Geologic controls on spring discharge in the Miller Creek basin, New World Mining District, Montana
by Alexander Daniel Durst

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

Abstract:
Miller Creek flows from an alpine drainage basin which contains near surface sulfide rich bedrock ore bodies. There has been concern regarding the potential impact of mining on spring discharge because the surface water in the upper Miller Creek basin forms a tributary which contributes water to Soda Butte Creek which flows into Yellowstone National Park.

Field mapping, spring water measurement, and data previously collected by other researchers allowed determination of whether springs derive water from the bedrock aquifer (fractured and faulted Precambrian crystalline rocks, Paleozoic sedimentary rocks, and Tertiary igneous rocks) or the surficial-deposit aquifer (rock glaciers, glacial deposits and colluvial deposits). Springs interpreted to derive water from the bedrock aquifer are located near faults, fracture traces, lithologic contacts, lineaments and mineralized veins and have high and variable specific electrical conductivity (SC) values. Surficial-deposit springs are located near the downhill contacts between surficial deposits and underlying bedrock outcrops and have low and more constant SC values. SC data collected by other researchers from wells corroborates the division of springs.

Discharge volumes collected with portable measuring devices allowed calculation of the contribution of the spring groups. The group of springs interpreted to derive water from the bedrock aquifer discharged more than half of the measured and estimated spring discharge during mid July, 1997. During the remainder of the field season (August through October) the group of springs interpreted to be bedrock persisted with cumulative discharges between 40-50% of the basin's total measured and estimated discharge. The cumulative discharge of the bedrock springs during mid-July is 6 times greater than the cumulative discharge of the bedrock springs in early October. If a mine were to intersect bedrock groundwater, volumetric impacts are expected to be larger in the early summer than in the fall.

GEOLOGIC CONTROLS ON SPRING DISCHARGE IN THE MILLER CREEK BASIN, NEW WORLD MINING DISTRICT, MONTANA

by

Alexander Daniel Durst

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

May, 1999

APPROVAL
of a thesis submitted by
Alexander Daniel Durst

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.

Dr. Stephan G. Custer — Stephan G. Custer — 14 May 1999
Chairperson, Graduate Committee — Date

Approved for the Department of Earth Sciences

Dr. Andrew W. Marcus — Andrew Marcus — 17 May, 1999
Department Head — Date

Approved for the College of Graduate Studies

Dr. Bruce R. McLeod — Bruce R. McLeod — 5-24-99
Dean of the Graduate College — Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University-Bozeman, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature [signature]

Date May 17, 1999

ACKNOWLEDGEMENTS

This work would not have been possible without the help of the following people. Committee members, Stephan G. Custer, William W. Locke III, and David W. Mogk provided guidance. Jeannie M. Heltzel, Paola Feher, Stewart Dixon, and Susan Kelly gave needed assistance in the field. Joe Gurrieri at the Montana State Department of Lands gave advice and provided helpful documents. Terry Kellog of the Greater Yellowstone Coalition provided helpful documents. Daniel R. Stanley of Crown Butte Mines provided a flume and gave a tour of the Miller Creek basin. Dan McLaughlin of Crown Butte Mines, provide helpful information and permitted me to conduct research on the company's owned and leased lands in the Miller Creek basin. Mark Story, Sherm Sollid, Ron Johnson, John Logan, and Greg Kujawa of the United States Forest Service provided advice, permitted the project and waived the permit fee. Larry Dolan from the Montana State Department of Natural Resources and Conservation sent Cooke City area hydrologic data. Amy Beddell at the Wyoming Water Resources Center provided weather data from the Fisher Creek SNOTEL site. Melvin K. White from the United States Geological Survey (USGS) provided Miller Creek and Fisher Creek discharge data. Bob Anderson of Hydrometrics provided groundwater data and spring data collected during a baseline study for the New World Mining Project. Bryan Allen of URS Operating Services provided data collected during remediation efforts in the Daisy Creek area. Robert J. Carson of Whitman College lent his expertise in the field during the 1997 summer field season. Andrea Wright at Montana State University's Geographic Information and Analysis Center digitized data and provided helpful advice and information. Susanne Durst, Douglas D. Durst, and Helena R. Durst helped enter and check data. Kathryn Mauz provided much needed and useful proofreading advice. I would like to thank each and every one of these people for making this project possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABSTRACT

Miller Creek flows from an alpine drainage basin which contains near surface sulfide rich bedrock ore bodies. There has been concern regarding the potential impact of mining on spring discharge because the surface water in the upper Miller Creek basin forms a tributary which contributes water to Soda Butte Creek which flows into Yellowstone National Park.

Field mapping, spring water measurement, and data previously collected by other researchers allowed determination of whether springs derive water from the bedrock aquifer (fractured and faulted Precambrian crystalline rocks, Paleozoic sedimentary rocks, and Tertiary igneous rocks) or the surficial-deposit aquifer (rock glaciers, glacial deposits and colluvial deposits). Springs interpreted to derive water from the bedrock aquifer are located near faults, fracture traces, lithologic contacts, lineaments and mineralized veins and have high and variable specific electrical conductivity (SC) values. Surficial-deposit springs are located near the downhill contacts between surficial deposits and underlying bedrock outcrops and have low and more constant SC values. SC data collected by other researchers from wells corroborates the division of springs.

Discharge volumes collected with portable measuring devices allowed calculation of the contribution of the spring groups. The group of springs interpreted to derive water from the bedrock aquifer discharged more than half of the measured and estimated spring discharge during mid July, 1997. During the remainder of the field season (August through October) the group of springs interpreted to be bedrock persisted with cumulative discharges between 40-50% of the basin's total measured and estimated discharge. The cumulative discharge of the bedrock springs during mid-July is 6 times greater than the cumulative discharge of the bedrock springs in early October. If a mine were to intersect bedrock groundwater, volumetric impacts are expected to be larger in the early summer than in the fall.

INTRODUCTION

The objective of this study was to determine whether spring discharge in the upper Miller Creek basin (Fig. 1 and Plate 1) derives a greater quantity of water from the bedrock aquifer or the surficial-deposit aquifer. Determining the origin of spring discharge has implications regarding the potential affect of mining near-surface bedrock ore bodies in the upper Miller Creek basin. If the springs in the upper Miller Creek basin derive a greater quantity of water from the bedrock aquifer then mining near-surface bedrock ore bodies in the upper Miller Creek basin would be more likely to disrupt spring discharge and possibly other forms of groundwater discharge, such as seeps or baseflow. On the other hand, if springs derive a greater quantity of water from the surficial-deposit aquifer, then mining near surface bedrock ore bodies would be less likely to disrupt spring discharge and other forms of groundwater discharge.

Whether mining the Miller Creek ore bodies would disrupt groundwater discharge to Miller Creek has been the subject of much controversy and could continue to be so in the future. The most recent proposal to mine the ore bodies (Crown Butte Mines (CBM), 1992) caused enough concern about environmental impact to prevent the inception of full scale mining operations. The U.S. government bought the land above and near the ore bodies and the Secretary of the Interior placed a 20 year mineral withdrawal in the area in August of 1997. The mineral withdrawal must be reviewed and re-approved every 20 years by the Secretary of the Interior. If the mineral withdrawal is not re-approved, another plan to mine these ore bodies could be proposed and the controversies and concerns surrounding the mining of these ore bodies could begin anew.

A principal concern regarding the underground mining of the ore bodies was whether or not underground mining could disrupt the quantity and/or quality of surface water in the upper

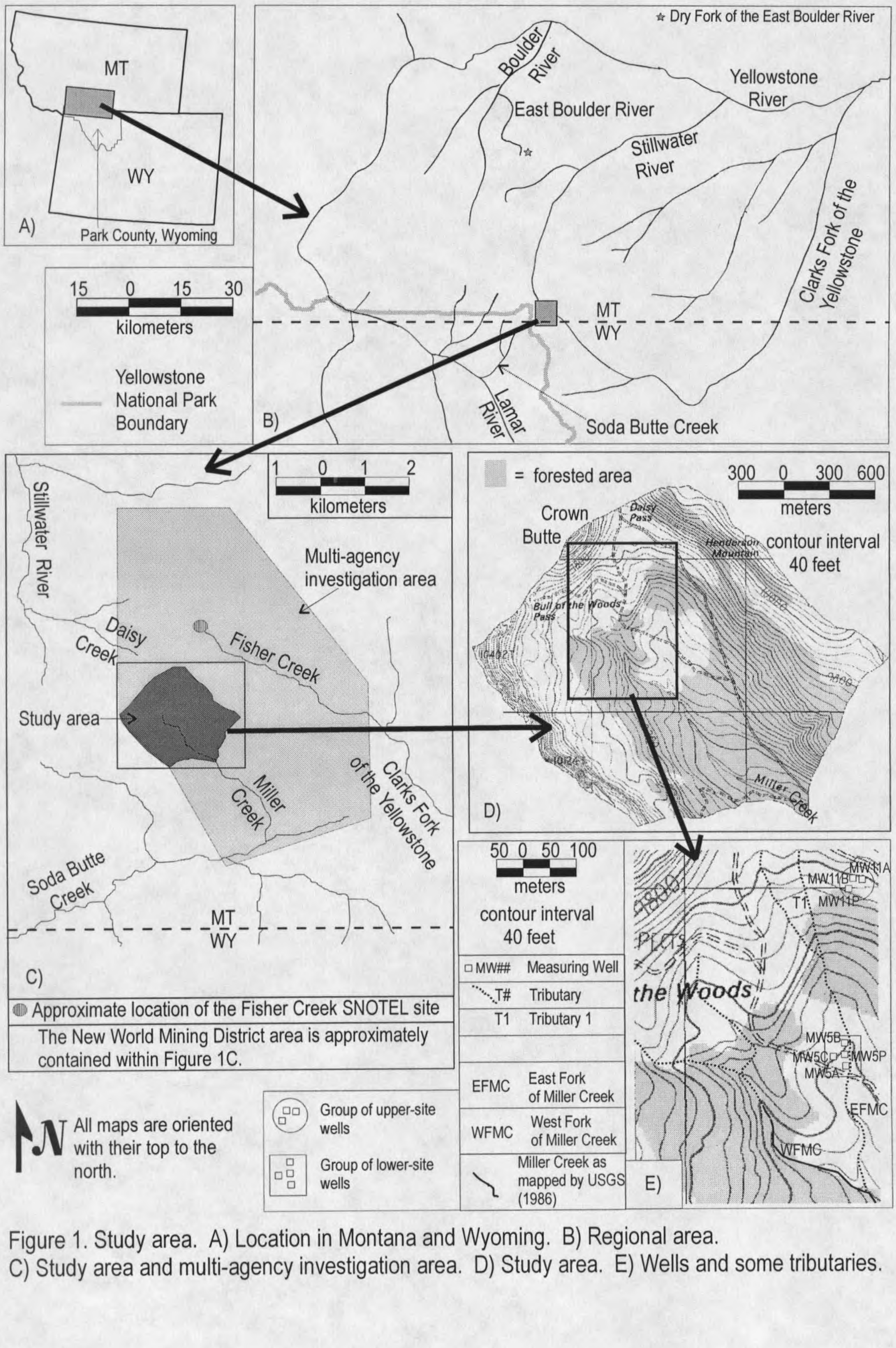

Figure 1. Study area. A) Location in Montana and Wyoming. B) Regional area. C) Study area and multi-agency investigation area. D) Study area. E) Wells and some tributaries.

Miller Creek basin. Quantity is an especially important issue because Miller Creek flows into Soda Butte Creek which joins the Lamar River in Yellowstone National Park (Fig. 1B). Given the design of historically proposed mining operations, (CBM, 1992) mine adits could intercept groundwater flow destined for Miller Creek and divert or delay the water away from surface flows in the Miller Creek basin. A compact between Yellowstone National Park and the state of Montana would require the replacement of any water diverted from Miller Creek. The water replacement must occur at the exact rate, timing and volume that water is removed from the upper Miller Creek basin (United States Department of the Interior and the State of Montana, 1994).

Determining the exact rate, timing and volume of water diverted from Miller Creek by underground mining could be very difficult. The difficulty stems from the poor understanding of groundwater flow systems in alpine basins. The groundwater flow system is important because underground mining would have to disrupt the groundwater flow system in order to be able to disrupt surface flows. Alpine groundwater flow systems are poorly understood because there is a general lack of wells in alpine basins (Schwartz and Domenico, 1997), and the interpolation of data gathered in other alpine basins is difficult because of the diverse geology of alpine basins throughout the world.

Despite the difficulty in determining the relative contributions of groundwater in alpine basins, some researchers have been able to determine that groundwater contributions in alpine basins can be significant either volumetrically or temporally. Modeling studies in the Reynolds Creek experimental watershed near Boise, Idaho indicate that a significant portion of streamflow is derived from shallow (<25 m) aquifers (Flerchinger et al., 1993). In the Dischma basin, Italy, 60% of the basin's total stream discharge was determined to be groundwater discharge during snowmelt periods (Martinec et al., 1982). At a headwater basin of the Kaweah river in the Sierra Nevada, California, the percentage of streamflow which consists of groundwater during snowmelt periods is low, but subsurface flow is the primary input to streamflow for the 8-9 months of the year which are non-snowmelt periods thereby controlling stream chemistry for more than two-thirds of the year (Kattleman, 1989).

Groundwater can discharge to streams in alpine basins via flow from the groundwater system into the bed of the stream, as well as via seeps and springs. This study focuses on the determination of spring discharge origin in the upper Miller Creek basin because the mapping of springs and the measurement of specific electrical conductance (SC) and temperature of springs provides a fairly simple means of determining whether springs derive water from the bedrock aquifer or the surficial-deposit aquifer. If spring discharge derives a majority of water from the surficial-deposit aquifer, then underground mining of the near-surface bedrock ore bodies would be less likely to disrupt spring discharge. If spring discharge derives a majority of water from the bedrock aquifer then mining would be more likely to disrupt groundwater discharge. The possibility exists that there is extensive mixing between the bedrock and surficial-deposit aquifer in the Miller Creek basin. If a mixing scenario exists then distinguishing water from the two aquifers would be difficult.

Bedrock and Surficial-Deposit Aquifers

Bedrock and surficial-deposit aquifers must be defined in order to be able to distinguish bedrock-aquifer spring discharge from surficial-deposit aquifer spring discharge. A bedrock aquifer is defined as a body of bedrock that contains sufficient saturated permeable material or cavities to conduct groundwater and yield water to springs and wells. Surficial-deposit aquifers are comprised of materials which lay above the bedrock surface and contain sufficient saturated permeable material to conduct ground water and yield significant quantities of water to wells and springs (definitions in part from Jackson, 1997, p. 32). Most materials that make up surficial-deposit aquifers are unconsolidated.

Relative Contribution of the Bedrock and Surficial-Deposit Aquifer to Groundwater Discharge

Flow from the bedrock aquifer may dominate baseflow in alpine basins. At a headwater valley in northwestern Nevada, SC measurements, demonstrated that bedrock-derived baseflow contributed 84-90% of total stream discharge (Hill, 1990). In the Reynolds Creek experimental watershed near Boise, Idaho a mathematical model demonstrated that subsurface flow through high permeability bedrock, (e.g. faulted bedrock) can be the sole source of streamflow (Stephenson and Freeze, 1974); other modeling studies in the same watershed provided additional evidence that the bedrock aquifer plays a significant role in delivering discharge to the stream (Flerchinger et al., 1993).

Conversely, surficial-deposit aquifer dominance of groundwater discharge is also possible. Specific electrical conductance (SC) and pH measurements indicated that a spring near Mt. Rushmore derived water largely from surficial-deposit materials (Rahn, 1990). At a headwater basin of the Kaweah river in the Sierra Nevada, California the available groundwater storage of the bedrock aquifer was determined to be much less than the available groundwater storage of the surficial-deposit materials (Kattleman, 1989).

Springs

A spring is a place where groundwater flows naturally from the ground onto the land surface (Jackson, 1997). The occurrence of springs depends on the nature and relationship of rocks, on the position of the water table and on topography. Knowledge regarding the types of geologic features where a spring may occur helps to determine whether a spring derives water from the bedrock or surficial-deposit aquifers. Features studied in this thesis which produce springs are herein termed potential spring-producing geologic features (Table 1). Though there are other factors which can control the location and origin of springs which are not listed in Table 1, such as topography, changes in hydraulic gradient and joint frequency, only the geologic factors which are most likely to occur in the Miller Creek basin and are best suited for discovery using the methods outlined in this thesis are discussed in this section.

Table 1. Potential spring-producing geologic features.

Bedrock features		Surficial-deposit features
Faults	Lineaments	The downhill contact between a surficial deposit and underlying bedrock.
Lithologic Contacts	Fracture Traces	
Mineralized Veins		

In the Miller Creek basin there are several bedrock features and one dominant surficial-deposit feature which can produce springs. Faults can be potential groundwater conduits (Huntoon and Lundy, 1979; Huntoon, 1986; Rahn, 1990) which may discharge groundwater in the form of springs. Lithologic contacts between bedrock units are potential groundwater conduits which may discharge "contact springs" at the surface expression of the contact (Fetter, 1994).

Faults and lithologic contacts can also be barriers to groundwater flow, and springs may form at the surface expression of these features (Huntoon, 1985; Fetter, 1994). Lineaments and fracture traces are also known to be sources of groundwater (Lattman and Parizek, 1964), and a line of springs may form on these features if they discharge groundwater (Fetter, 1994). The downhill contact between a surficial deposit and underlying bedrock is where a surficial-deposit spring is most likely to form. Such a spring is called a gravity contact spring (Taylor, 1964). Thus, there are several features which may form springs, and the determination of whether a spring is associated with a certain type of feature can help to segregate springs as either deriving water from the bedrock aquifer or from the surficial-deposit aquifer.

Study Area

The Miller Creek basin study area lies in the Beartooth mountains approximately 2 km north of Cooke City, Montana, in the New World Mining District (Fig. 1C). The entire Miller Creek basin has a drainage area of 6.0 km^2 (2.3 mi^2). However, only the upper 3.6 km^2 (1.4 mi^2) of the basin encompasses the study area. Only the upper portion was studied because this area is where the ore bodies are located and is the most relevant area to the evaluation of the potential effects of mining on Miller Creek basin springs. The study area lies between 2450-3170 m (8040-10402 ft) altitude (Fig. 1D and Plate 1). An east and west fork join to form Miller Creek (Fig. 1E). These forks each have two main tributaries. The easternmost tributary to the east fork is named Tributary One (T1). Tributary One becomes important in a test discussed in Appendix A. Miller Creek is a tributary to Soda Butte Creek which joins the Lamar River in Yellowstone National Park.

Climate

A Natural Resources Conservation Service snow telemetry (SNOTEL) station in the Fisher Creek Drainage (Fig. 1C) provides an excellent approximation of weather conditions in the Miller Creek basin because the Fisher Creek basin has the same aspect as the Miller Creek basin and the altitude of the SNOTEL site (2775 m (9100 ft)) is near the mean altitude of the study area.

The Fisher Creek SNOTEL indicates that there is great variance in ambient air temperatures. The great variance in ambient air temperatures of the study area helps to distinguish surficial-aquifer-spring water from deeper-aquifer-spring water because an area with great fluctuations of ambient air temperature will cause shallow-surficial-aquifer-water temperature to vary, whereas deeper-aquifer water temperature will not vary (Taniguchi, 1993). The Fisher Creek SNOTEL indicates that the average annual minimum temperature is -32° C (-26° F) and the average annual maximum temperature is 26° C (79° F) (water years 1983-97). Minimum air temperature at ground surface may be moderated due to snow cover and not likely to be lower than 0° C (32° F) because the stored heat in the ground from summer warming and geothermal heat combine to warm the temperature at the base of most heavy snowpacks to 0° C (or close to 0° C (32° F)) (McClung and Schaerer, 1993, p. 45). Temperatures as low as -43° C (-45° F) and as high as 30° C (86° F) have been recorded. The average annual temperature is -1° C (30° F).

The large annual snowpack in the study area provides ample snowmelt recharge for the bedrock and surficial-deposit aquifers. The Fisher Creek SNOTEL indicates that the average maximum annual snow pack is 103 cm (40.9 in) in snow water equivalent units occurring on or about May 1 (water years 1967-97). The greatest recorded annual maximum snow water equivalent is 153 cm (60.2 in) and the smallest recorded maximum snow water equivalent is 52 cm

(20.4 in). Up to 450 cm (15 ft) of snow depth have been observed at elevations above 2774 m (9100 ft) elevation (United States Environmental Protection Agency (EPA), 1996). Because such large quantities of snowmelt recharge are available, the properties of snowmelt recharge must be taken into account because snowmelt recharge will affect the SC and temperature of bedrock-aquifer or surficial-deposit-aquifer-spring discharge.

Rainfall may also be an important source of recharge for aquifers. However, in the study area, the rainfall quantities are much smaller than snowfall quantities. During the time when precipitation is expected to fall as rain (approximately June 1-Oct. 31), the amount of precipitation recorded at the Fisher Creek SNOTEL is 27 cm and 46 cm for the 1996 and 1997 seasons respectively, whereas the maximum snowpack recorded at the Fisher Creek SNOTEL during the same years (130 cm and 150 cm, respectively) in snow water equivalent units is greater by a factor of three to four.

Springs

Spring discharge is an important aspect of groundwater discharge in the upper Miller Creek basin. Researchers have mapped in excess of 35 springs in the upper Miller Creek basin (Hydrometrics, 1989, 1990) and several agencies agree that groundwater discharges to the surface in the form of springs (Kirk, 1995; Maxim Technologies, 1995; BLM, 1997).

Wells

Though wells can be scarce in alpine basins, they can be very important in providing information which could lead to the determination of spring origin. Fortuitously, Miller Creek basin contains several wells. Previous researchers (Huntingdon Engineering and Environmental, 1995), have divided wells into two groups: the group of upper-site wells (*n*=3) and lower-site wells (*n*=4) (Fig. 1E). The upper-site wells (MW11A, MW11B and MW11P) fit the definition of a "bedrock well". A "bedrock well" is completed and/or screened in lithologies interpreted by previous researchers to be bedrock, grouted where surficial-deposit materials exist and has a packer at the base of the grouting material. The bedrock lithologies will be discussed in the section titled Bedrock Hydrogeology. Based on well log interpretations, the group of upper site wells do not intercept fracture zones. The lower-site contains three bedrock wells (MW5C, MW5B and MW5P) that intercept fracture zones, and one "surficial-deposit well" (MW5A). A "surficial-deposit well" is defined as a well which is capped at the base and screened only where the surficial deposit exists. The surficial-deposit materials will be discussed in the section titled Hydrogeology of Surficial Deposits.

In addition to the wells in the Miller Creek basin there are several other bedrock and surficial-deposit wells in the multi-agency investigation area (Fig. 1C). The pH, SC, temperature and depth-to-water have been measured at the two groups of wells in the Miller Creek basin and the various other wells in the multi-agency investigation area. Additionally, pump tests have been performed by other researchers at the Miller Creek basin wells which provide hydraulic conductivity and surface-water connectivity information. The information collected at the two groups of wells in the Miller Creek basin and the other wells in the Multi-agency investigation area provides some of the criteria used to determine whether a spring derives water from the bedrock aquifer or the surficial-deposit aquifer.

Bedrock Hydrogeology

The bedrock hydrogeology of the Miller Creek basin is of great importance in determining the origin of spring discharge in the upper Miller Creek basin. The various types of lithologies and their geologic properties control the hydrologic properties of the bedrock aquifer and the potential location of springs. The existence of faults and their behavior as fault barriers or conduits can also control the location of spring discharge.

If the bedrock lithologies of the Miller Creek basin yield water, then they likely yield water from secondary permeability. The bedrock lithologies of the Miller Creek basin include Pre-Cambrian crystalline rocks, Paleozoic sandstone, limestone, dolomite, and shale and Tertiary intrusive and extrusive igneous rocks. In nearby Park County, Wyoming (Fig. 1A), the equivalent units of bedrock lithologies which exist in the Miller Creek basin have low water yields because primary permeability is low (Table 2; Plate 2) (Lowry et al., 1993). The only bedrock lithologies which have notable yields are the Flathead Sandstone and the Bighorn Dolomite. The Bighorn Dolomite has notable yields only because this unit contains secondary permeability (Lowry et al., 1993). In fact, other units throughout the Bighorn basin may contain water if fracturing, weathering and solution of carbonates has allowed the creation of secondary permeability through which groundwater can flow (Lowry et al., 1993). If the units in the Miller Creek basin have similar hydrogeologic properties to equivalent units in the Bighorn Basin, then most lithologies are more likely to have groundwater flowing through secondary permeability rather than primary permeability.

The only unit in the upper Miller Creek basin that may yield water from primary permeability in the upper Miller Creek basin is the Flathead Sandstone, but since there are no wells in the Flathead Sandstone in the upper Miller Creek basin or in the Multi-Agency investigation area, only speculations about the Flathead Sandstone's ability to yield water in the

Table 2. Hydrogeologic properties of surficial deposits and materials in Park County, Wyoming after Lowry et al., 1993. Equivalent Miller Creek basin lithologic units written in [brackets].

Quaternary	Glacial materials	Springs are common and yields of 100 gallons per minute are possible.	
	Landslide deposits	Springs are a source of water in some areas but wells generally do not yield much water because the deposits are from fine grained material, and deposition by mass movement increases heterogeneity.	
	Undivided surficial deposits (mostly alluvium, colluvium, and glacial and landslide deposits)	Availability [of groundwater] depends on type of deposit as already described.	
Tertiary	Intrusive igneous rocks	Availability of water should be similar to that of Precambrian rocks.	Secondary permeability as a result of fracturing, weathering, and/or carbonate solution or dolomitization may be present.
Ordovician	Bighorn Dolomite	Yield to wells differs greatly because the permeability is secondary.	
Cambrian	Snowy Range Formation	Not considered an aquifer.	
	Pilgrim Limestone	Not considered an aquifer.	
	Gros Ventre Formation [Park Shale] [Meagher Limestone] [Woisey Shale]	Not considered an aquifer.	
	Flathead Sandstone	Yields sufficient quantities of water for irrigation in parts of the Bighorn Basin.	
Precambrian	Granitic Rocks	Will yield water from fractures or weathered zones in adequate quantities for stock or domestic use. Obtaining a supply at shallow depth is uncertain and drilling to depths more than 200 feet often does not result in increased yield in this geologic unit.	

study area can be made. Despite the fact that there is evidence in Park County that the Flathead Sandstone may yield water from primary permeability (Lowry et al., 1993), the hydrogeologic properties of the Flathead Sandstone are variable and may not yield water in the upper Miller Creek basin. In parts of Montana such as Meagher County, the Flathead Sandstone is considered an aquifer which yields water only from fractures (Groff, 1965, p.18). In the upper Miller Creek basin, a metamorphic effect from the Tertiary intrusives may have caused the Flathead Sandstone's permeability to decrease. Therefore, all lithologies including the Flathead Sandstone may have low primary permeability in the upper Miller Creek basin.

Evidence from within the Miller Creek basin indicates that some of the bedrock lithologies have low primary porosities and permeabilities. Pump tests of the upper-site wells completed in Meagher Limestone indicate unfractured bedrock hydraulic conductivities range from 1.4×10^{-6} to 3.9×10^{-6} cm/sec (0.004-0.011 ft/day) (Maxim Technologies, 1995). The low primary porosity and permeability of the bedrock enhance the formation of surficial-deposit springs because the interstitial surficial-deposit water at the contact of the bedrock and the surficial deposit will flow along the bedrock surface rather than infiltrating into the bedrock.

Despite the low primary porosities and permeabilities of the lithologies in the upper Miller Creek basin, the structural geologic setting of the region allows for ample faults and fractures which can provide secondary permeability for the bedrock aquifer. The Miller Creek basin is in the Cooke City Structural Zone, a northwest-trending lineament and area of crustal weakness in the Beartooth uplift. This lineament is an area of extensive faulting (Foose et al., 1961). Miller Creek basin exists in a region classified as an area whose fractures have the greatest potential effect on fracture permeability in the northern Great Plains and the Rocky Mountains region (Cooley, 1986).

An example of how faults may affect the groundwater flow system and produce large springs exists in the nearby Dry Fork-East Boulder River (Fig. 1B) where springs likely related to the Dry Fork Thrust Fault discharge up to 7600 l/min (2000 gpm) from Paleozoic units (Feltis, 1986).

The regional trend of faults and fractures with pronounced affects on groundwater flow appears to also occur in the Miller Creek basin. Pump tests indicate that fractures have a pronounced affect on groundwater flow and several researchers conclude that subsurface water moves primarily through fractures and faults (Maxim Technologies, 1995; BLM, 1997). Pump tests in the group of lower-site wells indicate hydraulic conductivities of fractured bedrock range from 1.5×10^{-2} to 2.1×10^{-2} cm/sec (42-60 ft/day) (Maxim Technologies, 1995) which is four orders of magnitude greater than the unfractured bedrock aquifer conductivities mentioned previously. Because faults and fractures control groundwater flow through bedrock, bedrock-aquifer springs are expected to occur along the surface expression of fault locations in the Miller Creek basin.

A regional scale sub-horizontal detachment may produce spring discharge in the upper Miller Creek basin. The Heart Mountain Detachment is a sub-horizontal fault surface which extended over a large (1800 mi^2) portion of northwestern Wyoming and parts of southern Montana (Pierce, 1957). The fault surface is presently dissected, and a portion of the detachment fault is located in the Miller Creek basin (Elliot, 1979). Fluids migrated along this feature during the genesis of the feature in the Eocene, (Templeton et al., 1995; Beutner and Craven, 1996). If groundwater does flow through the Heart Mountain Detachment, springs may form at the surface expression of this feature. Admittedly however, there is no information which indicates groundwater presently flows from the surface of the Heart Mountain Detachment.

The elevation of the water table in the study area's bedrock aquifer fluctuates (Fig. 2).