GILLETTE MADISON PIPELINE PROJECT (GMPP)
TECHNICAL MEMORANDUM #2
FINAL

TO: Mike Cole, P.E., City of Gillette

FROM: Mike Kaczmarek, P.G., MMI

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EXECUTIVE SUMMARY

This technical memorandum presents factors considered for selection of two locations for Madison aquifer test wells to be drilled as part of an expansion project for the existing City of Gillette (COG) Madison aquifer well field. The firm capacity of the COG well fields is currently 6,565 gpm. The required firm capacity from COG aquifer sources by year 2040 is projected to be 24,500 gpm, including an increase of 16,000 gpm from the Madison aquifer well field. Assuming new wells can produce the design rate of 1,400 gpm, a total of 13 new wells are required to satisfy the required firm capacity, if the existing wells remain in production at their existing rates.

Tests conducted in the original eight wells in the City of Gillette Madison well field in 1979 and 1980 and tests conducted in two newer wells in 1996 show that wells located along the alignment of a regional fracture exhibit linear flow aquifer response as well as the best hydraulic performance and largest yields. The liner flow response indicates the high-capacity flow to the wells on the regional fracture alignment is controlled by a relatively narrow feature that is highly

transmissive of groundwater; most likely a solution enlarged fracture. The wells exhibiting linear flow response provide the largest well yields in the well field, except where they are limited to small pumps by inadequate casing diameter. Even where the linear flow well yields are limited by casing diameter and pump size, their hydraulic performance is the best of all the wells in the well field. Some of the linear flow response wells required hydraulic fracturing of the aquifer to establish a good hydraulic connection with areas of high-capacity flow along the fracture.

Other wells in the well field, that are not located on the regional fracture system, exhibit radial flow response to tests and provide much less well yield than the wells penetrating the fracture. Likewise, the hydraulic performance of the radial flow wells is an order of magnitude less than that of the wells penetrating the fracture and exhibiting linear flow response. These wells produce from porous carbonate rock that does not offer the enhanced hydraulic properties provided by the solution enlarged fracture.

Considering the foregoing relationships, an exploration strategy for expanding the Madison well field is proposed based on evaluation of the fracture patterns in the area. An assessment of the fracture patterns related to geologic structures in the area has identified four potential areas for expansion of the well field. The four areas are ranked with respect to the most favorable geologic conditions for high-capacity wells, based on the fracture pattern theory, and an area on State land in Section 36 on the south end of the Oil Butte anticline is selected as the most favorable area. A second favorable area is identified along the crest and western flank of the Pine Ridge anticline. A third less favorable area is identified contiguous to and east and south of the existing well field. A fourth area is identified in the saddle between the Oil Butte and Pine Ridge anticlines; however, its suitability is hard to assess and an exploration well in this fourth area would be strictly a wildcat exploration effort.

Sites for two exploration/production wells are identified on the locations of major fracture alignments and/or fracture intersections in the Section 36 area on State land on the Oil Butte anticline. Two additional sites for exploration/production wells are identified on the Pine Ridge anticline.

An exploration well design that is suitable for use as a future production well is recommended. The exploration well configuration is designed to produce a high-capacity well yield, even if the well does not penetrate a high-capacity solution enlarged fracture. The design is based on the hydraulic performance (specific yield) of the radial flow wells in the existing field. Specifically, it is recommended that the exploration wells be designed to produce 1,400 gpm from the porous carbonate rock, even if a solution enlarge fracture is not penetrated and the well performance is limited to that exhibited by the existing radial flow wells. A pumping chamber with a depth of 1,800 feet is recommended for this purpose.

If the well does penetrate a solution enlarged fracture or the hydraulic performance of the well initially does not require a pumping chamber to 1800 feet, the 1800-foot pumping chamber will be available for operation of the well under long-term drawdown of groundwater levels in the well field. This latter aspect of the well design is important because the aquifer tests of the existing well field indicate the relatively small long-term decline of groundwater levels in the field is due to the presence of a large volume of groundwater storage in the vicinity of the well field. New wells located in other areas may not be subject to the benefits of a similar volume of groundwater storage and may, therefore, exhibit considerably more long-term groundwater level decline than experienced with the existing well field. A pumping chamber to a depth of

1800 feet will increase the useful life of wells exhibiting significant long-term drawdown in response to pumping.

The recommended design for future use as a production well consists of 16-inch casing to 1800 feet for a pump chamber, 10-3/4 inch casing from 1800 to the top of the Madison at an estimated 2500 feet, and 9-3/4 inch diameter open hole through the Madison below 2500 feet. A minimum standard well design and an intermediate well design are discussed, but not recommended.

INTRODUCTION AND BACKGROUND

This technical memorandum presents factors considered for selection of two locations for Madison aquifer test wells to be drilled as part of an expansion project for the existing City of Gillette (COG) Madison aquifer well field. Also discussed are the factors considered in the design and sizing of the test wells. Figure 1 shows the locations of the existing wells, M-1 through M-10.

In 1980, the sub-consultants for wells M-1 through M-8, Anderson & Kelly, recognized that the eight new wells exhibited two types of hydraulic response, one associated with very high specific capacities and the other with moderate specific capacities. They also recognized that the wells with high yield were ones where the well had penetrated caverns or cavities in the limestone, as demonstrated by “rod drops”; i.e., instances where the drilling tools penetrated open voids. Accordingly, they referred to the wells as “cavity” wells and “non-cavity” wells. Subsequently, consultants Wester-Wetstein and Associates, who designed and supervised the construction and testing of wells M-9 and M-10, continued the “cavity” versus “non-cavity” well concepts, recognizing the same relationships that were observed by Anderson and Kelly in the first eight production wells. The specific capacity of the wells was not a criterion for assigning them to cavity or non-cavity well status and assignment of wells with high specific capacity to cavity status was dependent on penetration of voids and incidental to well yield.

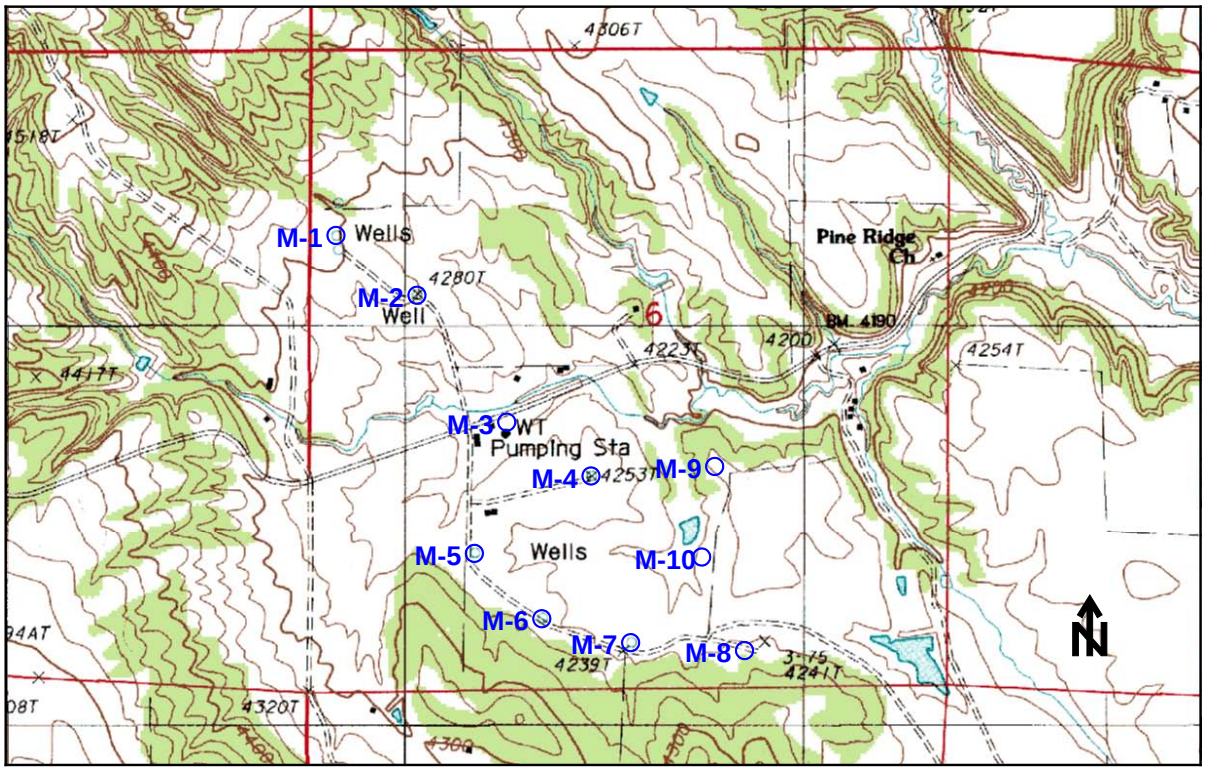
Table 1 summarizes information from the tests of the first ten wells drilled in the COG Madison aquifer well field, and groups them as radial versus linear flow wells, based on new interpretations of the aquifer test data.

Table 1: Summary of hydraulic performance factors for wells M-1 through M-10.

Well	Pre-Frac Yield and Drawdown		Post-Frac Yield and Drawdown		Initial SWL When Well Drilled (ft)	Aug to Nov 2006 SWL (ft)	2005-2006 Elevation Lift to Top of Well		Specific Capacity Pre/Post Frac (gpm/ft)
	Yield (gpm)	Draw-down (feet)	Yield (gpm)	Draw-down (feet)			PWL (ft)	Yield (gpm)	
Radial Flow Wells									
M-5	306	375	750	475	395	476	892	580	0.82/1.39
M-6	596	270	---	---	394	590	819	530	2.31/---
M-7	507	319	---	---	387	539	909	600	1.62/---
Linear Flow Wells									
M-1	171	743	635	723	420	570	724	500	1.23/3.25
M-2	600 800	59 76	- -	- -	424 -	488 -	532 -	800 -	18.2/--- 10.5/---
M-3	650	218	750	30	383	404	448	900	3.0/20.5
M-4	656	63	---	---	404	415	492	750	9.7/---
M-8	500	352	---	---	391	476	987	500	0.98/---
M-9	1150	11.5	---	---	395	420	452	1400	43.8/---
M-10	825	202	1150	27.7	406	413	458	1400	4.1/31.1

The response of the Madison aquifer to pumping tests conducted in the ten Madison wells in the COG Madison aquifer well field provides a crucial concept for developing an exploration plan for

Figure 1: Existing well locations.



future wells. The crucial concept is that the zones which provide high-capacity yields to the wells with large values of specific capacity, as well as high specific capacity values in low yield wells, are relatively narrow, highly bounded zones of very high aquifer transmissivity which direct the flow to the pumped wells through linear flow paths bounded by less transmissive rock The explanation for the linear flow response to pumping most consistent with the geology of the local Madison aquifer is that the high-capacity flows to wells are provided by relatively long, solution enlarged joints in the carbonate rocks of the aquifer.

The early studies of the well field recognized that fractures played a role in promoting high-capacity well yields. In the early studies, the fractures were regarded simply as a source of large openings in the carbonate rocks which offered the opportunity for large groundwater flows to a well. There was no consideration of how the fractures and the openings associated with the fractures might influence the hydraulics of groundwater flow through the aquifer, other than to provide enhanced hydraulic properties for the flow. All of the original analyses of aquifer tests of the Madison wells applied analytical methods for radial flow. It was recognized that these concepts did not fully explain the observed hydraulic response of the aquifer to pumping. The influence of interconnected caverns and "double-transmissivity" were invoked to explain the departures of the aquifer response from typical radial flow response. **There was no recognition that the solution enlarged openings in the rock might exhibit a distinct**

pattern which constrained the distribution and availability of high-capacity zones in the aquifer to predictable locations.

In their summary report about the Madison aquifer after completion of the first eight wells, "***Summary Well-Field Report***", prepared for James M. Montgomery Consulting Engineers, Inc., Boise Idaho, October 1982; Anderson & Kelley described the Madison aquifer as follows:

> "***Ground water occurs within the full thickness of the Madison formation throughout the western flank of the Black Hills as a highly confined, artesian aquifer system. Lithologic characteristics of the formation units are such that the primary porosity of the rocks is minor and secondary porosity plays the major role in water transmission and yield to wells. Jointing, fracturing, and separation along bedding plains has*** (sic) ***been enhanced by tensional forces associated with the folding of the formation into the various anticlines and synclines. At many localities, enlargement of these secondary openings has occurred through dissolution of the limestone and dolomite. An obvious example of this secondary porosity development can be seen in the numerous caves within the Black Hills. In general, it is these secondary openings, whether actual caves or slightly enlarged openings, within the rock mass that create the aquifer zones for occurrence and movement of water within the formation.***" (Anderson & Kelly, 1982; pp.4-5)

Anderson & Kelly further describe the effects of the "cavity system" on aquifer response to pumping and reinforce the concept of the "cavity well" versus "non-cavity well" nomenclature as follows:

> "***The results of numerous individual well test analyses all point to the cavity system, which was penetrated by M-2 and M-4, as being the dominant factor in the response to pumping at any well. This system has been shown to be extensive by numerous well-test data analyses, by water quality data, and by computer model simulation. Consequently, when the wells within that system (M-2 and M-4) are pumped, the rest of the aquifer is essentially unaffected. When wells in the non-cavity system are pumped, the cavity system "absorbs", so to speak, the effects and little response is observed in the cavity system wells.***
>
> ***On the other hand when the non-cavity wells are pumped the other wells within that system react quickly and large drawdown effects are observed in those wells. After several hours of pumping, however, the presence of the cavity system become dominant and the drawdown cone is stabilized. This is because the cone does not have to expand to supply water to the pumping well – the cavity system supplies the demand instead.***" (Anderson & Kelly, 1982; p. 13)

Anderson & Kelly were correct that the "cavity system" must be penetrated to obtain high-capacity well yields and that it greatly influenced the aquifer responses obtained in their pumping tests. However, there was no recognition of the profound effect that the "cavity system" has on the hydraulics of groundwater flow through the aquifer or how that influence is

related to the geometry of the "cavity system". Anderson & Kelly, with the assistance of S.S. Papadopulos & Associates, prepared a model of the aquifer, providing the following conceptual description of the Madison aquifer system at the COG Madison aquifer well field:

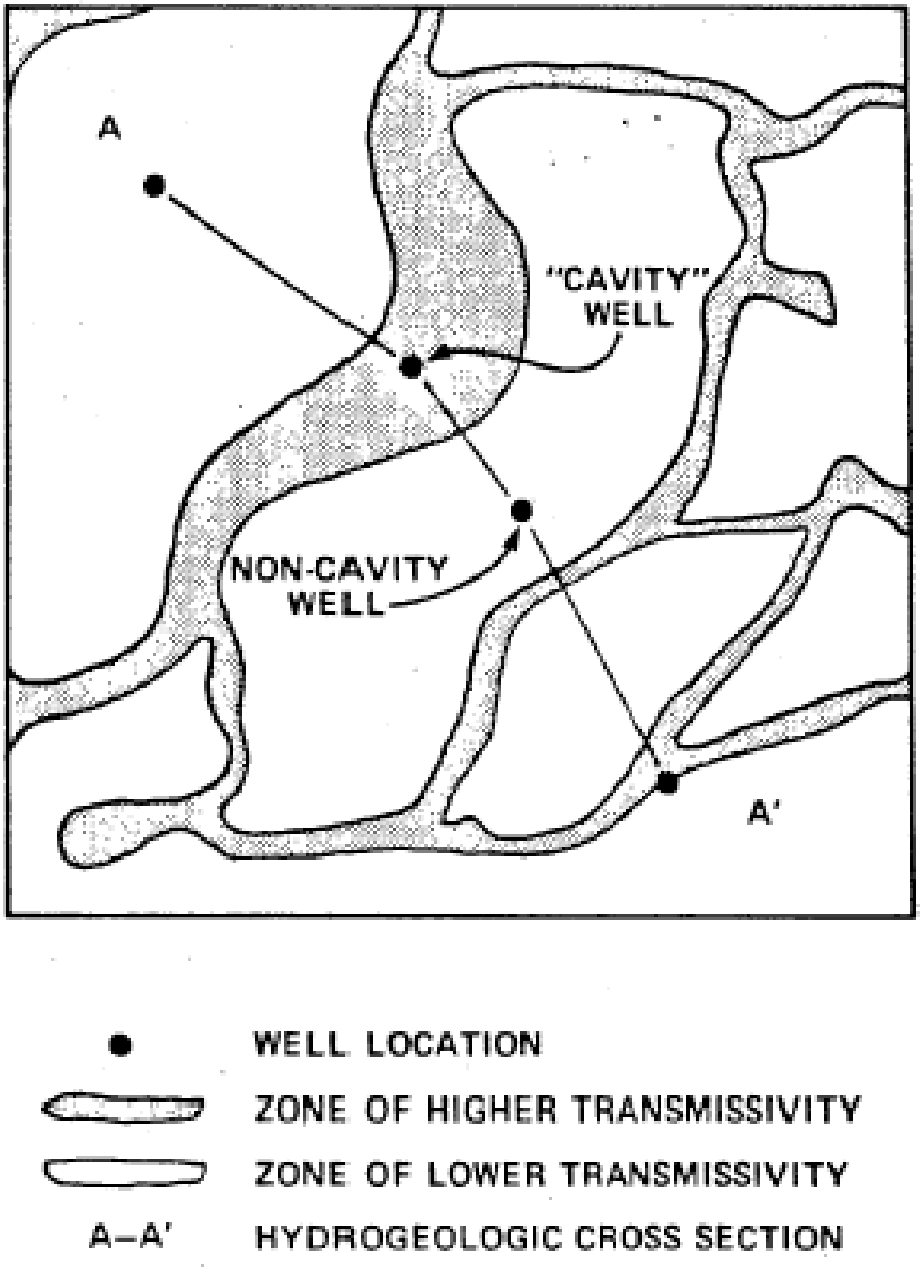
> "***It was concluded that the conceptual model that most satisfactorily explains the observations is one of a vertically zonated double-transmissivity aquifer in which the majority of the aquifer has a relatively low transmissivity but contains a randomly oriented zone of high transmissivity. This high-transmissivity zone corresponds to the paleokarst system that was penetrated by the two cavity wells (M-2 and M-4). The following figures illustrate the general concept of such a system. The determination of aquifer properties from the test data was complicated by the lack of appropriate analytical models that describe such a double-transmissivity system. This concept of a high permeability-low permeability system, in hydraulic interconnection, has been verified by some computer model simulation. The simulation further showed the proximity of non-cavity wells to the cavity system overrides the usual distance-drawdown concepts.***" (Anderson & Kelly, 1982; p.14)

It is well known to geologists that leaching of soluble evaporate beds in the uppermost part of the Madison sequence of strata resulted in large voids which subsequently collapsed. The geologic term for the topography that developed over these features is "karst". Karst is characterized by sinkholes, caves, underground drainage, and thick breccias (broken rock rubble) associated with the collapsed voids. The karst zone at the top of the Madison is referred to as a "paleokarst" because it has been buried by younger strata. The foregoing description of the Madison aquifer by Anderson & Kelly indicates their thinking was influenced by the concept of known paleo-karst near the top of the Madison sequence and the associated solution cavities along the bedding planes of the rock, generally within a specific interval. Although they mention fractures as a factor in development of secondary openings in the rock, they fail to relate the fractures to the pattern in which the secondary openings developed. This is evident on Figures 6 and 7, copied from their 1982 report and reproduced below, which show the cavities as a randomly oriented cavern system.

In their report about Madison wells M-9 and M-10, Wester-Wetstein & Associates, Inc., "***Drilling, Construction, Development and Testing of the Madison M-9 and M-10 Water Supply Wells; Gillette Well Rehabilitation Project Phase II – Madison Wells***", prepared by Wester-Wetstein & Associates for the City of Gillette and the Wyoming Water Development Commission, July 1996; the concepts expressed by Anderson & Kelly are refined, as shown by Figure 1-6 of the Wester-Wetstein report, reproduced above as Figure 4.

As is discussed later in this report, the wells shown in the cavernous zone of Wester-Wetstein (1996) do not include all of the wells that exhibit highly linear flow response to pumping tests and relatively high specific capacity, i.e., hydraulic connection to the solution enlarged linear flow paths providing the high-capacity yields to the wells. Accordingly, the pattern of the "postulated cavernous zone" shown on the figure is misleading as to which wells are in hydraulic communication with the high-capacity flow zones and those that penetrate aquifer material outside of those zones.

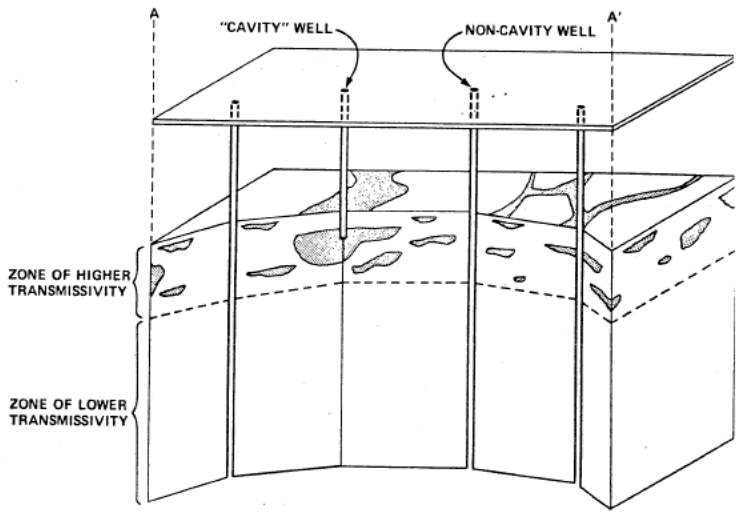
Figure 2: Reproduction of Figure 6 from Anderson & Kelly (1982).



RADIAL AND LINEAR FLOW RESPONSES

In order to appreciate the basis for the conclusions presented herein, it is necessary to understand the typical radial flow and linear flow responses of an aquifer as revealed by time-drawdown plots of the test data. Hydraulic responses for different types of flow in an aquifer are characterized by “type curves”. Type curves, also referred to as “diagnostic plots”, are plots of

Figure 3: Reproduction of Figure 7 from Anderson & Kelly (1982).



IDEALIZED HYDROGEOLOGIC CROSS SECTION A-A'

Figure 4: Reproduction of Figure 1-6 from Wester-Wetstein (1996).

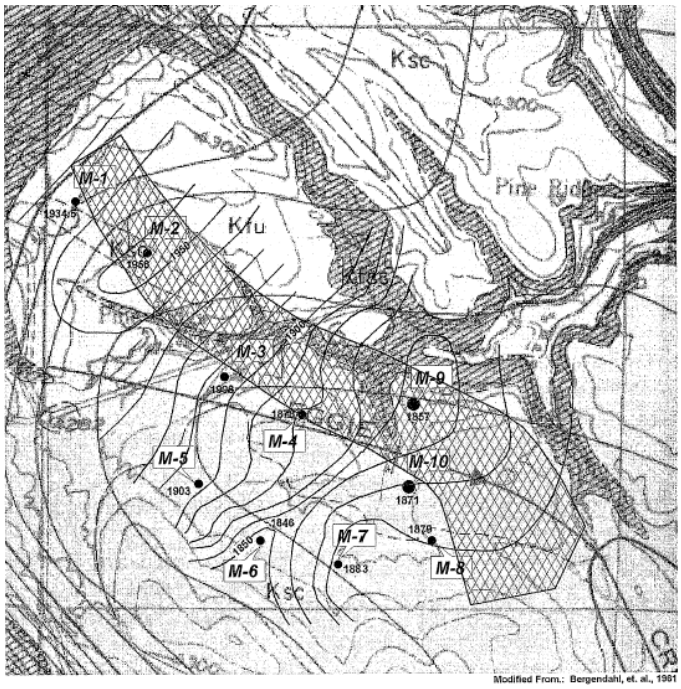


Figure 1- 6
Madison Well Field
Postulated Cavernous
Zone Location

drawdown versus time showing the responses to pumping that represent specific conditions in the physical properties of the aquifer. The time-drawdown relationships for various type curves are defined by mathematical equations referred to as "analytical solutions" or, more recently, "analytical models".

Figure 5 is the diagnostic log-log plot of drawdown versus time for radial flow. This plot is referred to as the Theis type curve and is based on the Theis equation (Theis, 1935), which was the first equation that took into account changes in groundwater storage related to pumping duration in order to mathematically describe transient drawdown conditions during rapidly changing drawdown early in a pumping test.

Figure 6 shows various elements of diagnostic plots of linear flow response to a pumped well compared to the diagnostic radial flow response. The principal diagnostic feature of a log-log, time-drawdown plot indicating linear flow is a log-log straight line. A straight-line time-drawdown response on a log-log plot is diagnostic of linear flow, no matter the slope of the line, with the exception of a unit slope line indicating uniform drawdown of storage for either linear or radial flow. The slope of the log-log straight-line for linear flow depends on the factors controlling the rate of drawdown in the linear flow feature.

The linear flow curves on Figure 6 start with a log-log straight line with a unit slope (one log cycle of drawdown for one log cycle of time). This may be a linear or radial flow response and occurs as the result of casing storage effects in pumped wells penetrating both radial flow and linear flow aquifer conditions. The unit slope results from drawdown of well casing storage or drawdown of storage in a large natural void where drawdown is uniform throughout the void, i.e., drawdown in the void occurs with no hydraulic gradient developing through the void to the pumped well. If a hydraulic gradient develops to the pumped well in a geologic feature that includes large voids penetrated by the well, unit slope response will not occur. Instead, one of three potential log-log linear flow responses will occur, as shown on Figures 6 and 7.

Two of the three log-log linear flow responses are shown on Figure 6; the half unit and quarter unit slope responses. A less-than-quarter unit slope response is shown on Figure 7. All three diagnostic linear flow responses are characterized by a log-log straight line.

Linear flow responses occur in various situations in nature, including in unconfined alluvial valley aquifers bounded by less permeable bedrock walls. Such aquifers are referred to as "strip aquifers". The following discussion; however, is limited to linear flow in fractured rock. The term "fracture" is used for simplification throughout this discussion; however, fractures encompass several different types of discontinuities in rocks including joints, compression fractures, shear zones, and faults. In addition, voids in a rock mass often exhibit linear flow. For example, pumping tests of flooded underground coal mines have exhibited all phases of linear flow, followed by pseudo-radial flow response. The fractures providing high yields to the COG Madison wells are likely solution enlarged joints that include significant amounts of voids along their length, but which offer enough restriction to groundwater flow to pumped wells to develop a hydraulic gradient to those pumped wells. These features are referred to in the discussion of diagnostic curves simply as "fractures".

Figure 5: Diagnostic plot for radial flow response to a pumped well.'

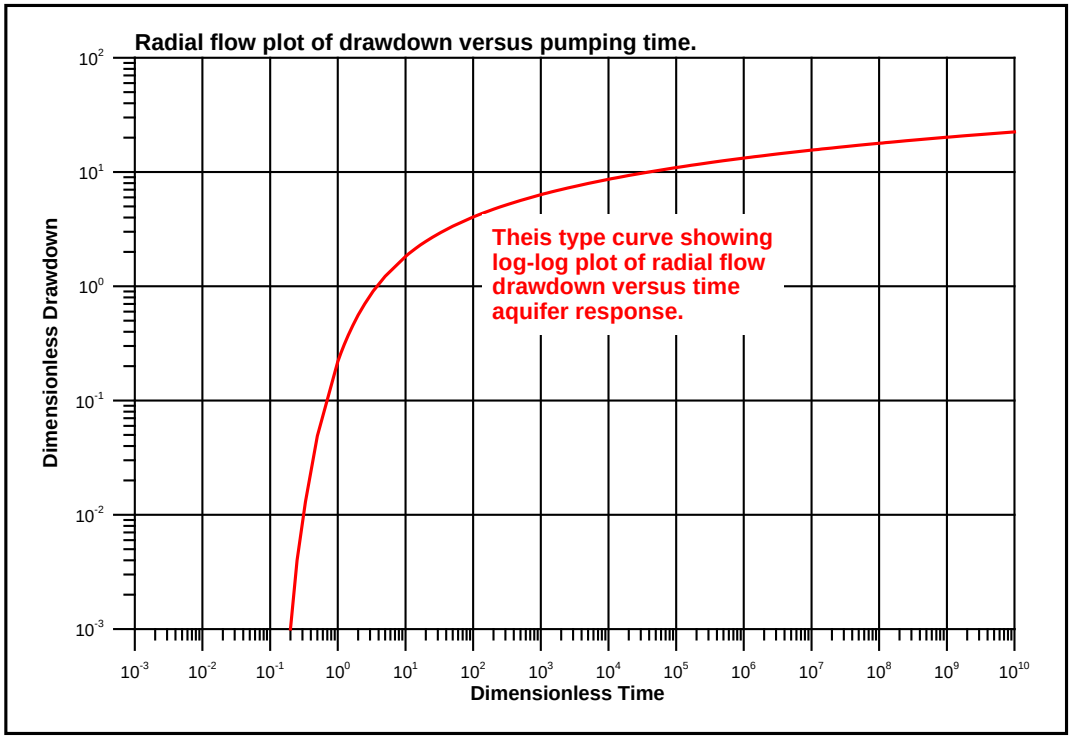


Figure 6: Conceptual comparison of radial and linear flow to a pumped well.

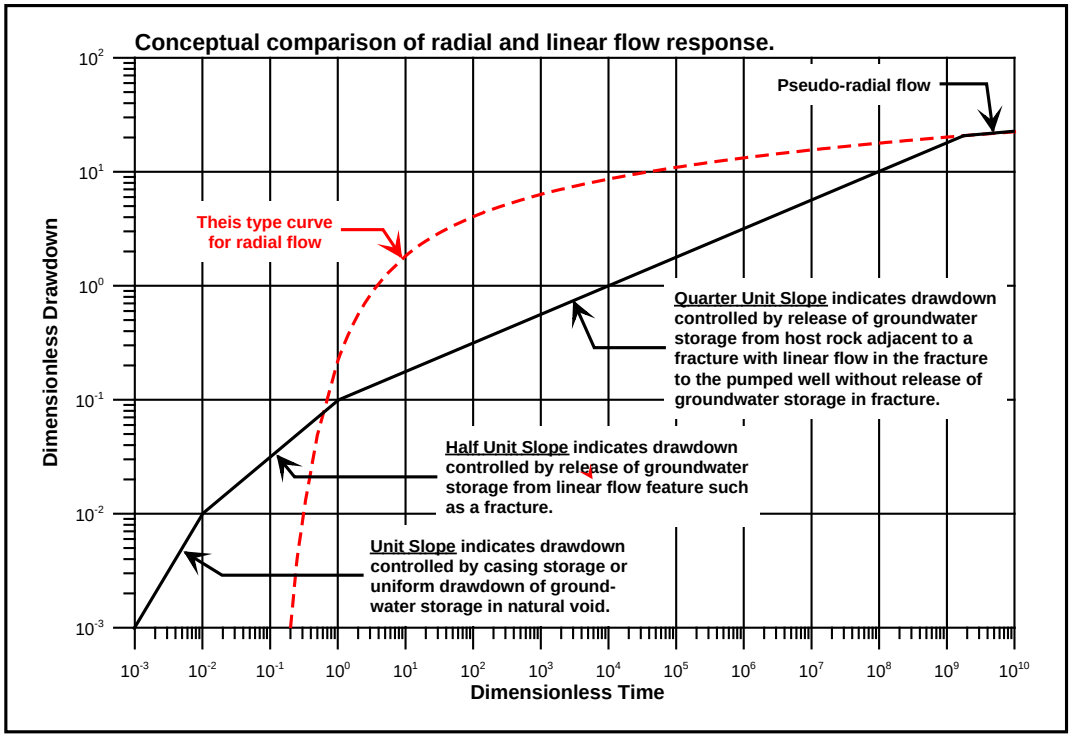
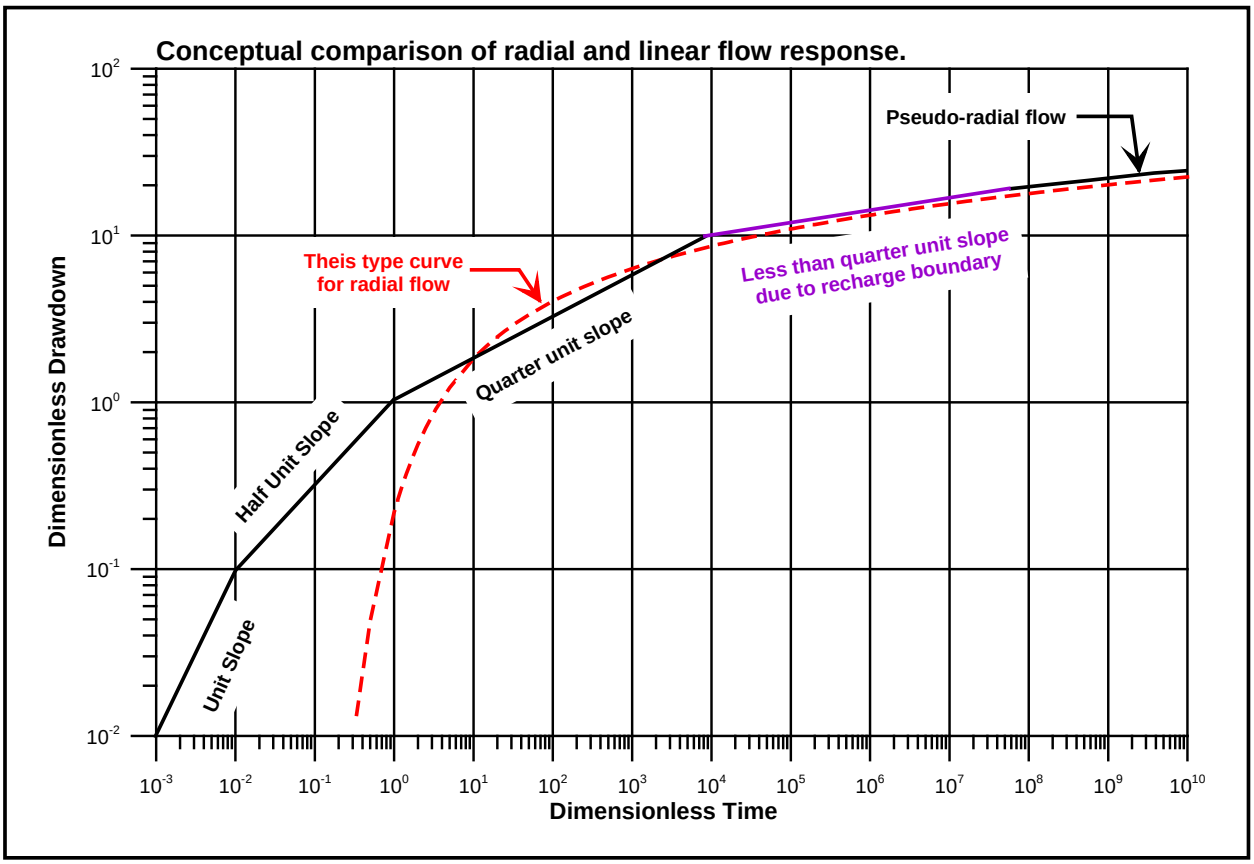


Figure 7: Linear flow to a pumped well affected by a cross-cutting recharge boundary.



The first stage of linear flow response in highly bounded linear flow, such as that in a fracture, is often a log-log straight line with a half unit slope (one log cycle of drawdown for two log cycles of time) as shown on Figure 6. In this phase of linear flow, the rate of drawdown is controlled by the release of groundwater storage from the pumped fracture or shear zone. The fracture not only provides groundwater storage, but a hydraulic gradient develops in the fracture to the pumped well, i.e., drawdown is not uniform as in a planar fracture and the fracture has storage properties unlike a planar fracture which has no storage. These are important considerations because most of the published solutions for linear flow, based on petroleum reservoir mathematics, are for planar fractures, particularly those solutions available at the time the COG Madison wells were tested, and do not apply to the Madison aquifer conditions. The half unit response is referred to in the literature as “linear” flow.

The next stage of linear flow response is a log-log straight line with a quarter unit slope (one log cycle of drawdown for four log cycles of time), as shown on Figure 6. This response indicates that the rate of drawdown is controlled by the release of groundwater storage from the rock hosting the fracture. The flow of groundwater released from the host rock is perpendicular to the fracture, i.e., linear to the fracture. Accordingly, the linear flow to the fracture combined with the linear flow along the fracture to the pumped well is referred to in some of the literature as “bilinear” flow. In this type of response, the rate of drawdown is controlled by the rate of

groundwater storage release from the host rock and the fracture is merely a conveyance system to the pumped well. Obviously, if the host rock is impervious and will not release groundwater from storage, this phase of linear flow will not occur. If it does occur, the host rock is transmissive and may yield groundwater to wells that do not penetrate the fracture system, albeit at a lower yield and/or smaller specific capacity than wells penetrating the fracture.

A variation on the quarter unit slope log-log straight line is a log-log straight line with less than a quarter unit slope. This response generally reflects the influence of cross-cutting fractures acting as a recharge boundary. Drawdown expands along a linear flow feature such as a fracture at a half unit or quarter unit slope rate of drawdown until it reaches the cross-cutting feature which provides an additional source of release of groundwater storage into the pumped fracture. The additional groundwater storage released into the pumped fracture does not act as a constant head boundary because drawdown expands into the cross-cutting source of groundwater storage, but the net effect is that the rate of drawdown in the pumped fracture becomes less than a quarter unit slope while the response remains a log-log straight line. This response is shown on Figure 7 where the less-than-quarter unit slope line and the subsequent pseudo-radial flow response are intentionally shown in close juxtaposition to the radial flow type curve. This juxtaposition demonstrates that it is often easy to mistake linear flow for a recharge boundary response in radial flow, particularly if the less-than-quarter unit slope transitions into pseudo-radial flow during the test.

If the duration of bilinear flow, or quarter unit slope response is sufficiently long, the quarter unit slope response will make a transition into pseudo-radial flow, as shown on Figures 6 and 7. Pseudo-radial flow is the result of a drawdown expanding out from the depressurized fracture into the host rock such that an elongate or oval “cone of depression” develops in which the flow to the fracture is no longer perpendicular to the fracture at distance. In other words, the fracture begins to mimic a large-diameter well. In this case, a plot of the late time, pseudo-radial portion of the test data will also plot as a semi-logarithmic straight line. A semi-logarithmic straight line response is a diagnostic special case of radial flow referred to as the modified Theis nonequilibrium equation or the Cooper-Jacob solution (Cooper and Jacob, 1946). In practical terms, the basis for the Cooper-Jacob plot is that the late part of the log-log Theis type curve shown on Figures 5, 6 and 7 is changing so slowly that it can be represented by a semilogarithmic straight line. Pseudo-radial flow is shown as the last phase of the linear flow response on Figures 6 and 7. Again, this phase of the response will not occur unless the rock containing the fracture is capable of releasing groundwater storage to the fracture. If a quarter unit slope response is observed during a pumping test, it is an indication that pseudo-radial flow will likely occur at late pumping times.

The foregoing presentation of linear flow responses is idealistic. In actual pumping tests, the linear flow responses are seldom as clear cut as depicted in this conceptual presentation. Very seldom do all phases of linear flow response occur in a single test. Fractures in hard crystalline rock such as granite may start with a half unit slope response and maintain that response until drawdown in the well reaches the pump inlet and the pumping rate is impaired. Depending on the hydraulic properties of the pumped fracture and the porous host rock, the half unit slope response may be too fleeting to detect and the response may transition into a quarter unit slope response early in the pumping test. In almost all cases, the transition from one type of response to the next is not clear cut and abrupt as shown on Figures 5, 6 and 7. Instead, the transitions are slow and represented by curved lines on the log-log plot.

In theory, all linear flow features should exhibit an initial stage of radial flow response until the "cone of depression" or drawdown around the pumped well reaches the lateral boundaries of the linear flow feature. In reality, the theoretical period of radial flow is generally too fleeting to detect; however, as the width of a linear flow feature increases, radial flow duration increases and becomes easier to detect. In wide alluvial valleys bounded by relatively impermeable rock (strip aquifers), radial flow may last hours or days before the transition into linear flow response occurs. In large shear zones, radial flow is often detected in the early response of a pumping test, prior to a transition into linear flow after the drawdown reaches the boundaries at the lateral limits of the shear zone. Accordingly, a radial response in a fractured rock aquifer followed by linear flow response is indicative of highly fractured materials within a relatively broad linear flow zone, such as a large shear zone or an elongate zone of breccia, capable of supporting a radial flow pattern to the well until the drawdown expands to the lateral boundaries of the highly fractured material and linear flow ensues.

MADISON WELL RESPONSES

Ultimately, the layman to pumping test analysis does not have to understand much more than that the diagnostic plot for radial flow on a log-log graph is a curve whereas the diagnostic plot for linear flow is a straight line on a log-log graph. Using these basic principles, the reader can appreciate the following interpretive plots of the pumping test data from the COG Madison wells and readily distinguish between wells exhibiting linear flow response versus radial flow response.

An additional concept that applies to interpretation of time-drawdown data from the pumped wells (as compared to observation wells) is that of "well loss". Well loss is the amount of drawdown that occurs in a well due to head loss associated with the flow of water through the formation near the well and through the openings into the well. A number of factors contribute to well loss; however, collectively the well loss is the differential in head or pressure that must exist between the water level inside of the well and the water level in the aquifer outside the well to cause water to flow into the well at the desired rate. The well loss drawdown is subtracted from drawdown observed in the pumped well to correct drawdown to the level of water in the aquifer outside the area of well loss around the well. In the following examples, semi-logarithmic time-drawdown plots or drawdown versus square root of time are used to determine well loss at the prevailing pumping rates. Data corrected for well loss are plotted on a log-log plot and interpreted.

Radial Flow Wells

The response of the aquifer at well M-5 to constant rate pumping is affected by two complications. One complication is a significant amount of drawdown in the pumped well due to well loss, i.e., the differential head required to overcome resistance to radial convergence of groundwater flow in the area near the well. A second complication is that the pumping rate was increased from 250 gpm to 305 gpm at approximately 1,420 minutes, thus shifting the time-drawdown curve.

Figure 8 is a Cartesian plot of the time-drawdown data providing the clearest presentation that drawdown stabilized at the end of both the 250-gpm and 305-gpm pumping rates. The data shown on Figure 8 are corrected for the well loss drawdown depicted on Figure 9. Well loss drawdown in well M-5 is significant and affects the shape of the diagnostic log-log plot. The

Figure 8: Cartesian plot of well M-5 time-drawdown response.

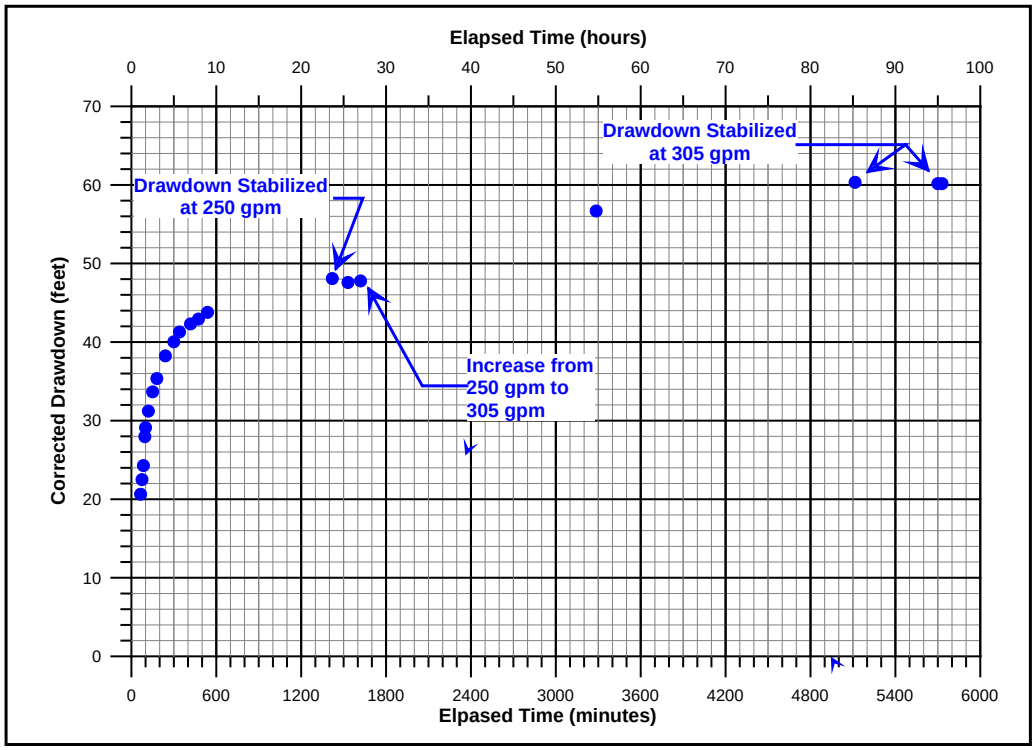
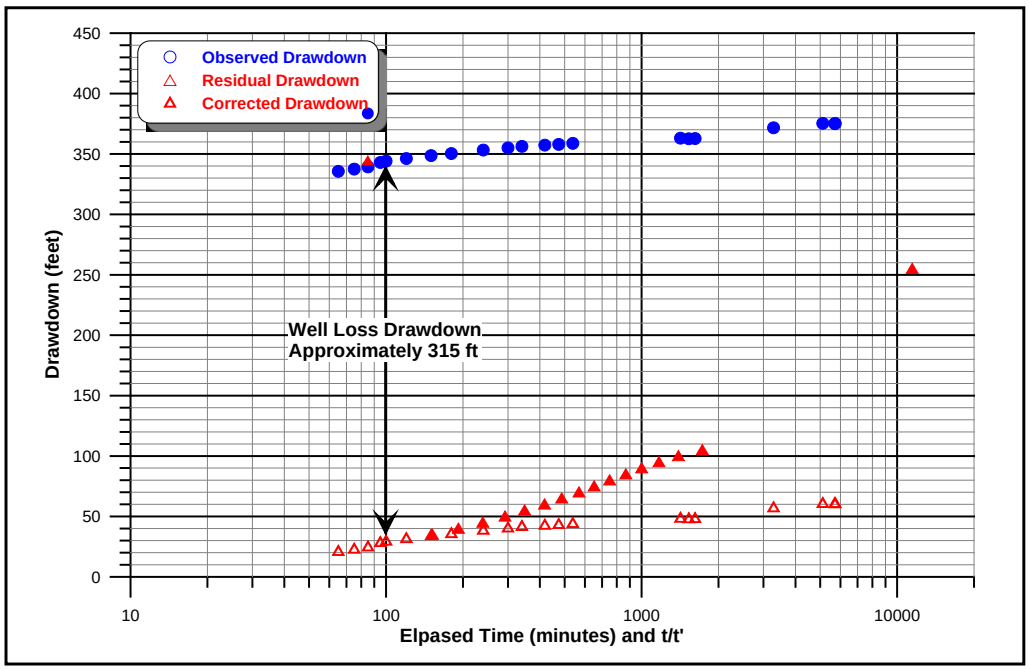


Figure 9: Well loss and drawdown corrected for well loss in well M-5.



estimation of well loss drawdown shown on Figure 9 is subtracted from observed drawdown to obtain corrected drawdown on Figures 8 and10.

Figure 11 is a Cartesian plot of the M-6 pumping test showing stabilized drawdown. Figures 12 and 13 are the diagnostic log-log plot and a specialized semi-logarithmic plot, respectively, both demonstrating radial flow response at well M-6.

Linear Flow Wells

Figures 14 and 15 show the plots for the test of well M-1 which reveal a linear flow response.

The aquifer response observed in well M-2 requires careful interpretation. The initial pumping rate was very high. Subsequent reduction of the pumping rate resulted in a fluctuation in the observed drawdown during the early part of the test. The fluctuation obscures most of the usable aquifer response obtained before water levels stabilized. A log-log straight line of quarter unit slope fits through the three corrected data points (Figure 16) between response to the fluctuation in discharge rate and stabilization of drawdown in the later part of the test. The log-log straight-line through the intermediate data indicates a linear flow response, despite the paucity of useable data. This is consistent with the high specific capacity of the well and the fact that the well penetrated a void.

Figures 17 and 18 show correction of the M-3 data for well loss and a two-part linear response, initially with storage released from the fracture and later with storage released from the rock hosting the fracture (quarter unit response).

Figure 19 shows an alternative method of determining well loss. A plot of drawdown versus the square root of elapsed pumping time is a specialized plot on which linear flow appears as a straight line through the origin of the graph. Well loss in a single-well test shifts the straight-line plot away from the origin. Therefore, shifting the plot back to the origin of the graph provides the drawdown corrected for well loss. The data on Figure 19 are corrected for well loss and then plotted on Figure 20 which shows linear flow with release of groundwater from storage in the rock adjacent to the fracture.

Figures 21 and 22 show a similar correction to the test for well M-8; however, the late response exhibits a less-than-quarter-unit response indicating the segment of fracture penetrated by the well has restricted hydraulic connection to a more distant part of the fracture which acts as a partial recharge boundary. This well would benefit from hydraulic fracture stimulation, assuming the casing is large enough to accept larger pumping equipment.

Figure 23 shows uncorrected and corrected time-drawdown data for well M-10. The corrected data reveal a pressure surge at the beginning of the test followed by a quarter unit slope response. The data reflect various influences during the course of the test, but are diagnostic of linear flow. External influences at the end of the test, perhaps from another pumping well, obscure stabilization of the drawdown; however, there is a suggestion that it did occur.

Figure 10: Theis solution for aquifer transmissivity at well M-5.

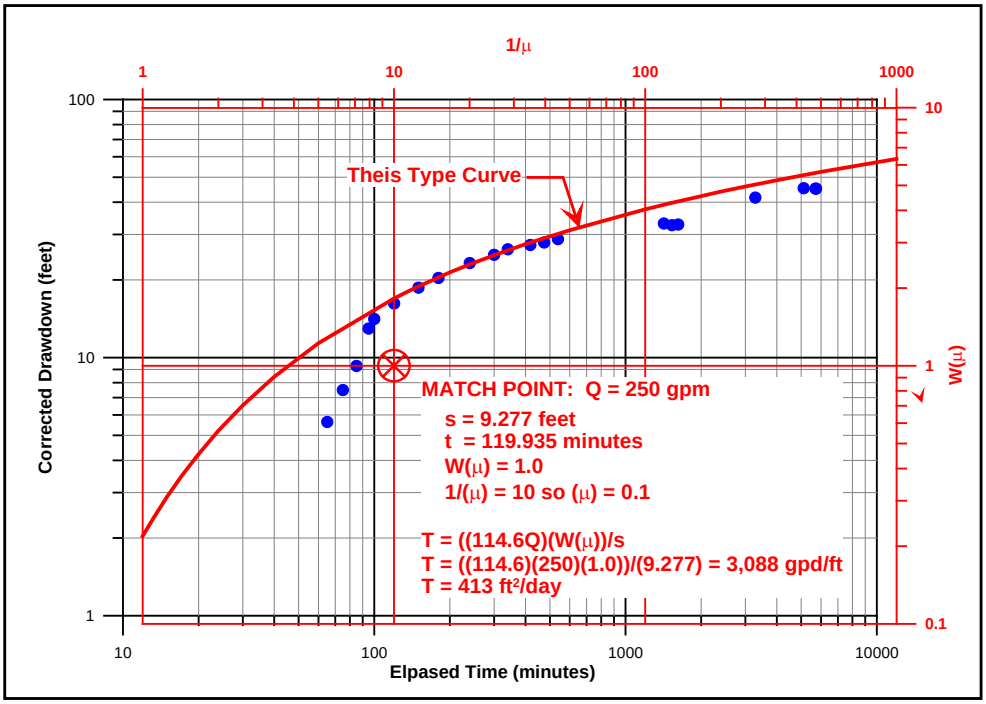


Figure 11: Arithmetic plot of well M-6 data showing stabilized drawdown.

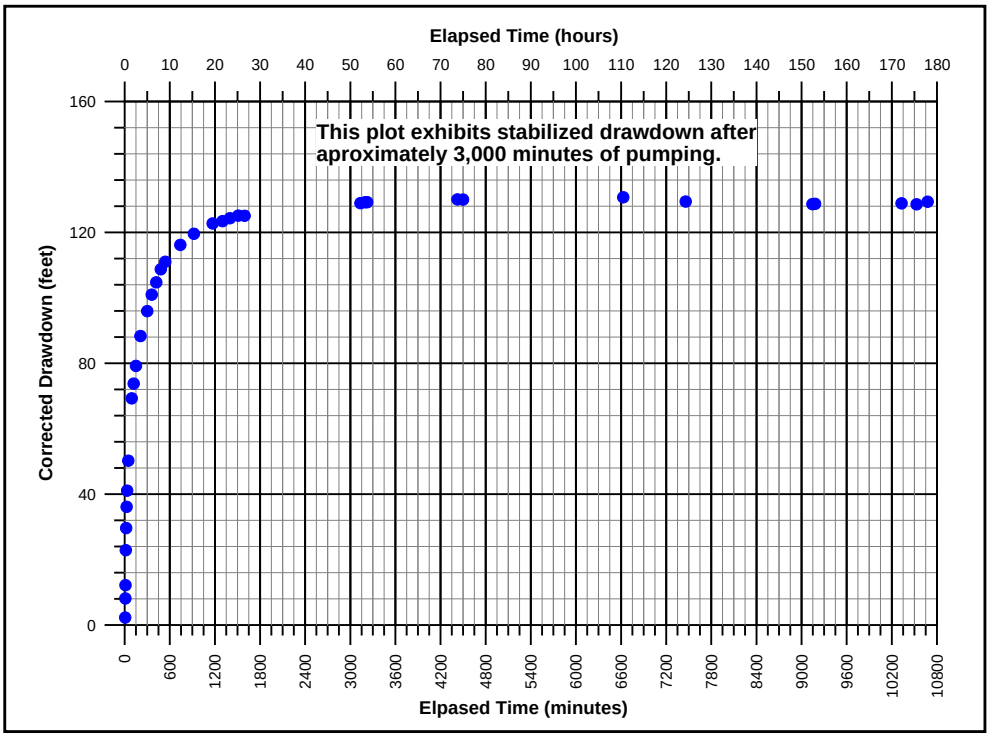


Figure 12: Log-log time-drawdown plot of well M-6 constant rate test.

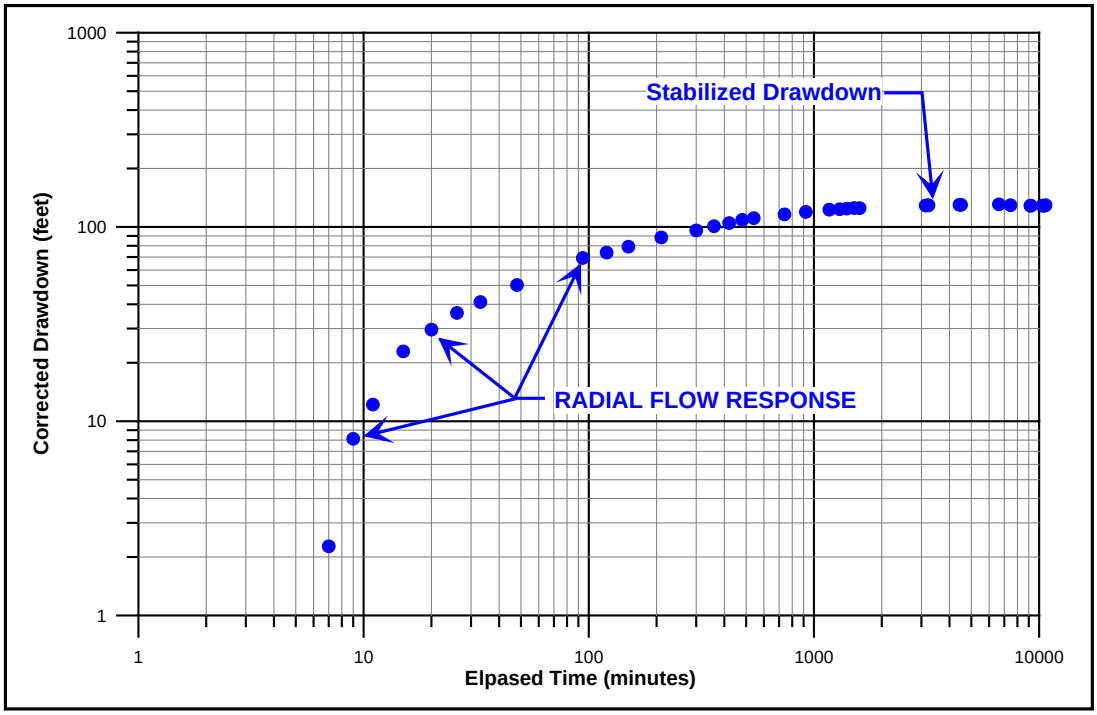


Figure 13: Cooper-Jacob solution for well M-6 constant rate test.

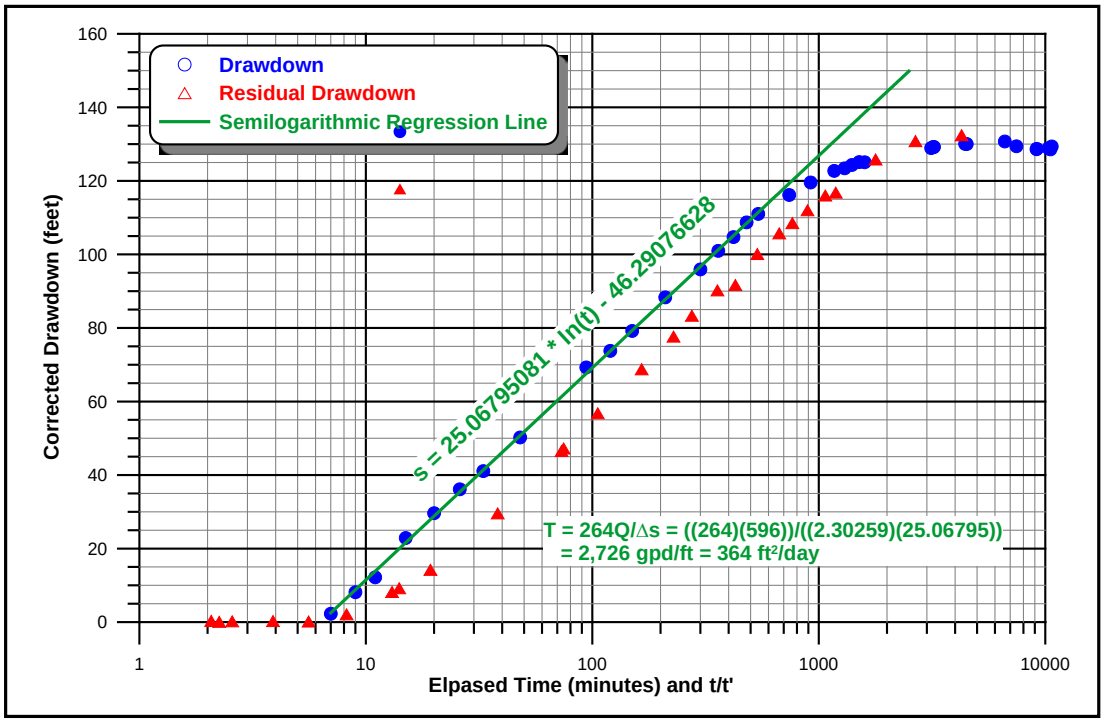


Figure 14: Specialized plot used to determine well loss for well M-1 at 636 gpm.

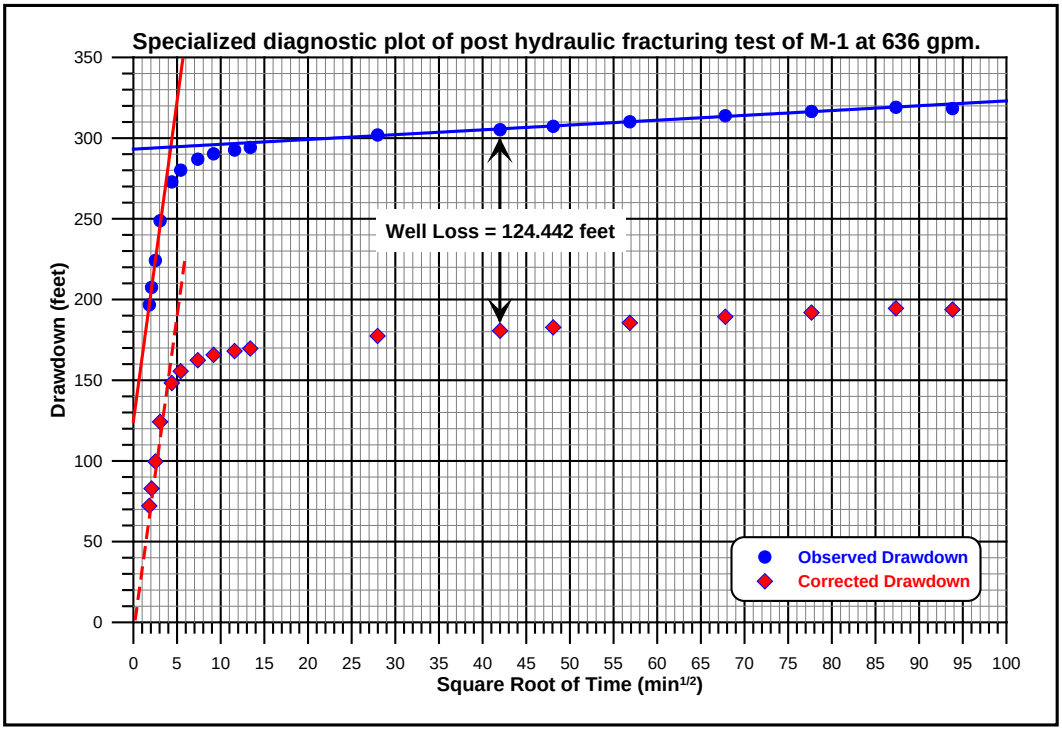


Figure 15: Diagnostic plot of linear flow at well M-1 during 636-gpm test.

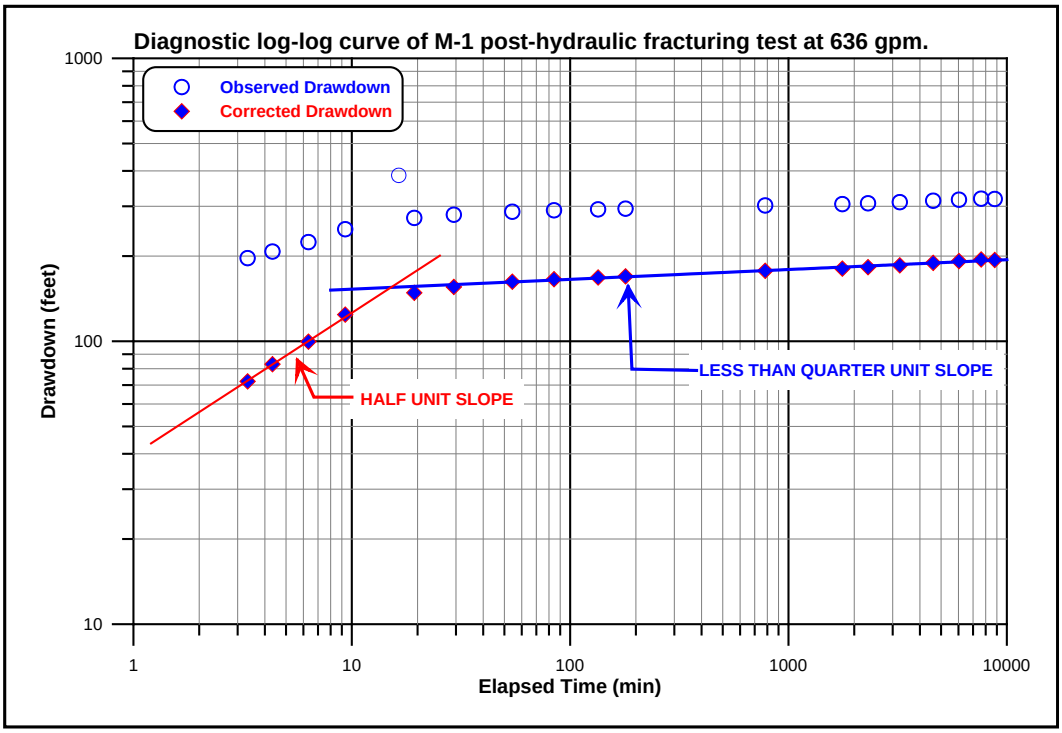


Figure 16: Log-log plot of 600-gpm test data from well M-2.

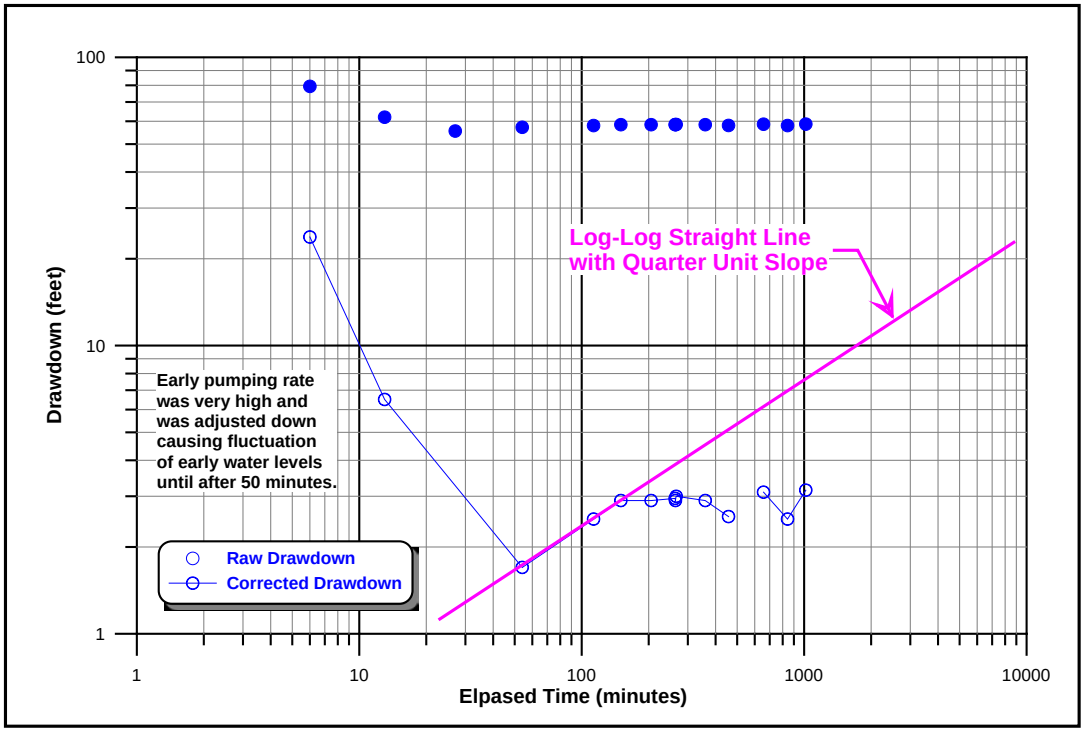


Figure 17: Pre-frac test of well M-3 with residual drawdown and well loss.

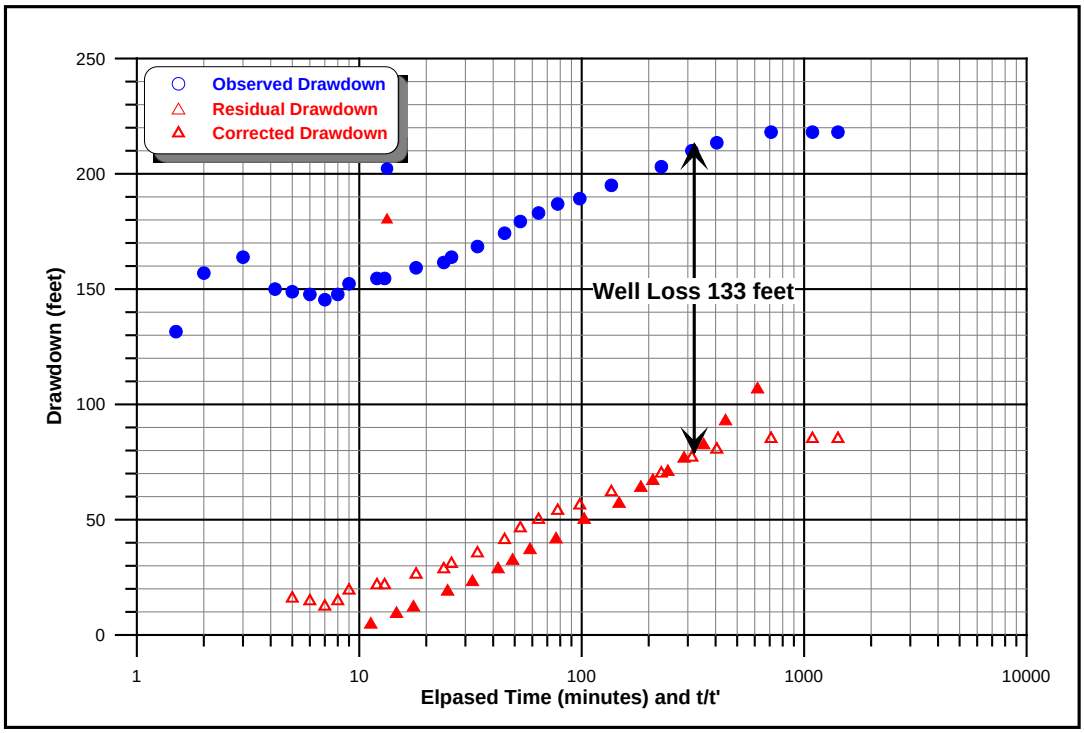


Figure 18: Diagnostic log-log plot of corrected pre-frac drawdown at well M-3.

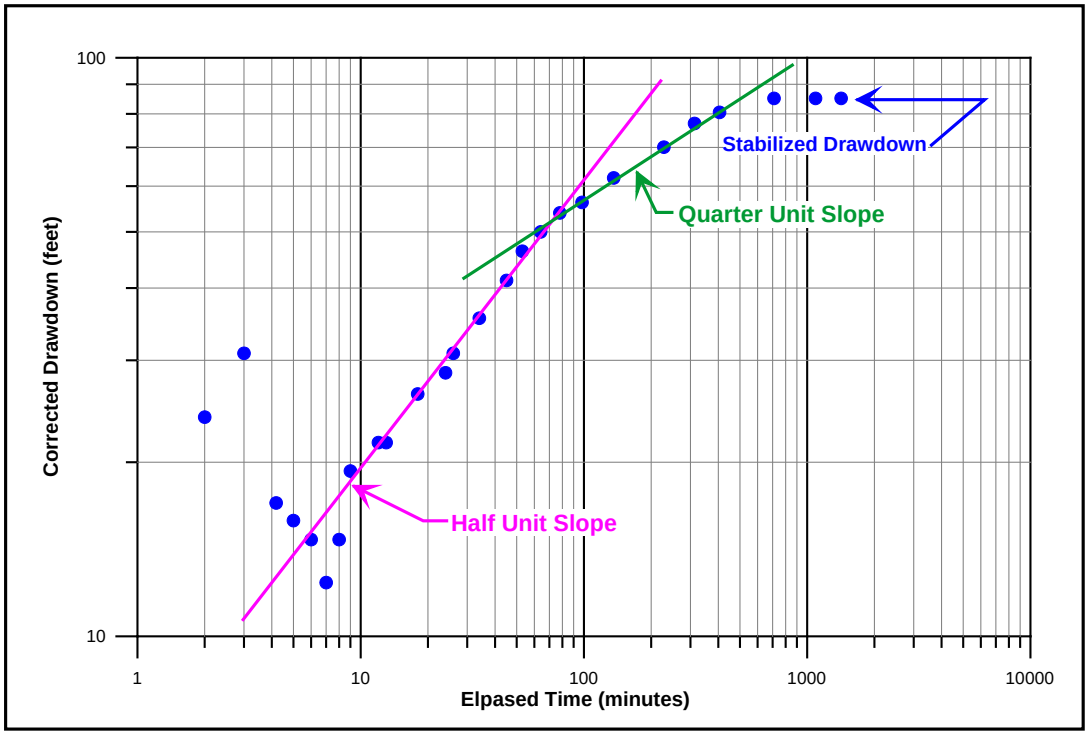


Figure 19: Plot of drawdown versus the square root of time for well M-4.

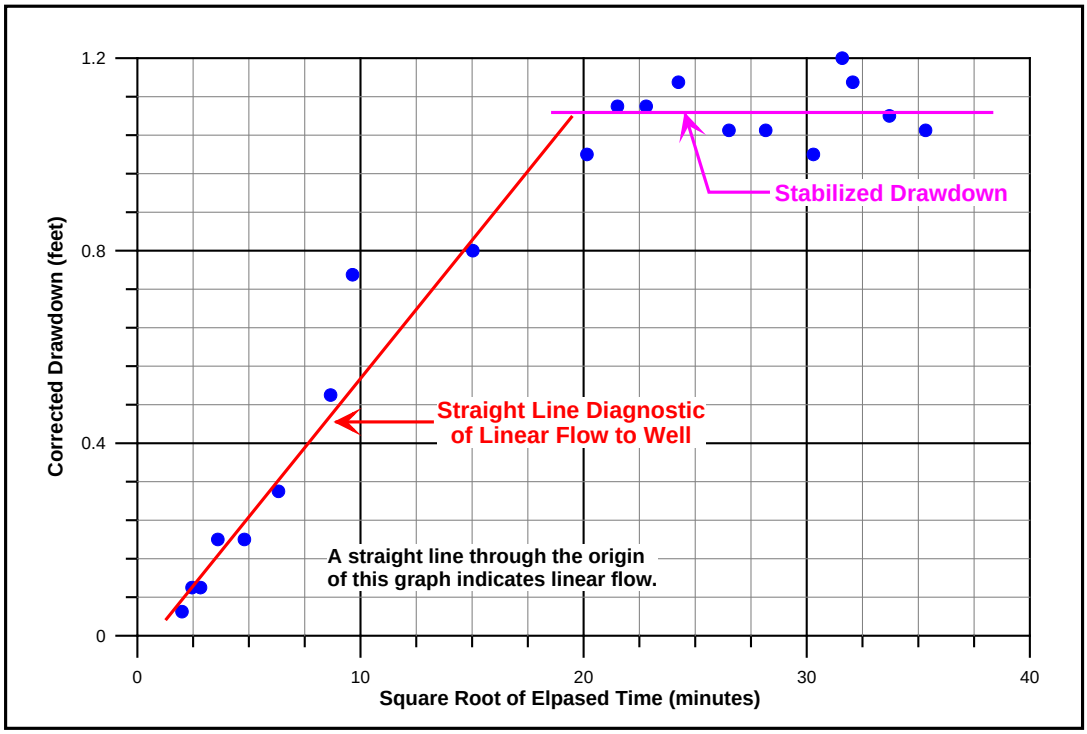
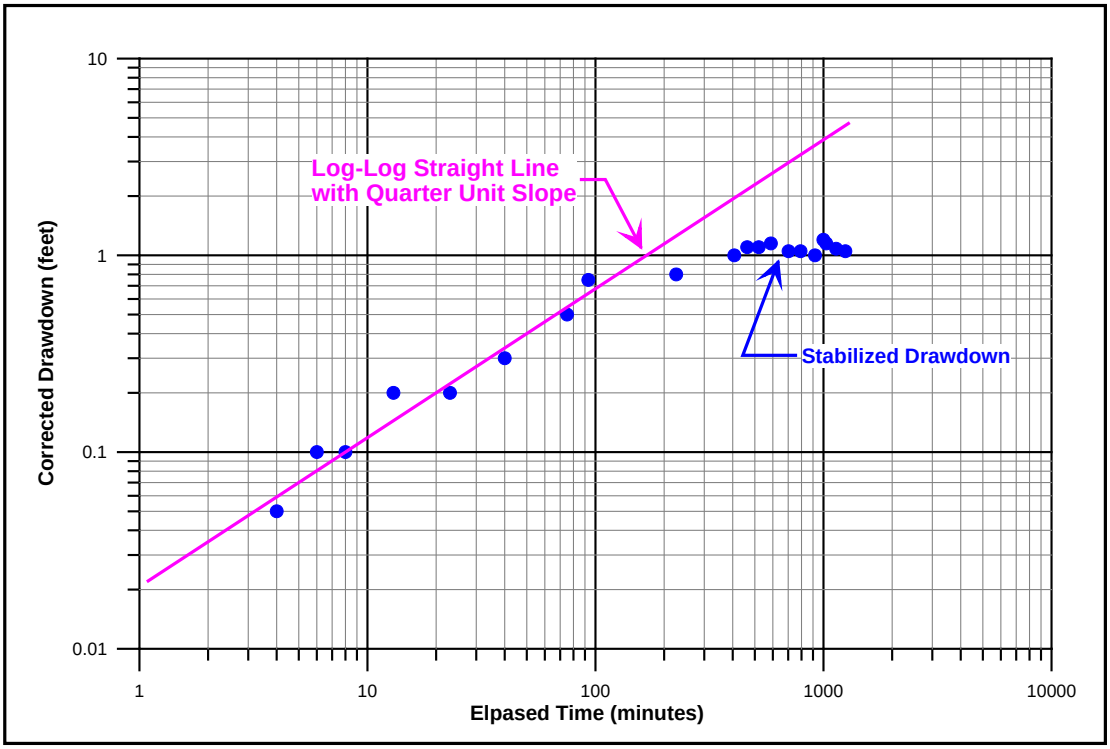


Figure 20: Diagnostic log-log plot for well M-4 at 656 gpm.



The foregoing wells all exhibit linear flow response indicated by the diagnostic log-log straight-line plots. Wells M-2, M-3, and M-4 exhibit stabilized drawdown in the last part of the tests. Well M-8 does not exhibit stabilized drawdown at the end of the test as indicated by the data plotted on Figure 21. Even after the test pump was turned off for a significant amount of time, resumption of pumping results in drawdown that has not stabilized at the end of the test as indicated on Figure 21.

Linear and Radial Response at Well M-9

Drawdown measurements in pumped well M-9 during the 1150-gpm test of that well did not provide sufficient resolution to distinguish between well loss and aquifer drawdown so that a plot of corrected drawdown versus time could be made. The recorded measurements indicate drawdown stabilized after the first two minutes of pumping and the residual drawdown data show a slow increase in residual drawdown throughout the recovery period, obviously the effect of an external influence, since the well should have exhibited recovery of water levels after the test pump stopped. Observations taken at other wells during the test, of course, reveal ongoing drawdown and recovery as expected; therefore, it is not reasonable that similar drawdown and recovery did not occur at the pumped well; however, the recorded data are not amenable to reliable analysis. Therefore, the interpretation of the test of well M-9 is based on the observations made in well M-10 while M-9 was pumped.

Figure 21: Specialized plot used to determine well loss for well M-8 at 503 gpm.

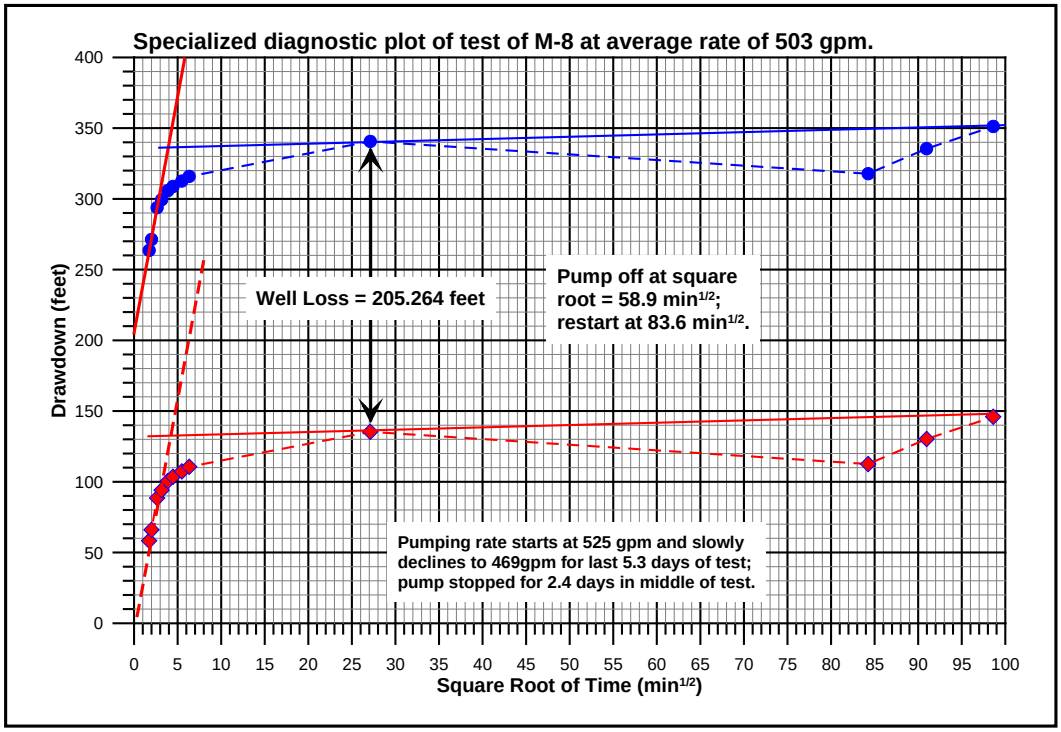


Figure 22: Diagnostic plot of linear flow at well M-8 during 503-gpm test.

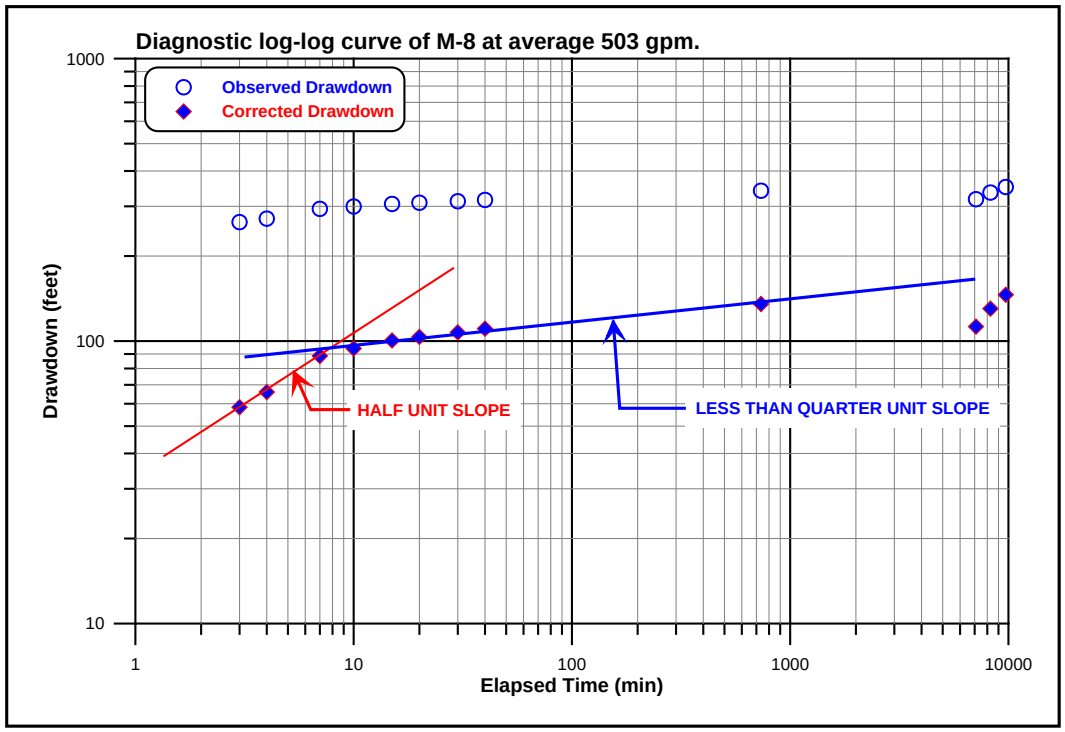


Figure 23: Diagnostic plot of linear flow at well M-10 pumped at 1150 gpm.

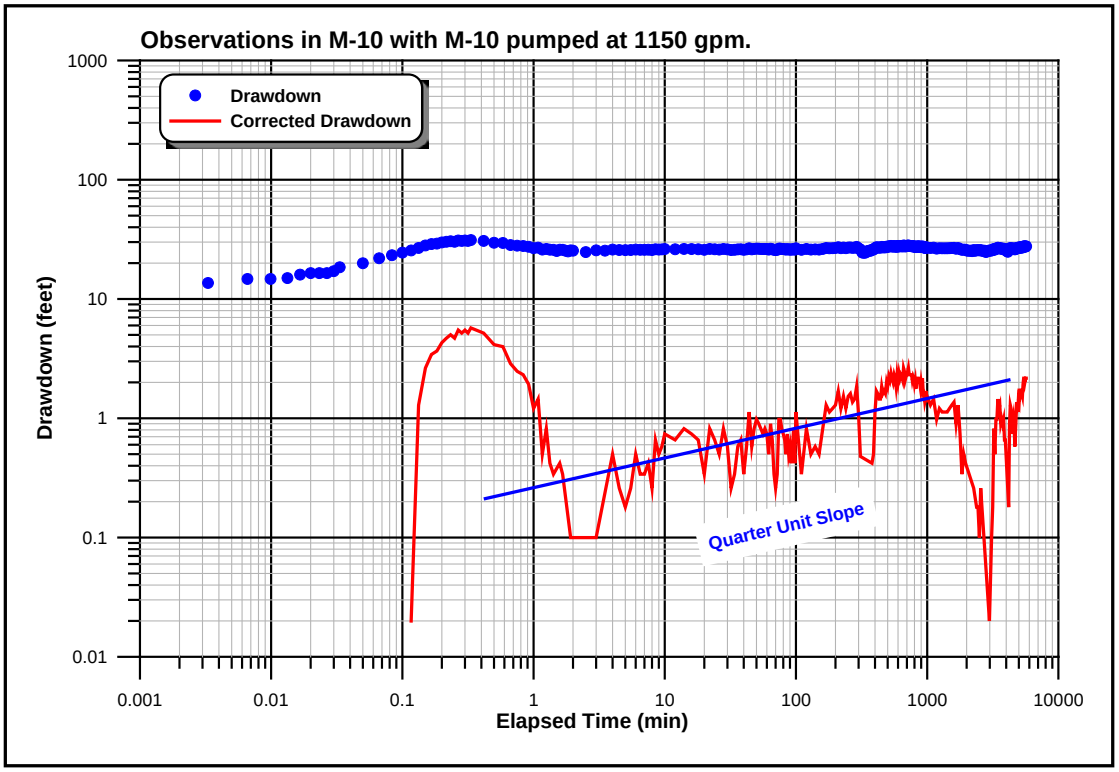


Figure 24 is a diagnostic log-log plot of the test data observed in well M-10 during the 1150-gpm constant rate test of well M-9. The purpose of the graph is to show the initial pressure wave due to surge when the pump was started. The pressure surge on Figure 24 is typical of an initially high pumping rate while an empty pump column fills followed by water hammer or surge when the column of water from the pump hits the throttling top of the pump column. An alternate, but less likely possibility is that the pressure surge resulted from an abrupt adjustment of an open throttling valve to reduce the initially high pumping rate back to the desired rate. As shown on Figure 24, the pressure wave from the surge dissipated in about five minutes. This response reflects the highly confined nature of the aquifer.

Figure 25, a diagnostic log-log plot, shows that the M-10 response to pumping M-9 after dissipation of the pressure wave is hard to interpret. The plot may define a log-log straight line diagnostic of radial flow or a log-log curve indicative of radial flow. Because this line is so hard to interpret on the log-log plot, a different type of plot is required to make a reliable interpretation. However, the data in the late part of the test clearly define a log-log straight line with a half unit slope, diagnostic of linear flow after approximately 1000 minutes of pumping.

Figure 26 is a Cooper-Jacob plot wherein a semilogarithmic straight line is diagnostic of radial flow. As shown on Figure 26, the data from observation well M-10 with well M-9 pumped at 1150 gpm describe a semi-logarithmic straight line from the time the initial pressure surge dissipates until about 300 minutes. From approximately 300 to 1000 minutes, water levels recover in response to an unknown influence on the constant rate test, followed by a highly

bounded flow response in the form of a diagnostic straight-line response with a half unit slope as previously shown on Figure 19. The Cooper-Jacob plot on Figure 26 indicates early radial flow followed by late linear flow.

Figure 27 is another type of specialized plot with drawdown plotted as an arithmetic value versus the square root of elapsed pumping time. A straight line through the origin of this type of plot is diagnostic of linear flow. The straight line may be displaced away from the origin by boundary conditions or, in this case, by the period of radial flow before the onset of linear flow. Figure 27 is consistent with the other diagnostic plots, showing a period of radial flow followed by linear flow. The linear flow on the log-log plot (Figure 24) exhibits a half unit slope indicating the pumped water during the linear flow part of the response was withdrawn from groundwater storage in the linear flow feature, not from the rock surrounding the linear flow feature.

Figure 28 shows the response of well M-9 when well M-10 is pumped at 1150 gpm. The observation well data from well M-9 exhibit the pressure wave from an initial surge when the pump starts as do the other tests in this aquifer. The pressure wave dissipates in approximately 10 minutes after which the time-drawdown data describe a semi-logarithmic straight line throughout the remainder of the test with interference effects from some other pumped well appearing after approximately 45 minutes of elapsed pumping time. Figure 28 also shows the residual drawdown data. A transient pressure wave developed when the pump stopped and dissipated over a period of time similar to the response to starting the pump. Aside from the pressure wave, the residual drawdown data describe a semi-logarithmic straight line parallel to the drawdown data. The vertical offset of approximately 0.9 feet between the drawdown and residual drawdown data appear to be the result of error induced during data collection.

The semilogarithmic drawdown and residual drawdown straight-line responses are diagnostic of a radial flow response at the M-9 well used as an observation well while well M-10 is pumped, even though the response in the pumped well, M-10 indicates linear flow response as indicated on Figure 23. The data on Figure 23 describing a quarter unit slope log-log straight line have been corrected for well loss so as to reflect only the aquifer drawdown at the pumped well. The quarter unit slope response in well M-10 indicates the linear flow feature was receiving water released from discharge in the adjacent porous rock, a fact seemingly inconsistent with the response when well M-9 was pumped, but which is explained when the significance of the response at well M-9 is understood. Interference with the test after slightly more than 700 minutes of pumping makes it impossible to know if the drawdown stabilized after 700 to 800 minutes of pumping or did something else; however, other factors discussed later suggest the drawdown most likely stabilized.

The relationships between the different aquifer responses when wells M-9 and M-10 are pumped indicate that although there is a hydraulic connection between the flow systems penetrated by the two wells, the two wells penetrate significantly different flow conditions. The yield and specific capacity of well M-9, combined with reported rod drops when the well was drilled, indicates the well penetrates a zone of high transmissivity enhanced by the presence of large openings through the limestone in the zone of groundwater flow to the pumped well. The onset of linear flow after approximately 1000 minutes of pumping indicates the pumped zone is very long with respect to its width and is bounded by relatively lower transmissivity material that acts as lateral boundaries, forcing the linear flow response after drawdown around the pumped well M-9 during radial flow expanded to the lateral boundaries. The persistence of the initial

Figure 24: M-9 pumped well data exhibiting pressure surge wave.

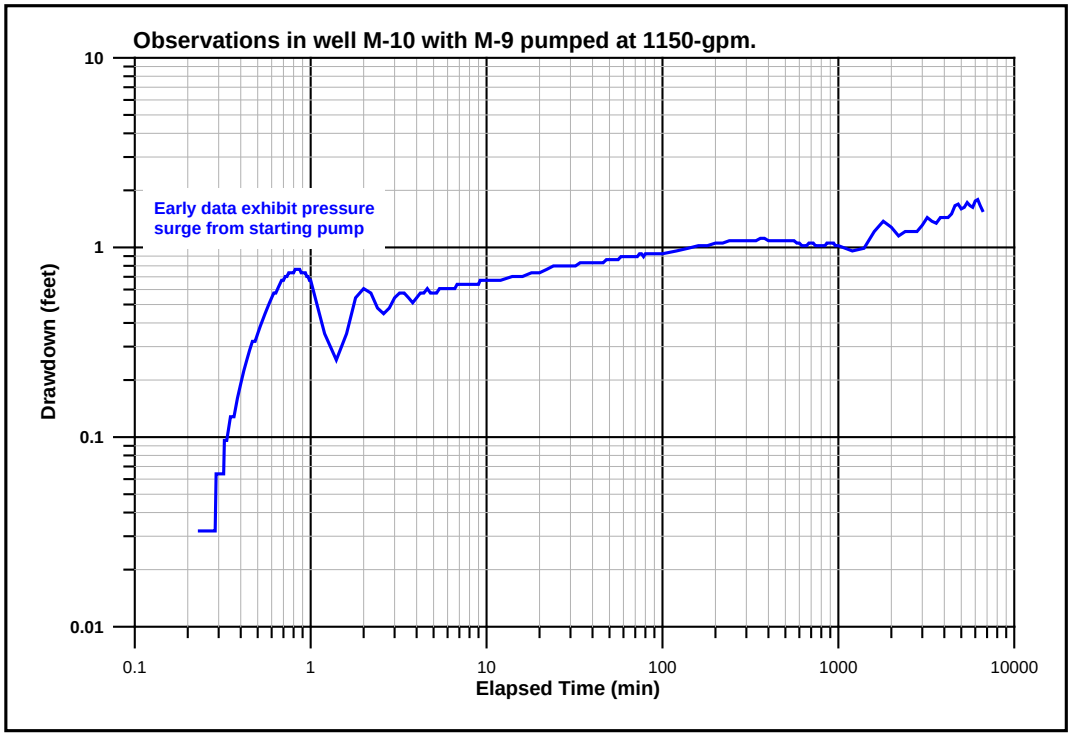


Figure 25: Log-log diagnostic plot of data from pumped well M-9 at 1150 gpm.

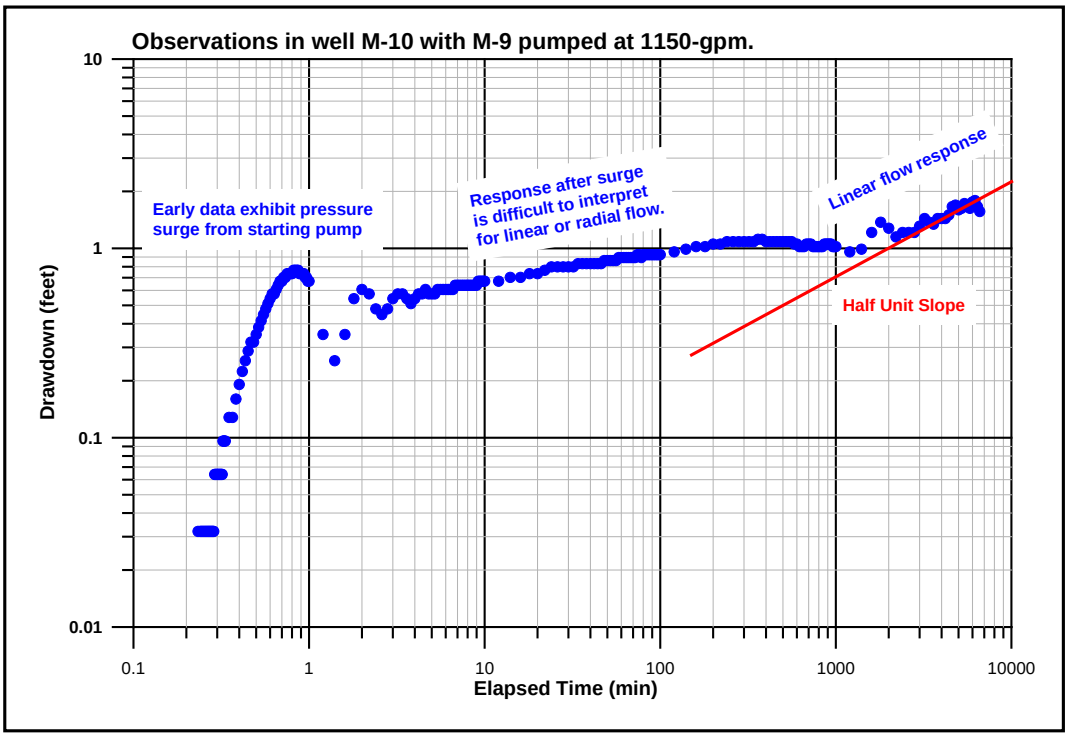


Figure 26: Specialized plot with straight line diagnostic of radial flow.

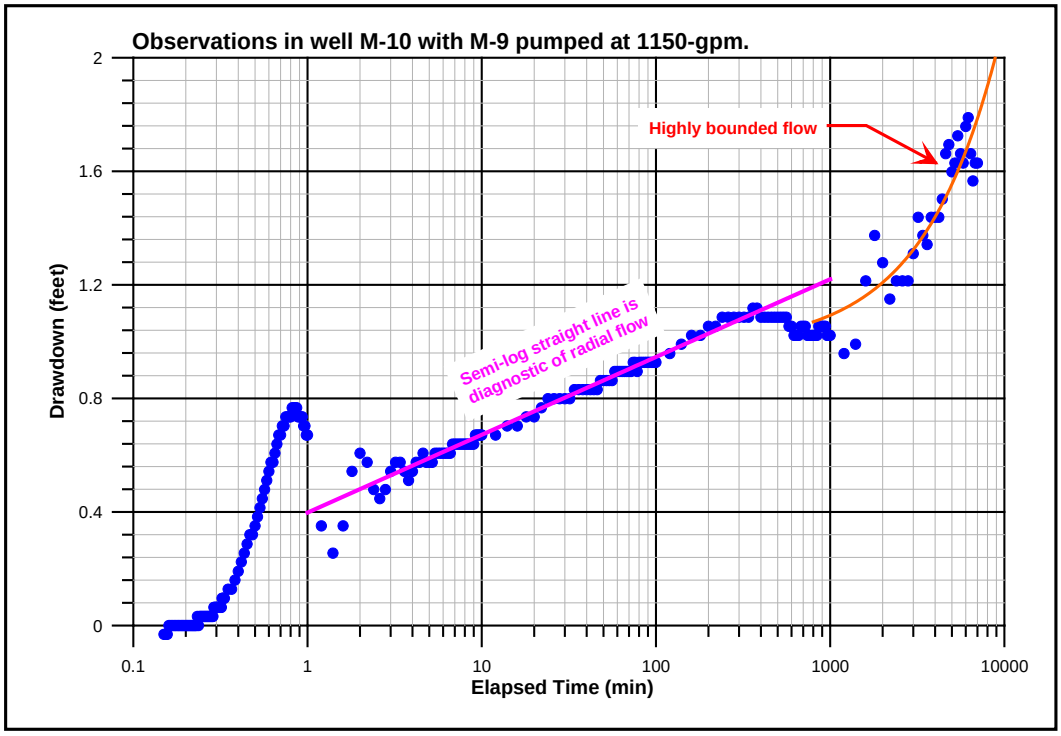


Figure 27: Specialized plot with straight line diagnostic of linear flow.

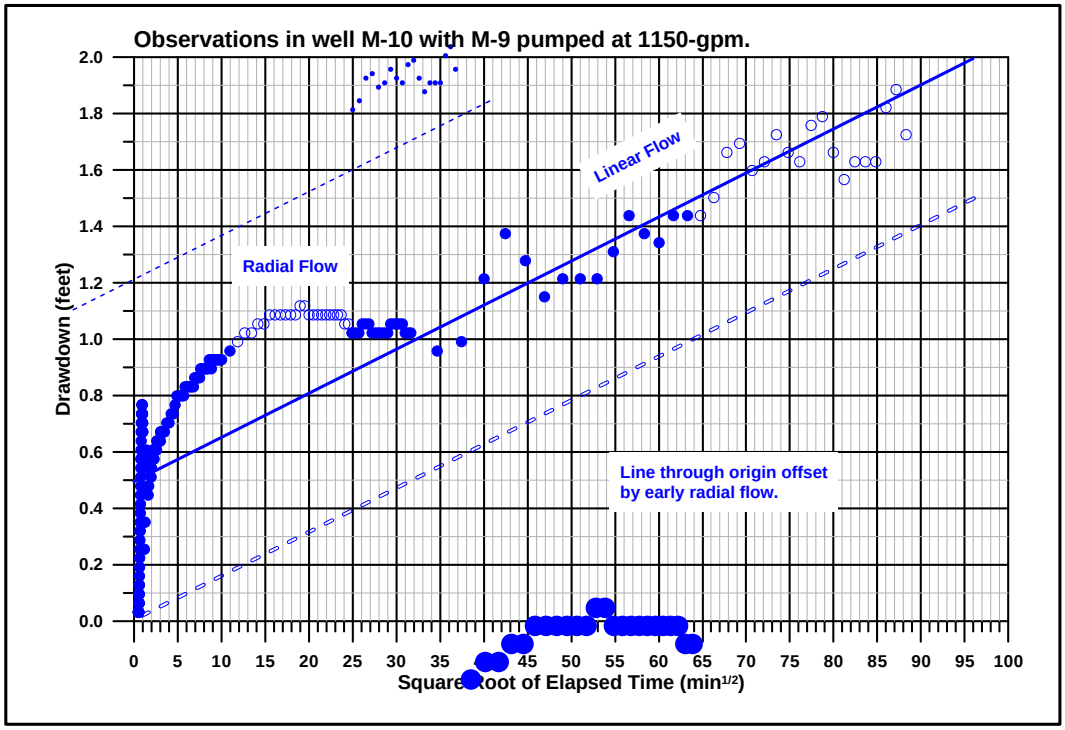
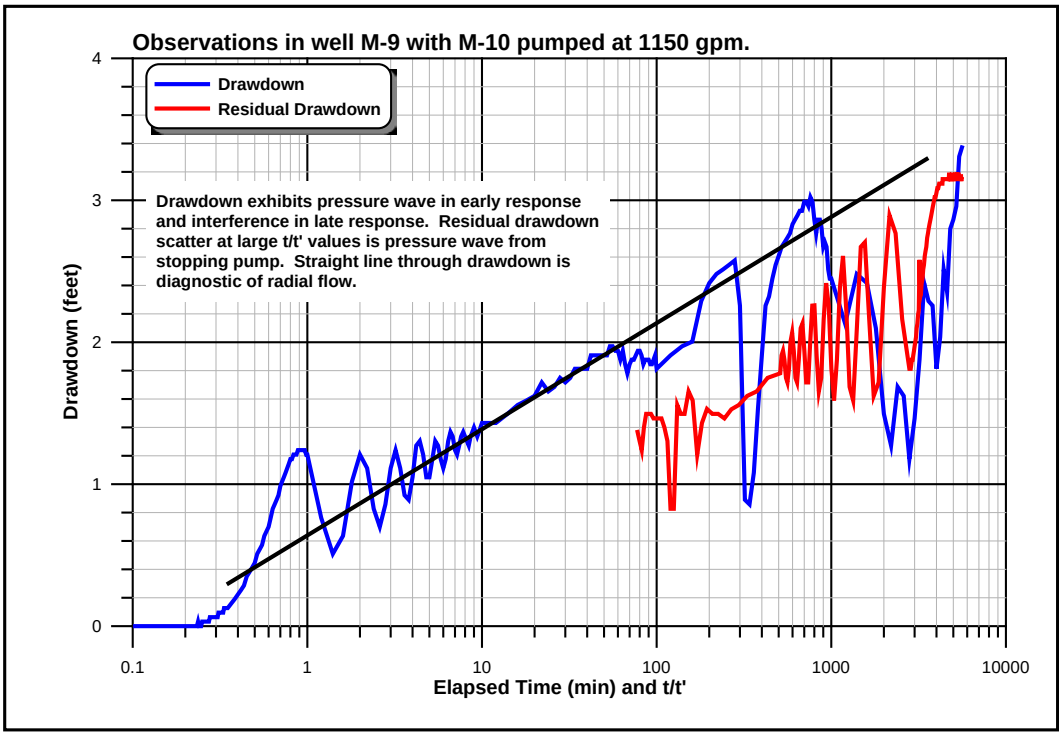


Figure 28: M-9 response to M-10 pumped at 1150 gpm.



radial flow response for approximately 1000 minutes of pumping well M-9 at 1150 gpm indicates the distance to the lateral boundaries is relatively large, allowing the radial flow cone of depression to expand for 1000 minutes before it became constrained by the lateral boundaries of the high transmissivity zone.

The geologic framework most likely to provide the M-9 aquifer response is a collapse breccia zone. Penetration of a collapse breccia zone is consistent with the observed rod drop while the well was drilled. A collapse breccia zone can provide the width necessary between lateral boundaries to support the 1000-minute expansion of a cone of depression during radial flow in the highly confined aquifer while offering the lateral boundaries and geometry necessary for the linear flow response to occur later in the aquifer test response. Accordingly, it is concluded that well M-9 penetrated a collapse breccia zone or some similar type of highly fractured rock zone which offers very different hydraulics compared to a solution enlarged fracture or narrow zone of densely fractured rock penetrated by the other wells exhibiting linear flow.

The fact that the M-9 well can provide radial flow in response to pumping at well M-10, which exhibits linear flow response, is consistent with a large collapse breccia zone, penetrated by M-9, hydraulically connected to a cross-cutting fracture or zone of closely spaced fractures penetrated by well M-10. Flow to the pumped well M-10 is controlled by the hydraulics of a long, narrow, linear flow feature whereas the relatively large collapse breccia zone responds to the withdrawal of groundwater by M-10 at the localized intersection with the M-10 fracture the

same way it would to a pumped well, providing a radial flow response, as observed in M-9 when M-10 is pumped.

This implies that the collapse breccia zone must act as a constant head recharge boundary to the fracture zone penetrated by well M-10, after the drawdown in the fracture zone extends from M-10 to the intersection between the collapse breccia zone and the fracture zone, causing stabilized drawdown at M-10. Interference with the data toward the end of the constant rate test of well M-10 obscures the aquifer response after about 700 to 800 minutes of pumping (Figure 23); however, a case can be made that the drawdown after that time stabilized as would happen if the collapse breccia zone acted as a constant head boundary throughout the remainder of the test.

BOUNDARY EFFECTS

All of the tests except those of wells M-1, M-8 and M-9 exhibit stabilized drawdown before pumping stops. The weakest case for stabilized drawdown is in well M-10 where interference from other pumped wells obscures the response defined by the late test data; however, all of the other pumping tests except those of wells M-1, M-8 and M-9 clearly show stabilized drawdown.

Wells M-1 and M-8 do not exhibit stabilized drawdown during their pumping tests because the fractures penetrated by those wells have poor hydraulic connection with the parts of the fracture providing high-capacity well yields. The hydraulic properties of the parts of the fracture penetrated by those wells prevented the drawdown from expanding far enough along the flow zone to encounter the intersection with the collapse breccias hypothesized at well M-9. Instead, the drawdown from wells M-1 and M-8 expanded to areas of better hydraulic properties in the fracture and the result was the less-than-quarter-unit slope response observed during the tests. Well M-9 does not exhibit stabilized drawdown because its drawdown is caused by release of groundwater storage that is at least an order of magnitude greater than groundwater storage in the adjacent porous carbonate aquifer rock.

The less-than-quarter-unit slope response in the late part of the M-1 and M-8 tests indicates these two wells penetrate parts of the linear flow zone alignment that offers lesser hydraulic properties than the parts penetrated by the other two wells, i.e., their yield and hydraulic performance are affected by non-uniform distribution of hydraulic properties along the fracture. However, the response to aquifer testing at well M-9 is of a different nature.

When well M-9 is pumped at 1150 gpm, the aquifer response observed at well M-10 is approximately 1000 minutes of radial flow followed by linear flow with a half unit slope response. When well M-10 is pumped at the same 1150-gpm rate, the aquifer at well M-10 exhibits a quarter unit response and well M-9 exhibits a radial flow response to the pumping at M-10. How can all of these ostensibly contradictory responses be possible in one aquifer system?

Initially, in the report titled, "***Long Term Water Supply, Level II Study***", (Morrison-Maierle and Burns & McDonnell, 2007), it was concluded that the stabilized drawdown represented the effects of vertical leakage into the Madison aquifer from another aquifer such as the Minnelusa Formation. In other words, the stabilized drawdown was concluded to indicate a leaky aquifer response. In a leaky aquifer response, vertical flow from an aquifer above or below the pumped aquifer "leaks" through the confining beds separating the two aquifers and enters the pumped

aquifer. The rate of leakage is very small per unit of confining bed surface area in the cone of depression because of the limited vertical permeability of the confining beds; however, as the area of the footprint of the cone of depression expands, the collective leakage over the entire area of the cone of depression eventually equals the pumping rate and drawdown in the cone of depression stabilizes.

The conclusion that the Madison aquifer is a leaky aquifer was reached before the aquifer test data from wells M-1, M-8, M-9 and M-10 were obtained and independently analyzed. The radial flow response observed at well M-9 and the absence of stabilized drawdown at wells M-1 and M-8 change this opinion. It is inherent in the M-9 radial flow response during as much as 1000 minutes of pumping at 1150 gpm that a relatively large cone of depression must have formed around this pumped well. Therefore, if any cone of depression or depressurized area in the Madison aquifer would provide enough surface area on the confining beds to obtain enough total flow of vertical leakage to stabilize drawdown, it would be the cone of depression developed around pumped well M-9 which would undoubtedly offer the largest cone of depression footprint on the confining beds for vertical leakage of any of the tests. However, the 1000-minute cone of depression resulting from radial flow response at pumped well M-9 did not stabilize during the pumping tests, a fact that can only indicate that stabilization of the drawdown in the other wells was not the result of vertical leakage and a leaky aquifer response.

In the absence of a leaky aquifer system as an explanation for the stabilized drawdown, an alternate explanation must be sought. In conventional analytical solutions to aquifer response to pumping, stabilized drawdown indicates either leaky aquifer effects, delayed yield in an unconfined system, or a constant head boundary. The Madison aquifer is a highly confined aquifer system that will not exhibit delayed yield – assuming a constant discharge rate is maintained. Dual porosity aquifer response can also provide what appears to be stabilized drawdown for short periods of time while the control of the rate of drawdown changes from storage in fractures to storage in blocks of porous rock surrounded by the fractures; however, dual porosity response is a radial flow response and is ruled out by the strong linear flow responses obtained in the tests of the Madison wells.

With leaky aquifer conditions, delayed yield, and dual porosity responses ruled out, the only remaining possibility to explain the stabilized drawdown response is a constant head boundary. A constant head boundary is a source of recharge with such a large volume of storage that when it is intercepted by a cone of depression, it can provide recharge equal to the pumping rate without suffering a discernable change in water level as water flows from it into the cone of depression. Thus, the source of recharge does not exhibit drawdown or a change in head and is therefore referred to as a “constant head” source. A typical constant head source would be an aquifer-connected stream, river, or lake that provides recharge equal to the pumping rate of a well after the cone of depression around the well reaches the surface water source.

Surface water cannot be a source of constant head recharge to a cone of depression in the Madison aquifer, confined 2300 feet or more below the land surface by overlying strata. Accordingly, another source of constant head recharge must be identified. The odd combinations of aquifer responses observed between wells M-9 and M-10 indicate that the groundwater storage in a large and extensive collapse breccia zone is the most likely cause of the stabilized drawdown observed at the other wells.

Confined aquifer storage, prevailing in the Madison aquifer at the COG Madison well field, is considerably different than the volume of porosity in the aquifer rock. Part of the load of the rock strata overlying a confined aquifer is supported by the pressure of the water in the aquifer, i.e., the artesian pressure or pore pressure. When water is removed from storage in the confined aquifer by a pumped well, the reduction in pore pressure in the aquifer transfers that portion of the overlying rock load formerly supported by the pore pressure to an increase in the load on the rock matrix of the aquifer. The increased load on the rock matrix of the aquifer results in compression which in turn reduces the volume in the pores in the aquifer which store the groundwater. The reduction in pore space in the aquifer due to compression, and a slight expansion of the confined water as pressure on it is reduced, constitute the source of groundwater storage volume released from the confined aquifer when it is pumped. This confined storage is generally referred to as aquifer "storativity" and is the unit volume of water released or stored in a unit volume of confined aquifer under a unit change in head.

Confined aquifer storage (aquifer storativity) is the water released from the voids in the confined aquifer by a reduction in pore volume by compression when pore pressure is reduced by pumping abstractions and load shifts from the water to the rock. The confined storage is typically compared to unconfined aquifer storage which is the effective porosity that will drain from the pores under gravity (aquifer specific yield). Specific yield is generally two or three orders of magnitude larger than storativity. In comparing the response of the tests of wells M-9 and M-10, it is more important to compare the aquifer storativity at well M-9 to that at all the other wells. Specifically, if the porosity of a unit volume of aquifer rock in the part of the aquifer penetrated by well M-9 is significantly greater than the porosity of a unit volume of aquifer rock in that part of the aquifer penetrated by the other wells, a unit change in head at well M-9 will result in an absolute volume change in a unit volume of aquifer rock much larger than that at the other wells. Moreover, if the rock matrix of the aquifer material penetrated by well M-9 is more elastic than that at the other wells, i.e., offers a greater modulus of elasticity, it will offer an even greater change in absolute void volume under compression than will the aquifer at the other wells. Specifically, if well M-9 penetrates a collapse breccia, its absolute void volume may change an order of magnitude more under a unit change in head in the aquifer than the absolute void volume in other parts of the aquifer penetrated by the other wells.

The volume of water released from groundwater storage during an 1150-gpm test is the same for tests of equal duration whether it comes from well M-9 or M-10. However, if pumping of well M-9 causes initially radial flow until the boundaries of a collapse breccia zone are reached and subsequent linear flow as the cone of depression expands longitudinally along a linear flow path constituted by a collapse breccia zone that is much, much longer than its width, the linear flow response can take a half unit slope so long as the confined storage released from the collapse breccia zone is much larger than that released from the rocks bounding the collapse breccia zone. If that response is hydraulically transmitted through a connecting fracture to an observation well, such as well M-10, the response will remain a radial response followed by a half unit slope response because the absolute volume of groundwater storage being released in the collapse breccia zone is so much larger than the storage released by the porous rocks bounding the breccias zone or the connected fracture that it overwhelms any release of storage from the less porous rocks and controls the rate of drawdown.

However, when the observation well in the fracture zone is pumped, such as well M-10, it exhibits an initial linear flow response because the fracture, even though solution enlarged, is not wide enough for the momentary radial flow response to be detected. The slope of the linear

flow response is a quarter unit slope because the porous limestone or dolomite along the fracture begins to release groundwater from storage and that groundwater flows perpendicular to the fracture and into the fracture where it is then conveyed to the well. As the ensuing area of lowered pressure in the fracture expands out from the pumped well, it eventually reaches the connection with the collapse breccia zone. The groundwater storage per unit volume of aquifer per unit volume of head change in the collapse breccia zone is so much larger than that in the fracture that when the depressurized area reaches the collapse breccia zone, it begins to function as a constant head boundary to the connected fracture. Accordingly, the drawdown observed at the pumped well, M-10, stabilizes.

When the drawdown at the pumped well, M-10, stabilizes, this indicates that essentially all of the pumped water is now coming out of the collapse breccia zone, i.e., drawdown in the fracture producing to M-10 has expanded to where the fracture intersects the breccia zone. The breccia zone is therefore a constant head source of recharge to the fracture, at least in the short-term drawdown response of an aquifer test. The breccia zone responds to the flow into the fracture as if a pumped well is located at the connection to the fracture. The effect of the flow into the fracture as a proxy to a pumped well is a radial flow response in the collapse breccia zone, as was observed at well M-9 when well M-10 was pumped. Had the pumping duration at well M-10 been sufficiently long, the radial flow response observed at well M-9 would have ultimately transitioned into a linear flow response with a half unit slope.

Accordingly, the release of groundwater storage from the collapse breccia zone into the fracture zones penetrated by the wells exhibiting linear flow is an alternative to leaky aquifer conditions as an explanation for the stabilized drawdown. While the flow of groundwater storage from the collapse breccia zone into the narrow linear fractures or fracture zones producing to the other wells causes their drawdown to stabilize, it results in on-going drawdown in the collapse breccia zone. Accordingly, the drawdown observed at well M-9 does not stabilize whether it is pumped or if well M-10 or any of the other wells are pumped. Drawdown is always occurring in the collapse breccia zone when any of the other wells are pumped (assuming their drawdown extends to the collapse breccia zone as indicated by stabilization of drawdown at all of the other wells when they were tested).

The collapse breccia zone likewise acts as a source of constant head recharge to the wells producing from porous carbonate rock and exhibiting radial flow. The hydraulic properties of the radial flow part of the aquifer, and to some extent the large distances from the collapse breccia zone to the radial flow wells, require a longer period of pumping for drawdown to stabilize in the radial flow wells than needed for the linear flow wells.

The presence of an internal constant head boundary indicated by the pumping test responses confirms the conclusions of Anderson & Kelly in 1982 who concluded that:

> "***The time-drawdown behavior during tests is typical of leaky aquifers that conform with the Hantush-Jacob (1955) prototype, where the drawdown stabilizes after a relatively short period of time . . .***
>
> ***Based solely on the stabilization of drawdown, the most direct explanation of this behavior would be to assume that leakage into the Madison is occurring from the overlying and/or underlying formations. However, analysis of test data by the leaky aquifer theory result in high leakage***

> ***properties that are not consistent with the geologic character of the adjacent formations. An alternative explanation could be to assume a region of high transmissivity near the well site acting as a "perfect recharge boundary". However, the data from several tests suggest that the effective transmissivity increases with distance from the pumped well. This is inconsistent with results that would be expected from a nearby high transmissivity region that acts as a perfect recharge boundary.***" (Anderson & Kelly, 1982; pp.13-14)

The problem of effective transmissivity increasing with increased distance from the pumped well is solved when the possibility of a zone within the aquifer that offers one or two orders of magnitude greater confined aquifer storage than the remainder of the aquifer is considered, i.e., a solution breccia zone. Wells penetrating porous but non-fractured aquifer rock have lower effective transmissivity than those in fractured rock. The expanding cone of depression around such a well encountering a zone capable of acting like a constant head boundary by virtue of greater storativity properties will stabilize. Likewise, drawdown expanding along a solution enlarged fracture with limited groundwater storage volume will stabilize when it encounters the area of relatively larger storage volume.

It is important to recognize that the stabilized drawdown exhibited during the pumping tests is not due to vertical leakage from the overlying Minnelusa formation. This means that water quality in the Madison aquifer will not be affected by vertical leakage from overlying strata. On the other hand, it indicates that when enough groundwater has been abstracted from storage in the zone of greater aquifer storativity, groundwater levels throughout the entire well field may begin to decline at an accelerated rate. Therefore, a desire to develop more high-capacity wells in the zone of greater storativity (assuming it can be consistently located) must be tempered by the need to thoroughly test the zone and predict long-term drawdown rates in it for various pumping scenarios. It may be necessary to spread pumping abstractions over a larger area than the local well field, even though a highly transmissive zone of considerable groundwater storage capacity has been identified.

STRUCTURAL CONTROLS

Figure 29 shows the locations of the "cavity" and "non-cavity" wells of the Anderson & Kelly (1982) and Wester-Wetstein (1996). The pattern of the cavity and non-cavity well distribution supports the concept of a randomly distributed cavern system as shown on Figures 2 through 4.

Figure 30 shows the locations of the radial flow wells and the linear flow wells. The location of well M-9, which initially shows radial flow but exhibits linear flow later in the test, is also shown.

On Figure 30, wells M-1, M-3 and M-8, which are non-cavity wells on Figure 29, are recognized as linear flow wells according to the aquifer response to pumping at those locations. The locations of linear flow wells M-1, M-2, M-3, M-4, M-8 and M-10 are aligned along a reasonably straight line, as shown on Figure 30. The straight line through the latter wells coincides with a larger alignment of topographic features. The larger alignment of topographic features is referred to as a "lineament" and extends from the nose of the Oil Butte anticline to at least Keyhole Reservoir, as shown on Figure 31.

Figure 29: Distribution of cavity and non-cavity wells.

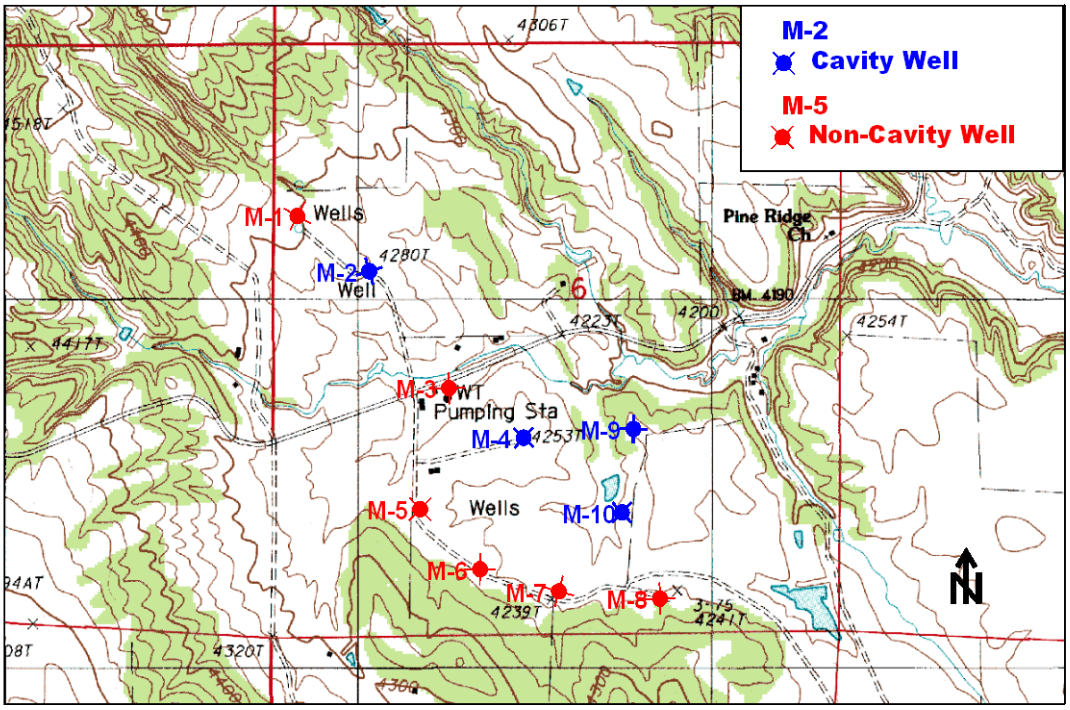


Figure 30: Alignment of linear flow wells.

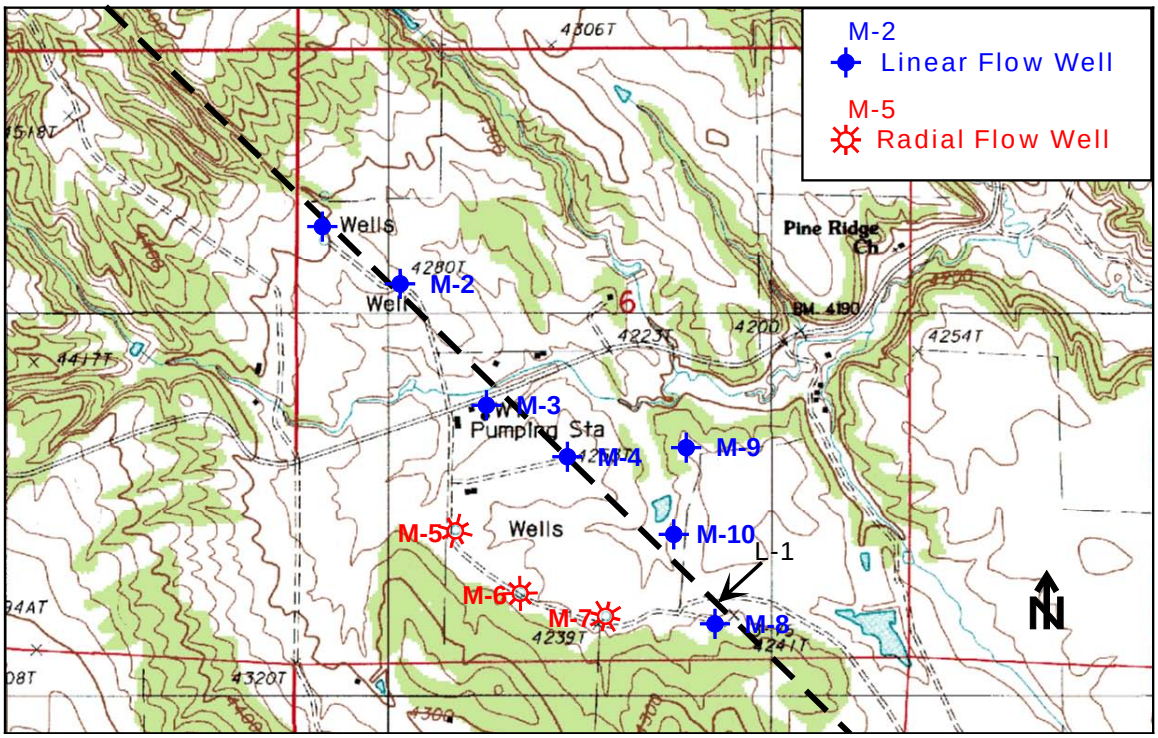
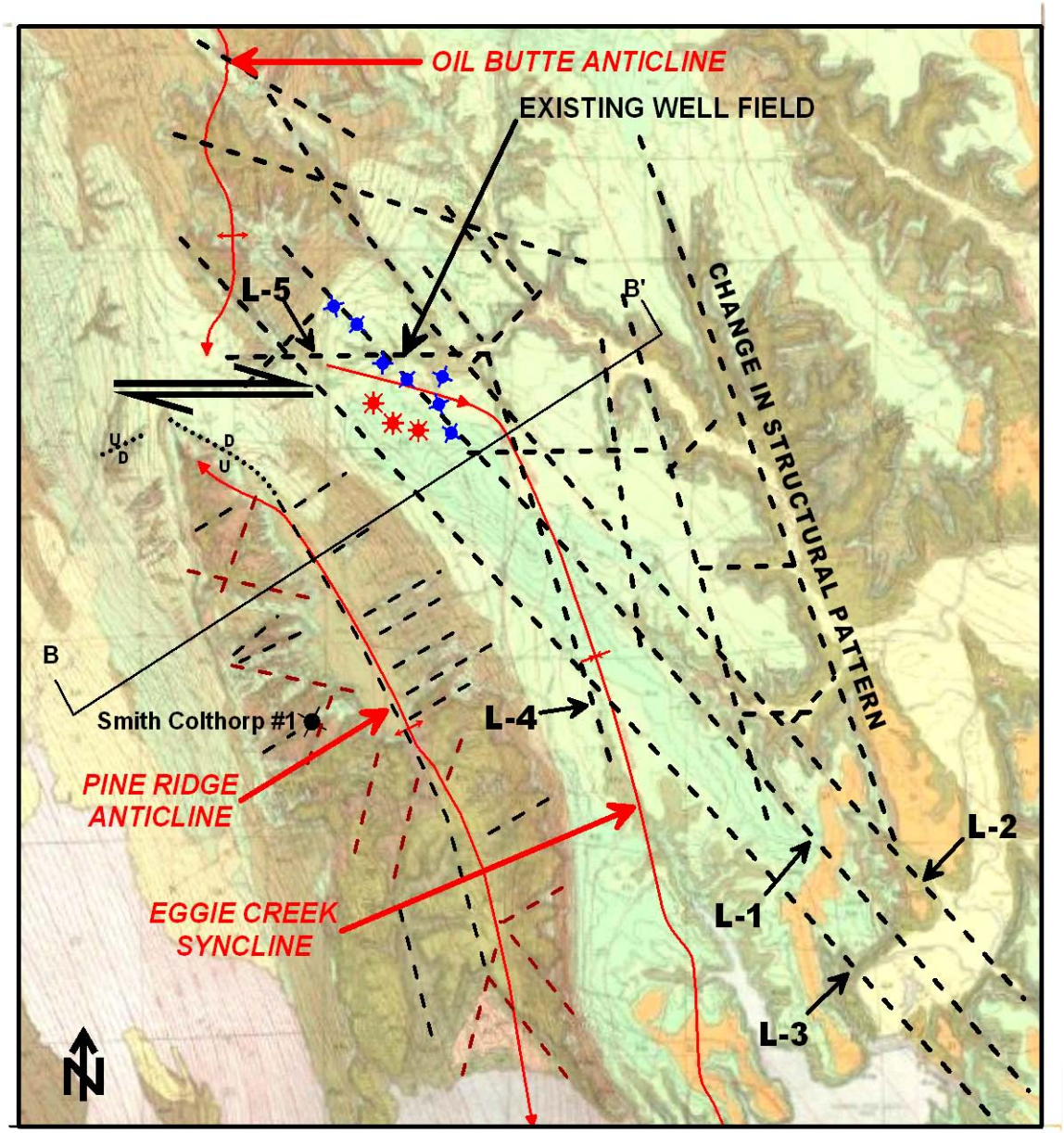


Figure 31: Regional lineament pattern in Eggie Creek syncline and Pine Ridge anticline.



As shown on Figures 29 and 30, replacement of the cavity versus non-cavity well concept with that of linear flow versus radial flow to the pumped wells, demonstrates that all of the wells obtaining a linear flow pattern from the aquifer system are located along a single linear alignment. The alignment is shown on Figures 30 and 31 as lineament L-1. It is parallel to two other distinct lineaments of equal length plus shorter local lineaments. That all of the linear flow wells are distributed along a reasonably straight line which coincides with a regional lineament is compelling evidence that they penetrate the same highly-bounded groundwater flow zone.

The geology of the Madison aquifer at this site indicates the linear flow feature is most likely solution enlarged fracture.

Wells M-2, M-3, M-4 and M-10 exhibit very high specific capacity (Table 1) and very little well loss drawdown, at least after hydraulic fracturing of M-3 and M-10, indicating they are well-connected hydraulically with the hypothesized solution enlarged fracture. Wells M-1 and M-8 exhibit less hydraulic performance than the latter wells; a fact that appears to be the result of non-uniform hydraulic properties along the solution enlarged fracture than due to poor hydraulic connection between the wells and the fracture. It must be noted that during the pre-hydraulic fracture treatment of well M-1, a pumping test of the well exhibited a sudden decrease in well capacity and hydraulic performance. Evidently this resulted from some type of collapse or plugging of the fracture openings during the test. Subsequent hydraulic fracturing of the well improved its performance; however, it continues to exhibit a hydraulic response indicating restricted hydraulic connection to other parts of the fracture that offer greater hydraulic capacity, as does well M-8. These responses indicate that the hydraulic properties along the fracture are not uniform.

Three of the wells tested, wells M-5, M-6, and M-7, exhibit radial flow when tested. The latter wells are located south or southwest of the linear flow zone and do not penetrate voids, open joints, or fractured rock. The results of the pumping tests indicate these three wells most likely produce from porous limestone and/or dolomite. The extent and distribution of the porosity is not known; however, porosity associated with post-depositional recrystallization of dolomite in the Madison strata is reportedly wide spread and may be ubiquitous in certain layers of the Madison strata.

Aquifer response at well M-9 is different than that at all of the other wells for which pumping test data were found. Well M-9 exhibits radial flow for approximately the first 1000 minutes of pumping followed by the onset of linear flow. This response is interpreted to indicate that well M-9 penetrates a large collapse breccia zone caused by the collapse of a large void created by solution of one or more gypsum or anhydrite layers by groundwater. The aquifer test response indicates the zone is wide enough for a cone of depression to form under radial flow and persist for up to 1000 minutes before encountering the lateral boundaries of the collapsed zone which then force the flow to become linear along the breccias zone which is evidently very long with respect to its width. It is further concluded that the aquifer storativity (coefficient of confined aquifer storage) in the hypothesized collapse breccia zone is at least an order of magnitude larger than that in fractured rock or porous rock outside the collapse breccia zone. Accordingly, the groundwater stored in the collapse breccia zone acts as a source recharge to interconnected fractures and porous rock, mimicking a constant head source of recharge during the pumping tests. Consequently, the response of the collapse breccia zone to pumping of well M-9, which directly penetrates the zone and penetrated through open voids in the breccias, is ongoing drawdown as groundwater is removed from storage in the collapse breccias. The late test response of the other eight wells is stabilization of drawdown after the zone of drawdown around each pumped well extends to the collapse breccia zone.

The latter response supports two additional conclusions. One conclusion is that the long, narrow linear flow feature penetrated by the linear flow wells; M-1, M-2, M-3, M-4, M-8 and M-10, intersects the collapse breccia zone or passes very near to it and is hydraulically connected to it. Hydraulic limitations in the linear flow feature at wells M-1 and M-8 prevent the drawdown at those wells from reaching the collapse breccia zone. The second conclusion is that the zone

of porosity and permeability penetrated by the wells with radial flow response; M-5, M-6, and M-7, extends to and is hydraulically connected with the collapse breccia zone as well as the solution enlarged fracture producing linear flow.

FRACTURE ZONE AND SOLUTION BRECCIA EXPLORATION CONSIDERATIONS

The foregoing assessment of the pumping test responses at the ten existing wells indicates that groundwater flow to pumped wells in the local Madison aquifer at the COG Madison well field occurs in three different physical conditions, as follows:

1. Radial flow through ubiquitous vuggy porosity and permeability in the carbonate rock ("vuggy porosity" is voids from the size of a small pea upwards resulting from recrystallization of carbonate rock and is generally associated with dolomite in the Madison strata). Wells M-5, M-6 and M-7 penetrate this type of production zone and yielded from 0.82 to 2.31 gpm/ft of drawdown (Table 1) which was increased from 0.82 to 1.39 gpm/ft of drawdown by hydraulic fracturing at M-5.

2. Linear flow through long, hydraulically narrow paths most likely provided by solution enlarged fractures with variable or non-uniform transmissivity along their length and thought to have developed in structurally controlled joints caused by regional folding of the Madison rocks. Wells M-1, M-2, M-3, M-4, M-8 and M-10 penetrate this type of production zone. Wells M-2 and M-4 provided 18.2 and 9.7 gpm/ft of drawdown respectively. Wells M-3 and M-10 initially provided 3.0 and 4.1 gpm/ft of drawdown respectively, which was increased to 20.5 and 31.1 gpm/ft of drawdown, respectively, by hydraulic fracturing. Wells M-1 and M-8 provided 1.23 and 0.98 gpm/ft of drawdown, respectively. Hydraulically fracturing well M-1 increased its performance to 3.25 gpm/ft of drawdown, indicating the non-uniform hydraulic properties along the length of the fracture. Well M-8 or a new well drilled at this location is a good candidate for hydraulic fracture stimulation.

3. Production from an extensively large area of solution collapse breccia where layers of evaporites such as anhydrite were interbedded with the limestone and dolomite strata and have been leached out, resulting in caverns that have collapsed, leaving internal rubble zones of broken rock called "breccia" within the Madison strata. The single breccia of this type penetrated in the COG Madison well field gives a hydraulic response indicating it is very wide, yet relatively long enough to cause linear flow to the pumped well after about 1000 minutes of pumping at 1150 gpm. Well M-9 penetrates this type of production zone and provided 43.8 gpm/ft of drawdown.

The goal of the Madison well field expansion is to utilize the above knowledge of the aquifer to maximize production per well and therefore minimize the number of wells and total costs for wells needed to obtain the desired increase in well field capacity. As summarized above and shown in Table 1, the most attractive drilling targets are solution enlarged fractures and collapse breccia zones, both of which yielded up to 1150 gpm to individual wells with hydraulic performance indicating the potential to yield up to 1400 gpm per well.

It has been speculated that the position and alignment of solution enlarged fractures is related to the axes of structural folds which include the Eggie Creek syncline (downward fold) and the Pine Ridge and Oil Butte anticlines (upward folds), shown on Figure 31. However, the

assumption of fractures and enhanced hydraulic properties along the fold axes in the area, as delineated on the geologic map (Figure 31), is not correct. The alignment of the linear flow wells in the existing well field does not correlate well to either the local or regional axis of the Eggie Creek syncline; thus indicating the idea that wells can simply be sited along the axis of the syncline and penetrate zones of enhanced permeability along solution enlarged fractures is not correct. The synclinal axis referred to is that drawn on the USGS geologic map of the Carlile Quadrangle shown as Plate 34 of Bulletin 1082.

The hypothesized solution collapse breccia penetrated by well M-9 offers an even more challenging exploration target because the factors controlling the extent and distribution of the breccia are not known. The hydraulic response of the fracture penetrated by wells M-2, M-3, M-4 and M-10, all of which exhibit stabilized drawdown, indicates the collapse breccia penetrated by M-9 is hydraulically connected to the linear fracture. If the collapse breccia zone were connected to the regional fracture by cross cutting fractures, the wells should exhibit a less-than-quarter unit slope before drawdown stabilizes. If such a response occurs, it is of too short a duration to be detected by the frequency of data collection used during the aquifer tests.

The fracture zone along lineament L-1 on Figure 31 extends well past a perpendicular line from the fracture to well M-9. This implies the hydraulic connection with the breccia zone occurs somewhere in the vicinity of wells M-4 and M-10, a conclusion consistent with the rapid stabilization of drawdown at those two wells when they are pumped. Wells south of the M-2 through M-4 alignment do not exhibit linear flow or large specific capacities. Therefore; it is concluded they do not penetrate the breccias zone. However; they do eventually exhibit stabilized drawdown indicating they respond to a flow of water from the breccia zone. The combination of the distribution of the wells and the observed aquifer responses indicates that the breccia zone is located north or northeast of the M-2 through M-4 alignment and is in hydraulic connection with the M-2 through M-4 fracture. The latter fracture can therefore act as a constant head boundary to the radial flow wells south of the fracture.

It should be noted that in this interpretation of the aquifer test results, it is concluded that the source of water to stabilize drawdown at all of the wells except well M-9 is a large volume of groundwater storage in the collapse breccia zone. This interpretation is an alternative to the conclusion that drawdown in the wells is stabilized by vertical leakage from another aquifer such as the overlying Minnelusa. If vertical leakage from the Minnelusa caused stabilized drawdown, the aquifer test of well M-9 should stabilize, since it logically would have the largest “cone of depression”, i.e., the largest footprint of depressurized area through which vertical leakage could occur. However, drawdown did not stabilize during the test of well M-9. As explained in detail in the **BOUNDARY EFFECTS** section of this report, it is thought that this indicates that the collapse breccia zone is the source of a pseudo-constant head boundary to the other pumped wells.

If the latter interpretation is correct, the implication is that production wells drilled in distant parts of the Madison aquifer, for example on the crest of the Pine Ridge anticline, may not be hydraulically connected to the collapse breccia zone and therefore not exhibit stabilized drawdown. This emphasizes that the extent and distribution of the collapse breccia zone are unknown. From a geologic standpoint, it might be expected to be extensive enough to cross both the Eggie Creek syncline and the Pine Ridge anticline, but this simply is not known.

If production wells distant from the existing COG Madison well field do not exhibit stabilized drawdown, they will likely exhibit more long-term drawdown than has been the historic case in wells at the COG Madison well field if their source of water is strictly limited to linear flow along solution enlarged fractures and contributions from the adjacent rock strata. On the other hand, clustering too many wells at locations that deplete the known collapse breccia zone may ultimately accelerate the drawdown in that area and increase long-term drawdown in the existing well field to an undesirable amount. Accordingly, there are arguments for placing a few more wells somewhere southeast or northeast of the existing well field, along the Eggie Creek synclinal axis or in an attempt to penetrate the high-yield breccia zone; but other arguments exist to establish production from other parts of the aquifer so as not to concentrate too much drawdown of groundwater levels in one location. The latter consideration suggests the crests of the Pine Ridge and Oil Butte anticlines would be good exploration targets.

Taking all of the foregoing ideas into consideration, it is worth evaluating the factors that might affect the orientation, density and openings (aperture) of fractures in the area. Not only are the linear flow zones believed to be controlled by the fractures, it is thought that the leaching of evaporite layers, leading to formation of collapse breccias, initially followed fractures in the evaporites. Accordingly, the extent and distribution of the collapse breccias may be related to geologically old regional fracture patterns in the Madison rocks.

FRACTURE ORIENTATION

It has long been recognized that fractures, which include joints, faults and shear zones, may enhance the local hydraulic properties of rocks by increasing the size of the interconnected openings that transmit groundwater. The performance of the existing COG Madison wells shown in Table 1 adequately demonstrates this principle with the wells penetrating the solution enlarged fracture zone and collapse breccia zone exhibiting specific capacity an order of magnitude greater than that of wells producing from the unenhanced hydraulic conductivity of the porous limestone aquifer distant from the fracture zones. Therefore, one goal of an exploration program for new production wells in the Madison aquifer may be to locate sites where additional new solution enlarged fractures or collapse breccia zones can be penetrated by production wells distant from the existing well field. A related goal might be to locate sites where production wells can penetrate extensions of the known fracture zone and collapse breccia zone penetrated by the wells in the existing COG Madison well field.

In discussions and correspondence leading to this technical memo, it was speculated to the City of Gillette and the Wyoming Water Development Commission staffs that the wells with linear flow response and large specific capacities were in close proximity to the axis of the Eggie Creek syncline and that solution enlarged joints along the synclinal axis were the likely source of the enhanced aquifer hydraulic properties that make the high-capacity well performance possible. The speculation about correlation of the wells to the synclinal axis was made before the test data for wells M-1, M-8, M-9 and M-10 were obtained and evaluated. Those additional data further define the alignment of the zone penetrated by the wells and show that it presents an extensive linear flow path, as discussed above.

The axis of the Eggie Creek syncline is shown on Figures 31 and 32 in this memorandum. Figure 31 is a reproduction of a portion of Plate 34 from, "***Geologic and Structure Contour Map and Sections of the Carlile Quadrangle, Crook County, Wyoming***,", United States Geological survey Bulletin 1082-J, "***Geology and Mineral Deposits of the Carlile Quadrangle,***

Crook County, Wyoming." As shown on Figure 31, the alignment of the linear zone defined by wells M-1, M-2, M-3, M-4, M-8 and M-10 does not correlate to the axis of the Eggie Creek anticline as drawn on the geologic map. However, the linear flow path defined by the wells correlates strongly to a large lineament. Accordingly, the location and alignment of the lineament, not the axis of the syncline as drawn on the geologic map, should guide site selections for future exploration wells.

Lineaments are topographic features of regional extent that are believed to reflect the underlying crustal structure. In this case, the trace of the lineament penetrated by the linear flow wells at the COG Madison well field is defined by the alignment of surface drainages that have enlarged the lineament trace by erosion. Particularly noticeable are locations along the lineament trace where the upstream ends of drainages "hook" into alignment with the lineament, rather than following the course of the remainder of the drainage. These types of abrupt realignments of topographic features that line up over long distances are typical evidence of a lineament that reveals the present of a joint or fault. A joint is a discontinuity or fracture in the crustal strata that does not exhibit any evidence of offset of strata across the discontinuity whereas a fault is a discontinuity in the strata that exhibits offset of the strata.

As shown on Figure 31, there are at least two sets of fracture patterns in the Eggie Creek syncline. One set is oriented generally northwest by southeast as shown by three parallel lineaments labeled L-1, L-2 and L-3. The second set of fractures consist of a number of parallel lineaments, three of which are shown, with the one passing nearest to the COG Madison well field labeled L-4. These lineaments are one part of a set, with the other part of the set consisting of the lineament labeled L-5 on Figure 31. The L-4 and L-5 fracture set corresponds to the typical alignment of a conjugate fracture pattern cause by compression and shear in a fold, as shown on Figure 33. The L-1, L-2 and L-3 lineaments correspond to the typical alignment of dilation fractures caused by tension and the extension of the rock mass in a fold, as shown on Figure 33.

Figure 33 shows the classical concept of the relationship between a fold and fracture patterns. In part A of Figure 33, a zone of closely spaced joints (extension fractures) is shown along the crest of an anticline. The density of fractures in this zone is exaggerated for a mild fold of this type, where only one or two joints might actually be present, but is shown to explain the relationship between fracture density and increased deformation in a fold. It should also be recognized that the joints shown on Figure 33 may not penetrate entirely through a layer of rock, particularly in units that include soft strata interbedded with hard strata. The Madison strata are essentially all hard strata, but the thickness of the Madison rocks, approximately 600 feet in this area, may also influence whether or not a joint penetrates the entire thickness of the unit. Other extension fractures are shown on the flanks of the fold as joints parallel to the axis of the fold in Part A of Figure 33, in addition to those on the axis or crest of the fold. All of these types of joints are thought to be analogous to the L-1, L-2 and L-3 lineaments in the Eggie Creek syncline.

Figure 33, Part A also shows a joint set perpendicular to the axis of the fold. These are also extensional fractures that typically form at the same time as the joints parallel the fold axis. These joints are quite pronounced in the shallow sandstone strata on the flanks of the adjacent Pine Ridge anticline but are generally not evident in the Eggie Creek syncline, except for the short portion of drainage followed by Highway 14 northeastward from the existing well field to the confluence with Spring Creek.

Figure 32: Major structural trends.

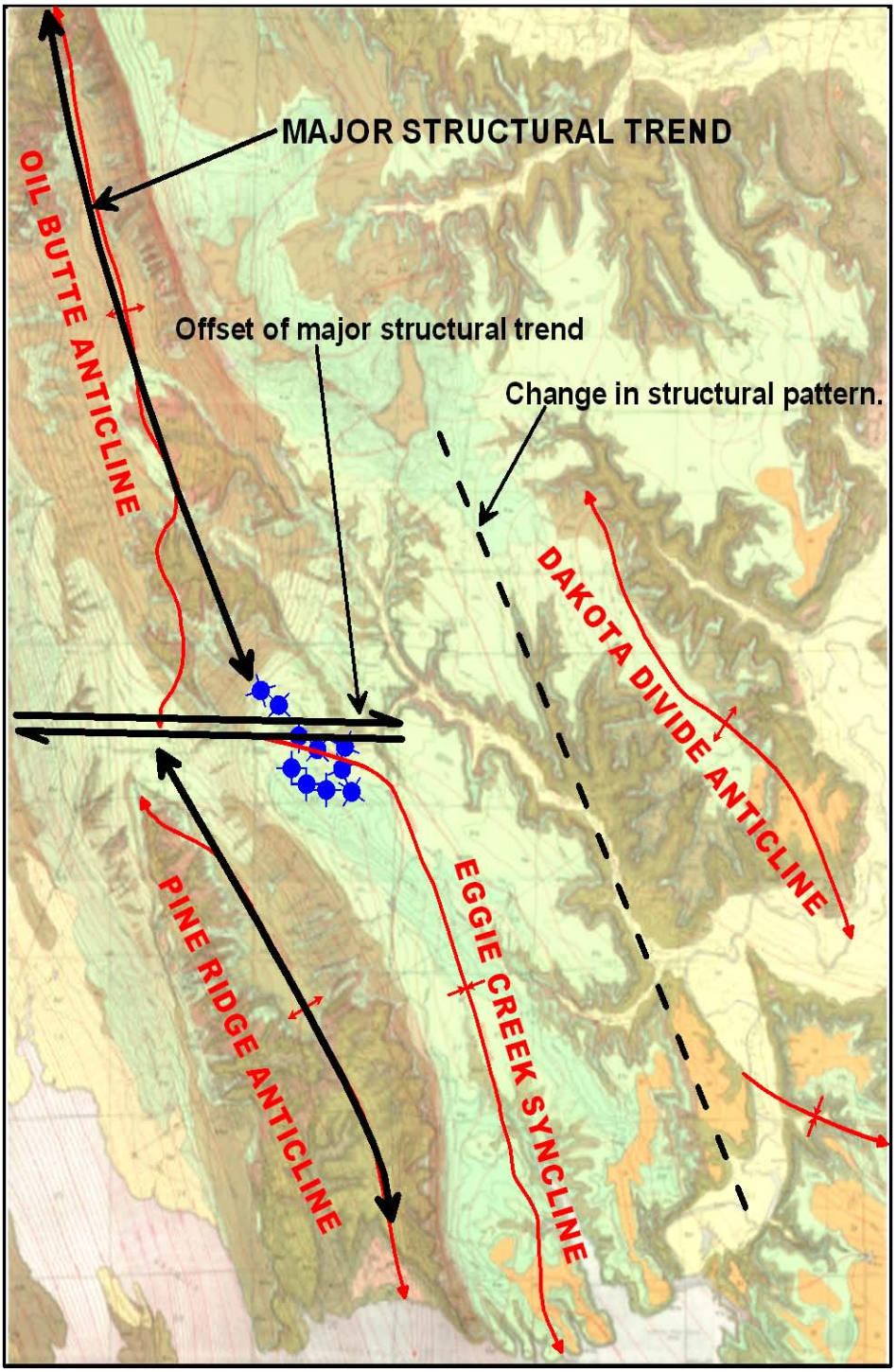


Figure 33: Classical concept of fracture patterns on a fold.

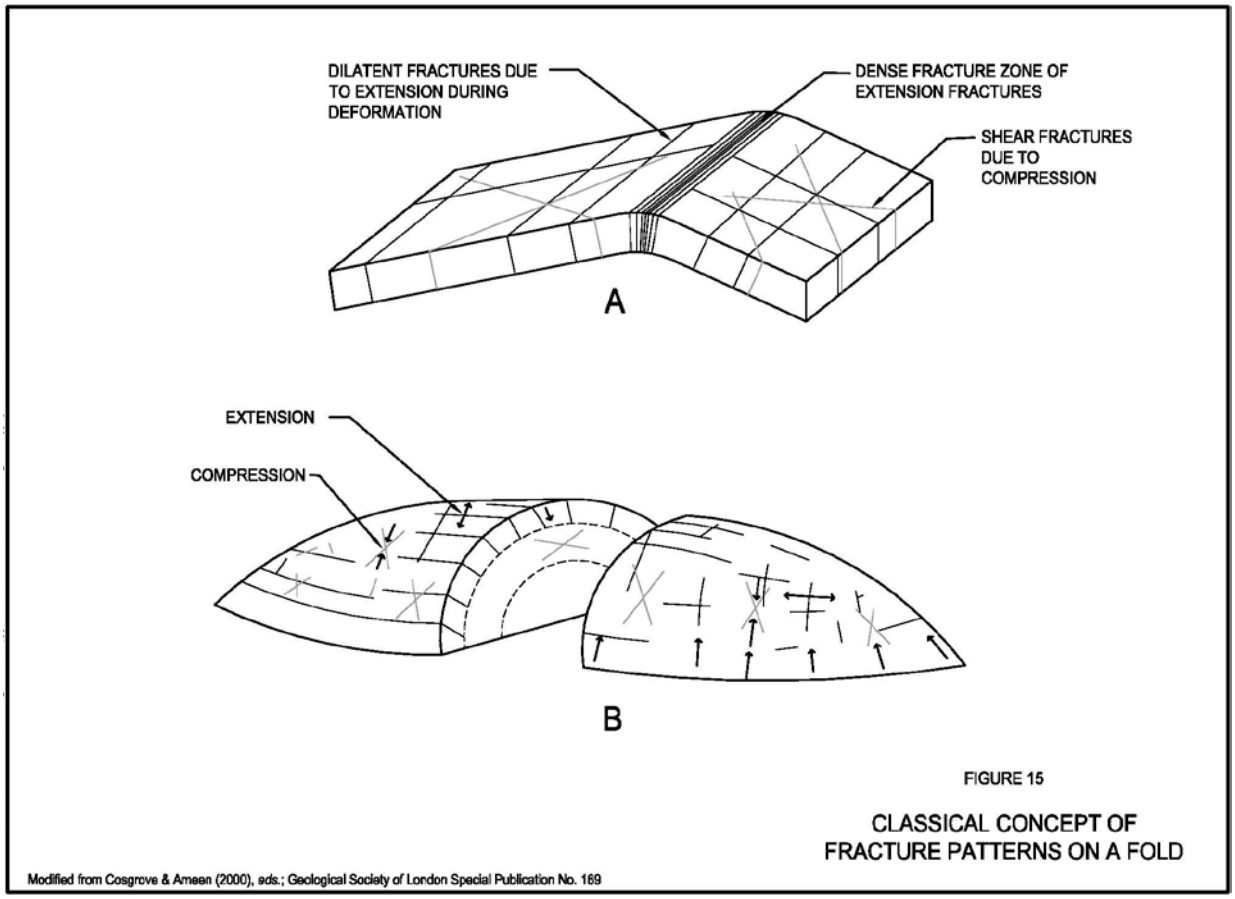


Figure 33, Part A also shows a joint set labeled as “shear fractures due to compression”. These compression joints result from compressive stress exceeding the strength of the rock. Initially, they simply relieve strain and may not penetrate through the entire thickness of the strata; however, with enough deformation of the rock they may transition into shear zones or strike-slip faults with definite offset of the strata across the joints. In the latter case, the broken rock in the shear zones in hard strata such as limestone, may become local or regional paths of groundwater flow. Even without movement across the compressive joints, later relaxation of tectonic compressive forces may result in opening of the shear joints such that they become paths of enhanced permeability for groundwater flow. In the latter case, open shear joints in limestone and dolomite may become solution enlarged, further enhancing their capacity to store and transmit groundwater.

If such zones are present in porous rock, such as the Madison aquifer strata, wells penetrating the joints, whether extensional or compressive, often have penetrated what amount to long, high-permeability drains in the porous aquifer rock, capable of draining groundwater out of storage in the porous rock over long distances. If these features contain large openings, such as a solution enlarged fracture that is essentially a cavern, the water drained out of the porous

host rock can be transmitted quickly over large distances along the fracture to support high-capacity abstraction of groundwater by a pumped well, often at rates much larger than can be sustained by radial flow through the porous host rock.

STRUCTURAL TREND CONSIDERATIONS

Figure 32 is a reproduction of the geologic map of the Carlile Quadrangle provided as Plate 34 in USGS Bulletin 1082-J. The reproduced geologic map is provided herein for the purpose of comparing the geologic structures of the Oil Butte and Pine Ridge anticlines.

The structural contours on the geologic map (Figure 32) are the elevation at the base of the Fall River formation. The data points for the structural contours are presumably elevations observed at locations where the topography has cut through the Fall River formation, exposing the base of the unit so that its elevation can be measured. Accordingly, the structural contours represent the uppermost part of the folds – the Oil Butte and Pine Ridge anticlines and the Eggie Creek syncline. The approximately 2300 feet of strata above the top of the Madison strata consist predominantly of soft, plastic shale, mudstone and claystone. Harder, more brittle units of sandstone are generally relatively thin. Therefore, the structural contours drawn on the base of a statum high in the folds, at the top of approximately 2300 feet of soft, easily deformable geologic strata, may not exactly represent the structure of a hard, brittle unit like the Madison limestone, some 2300 feet deeper. For example, the axis of the Eggie Creek syncline, based on the structural contours, does not conform to the regional lineaments thought to represent deep-seated fractures penetrating to the Madison strata. The discord between the trace of the synclinal trough drawn at the top of the soft strata and its location in the deep, thick and hard Madison carbonates (as implied by the locations and alignment of the lineaments) reflects the distortion in the structure that took place in 2300 feet of relatively soft strata between the land surface and the top of the Madison strata.

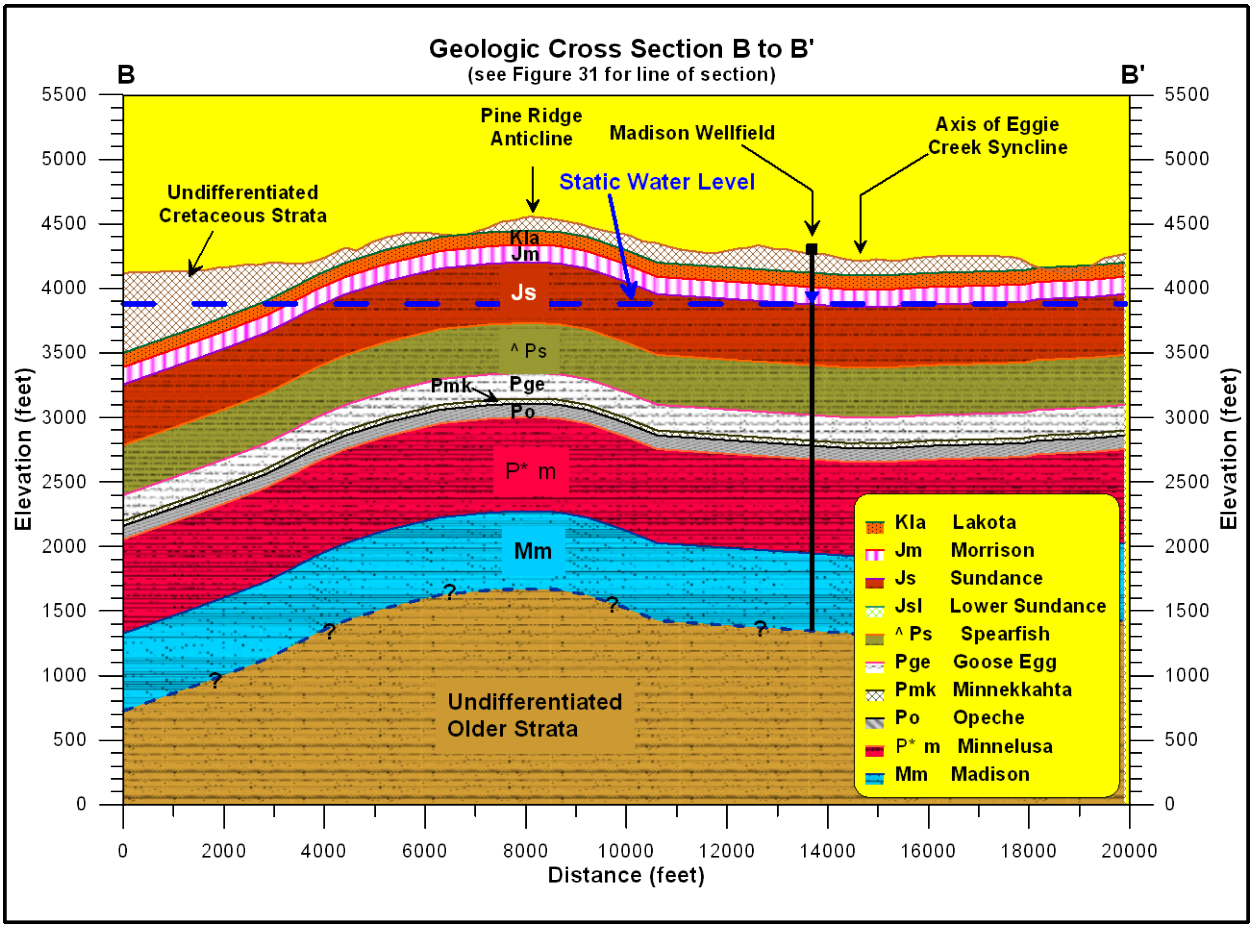
Nonetheless, the structural contours provide a good general definition of the folds. Figure 34 is a geologic cross section through the Pine Ridge anticline. Line of section B-B' on Figure 31 shows the cross-section alignment. The cross section was constructed as a congruent fold, i.e., the thickness of the strata remain constant throughout the fold and adjustments for differing radii of curvature throughout the fold are assumed to have been adjusted by slippage parallel the bedding planes and joint openings. The Pine Ridge anticline is a doubly-plunging anticline, similar to the fold shown as Part B of Figure 33.

As shown on Figure 32, the axes of the Pine Ridge and Oil Butte anticlines are reasonably parallel or congruent; however, the Oil Butte anticline is located further east than the Pine Ridge anticline; therefore, there is an east-west offset between the two structures which is expressed as a structural saddle in the anticlinal ridge directly west of the COG Madison well field. In addition, the Oil Butte anticline is asymmetric with its east flank (27-degree dip) steeper than the west flank (7 – 10 degree dip) whereas the Pine Ridge anticline is relatively more symmetrical, dipping 7 degrees on the west flank and an average of 18 degrees on the east flank. The differences in crustal shortening and symmetry of the two anticlines may indicate the presence of a deep high-angle reverse fault at depth, possibly extending upward into the Madison limestone, parallel the major structural trends shown on Figure 32, acting as a structural hinge for the deep parts of the two folds.

The crustal shortening associated with the asymmetric structure in the Oil Butte anticline is greater than that in the Pine Ridge anticline. The latter fact, combined with the relative east-west offset between the axes of the two structures, requires some type of lateral adjustment in the strata between the two folds. Figure 32 shows that the most likely location of any lateral adjustment between the two folds took place in the structural saddle in the axis of the two anticlines, directly west of the COG Madison well field. The offset of the major structural trend shown on Figure 32 is also shown on Figure 31.

Figure 32 shows a fault at the north end of the Pine Ridge anticline, roughly parallel the axis of the anticline as drawn on Figure 32. As described in USGS Bulletin 1082-J, "***The fault is inferred to be about 3,500 feet long, and the maximum displacement (30-35 feet) is near the northwestern end . . . The displacement along the fault decreases toward the southeast.***" The latter description does not indicate if the fault is a high-angle reverse fault (compressive) or a high-angle normal fault (extensional). As shown on Figure 31, lineament L-5 extends into the north side of the structural saddle between the two anticlinal folds. Although

Figure 34: Geologic cross section through the Pine Ridge anticline.



the structural contours on Figure 32 indicate that the misalignment or displacement of the anticlinal axes between the two folds can be encompassed by folding of the shallower, soft

strata, it is not as evident that the displacement between the two folds that must take place in the Madison strata can be explained by folding of thick, brittle Madison strata.

The possibility exists that the Madison strata in the vicinity of the structural saddle experienced a significant east-west "wrench". If so, the Madison strata in the area of the structural saddle may be highly fractured and offer a good target for exploration drilling. Likely locations for exploration wells associated with the structural saddle and the Pine Ridge anticline are as follows:

1. The intersection of lineaments L-3 and L-5 on the north side of the structural saddle also includes a west-southwest by east-northeast aligned cross-cutting lineament apparently related to the east flank of the Pine Ridge anticline and is a good location for an exploration well.

2. The northwest end of the fault on the north end of the Pine Ridge anticline is a target for an exploration well.

3. The entire structural saddle between lineament L-5 and its westward extension and the fault on the north end of the Pine Ridge anticline with locations both sides of Highway 14 is the location for an exploration well to determine the amount of fracturing in the Madison aquifer rock strata throughout the structural saddle for a multiple-well expansion of the well field.

4. The crest of the anticline along Pine Ridge is a good location for exploration wells.

5. The topography of the southern nose of the Oil Butte anticline indicates a high density of fractures, making the entire nose of the anticline an excellent target for exploration wells.

OIL AND GAS EXPLORATION WELLS

Two oil and gas exploration holes on the west flank of the Pine Ridge anticline verify that the Madison strata in the anticline are folded. In other words, the oil and gas exploration holes show that the strata above the Madison limestone did not fold independently of the limestone, as occurs in some areas. The oil and gas exploration holes indicate that the Madison strata folded similarly to the overlying strata. The location of test well Smith Colthorp #1 is shown on Figure 31 and is of particular interest to this study in that it penetrated into the top of the Madison strata. The geological report for this well, including the log of the geologic materials penetrated by the well concludes with the following description:

> "**MADISON TOP @ 2303' – NOT RECOVERED IN SAMPLES DUE TO LOST CIRCULATION AT 2308-2310.**"

The latter typed entry at the end of the geologic log is followed by a hand-written note, as follows:

> **"At this time well went on a vacuim** (sic) **for about 15 min. then returned a fluid level of water within 400 feet from top of hole.**"

An early part of the geological report stated that subsequent testing of the fluid in the hole showed fresh water at a static level of 550 feet. The well was offered to the cities of Gillette and Moorcroft for sale as a water well.

The latter report provides encouragement that the Madison strata in the Pine Ridge anticline will produce groundwater. As previously mentioned, the anticline is essentially the same type of structure generally represented by Part B of Figure 33. The many drainages on the flanks of the anticline mostly appear to enlarge joints perpendicular to the axis of the fold, i.e., extensional joints perpendicular to the extensional joints that are expected parallel the axis of the fold, but which are generally not evident as regionally visible lineaments in the topography. In addition to the joints perpendicular to the fold axis, there are a number of joints lightly outlined on Figure 31 that appear to be a conjugate joint pattern of the type shown on Part B of Figure 33 as compression joints. These general observations, combined with the report from the Smith Colthrop #1 well, support the expectation that wells drilled into the Madison aquifer from the top or flanks of the Pine Ridge anticline should produce good yields of groundwater. As shown on Figure 16, the drilling depths near the crest of the fold should be equal to or slightly less than the drilling depths in the existing COG Madison well field; however, the depth to static water level will likely be 100 to 150 feet more than the initial static water levels in the existing well field.

DESCRIPTION OF POTENTIAL EXPLORATION AREAS

Four areas are identified for groundwater exploration, based on the fracture pattern analysis. The four areas are referred to as follows:

1. Eastern exploration area
2. Structural Saddle Area
3. Pine Ridge exploration area
4. Oil Butte Anticline – Section 36

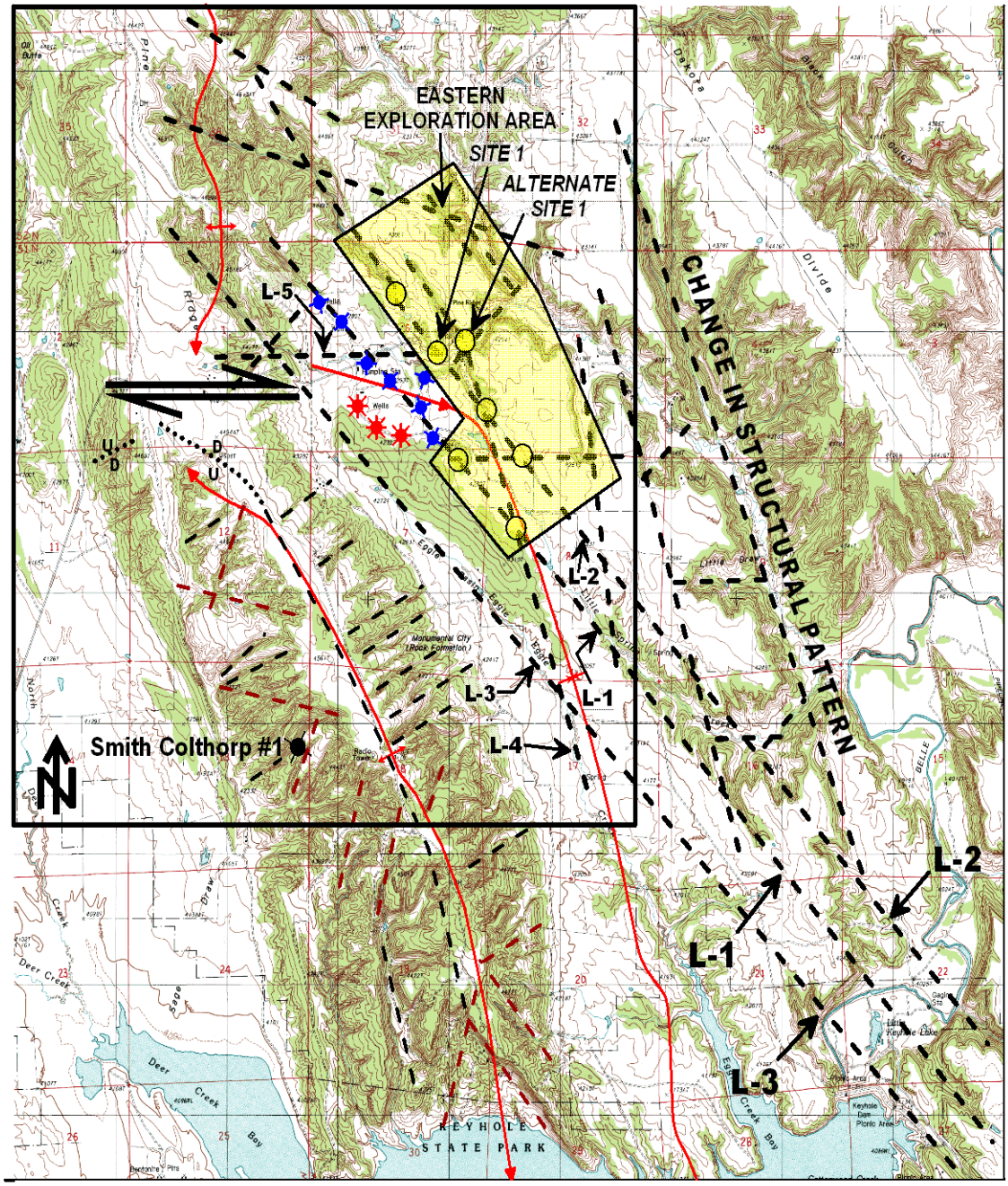
Each area is discussed in terms of potential sites for one or two exploration wells. In addition, each area is discussed in terms of potential sites for up to seven production wells per area. Production well sites within a given area include the recommended exploration well sites, based on the recommendation that the exploration wells be constructed in such a manner that they will be suitable for use as production wells, when completed.

Eastern Exploration Area

The fracture patterns in the Eggie Creek syncline shown, on Figure 35, suggest locations for two test holes to explore the potential to expand the existing COG Madison well field, as follows:

1. **Site 1**: An exploration well should be drilled near the intersection of lineaments L-2, L-4 and L-5 at locations identified as Site 1 or Alternate Site 1. The intersection of one of more lineaments often offers highly fractured rock and enhanced aquifer properties to support a production well. In addition, this may be a good location to explore for the solution breccia zone penetrated by well M-9. Widespread fracturing around the

Figure 35: Eastern exploration area.



intersection of lineaments L-2, L-4 and L-5 and the two other short lineaments intersecting this area may be an alternative explanation to the collapse breccia hypothesized at well M-9.

2. **Site 2**: An exploration well should be drilled on the L-1 lineament southeast of the existing well field, at Site 2, for the purpose of verifying that the hypothesized joint or fracture along the lineament continues to provide enhanced aquifer properties and the potential to support high-capacity wells. A good potential site for the exploration well is the intersection of the L-1 and L-4 lineaments. The well will determine the aquifer characteristics and yield at this location, determine the continuity of linear flow along the lineament, and potentially determine the response of the linear flow feature to hydraulic fracturing if initial tests demonstrate it is not well-connected to the portion of the flow system penetrated by wells M-1, M-2, M-3, M-4, M-8 and M-10.

Interest in the area where lineaments L-2, L-4 and L-5 intersect is reinforced by the presence of a short lineament parallel to L-2 that also intersects these trends. In addition, the short section of the unnamed tributary of Spring Creek along Highway 14 that is aligned northeast by southwest intersects these trends. The latter alignment may represent a joint perpendicular to the L-1, L-2 and L-3 trends in the classic pattern shown on Figure 33. Accordingly, this area in the NE, NE, SE, section 6, T51N, R66W is a prime area for an exploration/production well.

One possible interpretation of the less than quarter unit slope hydraulic response of wells M-1 and M-8 to pumping is that they are located at the extreme ends of a limited length of highly transmissive solution enlarged fracture aligned with lineament L-1 and that outside the length of fracture between these two wells, the hydraulic properties of the fracture are less favorable. In this interpretation, the presence of the “constant head” boundary in the area penetrated by well M-9 is crucial to the long-term reliability of production from this fracture, as has been experienced to date.

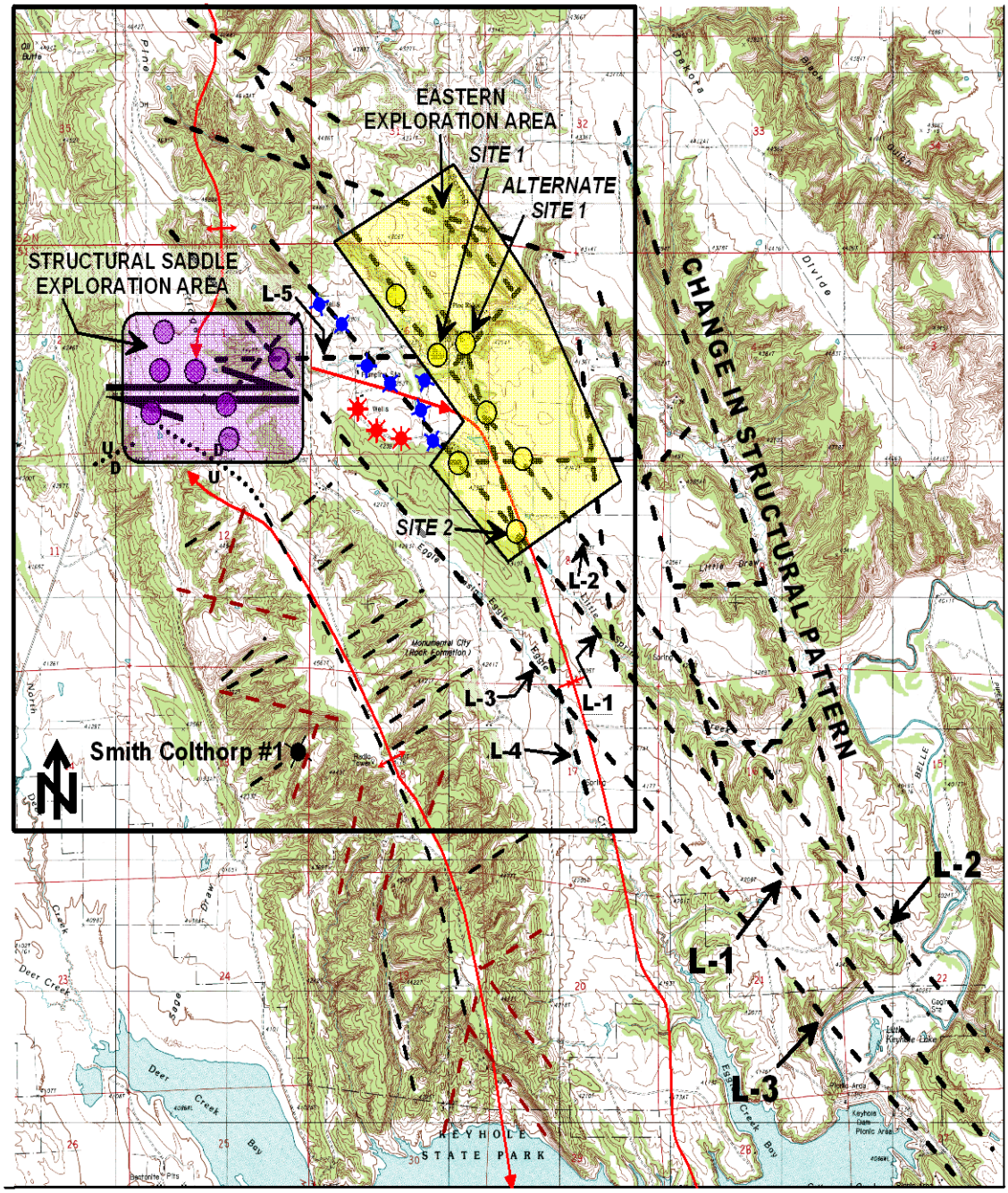
Presumably, wells sited on a fracture along lineament L-2 north and south of Site 1, as shown in Figure 35, would potentially enjoy similar constant head boundary effects. Wells at Site 1 and Alternate Site 1 might penetrate the same flow system penetrated by well M-9. The advantage of this would be long-term reliability of yields from wells along lineament L-2 due to the constant head boundary effects. The disadvantage of this approach is that imposition of too much diversion of water from the large groundwater storage feature penetrated by M-9 might cause an undesirable rate of depletion and lowering of the groundwater levels in that feature. That would result in an increase in the rate of decline of groundwater levels in response to pumping throughout the existing well field and any new wells in the Eastern exploration area.

The Eastern exploration area boundaries are expanded to the east to encompass three locations of multiple lineament intersections, one in the Spring Creek valley and two along the east side of Spring Creek on tributary canyons. The latter three intersections are not called out on the map, but are evident where the lineament lines on the map intersect.

Structural Saddle Exploration Area

As shown on Figure 32, the southern end of the Oil Butte anticline and northern end of the Pine Ridge anticline are the location of an offset in the overall structural trends of the axes of the two folds. That offset is depicted on Figures 31, 32, 35 and 36 by opposing shear arrows. The structural contours shown on Plate 34 of USGS Bulletin 1082-J appear to adequately explain the misalignment of the structural axes in terms of folding. However, it must be noted that the structural contours are drawn on a unit in relatively soft, plastic Cretaceous strata some 2300

Figure 36: Structural saddle exploration area.



feet or more above the relatively thick layer of hard, brittle limestone presented by the Madison group strata. The thick layer of relatively hard, brittle Madison limestone may not have accommodated the differential folding in the structural saddle area as easily as the soft

Cretaceous strata. The fault along the south margin of the saddle appears to have occurred after the folds took place, and therefore, does not appear to play a role in explaining the offset of the structures.

Lineament L-5 on Figure 36 may indicate a line of east-west shear through the saddle between the two folds. If so, the opposing shear arrow symbols should straddle the lineament, not the topographically low part of the saddle as shown. The small drainage that follows the north end of lineament L-3 (Figure 31) off the nose of the Oil Butte anticline is offset a few hundred feet by the L-5 lineament, thus indicating some shear along the lineament. However, the latter structural displacement of the L-3 lineament by the L-5 lineament is not nearly equal to the apparent offset of the structure, although some of the shear might have been absorbed by the thick sequence of Cretaceous strata. Lineament L-5 is not expressed as a lineament in the saddle and is not evident as a lineament west of the saddle. The 1964 USGS structural contours on the base of the Fall River sandstone do not reflect any displacement on the west side of the structural saddle and, in fact, require very little adjustment to make the transition from the Oil Butte anticline to the Pine Ridge anticline. The latter factors argue against displacement of the rock through the saddle by shear; however, the 1964 USGS structural contours are merely projections, a conclusion indicated by the absence of outcrops of Fall River sandstone on the west side of the structural saddle.

Taking all of the foregoing factors into consideration, the potential for shear of the rock in the saddle, including the deeper Madison limestone, is not likely as great as potentially implied by the offset of the two folds and folding of the strata in the saddle may account for most of the offset. The 1964 USGS structural contours indicate an area of unfolded rock in the middle of the structural saddle; however, the downward offset of the strata along the fault on the south side of the saddle contributes to the structurally flat area in the contours drawn in the saddle on the 1964 USGS geologic map. Without the fault displacement, the structural contours in the saddle would be similar to those on top of the anticlines. Recognition of the latter fact leads to the conclusion that folding in the structural saddle may not be substantially different than that along the crests of the anticlinal folds, at least in the Cretaceous strata. It is not clear how this translates to the deeper, thicker, and more brittle Madison strata; however, it may indicate that the thick, hard limestone of the Madison may not be highly fractured at depth or that fractures in the limestone do not fully penetrate its thickness.

The foregoing assessment of the observable elements of the structural saddle indicate that the potential for shear and the potential for a high fracture density in the saddle related to folding may not be any greater than on the axis of the Pine Ridge anticline, for example, and may not even be as great as that. The intersection of the L-5 and L-3 lineaments, as well as some smaller lineaments at that intersection, indicate a very favorable spot for an attempt to penetrate a solution enlarged fracture. That location is shown on Figure 36 as the furthest east potential well site in the Structural Saddle exploration area. Although this site is lumped with the other Structural Saddle exploration area sites by proximity, the factors making it a favorable site are independent of the factors considered in the foregoing evaluation of the structural saddle.

Locations for six other potential well sites are shown on Figure 36 for the Structural Saddle exploration area, based on the locations of lineaments in the topographic features that may correlate to fractures in the strata in the saddle. The potential well sites shown on Figure 36 are relatively closely spaced compared to the other exploration areas discussed herein, a fact that

does not matter if the Madison rocks in the saddle area are highly fractured, but which is a disadvantage if the fracture density is limited.

Pine Ridge Anticline

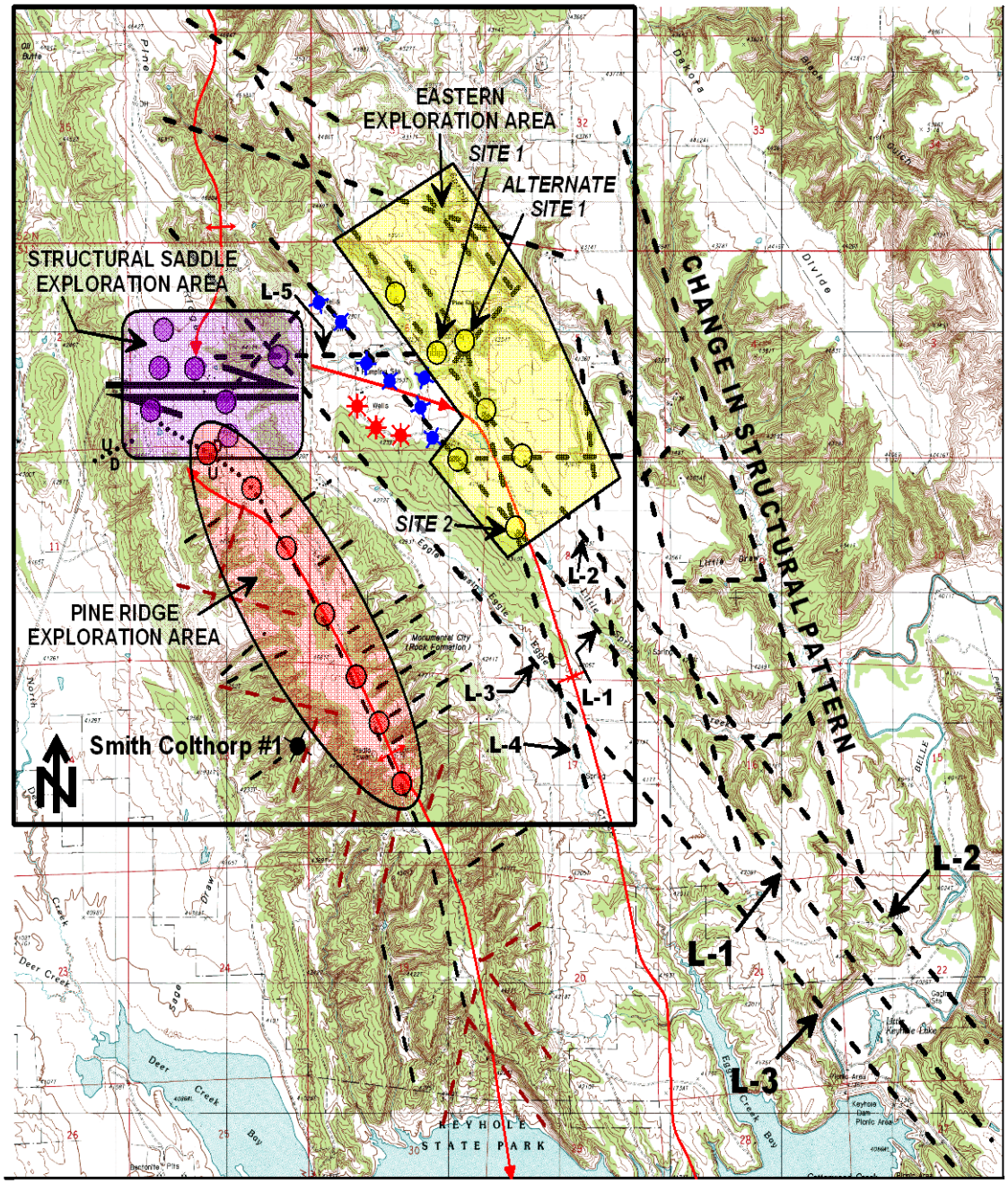
Figure 37 shows the Pine Ridge exploration area. A fault in the north end of the Pine Ridge anticline is aligned with the anticlinal axis and appears to be a northward extension of the axis. The map does not indicate if the fault is a normal fault or a high angle reverse fault. The anticlinal axis as drawn on the 1964 USGS geologic map deflects to the south of the fault, potentially indicating the strata north of the axis dip toward the fault. The latter condition has not been verified in the field for this study; however, if it is correct, the fault may be a high angle reverse fault. The presence of a high angle reverse fault in the axis of the anticline would be verification of a hinge fault in the fold and an indication that the Madison strata may be deformed by a fault-cored anticline in the subsurface, a condition very favorable to enhancement of aquifer hydraulic conductivity by secondary openings in fractures along the fault.

The Smith Colthorp #1 exploration well, previously described herein, is shown on Figure 37, on the west flank of the Pine Ridge anticline. The Smith Colthorp #1 well experienced lost circulation in the Madison aquifer. The only wells completed in the existing COG Madison well field that experienced lost circulation during drilling are those that exhibit linear flow aquifer response and which are located along lineament L-1 where they penetrated voids in the limestone. Penetration of a zone of lost circulation by the Smith Cothorp #1 well is therefore a strong indication that the well penetrated a void in the limestone.

Figure 37 shows a production well array along the axial crest of the anticline. The well spacing shown provides large separations between seven production wells on the crest of the fold. The crest of the fold is selected for the well field array because that is where the most fracturing of the rock is anticipated in the classic relationship between folds and fractures. However, the Madison limestone in the Powder River basin has been subjected to three different episodes of uplift and karst development over geologic time. Accordingly, cavernous limestone may be present at depth which developed prior to the Black Hills uplift that resulted in the current structures. Caverns, collapse breccia zones, and solution enlarged fractures that formed before the Black Hills uplift, if present, may have been controlled by structures that have since been obscured by younger Cretaceous strata. It is therefore not certain if the Smith Colthorp #1 well penetrated a void related to the present Pine Ridge anticline and its related fractures or some older feature such as a pre-Black Hills uplift solution breccias. Unfortunately, the contemporary structures and fractures may not reveal anything about the location, distribution, and extent of the older karst solution features.

Therefore, the well array depicted on Figure 37 was located on the crest of the existing fold. The relatively large well spacing was used to minimize drawdown along a fracture zone in the crest of the anticline, if present, in anticipation of linear flow in the main fracture zone. The well locations as shown also attempt to put the wells at the projected intersections of the hypothesized fracture zone along the crest of the fold and the perpendicular and/or conjugate fractures on the flanks of the fold. This does not rule out alternative sites, particularly on the west flank of the fold, where a number of canyons on the side of the ridge define the locations of conjugate fractures and/or fractures perpendicular to the fold axis. Most of the latter sites involve a certain amount of rough terrain that affects access to large drilling equipment.

Figure 37: Pine Ridge exploration area.

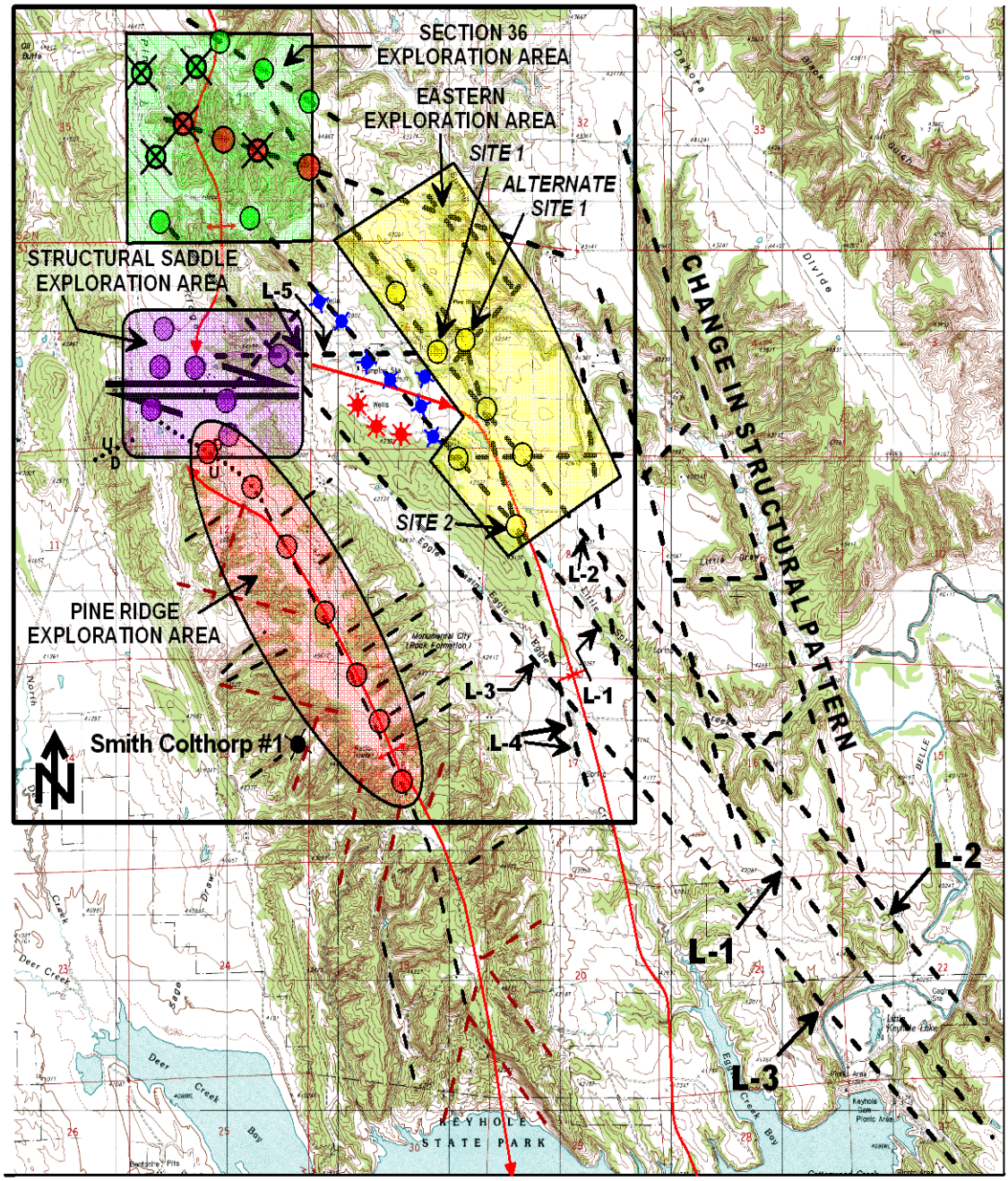


Oil Butte Anticline

The southern nose of the Oil Butte anticline offers a considerably different structural situation than provided by the Pine Ridge anticline. The fracture patterns on the Pine Ridge anticline are

limited to those associated with the fold. In addition to fracture patterns associated with the fold, the southern nose of the plunging Oil Butte anticline is traversed by two sets of regional lineaments that are unrelated to the local fold. Based on this fact, and the availability of State land in Section 36, Section 36 is recommended as a prime area for exploration/production wells, as shown on Figure 38.

Figure 38: Section 36 exploration area.



Lineaments L-1, L-2 and L-3 extend into the southern nose of the Oil Butte Anticline (Figure 38) where they have a pronounced effect on the pattern of the erosion-enlarged surface drainage canyons. The L-3 lineament is weak in the Eggie Creek structural basin. The lineament alignment may be present due to erosion along the strike of a soft layer of strata (upper Fall River Sandstone unit) along the base of more erosion-resistant strata in the Skull Creek Shale, rather than due to a strong fracture. However, the L-3 lineament is a very strong feature north of lineament L-5, on the nose of the Oil Butte anticline. Moreover, lineament L-3 appears to be offset by shear along lineament L-5 at their intersection. Accordingly, the intersection of lineaments L-3 and L-5 remain a prime target for an exploration well.

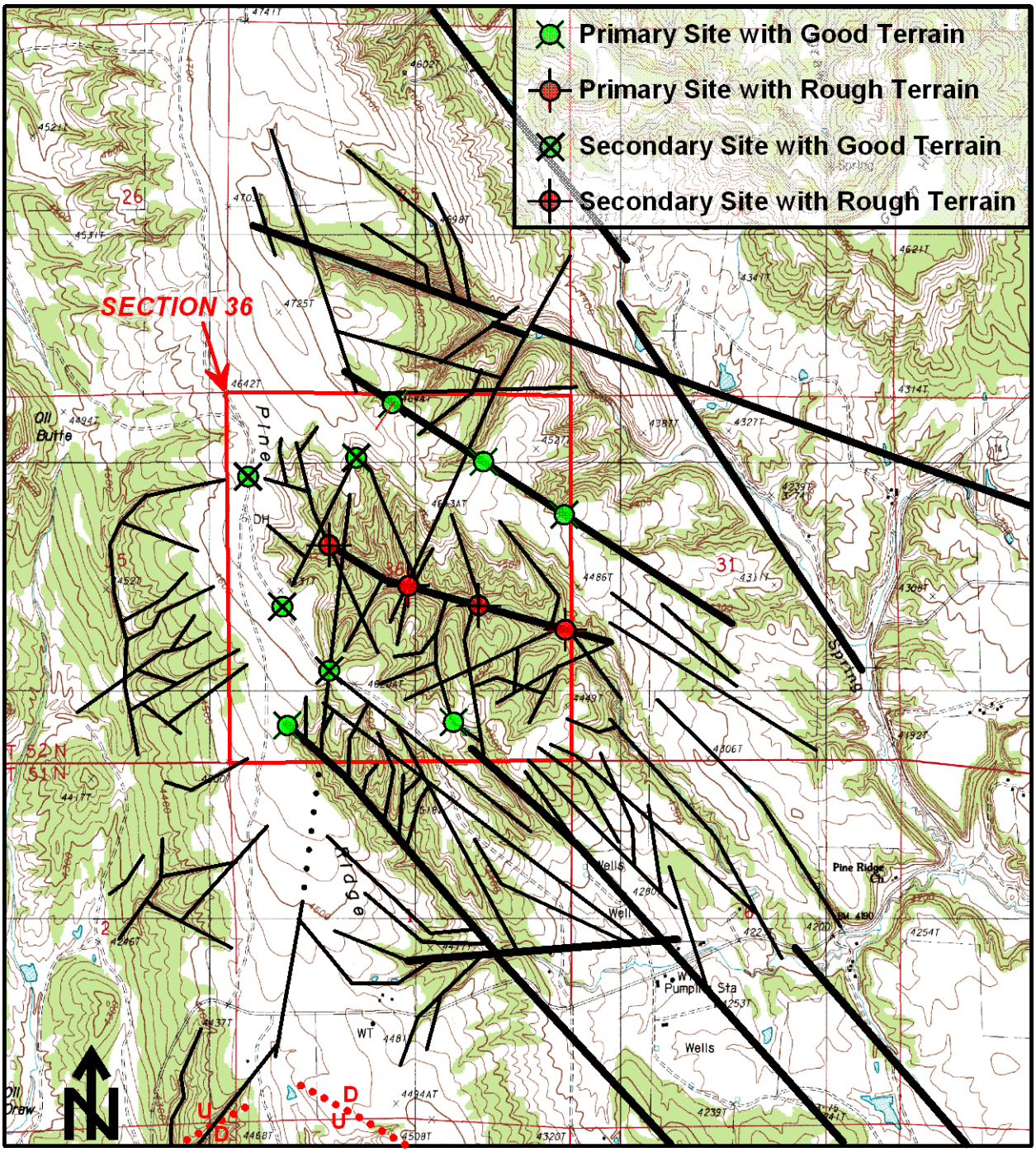
Lineaments L-1 and L-2 are relatively strong, persistent alignments of topographic features indicating that the lineaments align with robust structural joints. Those lineaments extend into the southern nose of the Oil Butte anticline where they appear to be paralleled by several local lineaments, presumably joints in the nose of the anticline, and are cross-cut by at least two major joints forming a conjugate compressive joint pattern on the nose of the anticline (Figure 38). The northwestern end of lineament L-1 and the extension of two smaller parallel lineaments are accessible by a trail on the top of Pine Ridge in the south half of the south half of section 36, T52N, R67W. This is a good location for a test well with reasonable access for large drilling equipment and is marked on Figure 38 with a solid green circle with a black outline.

The northwestern end of lineament L-2 is a stronger feature on the anticline than L-1; however, it follows the bottom of a local drainage on the southeastern slope of the plunging nose of the Oil Butte anticline, where rough terrain makes access for large drilling equipment difficult. At the very northwest corner of the southwest quarter of the southwest quarter of section 31, T52N, R66W, the L-2 lineament is intersected by a very strong west-northwest by east-southeast lineament that follows a deep canyon in the nose of the anticline. The intersection of the two lineaments is an abrupt bend west-northwest by east-southeast aligned canyon to the L-2 lineament. This is a favorable drilling site; however, it is on very rough terrain. It is marked on Figure 38 with a solid red circle with a black outline near the eastern boundary of Section 36.

Figure 39 shows a detailed lineament map of the southern nose of the Oil Butte anticline and the State land in Section 36. The map on Figure 39 shows the west-southwest by east-southeast aligned lineaments that are interpreted to represent a regional conjugate fracture pattern that is not limited solely to the Oil Butte fold, but which relates to the same compressive deformation that created the fold. The canyons following the conjugate lineaments are relatively deep, narrow, and steep and do not afford reasonable access for a rig to drill directly on the lineaments. However, the southwest side of the bend in the canyon at the intersection of the two lineaments in Section 36, as previously described, is a lightly timbered bench accessed by a rudimentary wheel track that can be improved into an access road for equipment such that an exploration hole could be drilled on the bench above the inside bend of the bench above the canyon floor. This would put the exploration well close enough to the lineaments for hydraulic fracturing to attempt to connect the well to the fractures along the lineament, if lost circulation during drilling did not occur to indicate a good hydraulic connection with the fractures. This site is the furthest east red circle in Section 36 on Figure 38 and Figure 39.

In addition to the two potential exploration well sites in Section 36 described above, additional sites are shown on Figure 38 and Figure 39, based on the lineament study. Sites on strong regional lineaments thought to represent major fracture zones are indicated as “Primary” sites.

Figure 39: Detailed lineament map of Section 36 and nearby area.



Primary sites with no significant terrain limitations for large drilling rig access are referred to as "Primary Sites with Good Terrain" on Figure 39. Primary sites on rough terrain in the canyons are referred to on Figure 39 as "Primary Site with Rough Terrain". Potential drilling sites that were located on projections of smaller local lineaments into good terrain are indicated as

"Secondary Site with Good Terrain" and similar sites on intersections of a major lineament with smaller local lineaments in rough terrain are designated "Secondary Site with Rough Terrain".

SUMMARY OF EXPLORATION SITES

The Section 36 area on the southern nose of the Oil Butte anticline appears to offer the most favorable geologic conditions for expansion of the COG Madison well field compared to any of the other sites described. The principal reason for this conclusion is the relatively high density of fracturing indicated by the topography in the area, including in the State land in Section 36. The principal factor contributing to the high degree of fracturing on the Oil Butte anticline compared to the Pine Ridge anticline is the confluence of the L-1, L-2 and L-3 regional lineaments with the west-northwest by east-southeast lineaments on the nose of the Oil Butte anticline. The coincidence of the latter regional fracture pattern with the nose and southeastern flank of the Oil Butte fold has resulted in a myriad of small fractures in the blocks of rock between the regional fractures.

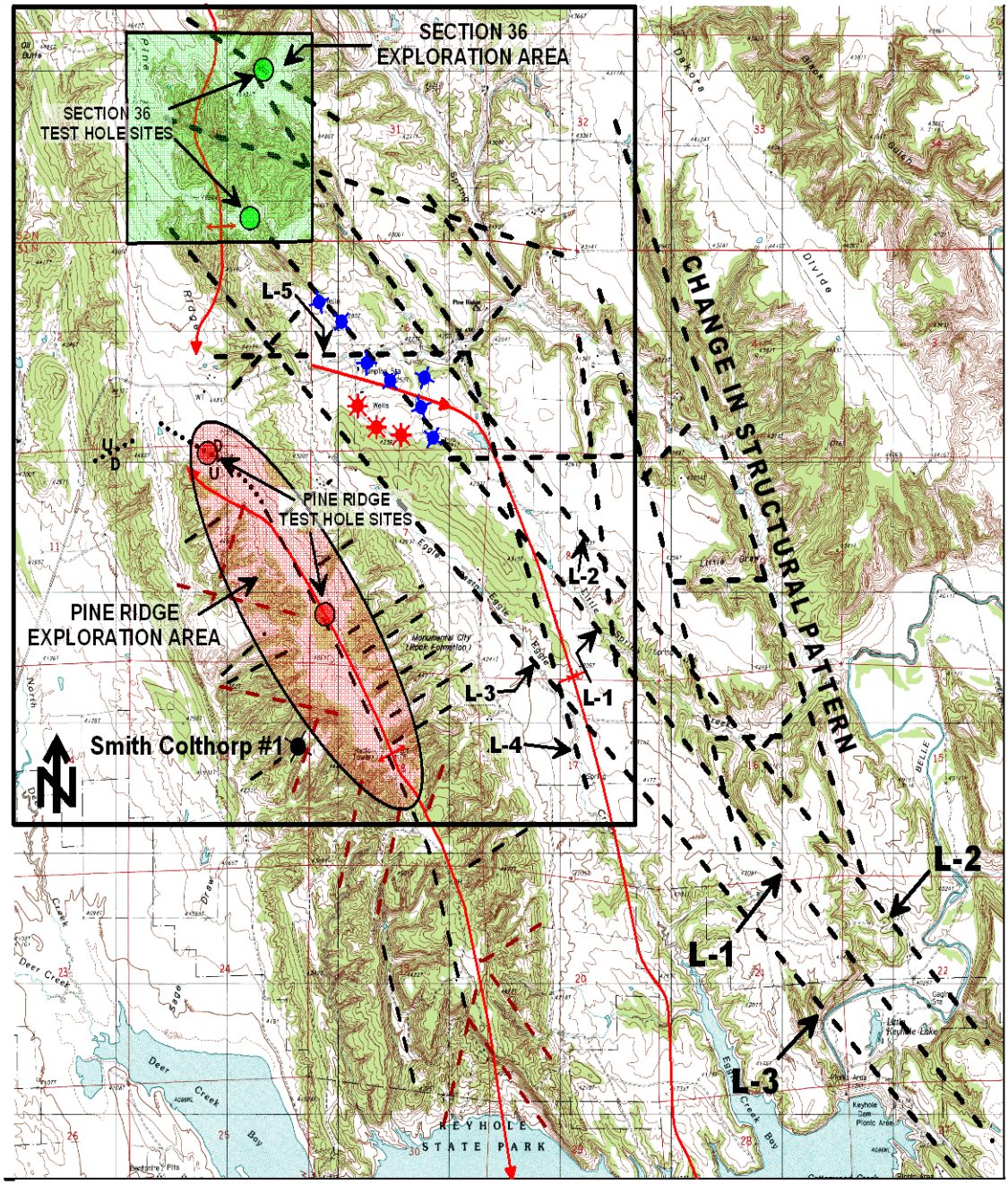
The numerous fractures in Section 36, many of which (but not all) are shown on Figure 39, suggest that exploration or production wells sited with care, can reasonably be expected to penetrate interconnected fractures which will enhance yield from the fractured limestone in the Madison aquifer in this area. Nine potential well locations are shown on Figure 39, selected first on the basis of major fractures or multiple fracture intersections on good terrain (primary sites on good terrain) and second on projection of smaller fracture alignments into good terrain (secondary sites on good terrain). Four additional sites are indicated on rough terrain. The distribution of primary and secondary sites on good terrain within Section 36 provides favorable distances between wells for adequate minimization of interference drawdown between high-capacity wells. Depending on the response of the local Madison aquifer system to short-term aquifer tests and long-term well field operation, the well spacing shown on Figure 39 is likely adequate to allow addition of a few more high-capacity wells in the future, particularly if some of the sites on rough terrain are used.

If Section 36 is selected as the area for expansion of the COG Madison well field, after non-geologic factors are taken into consideration, it is recommended that the first test hole be drilled in the northeast quarter of the section (Figure 40), to verify production from a location on a strong lineament trace that traverses the northeastern part of the section from northwest to southeast. A second test well is recommended in the southern part of the section, on the projected alignment of lineament L-1 (Figure 40). The latter test hole would test the production from an area of high-density fracturing.

The topography of the flanks of the Pine Ridge anticline includes numerous small canyons that appear to be fracture controlled and consistent with fractures perpendicular to the axis of the fold, as anticipated by classic fold-fracture concept. Presumably, fractures are likewise aligned with the axis of the anticline, along the crest of the fold at the top of the topographic feature called Pine Ridge. The drainage patterns in the canyons on the flanks of the fold also include some drainages oblique to the axis of the fold, consistent with anticipated conjugate fracture patterns on a fold.

One oil and gas exploration well drilled on the south flank of the fold penetrated a highly porous zone in the Madison aquifer as evidenced by loss of all the drilling fluid in the hole over a 15-

Figure 40: Recommended locations for two exploration wells.



minute period. Collectively, the foregoing factors indicate the potential for a system of interconnected fractures in the Madison strata in the anticline that may provide groundwater flow to high-capacity wells. The oil and gas exploration well (Smith Colthorp #1) indicates the presence of solution openings, at least locally, which may further enhance groundwater flow to

wells; however, it is not known if the solution openings enlarge fractures in the pattern evident on the structure or if they relate to some older event of solution opening development that is independent of the current structural pattern and unpredictable as to distribution and extent.

A fault at the north end of the Pine Ridge anticline opens the possibility of a hinge fault in the Madison aquifer rocks at depth in the structural fold. The Smith Colthorp #1 well is in a location such that it would penetrate through the hanging wall of such a fault, if the fault is present, and into highly porous fractured rock in the Madison aquifer strata along the fault. If the Smith Colthorp #1 well penetrates a fault in the core of the anticline, it may be possible to drill high capacity wells through the hanging wall of such a fault all along the western flank of Pine Ridge. Although the latter possibility is speculative, it is not inconsistent with the information presently available. The overall Pine Ridge anticline structure appears to offer favorable geologic conditions for groundwater exploration and development from the Madison aquifer, second only to the Section 36 area on the Oil Butte anticline, and is the most favorable area for groundwater exploration considered herein, if the Section 36 area on the Oil Butte anticline is not selected for exploration.

As shown on Figure 40, two exploration well locations are shown on the Pine Ridge anticline. One is at the north end of the fold where its purpose is to explore the productivity of the Madison aquifer along the fault zone. Selection of the exact site for this well should be preceded by an examination of the geologic structure of the outcrops exposed in the small canyons on the flanks of the ridge west and south of the proposed site. The purpose of this work would be to determine whether to locate the exploration well directly on the fault zone or offset it slightly southwest of the fault zone. A second test well location on the Pine Ridge anticline is shown on Figure 40, located approximately in the center of the length of the anticline. Again, the generalized site shown on Figure 40 should be refined by consideration of the lineament pattern on the flanks of the anticline so that the well site is at the projected intersection of perpendicular and/or conjugate fractures with the crest of the anticline. An alternative to this site might be to select a location on the west flank of the anticline, similar to the Smith Colthorp #1 well, assuming that a suitable site can be identified on fracture alignments where accessible terrain is present. The Smith Colthorp #1 well, for example, appears to be located on a fracture perpendicular to the crest of the anticline and near a conjugate fracture. A similar location might be selected for the second test well on the Pine Ridge anticline.

The area east and south of the existing COG Madison well field, referred to herein as the Eastern exploration area, is traversed by a number of large lineaments thought to represent the locations of regional fractures in the uppermost part of the earth's crust, presumably including the Madison aquifer strata. Six of the existing COG Madison wells penetrate the same lineament and provide high capacity or high performance well yields and linear flow aquifer response. Therefore, wells sited on this lineament or on nearby large lineaments, particularly at the intersections of lineaments, may produce high-capacity yields from the Madison aquifer. Some of the potential well sites are near the location of existing well M-9 which provides a hydraulic response indicating it penetrates a large volume of groundwater storage compared to other parts of the Madison aquifer currently penetrated by wells in this area. The sites near well M-9 may encounter the same large volume of groundwater storage, or at least benefit from its proximity in terms of limited decline of water levels as the result of pumping abstractions from the aquifer.

Hydrogeologic disadvantages of the Eastern exploration area are that the potential drilling sites are limited to a few large lineaments, requiring multiple wells pumping from the same fractures, and that high-capacity production from a few interconnected fractures may encounter hydraulic limitations due to non-uniform hydraulic properties along the fractures. If the hydraulic limitations in the fractures are too distant from the wells, they may not be responsive to stimulation by hydraulically fracturing the aquifer rock near the wells. High-capacity yields of groundwater from the fractures hypothesized along the lineaments have not been verified outside of the existing well field where the most distant wells in the field exhibit some evidence of hydraulic limitations in the fractures.

Hydrogeologic advantages of the Eastern exploration area are that the aquifer response to pumping of the existing wells indicates the Madison aquifer strata containing the large, regional fractures is porous and releases groundwater storage into the fractures when they are pumped by wells. Likewise, the area of large groundwater storage volume penetrated by well M-9 may help stabilize drawdown in wells developed in the major fractures in this area; a potential advantage, but too much mining of groundwater storage in this local area may result in depletion of the large volume of groundwater storage such that the water levels in the existing well field as well as in the new wells begins to decline and cause associated reductions in well yields. Therefore, this area is not as attractive for expansion of the existing well field as the more distant areas on the Oil Butte and Pine Ridge anticlines which will distribute the future drawdown of the aquifer water levels over a relatively large area and which may contain relatively more interconnected fractures than are evident in the Eastern exploration area.

The east-west offset of the axis of folding between the Oil Butte and Pine Ridge anticlines initially appears to demand considerable structural adjustment in the vicinity of the Structural Saddle exploration area. Such structural adjustment would theoretically cause considerable fracturing of the Madison aquifer strata in the structural saddle and make this a geologically favorable area for groundwater exploration in the Madison aquifer. The offset might be absorbed in one of two ways. One way would be an east-west shear zone through the saddle. The other would be folding of the strata to absorb the offset.

Close examination of the topographic maps and imagery of the Structural Saddle area does not reveal evidence of a large shear zone. A small east-west offset of lineament L-3 by lineament L-5 is evident in the offset of a stream course following L-3, but is not enough to explain the offset in the larger structures. The structural contours drawn on the 1964 USGS geologic map of the Carlile quadrangle suggest strata in the saddle are relatively undeformed, at least in the shallow Cretaceous strata. The detailed lineament study of the Oil Butte anticline nose (Figure 39) detected several lineament traces through the structural saddle, presumably the location of fractures. The partial pattern of fractures in the saddle shown on Figure 39 is not consistent with strong differential folding or shear in the saddle. These latter conditions may prevail because the relatively soft Cretaceous strata, 2300 feet or more thick at this location, absorbed all of the structural offset, even though hard Madison strata at depth could be fractured at depth due to the differential movement between the two large anticlines. Thus, fracturing of the Madison strata at depth cannot be ruled out in the structural saddle, but it cannot be proven.

As shown on Figure 37, construction of seven production wells in the structural saddle, located on the fracture traces (lineaments) evident on Figure 39, makes the distances between the wells relatively small. Even so, the spacing is greater than that in the existing COG Madison well

field; however, new wells in the structural saddle may not enjoy the benefit of a nearby large volume of groundwater storage such as that which stabilizes groundwater drawdown in the existing well field. Without the essentially constant head boundary that stabilizes drawdown in the existing well field, groundwater levels in the structural saddle potentially may decline rapidly in response to pumping abstractions from seven relatively closely spaced high-capacity wells in the structural saddle. Taking the foregoing considerations into account, the Structural Saddle exploration area is at best a location suited for a true wildcat well that would be drilled for the purpose of learning the actual conditions in the Madison aquifer in the saddle. The main advantage of the Structural Saddle exploration area is its proximity to the main transmission line route for the well field expansion project and an associated storage reservoir. Geologically, the area is an unknown compared to the other three areas considered.

EXPLORATION/TEST/PRODUCTION WELL DESIGN

The design of an exploration well depends on its purpose. Some exploration wells are drilled for the purpose of obtaining samples of a formation for well screen design or for determining the sequence of strata. Some explorations wells are drilled to verify the presence and depth of water-bearing strata before a more expensive well is drilled. Some exploration wells are drilled to obtain a sample of the groundwater to determine its chemistry and quality or to measure the static water elevation. Other exploration wells are drilled for to determine the local yield of an aquifer and the factors affecting that yield. Wells drilled for the latter purpose might better be considered as test wells rather than exploration wells, since the presence of the aquifer is a foregone conclusion and it is the hydraulic properties of the aquifer that are of interest.

The “exploration” wells for expansion of the COG Madison well field essentially belong in the latter category; however, they are exploration wells in the sense that part of their purpose is to attempt to locate zones of enhanced aquifer yield for high-capacity wells within broader areas of average aquifer properties that may not support the high-capacity yields. The Madison aquifer generally yields significant amounts of water. This is evident from wells M-5, M-6 and M-7 which obtain production from parts of the Madison aquifer that do not offer enhanced hydraulic properties due to natural fractures or solution enlarged fractures or voids. There is no question that wells in the Eggie Creek syncline or on the Pine Ridge anticline and the structural saddle between the Pine Ridge and Oil Butte anticlines will penetrate the Madison aquifer. Reasonable estimates of the depth to the Madison aquifer can be made, certainly with enough accuracy to draw up specifications and cost estimates for new wells. However, the goal in this exploration program is to find sites for high-capacity wells that offer high hydraulic performance, not to simply find the Madison limestone or develop wells with relatively low hydraulic perforamance.

Therefore, the only purpose of drilling exploration wells before expanding the Madision aquifer well field is to attempt to find the locations of areas where the aquifer properties have been enhanced with secondary openings in the rock due to fractures and solution enlargement of such fractures. If such zones are found, their yield and hydraulic performance must be evaluated. In this last step, the exploration well must become a test well with large enough diameter casing to accept the pumping equipment that will provide the desired design yields. Although it is theoretically possible to project or estimate ultimate well yields from tests conducted at less than maximum aquifer/well yields, several factors complicate such projections and usually make them less than satisfactory, particularly with regards to predicting hydraulic performance.

One such factor is well loss drawdown. Well loss in a relatively small diameter well at lower pumping rates cannot be projected or estimated for larger diameter wells at higher pumping rates where well and aquifer response involve linear flow. All methods for projecting well loss are based on radial flow concepts. A second factor is the effect of linear flow boundaries on the aquifer performance at higher pumping rates. Although mathematical theory may include a method for projecting aquifer response to different pumping rates in a linear flow aquifer, no practical method of readily applying the mathematics is currently available through commercial software or spreadsheet equations. At present, the only practical way of determining a reasonable design yield for a high-capacity production well in a linear flow aquifer system is to test a well in that aquifer at a pumping rate equal to or greater than the desired design flow to provide a practical demonstration of well and aquifer performance. The latter conclusion is based in large part on the fact that linear flow responses often, if not typically, depart in some manner from the theoretical type curves.

Therefore, it is strongly recommended that exploration wells for expansion of the COG Madison well project be constructed with large enough casing diameters to allow high-capacity testing with large amounts of drawdown. Exploration wells designed for high-capacity pumping can later be converted to production wells, if they are properly constructed for use as public water supply wells.

Figure 41 is a plot of specific capacity versus pumping rate for the ten wells in the existing COG Madison well field. Specific capacity values are divided between high-capacity wells and low-capacity wells. High-capacity wells are those that provide a specific capacity of approximately 10 gpm/ft-dd or more (including well M-4), whereas, low-capacity wells are defined here to have specific capacities of less than 10 gpm/ft-dd. Two sets of data are plotted for the high- and low-capacity wells; one plot for data collected during pre- and post-hydraulic fracturing aquifer tests of the wells and a second set of plots for specific capacity calculated from operational data as of year 2006, roughly 26 years after the first eight wells were put into production and approximately nine years after the last two wells were put into production. The well number followed by the letters PF means a post-hydraulic fracturing test and followed by OP means generalized specific capacity calculated from operating records.

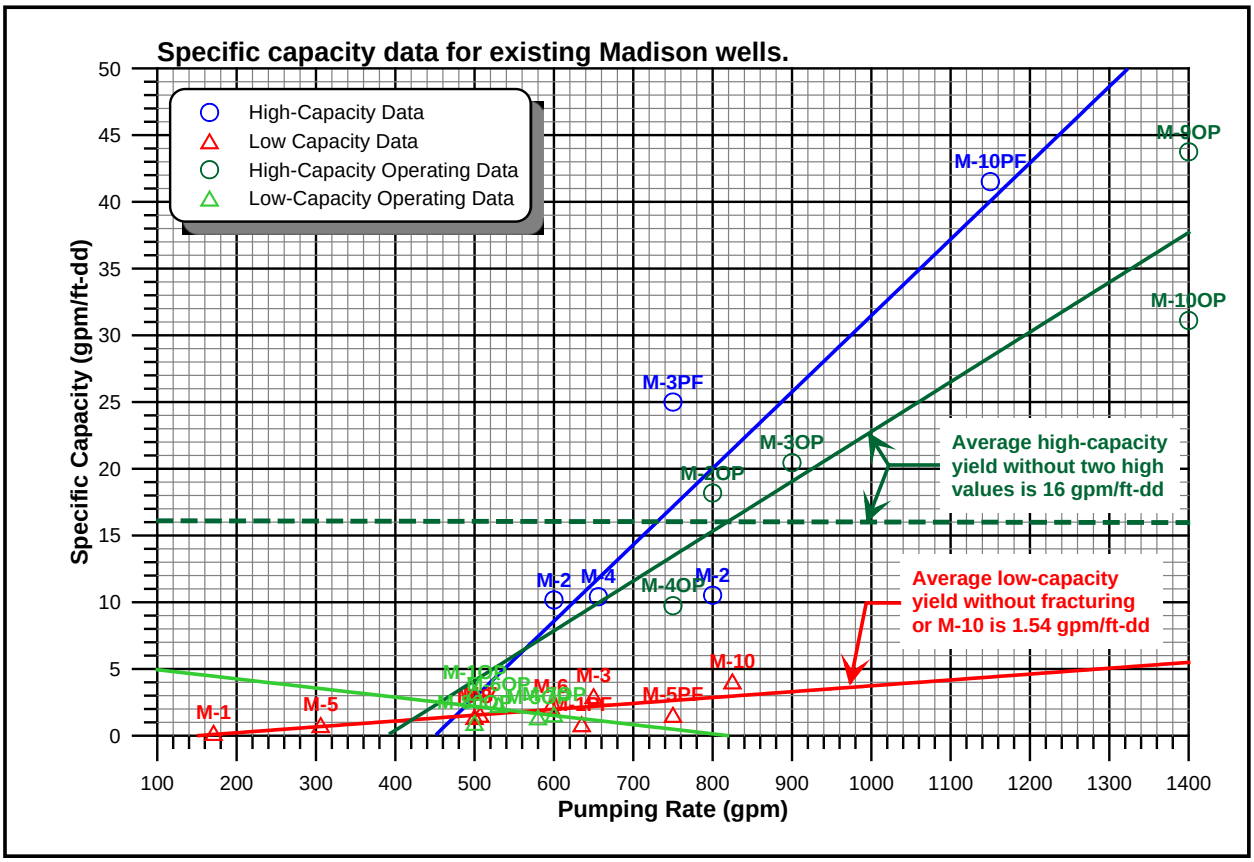
The data presented on Figure 41 are very peculiar in that they show specific capacity generally increasing with increased pumping rate. This is just backwards of what actually happens in a pumped well and is an artifact of the data which reflect the fact that the larger well yields are obtained from the parts of the aquifer with the greatest enhancement of hydraulic properties and which therefore provide the highest specific capacities. Accordingly, the plots on Figure 41 simply indicate that those parts of the aquifer with the greatest enhancement of hydraulic properties by fractures and solution enlarged fractures provide both the highest capacity well yields and the best hydraulic performance.

A value of specific capacity is required for planning test wells; however, it cannot range from 10 to 45 gpm/ft-dd, as shown on Figure 41. A more realistic planning value is obtained by excluding the data from the wells with the highest specific capacity and evaluating the performance of the remaining wells, after they have been in operation for a number of years.

The largest values of specific capacity on Figure 41 are for wells M-9 and M-10. The value for well M-9 is 100 gpm/ft-dd and is not shown on Figure 17 because it is a large outlier on the plot. Well M-9 was the only well to penetrate such productive aquifer material, hypothesized to be a

collapse breccia (or an extensive area of dense fracture distribution), an event that will not likely happen with most of the future wells, and therefore might be excluded from an estimate of specific capacity for planning purposes. Likewise, the values for well M-10 are very large and tend to skew the average of the range of specific capacity that might be expected.

Figure 41: Specific capacity plots for existing Madison wells.



Therefore, the average specific capacity that might be obtained by high-capacity exploration wells penetrating fractures or solution enlarged fractures is calculated by excluding the data for wells M-9 and M-10, resulting in an average specific capacity for high-capacity wells of 16 gpm/ft-dd, based on the operating values shown on Figure 41. Comparison of the 16-gpm/ft-dd line on Figure 41 to the measured values initially suggests it is quite conservative; however, it should be noted that the 20-gpm/ft-dd line for new wells on Figure 41 slowly declined at the 800-gpm rate to just a little more than 15 gpm/ft-dd over the operation of the wells through year 2006. Accordingly, the 16-gpm/ft-dd value is not too conservative for design for long-term well performance, at least in a test well drilled into a new area with unknown aquifer performance.

In a similar evaluation, the specific capacity for low-capacity wells is determined by excluding the wells M-9 and M-10 values, resulting in a pre-operating specific capacity of 1.64 gpm/ft-dd for low-capacity wells which decreases to 1.58 gpm/ft-dd by approximately year 2006. Again, this value may appear overly conservative, particularly for wells stimulated by hydraulic

fracturing, until one takes into account the history of slow, long-term decline in specific capacity in these wells.

One approach to designing an exploration well, based on the foregoing information, is to provide a pumping chamber designed for high-capacity wells penetrating a zone of enhanced aquifer performance, with a minimum specific capacity of 16 gpm/ft-dd. This pump chamber might be 900 to 1000 feet deep. The well diameter below 1000 feet would decrease to a casing sized for a smaller pump, providing a large enough casing that if the well failed to penetrate a high-capacity zone, it could be equipped with a pump capable of 500 gpm or so, depending on the well performance. Likewise, the larger pumping chamber from 900 to 1000 feet could be extended to 1200 feet to provide for long-term drawdown of the aquifer by pumping.

The perception of the foregoing approach is that it reduces the financial risk associated with the test well by limiting the cost of the well should it not provide a high-capacity yield. The corollary to reducing the risk is that an adequate pump chamber has been provided for high-capacity pumping, should the well penetrate a highly productive zone as is desired. The only risk is the differential cost between the larger high-capacity pump chamber casing and the casing for a lower capacity pump, assuming the well makes at least the average low-capacity yield. However, the latter approach may not be appropriate in the Madison well field setting if the drawdown associated with the desired 1400-gpm design yield exceeds the water column available at 900 to 1000-feet depth, such as would happen if a zone of enhanced permeability is not penetrated. The issue is therefore that of how to reduce the risk of not obtaining the desired 1400-gpm design flow.

In order to reduce the risk that the well cannot produce 1400 gpm, the design of the exploration wells can be based on the premise that even if a low-capacity part of the aquifer is penetrated, the exploration well must be designed to obtain the desired design yield of 1400 gpm. The basis for production of 1400 gpm from a relatively low capacity part of the aquifer is the specific capacity of 1.58 gpm/ft of drawdown. Given the decision to design the exploration well in such a way that it can obtain a yield of 1400 gpm under the defined range of specific capacity, the desired design yield of 1400 gpm will require the following drawdown at 16 gpm/ft-dd and 1.58 gpm/ft-dd, respectively:

1400 gpm ÷ 16 gpm/ft-dd = 88 feet of drawdown
1400 gpm ÷ 1.58 gpm/ft-dd = 886 feet of drawdown

The foregoing calculations show that it is not entirely unreasonable to attempt to produce 1400 gpm from a well that penetrates a part of the aquifer with a relatively small specific capacity. Therefore, it is advantageous to design initial exploration wells so that they can produce 1400 gpm, even if they do not penetrate the zones of enhanced aquifer properties that are the desired targets. After they are used to determine the local aquifer properties and performance, they can be converted to 1400-gpm production wells, assuming the aquifer offers the minimum assumed specific capacity of 1.58 gpm/ft-dd.

It is recognized that the representative specific capacity of 1.58 gpm/ft-dd is based on wells producing much less than 1400 gpm and that specific capacity decreases as pumping rate is increased. Therefore, it may not be reasonable to expect a well penetrating unfractured Madison aquifer rock to provide a specific capacity of 1.58 gpm/ft-dd at a 1400-gpm pumping rate. However, it is also planned that wells that exhibit radial flow response from unfractured

Madison rock will be hydraulically fractured to improve their hydraulic performance. Experience has shown that hydraulically fracturing Madison aquifer rocks will generally at least double the prevailing specific capacity. Anticipation of improved well performance after hydraulic fracturing is therefore the basis for use of 1.58 gpm/ft-dd as a general planning basis for the design of pump chamber depth on the first Madison aquifer exploration wells for expansion of the existing well field.

The Centrilift Pump Engineering Manager at Baker Hughes in Casper has provided information indicating that the Centrilift 1000 series pump can be used to produce 1400 gpm from wells over a wide range of total dynamic head (TDH) by adding stages to the pump as the TDH increases and increasing the horsepower, as necessary. The basic pump dimensions are a nominal 10-inch diameter pump to which 0.75 to 1.00 inches must be added for electrical cable clearance, providing an overall maximum dimension of 11.00 inches that must fit in the well casing. As stages are added to the pump, the motor horsepower is also increased. For TDH ranging from 650 to 1450 feet, the motor and pump seal diameters remain less or equal to the pump diameter, so the well casing diameter requirement for this pump remains the same over the entire range of 650 to 1450 feet TDH at 1400 gpm.

This size of pump requires a minimum well casing diameter of 12.750-inch outside diameter with 0.375-inch wall thickness in standard water well casing size. The latter casing is not an API size casing and therefore standard casing hangers and other oilfield industry tools are not available to use with this casing to reduce the casing diameter below the pumping chamber in the well and perform other tasks such as cementing or can be acquired only at an exorbitant cost. Therefore, the API casing should be used for deep well construction. The minimum API size casing suitable for use with the Centrilift 1000 series pumps for Madison exploration wells is 13-3/8 inch outside diameter, 72 lb/ft or lighter T&C casing. The inside diameter of the 72-lb/ft casing is 12.347 inches leaving a difference of 1.347 inches between the casing and the pump with cable guard or a clearance of 0.673 inches around the pump, not taking into account drift in the casing. Accordingly, the 13-3/8 inch, 72-lb/ft casing is the minimum casing diameter that can be used with the 1400-gpm pump for an exploration well.

A casing diameter of 16-inches O.D. in API casing is recommended for permanent deep set pump production well installations with the 1400-gpm pump. Since it is proposed that the exploration wells be configured to be converted to permanent pumping wells, it is recommended that 16-inch diameter API casing be used for the pump chamber on the exploration/production wells. Table 2 shows the range of pump chamber depths for wells with specific capacities ranging from 1.58 to 16 gpm/ft-dd and a 1400-gpm design yield.

Based on the information in Table 2, an exploration well equipped with a minimum well casing diameter of 13-3/8 inches O.D. to 1800 feet (including room for the rather long pump and motor assembly) would provide an exploration well that could be pumped at 1400 gpm under the defined range of potential aquifer performance. However, a 13-3/8 casing is not the best design for a permanent 1400-gpm production well at this depth as it provides only the minimum clearances needed for the pumping equipment and offers a higher risk for future problems with pumping equipment.

A better design for operation of a long-term production well is a 16-inch O.D. pumping chamber to 1800 feet depth. This will provide a desirable pump chamber for long-term production at 1400 gpm, even if a highly productive part of the aquifer is not penetrated. Equally as

important, a 16-inch pump chamber will allow drilling of 14-3/4 inch borehole below 1800 feet to accept 10-3/4 inch casing. A 9-7/8 inch open borehole can then be drilled through the production zones in the Madison aquifer. This is a good design for a long-term production well, but exceeds the minimum standards required for an exploration/test hole.

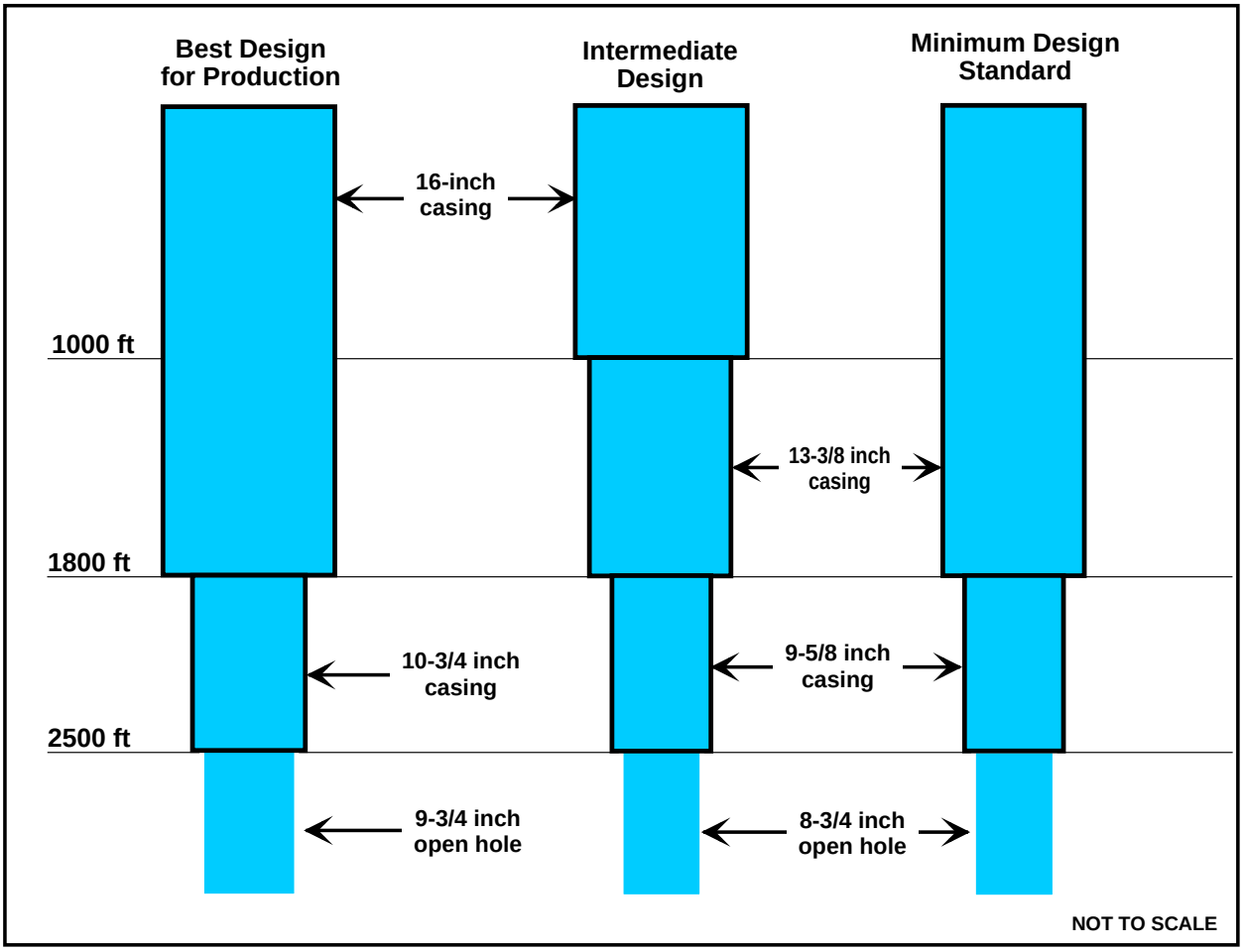
Table 2: Exploration/production well design factors.

Design Factors	Low-Capacity Well	High-Capacity Well
Design Flow (gpm)	1400	1400
Specific Capacity (gpm/ft-dd)	1.58	16
Drawdown (feet)	886	88
Depth to Static Water Level (feet)	450	450
Long-Term Groundwater Level Recession (feet)	50	50
Depth to Pumping Water Level (feet)	**1386**	**588**
Pump Submergence Requirement (feet)	150	150
Pump Column Length (feet)	1560	760
Pump Length (feet)	50	50
Pump Inlet Depth (feet)	1610	810
Pump Motor Length (feet)	50	50
10-in. Diam. Casing Head Loss at 1400 gpm (ft/100 ft)	1.44	1.44
Pump Column Loss at 1400 gpm (feet)	**22.4**	**10.9**
Total Dynamic Head at 1400 gpm (feet)	**1409**	**598**
Overlap for Casing Hanger and Deeper Casing (feet)	20	20
Total Depth of Pump Chamber – 50-foot tolerance (feet)	**1730**	**930**

The minimum standards for an exploration well that can be converted to use as a production well, although with minimum clearances for pumping equipment, would start with a 13-3/8 inch diameter casing to 1800 feet, based on the exploration well design philosophy recommended herein, followed by 9-5/8 inch diameter casing installed in 12-1/4 inch borehole to the top of the Madison aquifer. Open borehole with a bit diameter of 8-3/4 inches would be drilled through the 9-5/8 casing to the total depth of the well. This is not the most desirable approach because the larger diameter 9-7/8 borehole that can be drilled through a 10-3/4 casing will tend to develop better and yield more water. The minimum design standard well is shown conceptually on Figure 42.

It is desirable to limit the head loss in the smallest diameter casing used so that the casing size does not restrict the flow of groundwater from the aquifer, up the well to the pump. As the lower well casing diameter is reduced in a well with larger casing on top and smaller casing below, the head loss caused by reducing the lower casing diameter causes an equal increase in the amount of drawdown in the well. Therefore, it is necessary to determine if the head loss resulting from the smaller diameter casing is excessive. For example, 800 feet of 10-3/4 inch O.D. well casing flowing 1400 gpm will experience approximately 11.5 feet of head loss which

Figure 42: Exploration well design alternatives.



will cause 11.5 feet of drawdown of the pumping water level in the well in addition to the aquifer drawdown. In comparison, 800 feet of 8-5/8 inch O.D. well casing flowing at 1400 gpm will cause 33.8 feet of additional drawdown in a well.

Friction loss associated with 8-inch nominal diameter open hole may be greater due to borehole rugosity and less laminar flow along the borehole wall than in a smooth pipe. Head loss in 9-5/8 casing will be somewhere between that in 10-3/4 and 8-5/8 casing. Head loss in this range does not potentially limit the potential production of either well design described above with only a 22-foot increase in drawdown at 1400 gpm resulting from a decrease from a 10-3/4 inch to 8-5/8 inch diameter hole with smooth, pipe-like walls and wall roughness.

Another consideration is the effect of the borehole diameter on well development. From a mechanical standpoint, a 6-5/8 threaded and coupled eductor pipe may be used in either design for development of the well by air lifting through an eductor pipe, therefore the proposed range of open hole diameter from 8-3/4 inches to 9-3/4 inches will not affect the ability to develop the well with an eductor pipe.

An oft stated rule-of-thumb is that increasing the well by one diameter of pipe size will result in approximately a 10-percent increase in well capacity. The basis for this somewhat hoary concept is that the open area of a well screen increases from 10 to 12 percent for every pipe size increase in the screen diameter. The concept does not apply to open-hole completions in wells penetrating fractured rock. However, experience in developing wells generally shows that larger diameter boreholes clean up better than smaller diameter holes. By “clean up”, it is meant that the repair of borehole damage and removal of cuttings from the openings in the borehole wall generally is easier to accomplish with larger diameter hole and better performance of the well is therefore achieved. Another consideration is that larger diameter borehole provides some flexibility in how to drill and complete the hole. For example, it may be desirable to complete a deep Madison aquifer open hole with air rotary methods, including recirculation of water produced during the drilling. This will result in a well that is essentially developed when drilling is completed, as compared to a well completed with mud rotary methods utilizing drilling fluid or clear water, which leaves considerable cuttings and debris in the fractures around the borehole and subsequently requires additional development. Therefore, there are potential advantages to using a somewhat larger diameter borehole in the open-hole completion, if possible.

In summary, the recommended conceptual design of the Madison exploration wells is to provide 16-inch casing to a depth of 1800 feet, 10-3/4 casing to the top of the Madison at an estimated depth of 2500 feet, and 9-3/4 inch diameter open hole through the Madison below 2500 feet, as shown on Figure 42. This is the best design for a production well; however, it is also the most expensive alternative considered herein.

The minimum performance design is provision of 13-3/8 inch diameter casing to 1800 feet, 9-5/8 inch diameter casing to the top of the Madison at an estimated 2500 feet, and 8-3/4 inch diameter open hole through the Madison below 2500 feet (Figure 42). This approach is not recommended.

A design approach intermediate to the recommended production well and minimum performance designs is to provide 16-inch casing to a depth of 1000 feet, 13-3/8 casing from 1000 to 1800 feet, 9-5/8 inch casing from 1800 feet to the top of the Madison at 2500 feet, and 8-3/4 inch open borehole through the Madison aquifer strata (Figure 42). This design does not appear to provide much advantage in potential cost savings over the production well design and offers the same disadvantages to long-term production well operation as the minimum design standard. Therefore, it is not recommended.

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