2 GEOLOGY

The distribution, availability and long-term reliability of groundwater resources for water supply development by the City of Gillette, Wyoming, are dictated by the geology of the area. The differences between porosity and permeability of the various subsurface strata impose profound influence on which strata store and transmit groundwater that can be developed by water wells and which strata act as barriers to groundwater movement and do not yield practicably useable amounts of groundwater. Post-depositional deformation of the subsurface strata, including development of discontinuities in the rock that provide secondary permeability for groundwater flow, is an important factor in selecting sites where the most favorable yields will be obtained by wells. Likewise, structural deformation of the geologic strata often determines the depth of the strata below the land surface and the depths to which wells must be drilled to obtain groundwater from the strata. Geologic conditions that influence the relative volume of groundwater stored in different geologic strata are an important consideration regarding long-term reliability of groundwater production. All of these factors and others must be considered in selecting sites for construction of new wells.

2.1 Hydrogeologic Framework

Following a 2007 Level II study (Morrison-Maierle, 2007), additional geologic review and evaluation of the Madison aquifer was undertaken to identify favorable locations for future wells. The existing Madison Well Field for the City of Gillette is located east of a well-known regional geologic structure, the Black Hills monocline, where the relatively gently sloping strata west of the Black Hills abruptly plunge into the Powder River basin. East of the Black Hills monocline, the depth to the Madison aquifer, one of the largest sources of fresh groundwater in the region, are not unreasonable for water well construction and groundwater quality is relatively good. West of the Black Hills monocline, the Madison aquifer strata become progressively deeper and mineralization of groundwater in the aquifer increases, making this an unfavorable area to drill to the Madison aquifer. Therefore, an initial conclusion of the geologic evaluation was that expansion of the existing Madison Well Field would be in locations east of the Black Hills Monocline in order to avoid excessively deep drilling requirements and potentially poor groundwater quality.

The existing Madison Well Field is located east of where the strata dip abruptly into the Powder River structural basin, east of the Black Hills monocline. Secondary folds in the strata, upward flexures referred to as anticlines, are located between the existing City of Gillette Madison Well Field and the axis of the monocline. The topographic expression of the upward folds is a prominent ridge referred to as the "Pine Ridge", located east of and parallel to the Black Hills monocline. The south end of the Pine Ridge is supported by the Pine Ridge anticline and north end by the Oil Butte anticline. The existing City of Gillette Madison Well Field, east of the Pine Ridge, is in a gentle downward flexure of the strata, referred to as the Eggie Creek syncline.

The area between the Black Hills Monocline and the existing well field exhibits a number of strong linear alignments of topographic features. Such alignments are referred to as "lineaments" and may indicate the presence of faults or deep fractures in the underlying strata. The principal lineaments identified in the area of interest for expansion of the Madison Well Field were plotted on a topographic map. One of the major lineaments was found to pass through the existing Madison well field.

The existing well field includes wells with moderate hydraulic performance and other wells with extremely high hydraulic performance. The wells offering high-capacity hydraulic performance are closely associated with the lineament passing through the well field whereas the wells providing only moderate hydraulic performance are relatively distant from the location of the lineament. Moreover, a difference exists between aquifer hydraulic response at wells associated with the lineament and those located away from the lineament. Wells located away from the lineament exhibit a radial flow response typical of flow through porous rock, with groundwater travelling toward the pumped well from all directions. Wells located on or near the lineament exhibit linear flow response to pumping, typical of flow along a highly transmissive, highly bounded feature, such as flow to the pumped well along a fracture or solution-enlarged fracture.

The geologic history of the Madison strata in the eastern Powder River Basin is complex and beyond the scope of this report. However, it includes at least two periods of tectonic uplift of Madison strata in the earth's crust above sea level during which fresh water percolating down through the Madison strata dissolved openings in the rock strata and removed or partially removed layers of soluble rock, such as gypsum. The solution openings are present in two forms.

One form of openings is large caverns full of limestone rock rubble, potentially offering considerable groundwater storage capacity and highly permeable conditions for groundwater flow. These internal rubble zones resulted when layers of anhydrite and gypsum interbedded with the limestone were dissolved by fresh groundwater percolating down through the rock as it was uplifted above sea level. Removal of the soluble strata created voids into which the overlying hard limestone and dolomite rock strata collapsed. This process is referred to geologically as autobrecciation and the subsurface rock rubble deposits resulting from collapse of the voids are referred to as collapse or solution breccias. There is seldom any indication at the land surface of the presence of a collapse breccia zone in the deep Madison strata, although they are highly visible where they are exposed at the land surface as sink holes. The hydraulic response of the collapse breccias to pumping is a function of a number of variables which include the size and geometry of the area of interconnected voids and the amount of plugging of the voids in the collapsed materials by post-collapse sediments washed in from the land surface or provided by burial of the Madison strata by younger sedimentary deposits.

A second form of solution openings results from dissolution of the carbonate rock by groundwater flowing along fractures in the rock. The fractures generally resulted from compressive forces during tectonic deformation and from bending of the crust with tension opening fractures parallel the axes of the folds. The fractures provided zones of secondary permeability along which fresh groundwater could flow during the periods of uplift above sea level. Water tends to follow the path of least resistance and the groundwater flowing along the fractures dissolved materials from the walls of the fractures, thus increasing the size of the fracture openings (so-called fracture "aperture"), and in the case of Madison strata, often produced fracture-controlled caverns with large voids aligned along the fractures. Solution enlarged fractures act as the principal drains for both local and regional groundwater flow where fractures are hydraulically well interconnected. Such fracture systems have the hydraulic capacity to yield large amounts of groundwater to individual wells. Release of groundwater into the fractures by the surrounding porous rock provides enough groundwater storage to make the resource reliable for long periods of pumping abstraction. The distinctive hydraulic response of aquifers, with flow to the pumped well controlled by solution enlarged fracture flow paths, is that of linear flow.

The Madison strata offer intrinsic permeability in addition to highly enhanced permeability associated with collapse breccias and solution enlarged fractures. The intrinsic permeability is mostly due to recrystalization of the limestone strata after they were deposited. With the exception of reef complexes, most of the limestone strata were initially deposited in the sea flow as a lime mud which, when hardened into rock, was a microcrystalline rock with essentially no inherent permeability. However, some of the rock-forming processes caused the lime mud to recrystallize and during the recrystallization process, voids formed between the crystals. The voids formed in this process may provide up to 18% porosity in the rock, according to U.S. Geological Survey investigations in the 1970s, and when interconnected, offer permeability for groundwater flow through the porous rock. The typical hydraulic response anticipated from this type of material at a pumped well is radial flow towards the pumped well, like that exhibited by the existing Madison wells for the City of Gillette that are not located along the lineament passing through that well field or otherwise fracture-controlled.

The foregoing considerations indicate that the high capacity wells in the existing City of Gillette Madison Well Field, all of which exhibit linear flow response to pumping, likely penetrate and draw water from solution enlarged fractures. This conclusion is supported by driller's reports of drilling tools penetrating voids while drilling those wells, and typical high-capacity loss of drilling fluid into the Madison where high-capacity wells with high hydraulic performance have been obtained.

Therefore, the geologic assessment for future expansion of groundwater development from the Madison aquifer in the area of the existing well field and pipeline for the City of Gillette concentrated on identification of lineament patterns that might indicate the locations of large fractures and/or interconnected fracture systems. The rationale was if a solution enlarged fracture is the principal control for the high-capacity wells in the existing well field, and it is a sufficiently large fracture to cross all of the geologic strata above the Madison such that it effects topographic features at the land surface, other fractures large enough to cause lineaments at the land surface may also offer potential for high-capacity groundwater flow in solution enlarged fractures in the Madison strata of the subsurface.

The geologic assessment identified a number of large, interconnected lineaments in Section 36, T.52N., R.67W., which happens to be a parcel of State Land. In addition to long lineaments associated with the compressional and tensional axes of the Oil Butte and Pine Ridge Anticlines, the southern nose of the Oil Butte Anticline exhibits a large number of apparently interconnected fractures where the strike and dip of the strata change rapidly around the nose of the anticlinal fold. It is not known if the latter fractures extend to the Madison Limestone at depth or are shallow fractures limited to the Fall River and Lakota Formations. Based on the fracture patterns indicated by the land surface topography, a number of potential well locations were selected in Section 36. Those locations are generally at the intersections of significant lineament traces.

The location of Test Well #1 is on the alignment of a moderately strong northwest by southeast lineament along the northeast flank of the Oil Butte Anticline. The lineament is at least 1.7 miles long and can be traced diagonally from southeast to northwest through Section 31, T.52N, R.66W., and diagonally across the NE1/4 Section 36, T.52N., R.67W., where Test Well #1 is located. The lineament is characterized by an abrupt, nearly 90 degree turn in the heads of coulees draining east to Spring Creek where they begin draining southeasterly and then abruptly turn to slightly north of east. The lineament is the alignment of the abrupt change in direction at the tops of five separate coulees.

A sub-parallel and converging alignment is present to the west and terminates at the boundary between section 36 and section 25, at exactly the same location the target lineament terminates. Both lineament alignments are interrupted by two southwest to northeast draining coulees that drain to Spring Creek in the easternmost half of the north and do not exhibit the change in direction evident in the four coulees to the southeast and one coulee to the northwest. Test Well #1 did not penetrate a solution enlarged fracture along the lineament and aquifer response at this site during yield and drawdown tests was initial radial flow subsequently modified by recharge. The source of recharge is thought to be a solution enlarged fracture located between Test Well Sites #1 and #2. The basis for the latter conclusion is the response of Test Well #2A, used as an observation well, during tests of both Test Well #1 and Test Well #2A. A likely location for a solution enlarged fracture that provides recharge is the alignment of the large northwest by southeast trending coulee in the center of Section 36.

2.2 Formation Tops

The depths to the top of each of the geologic formations penetrated by Test Well #1 were estimated from drill cutting samples collected at every 10 feet of depth of the borehole as the well was drilled. Refinement of the depths to the formation tops was provided by GAMMA RAY and short and long normal electrical resistivity logs, as summarized in Table 1.

Table 1: Depths to tops of formations penetrated by Test Well #1.

Formation Top Depths (feet)		Formations and Members Test Well #1	
0		**Fall River Formation** – hole starts below formation top in mudstone unit	
	40		Lower Fall River Formation siltstone unit
70		**Lakota Formation**	
	70		Upper Lakota Fm.
	147		Basal sandstone unit Lakota Fm.
210		**Morrison Formation**	
307		**Sundance Formation**	
	307		Redwater Shale Member Sundance Fm.
	585		LAK Member Sundance Fm.
	640		Hulett Sandstone Member Sundance Fm.
	710		Stockade Beaver Shale Mbr. Sundance Fm.
770		**Spearfish Formation**	
1410		**Minnekahta Limestone**	
1430		**Opeche Shale**	
1470		**Minnelusa Formation**	
2315		**Madison Erosion Surface Deposit**	
2350		**Madison Formation** (Pahasapa Limestone)	
2690		**Whitewood Dolomite**	
2791		**Winnipeg Formation**	
2801		**Total depth** ending in Winnipeg Formation	

The drill cuttings were examined microscopically and descriptions (lithologic descriptions) of the materials in each sample are provided in Appendix C for Test Well #1. Based on the lithology of the strata penetrated, individual geologic formations were identified and their names are included on each of the descriptions of the 10-foot interval drill cutting samples in Appendix C.

Formation tops in Test Well #1 (Table 1) were picked from Gamma Ray logs of the natural radiation emitted by the formation, used in conjunction with the drill cutting samples, to refine the depths selected for changes in the formation. Some refinement of the latter basis for selection of formation tops was made by continuously observing samples on the shale shaker as the borehole penetrated through the interval containing the top of the Madison strata and the top of the Winnipeg Formation.

3 CONSTRUCTION

The drilling equipment used for this project was Layne Christensen Company Rig No. 490 consisting of a Challenger 360 draw works and a Challenger 200 Derrick