquifer throughout much of Montana, Wyoming, North Dakota, and South Dakota (Groff, 1966; Swenson, 1968; Anderson and Kelley, 1976; Huntoon, 1976a, 1976b, 1985a, 1985b; Head and Merkel, 1977; Krothe and Bergeron, 1981; Downey, 1982, 1986; Wyatt, 1984). The Madison Group is composed of the Mission Canyon and Lodgepole Formations in southwestern Montana (Table 1) (Roberts, 1966). The Mission Canyon Formation conformably overlies the Lodgepole Formation (Roberts, 1966). In the study area, the Mission Canyon Formation is composed of massive, very fine to medium crystalline limestone, dolomitic limestone, calcitic dolomite, and dolomite with interbedded solution breccias of dolomite and kaolinite clay (Roberts, 1966). Near the top, the Mission Canyon Formation contains discontinuous karst deposits infilled with red illite clay (Roberts, 1966). The Lodgepole Formation consists of massive to thinly bedded, fine to coarsely crystalline limestone, dolomitic limestone, calcitic dolomite, and dolomite (Roberts, 1966).

The Madison Group aquifer is defined as the Mission Canyon and Lodgepole Formations in the study area. However, from a groundwater standpoint, the Mission Canyon Formation is much more important than the Lodgepole Formation because the Mission Canyon Formation contains a greater percentage of thick-bedded limestones, dolomites, collapse breccias, dissolution features, and less insoluble residues than does the underlying Lodgepole Formation (Roberts 1966, Aram 1979). The fact that the Mission Canyon Formation is the principal component is attested to in the Lewis and Clark Caverns of southwestern Montana. The extensive cavern network is concentrated at the base of the Mission Canyon Formation due to the stoppage of downward groundwater flow by the underlaying relatively insoluble Lodgepole Formation (Aram, 1979).

The Madison Group aquifer yields water to wells throughout Montana at rates which range from 1.2 $m^3/s \times 10^{-3}$ to 5.6 $\times 10^{-1}$ $m^3/s$ (Taylor, 1978). In the Madison Group aquifer primary porosity and permeability is of lesser importance than secondary porosity and permeability (Huntoon, 1976, 1985a, 1985b; Miller, 1976; Head and Merkel, 1977; Budai and others, 1987). Limited primary porosity and permeability is present in the Madison Group as relict depositional intercrystalline porosity. Secondary porosity and permeability in the Madison Group results from dolomitization, tectonic fracturing, and dissolution by migrating meteoric waters. Secondary dolomitization of calcitic limestone to dolomitic limestone increases porosity and permeability (Blatt and others, 1972). Accordingly, permeabilities are greater in the dolomites than in the limestones of the Madison Group (Budai and others, 1987). Fractures within the dolomites are more open than in the limestone beds due to smaller amounts of carbonate cement in the dolomites (Budai and others, 1987).

Karst, solution breccias, and tectonic fractures are also significant to groundwater migration in the Madison Group (Sando, 1974; Aram, 1979; Huntoon, 1985a, 1985b, 1985c, 1987). Tectonic fractures in particular are important groundwater pathways. Dissolution of the carbonate aquifer promotes karst and solution breccia formation near these fractures (Sando, 1974; Aram, 1979). Roberts (1966) noted solution collapse breccias and discontinuous karst deposits within Madison Group outcrops of the study area. These features are pervasive in uplifted Mission Canyon rocks throughout Montana and Wyoming (Keefer, 1963; Sando, 1974; Aram, 1979; Huntoon, 1985a, 1985b). Paleozoic units younger than the Madison Group and Mesozoic rocks which are present in the study area generally produce only small groundwater yields in the region (Table 1) (Groff, 1962a, 1962b, 1965; Zimmerman, 1966, 1967; Konizeski, Brietkrietz and McMurtrey, 1968; Feltis, 1977; Miller, 1979; Wyatt, 1984; Downey, 1986). In some parts of southwestern Montana, however, Tertiary and Quaternary deposits do produce springs or large well discharges (Hackett and others, 1960; Groff, 1962a; McMurtrey, Konizeski, and Brietkrietz, 1965; Sondregger and others, 1982; Wyatt, 1984; Levings, 1986).

In order to provide a better interpretation of the source of the springs, the Cenozoic valley fill is separated into the alluvial fan aquifer and the Yellowstone aquifer (glacial outwash and recent alluvium) (Plate 1). These stratigraphic divisions are similar to Roberts' (1964a, 1964b) divisions. The glacial outwash and recent alluvium of Roberts (1964a, 1964b) have been grouped as the Yellowstone aquifer to reflect interpretation as a single hydrostratigraphic unit.

Alluvial Fan Aquifer

In the study area alluvial fans coalesce and descend to the Yellowstone River which truncates the toe of the fans to form bluffs. The alluvial fans consist of mixed silt, sand, pebble, cobble, and boulder size gravels which were probably deposited by fluvial and glacio-fluvial activity (Roberts, 1964a). Studies which have been conducted in the study area by other researchers have not identified the presence of

Tertiary-age deposits (Roberts, 1964a, 1964b; Bonini and others, 1972; and Personius, 1982). For the purpose of this study, the alluvial fan aquifer is considered to include all alluvial materials between the Beartooth mountain front and the Yellowstone aquifer below material mapped as alluvial fans.

The maximum thickness of the alluvial fan deposits is unknown, but well reports indicate the maximum thickness of the deposits exceeds 42 m. In the adjacent Gallatin Valley, the Bozeman alluvial fan, which is underlain by both Tertiary and Quaternary deposits, may yield small to moderate quantities of groundwater to wells according to the degree of sorting and the amount of silt and clay present (Hackett and others, 1960). In general, stringers and lenses of gravel and sand are the source of most of the groundwater within the Bozeman fan (Hackett and others, 1960). Transmissivities of the Tertiary Bozeman fan deposits range from $4 \times 10^{-7}$ $m^2/s$ to $3.8 \times 10^{-4}$ $m^2/s$. Transmissivities of the Quaternary Bozeman fan deposits range from $6.4 \times 10^{-4}$ $m^2/s$ to $9.3 \times 10^{-3}$ $m^2/s$.

Yellowstone Aquifer

Glacial outwash deposits (Pinedale) and Recent Yellowstone alluvium compose what is referred to as the Yellowstone aquifer (Plate 1). This aquifer may directly overlie Paleozoic bedrock if Tertiary basin-fill is absent in the study area. The aquifer is composed of semiconsolidated to unconsolidated interbedded clay, silt, sand, and gravel (Roberts, 1964a). The maximum thickness of the aquifer is unknown; however, Montana Power Company (MPC) RP624-Hobbs test well drilled approximately 12 km south of the study area encountered 243 m of alluvium (Montagne and Locke, 1989). The alluvium at the MPC test well site includes Pleistocene glacial outwash deposits, Holocene fluvial deposits, and possibly extensive pre-last-glacial (pre-Pinedale) gravel deposits (Pierce, 1979; Montagne and Chadwick, 1982; Locke, 1986; Montagne and Locke, 1989). The maximum thickness of the Pinedale glacial outwash deposits may be as much as 45 m, 9 km south of the study area based upon relationships between the height of the head of the glacial outwash above the current level of the Yellowstone River (Locke, 1986). The Pinedale glacial outwash deposits and Recent fluvial deposits are also present in the study area (Roberts, 1964a; Montagne and Chadwick, 1982; Locke, 1986; Montagne and Locke, 1989). The Yellowstone aquifer alluvium exceeds 22 m in thickness near the southern limit of the study area as indicated by domestic water well reports and is no more than 15.5 m thick at the northern terminus of Paradise Valley (Kirby, 1940). The presence of pre-last-glacial alluvium in the study area is unknown, but if present, it too must be greatly thinner than at the MPC test well site.

Yellowstone River alluvium is an important aquifer north of the study area near Livingston (Groff, 1962a). The thickness of the alluvium there is reported by Groff (1962a, Table 1) to be 16 m. The deposits are thickest adjacent to the Yellowstone River and thin laterally away from the river (Groff, 1962a). Groundwater is pumped from the recent alluvium for municipal, domestic, and industrial purposes. Reported well yields range from $1.2 \times 10^{-3} m^3/s$ to $57 \times 10^{-3}\ m^3/s$ (Groff, 1962a).

In the adjacent Gallatin Valley, Quaternary stream channel deposits yield copious amounts of groundwater to wells (Hackett and others, 1960). The Gallatin River channel deposits consist of cobbles and gravels with intermixed sand, clay, and silt. The deposits are generally thickest toward the center of the Gallatin Valley. Hackett and others (1960) calculated a transmissivity of $2.4 \times 10^{-3}$ $m^2/s$ for Tertiary-age stream channel alluvium in the Gallatin Valley. Transmissivities of the Quaternary stream channel alluvium in the Gallatin Valley range from $7.2 \times 10^{-3}$ $m^2/s$ to $9.6 \times 10^{-2}$ $m^2/s$.

## Structural Setting

Geologic structures often influence groundwater movement, occurrence, and spring development. Geologic structures have been recognized as particularly important in the Madison Group (Kiersch and Hughes, 1952; Maxey, 1968; Williams, 1970; Feltis, 1973; Huntoon, 1975, 1976a, 1976b, 1981, 1985a, 1985b, 1987; Miller, 1976; Stringfield and others, 1979; Trudeau and others, 1983; Mayo and others, 1985; Downey, 1986; Huntoon and Coogan, 1987). Both thrust faults and extensional faults are known to control spring development through: (1) juxtaposition of rock units with contrasting hydraulic conductivities so as to create a barrier to flow, (2) development of a semi-impervious zone or gouge layer along the fault zone which retards groundwater flow across the fault, and (3) development of fault breccias which increase the vertical/horizontal hydraulic conductivity ratio and which may induce greater vertical flow (Williams, 1970; Huntoon, 1981, 1985a, 1985b; Trudeau and others, 1983; Mayo and others, 1985). The presence of faults in the immediate vicinity of Armstrong and Nelson Springs suggests the structures may control groundwater migration. Therefore, an understanding of the local structures is critical to interpretations with respect to spring formation.