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October 18, 2006

Mr. Robert T. Hardcastle
President
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Bakersfield, CA 93380-2218

Subject: May 30, 2006 letter report from HWR to PSWID titled, "K2 Well Site Evaluation – Groundwater Resources Potential".

Dear Mr. Hardcastle:

I have completed a review of the subject report authored by Mike Ploughe, P.G., of Highland Water Resources (HWR) for the Pine/Strawberry Water Improvement District (PSWID). My review comments are based on my personal knowledge of the geology and hydrology of the Pine/Strawberry area obtained during the accomplishment of a detailed investigation of the availability and distribution of groundwater in the area, completed for the PSWID and released in an August 2003 report.

My conclusion is that the K2 site recommended by HWR is a reasonable site to drill a production well into the R-aquifer and deeper strata. There is no reliable way of predicting if a well at this site will yield 150 gpm or not. However, as discussed later in this report, yields at the Strawberry Hollow and Milk Ranch wells indicate that a 150-gpm yield from the R-aquifer system and deeper strata may be possible. The difference between the K2 site and the latter wells is the absence of significant faulting at the K2 site that undoubtedly influences the larger yields obtained at the latter two existing wells. However, strong lineament traces associated with the K2 site may indicate enhancement of the R-aquifer hydraulic properties by fractures and/or solution enlargement, a conclusion supported by the conditions penetrated by the Strawberry Borehole, 1.5 miles west of the K2 site. The basis for these conclusions is discussed in detail in the remainder of this report.

The HWR report assumes that information about the geology and hydrology of the area is familiar to the reader. Likewise, it assumes the reader has at least a rudimentary knowledge of the methods of hydrogeologic interpretation used to reach the conclusions presented in the report. Without the latter information, the HWR report may appear to present conclusions without foundation to certain readers; however, it is clear to readers with a good knowledge of the background information that is the basis for the HWR conclusions. Therefore, my review comments include presentation and discussion, as necessary, of some of the local geologic characteristics and basic hydrogeologic principles that are necessary background to understanding the conclusions of the HWR report and evaluating them.

HWR CONCEPTS

The subject report and recommendations by HWR are based on the following two broad theories:

1. The report assumes that a "deep aquifer" consisting of the Redwall, Martin, and other deeper formations is present throughout the area. The HWR report also refers to the deep aquifer as the "deep regional system", concluding it is part of a larger system that extends over a greater area than the Pine and Strawberry communities and which may include other strata in addition to Redwall and Martin.

2. The report assumes that discontinuities in the rock matrix of the deep aquifer system, i.e. fractures, enhance the hydraulic properties of the aquifer so that wells sited on such features will obtain greater production than would be obtained if the rock is not fractured.

In addition to the latter concepts, the HWR report provides information about potential drilling depth and depth to water at the proposed K2 site.

REVIEW COMMENTS

I have reviewed the HWR report for the K2 well site with respect to the following factors:

1. Presence of Redwall and Martin strata under the site.
2. Potential depth of strata and drilling depth requirements.
3. Depth to groundwater and saturated thickness.
4. Factors that may influence well yield.
5. Indication fractures that may enhance hydraulic properties at the site.

Distribution of Redwall and Martin Strata

The Redwall Limestone and Martin Formation, where present, comprise a deep, freshwater aquifer that until recently remained relatively unused in Arizona. The aquifer is referred to locally as the "R-aquifer system". In general, the R-aquifer strata are the only potential source of reasonably large groundwater yields available below the Coconino and Schnebly Hill strata of the shallower regional aquifer system north of Pine and Strawberry. Exceptions to this generality include highly fractured rock along fault zones such as developed by the wells for Payson, Arizona.

The R-aquifer strata extend northward from the Mogollon Rim, under the Colorado Plateau, providing a deep regional aquifer that has recently began to be developed by wells for municipalities such as Flagstaff and Williams. Fossil Springs, near Pine and Strawberry, is an area of natural discharge of groundwater out of the R-aquifer system. As summarized in my August 2003 report of groundwater availability and distribution in the Pine/Strawberry area, geologic maps prepared by a number of entities, including the Arizona Bureau of Mines and the U.S. Geological Survey, show that the R-aquifer strata extend under both Pine and Strawberry and are present in down-faulted blocks between the Mogollon Rim escarpment and the East Verde River along the Diamond Rim area.

Since the early 1990s, three wells have been drilled into the R-aquifer strata at Pine and Strawberry for which geologic logs and groundwater elevation data are available. The first well was the Strawberry Borehole that penetrated the R-aquifer near the center of the Strawberry community. The well, more than 1,400 feet deep, is presently equipped with a pressure transducer and digital logger to record fluctuations in the water level in the well and the water temperature.

The second well that recently provided information about the depth of the R-aquifer strata at Pine is the Strawberry Hollow well. Although Mike Ploughe at HWR recently advised me that he wrote a report about that well, I had not been aware of that fact and did not have the information. The PSWID was kind enough to provide me a copy of Ploughe's geologic log of the well for use in this review. When I plotted the well log on cross-section B-B" of my August 2003 report, I found it fits the geologic cross section almost perfectly, thus verifying my structural interpretation in that area. Mike Ploughe indicated the static water level in the Strawberry Hollow well generally fluctuates between depths of 887 to 918 feet below the top of casing (BTOC). Pumping test data are available for this well; however, I do not have that information. It would be useful information for additional assessment of potential well yields from the R-aquifer in this area.

The most recent well drilled into the R-aquifer system was drilled this year and is located at the south end of Pine. This well is referred to as the Milk Ranch well. The well has been step tested at rates up to 210 gpm. Mike Ploughe at HWR provided me with a verbal summary of the log for the Milk Ranch well over the telephone and it plots on my cross-section B-B" again almost perfectly, when corrected for offset by a fault identified just north of the well by Mike Ploughe.

The latter three wells not only confirm geologic mapping that indicates the R-aquifer strata are present under the Pine/Strawberry area, but that the strata produce groundwater in both communities.

Some confusion might result from the HWR use of the term "deep regional system", in connection with the R-aquifer strata. The HWR use of the term "deep regional system" appears to the Tapeats sandstone as well as locally faulted and fractured Precambrian basement rocks consisting locally of quartzite.

The U.S. Geological Survey (USGS) and Arizona Department of Water Resources (ADWR), refer to the Kaibab, Coconino, and Schnebly Hill formations collectively as the "regional aquifer system" in that part of the Colorado Plateau located generally between the Mogollon Rim and Flagstaff. The HWR use of the term "deep regional system" to refer to the R-aquifer strata and deeper strata should not be confused with the "regional aquifer system" defined by the USGS in the Schnebly Hill and Coconino strata.

It should be noted additionally, that the terms C-aquifer (Kaibab, Coconino and Schnebly Hill) and R-aquifer (Redwall and Martin) refer to the most productive strata within a thick sequence of strata that are to a large extent all hydrologically related, if not directly hydraulically connected. Therefore, there is an increasing tendency for some researchers to refer to the entire sequence of strata from the top of the Kaibab to the Precambrian basement rocks as a "regional aquifer system" without making distinction of the individual layers that must be penetrated by wells to obtain good production. This broad use of the term does not lend itself to precision when discussing potential targets for wells.

Accordingly, within this review report, the term "R-aquifer" is restricted to the Redwall and Martin Formations, the terms "C-aquifer" and "regional aquifer system" are restricted to the Schnebly Hill, Coconino, Kaibab formations, and the term "fractured basement rock aquifer system" is applied to faulted and/or fractured Precambrian quartzite and granite that yield groundwater.

Potential Drilling Depths

I have estimated the potential drilling depths to the top and the bottom of the R-aquifer strata, based on the information contained in my August 2003 report, specifically geologic cross-section B-B" which passes through the Strawberry Hollow well and very near to the Milk Ranch well. The geologic cross section is based on a precision GPS survey of the geologic structure from the south side of Pine, through the Pine/Strawberry area, to Calf Pen Canyon where the strata are again exposed. As previously stated, the logs provided for the Strawberry Hollow and Milk Ranch well plot directly onto the geologic cross section (with a fault shift for the Milk Ranch well), thus confirming the cross section is accurate.

The HWR report states the elevation at the proposed K2 well site is 5,858 feet. Comparison of the 5,868-feet surface elevation to my geologic cross section and structural contours indicates the drilling depth to the top of the Redwall (top of the R-aquifer strata) should be approximately 1,260 feet. The Redwall is approximately 200 to 240 feet thick; therefore the drilling depth to the top of the Martin Formation is approximately 1,460 to 1,500 feet.

Based on HWR (Ploughe's) logs of the Strawberry Hollow and Milk Ranch wells, the R-aquifer thickness is 500 to 550 feet. I used 580 feet on my August 2003 cross section, based on generalized information from the region. The range of 500 to 550 feet should be used instead of 580 feet, based on the logs provided by HWR. Therefore, the approximate drilling depth to the bottom of the R-aquifer at the K2 site is estimated to be 1,760 to 1,810 feet.

The HWR report is not specific about the depth to the R-aquifer strata at the K2 site. It states that, "***The primary producing geology may be within the Martin Fm. through the Tapeats sandstone and into the Precambrian basement rocks at depths approximately below 1,460 ft.***" The latter statement implies that the top of the Martin is 1,460 feet, a conclusion that agrees with my estimates from the data in the August 2003 report prepared for the PSWID and updated by the Strawberry Hollow well log.

The only strata likely to be present between the quartzite basement rocks and the bottom of the R-aquifer strata is the Tapeats sandstone. The Strawberry Hollow well penetrated approximately 112 to 122 feet of Tapeats sandstone. The Milk Ranch well penetrated approximately 140-150 feet of Tapeats sandstone. In an outcrop along the highway just south of the intersection with Control Road, the Redwall lies directly on the Precambrian quartzite with no intervening Martin or Tapeats. The variable thickness of the Tapeats is due to topographic relief on the surface where the Tapeats was deposited. High parts of the pre-Tapeats topography protruded above the level of deposition and the Tapeats is absent on those highs. Assuming there is 150 feet of Tapeats sandstone at the K2 well site, the total drilling depth to the top of the Precambrian quartzite is estimated to be approximately 1,910 to 1,960 feet.

All of the foregoing drilling depths are approximate and should be regarded as accurate only to about plus or minus 100 feet.

Depth to Static Water Level

The elevation of the Strawberry Borehole shown on the HWR log is 5,502 feet. The range of static water level fluctuations in the R-aquifer reported by Mike Ploughe of 887 to 918 feet indicates a static water level elevation ranging from 4,584 to 4,615 feet. The static water level elevation in the Strawberry Borehole, in round numbers, fluctuates around 4,368 feet or higher. Taking the foregoing groundwater elevations into account and projecting them on the geologic cross section, the estimated groundwater elevation in the R-aquifer at the K2 site is approximately 4,380 to 4,390 feet or a depth of 1,478 to 1,488 feet below ground surface, plus or minus seasonal and long-term fluctuations and a potential error of plus or minus 50 feet in projecting the groundwater elevations across the area.

The estimated elevation of the top of the Martin Formation is 4,438 to 4,398 feet at the K2 site. Therefore, the estimated groundwater elevation of 4,380 to 4,390 feet is below the probable top of the Martin Formation and the Redwall Limestone at this site will likely be drained out. The potential saturated thickness of the Martin Formation, based on the foregoing elevations may range from 277 to 327 feet. If the Tapeats sandstone is found to be a productive aquifer, as Mike Ploughe reports is the case at the Milk Ranch well, the saturated thickness at the K2 site potentially increases to approximately 427-477 feet.

The HWR report states, "***It is anticipated that the groundwater elevation of the deep regional system will be found between 4,600 ft. and 4,800 ft. (1,260 – 1,100 ft. depth to water) in the vicinity.***" The latter estimate is evidently based on groundwater elevation contours shown on the map provided in the report; however, the source of the groundwater elevation contours is not indicated. The estimated groundwater elevation of 4,600 to 4,800 feet in the HWR report is considerably different than the range groundwater elevations observed in the local wells penetrating the R-aquifer and appears to be anomalously high, i.e., 200 to 400 feet higher than a projection of the measured elevations.

The difference of 200 to 400 feet in the estimates of the groundwater elevation at the K2 site may have profound significance to the potential yield of a well completed at this site, as will be discussed below. I disagree with the HWR estimate of the static water level elevation and conclude that, realistically, it will be closer to the estimate of 4,380-4,390 feet elevation discussed above.

Well Yield Considerations

The common measure of well yield is well capacity, i.e., discharge per unit of time, typically expressed as gallons per minute. For the purpose of comparing well yields, it is more useful to express well capacity in relation to a constant standard. The accepted standard of comparison is the unit drawdown; for example, gallons per minute per foot of drawdown, also referred to as the "specific capacity" of a well.

I do not have the HWR report for the Strawberry Hollow well so I do not have the basis to calculate the specific capacity and do not know the relationship between yield and drawdown. However, I do have the approximate pumping rates and drawdown obtained during testing of the Milk Ranch well which produces from the Martin and Tapeats sandstone as well as from some fractured quartzite according to Mike Ploughe. At 120 gpm the drawdown was approximately 85 feet, indicating a specific capacity of 1.4 gpm/ft of drawdown. At 165 gpm and 210 gpm, specific capacities were approximately 1.3 and 0.7 gpm/ft, respectively. The stepped rate test indicates most of the drawdown was due to head losses in the formation near the well, where the flow of water converged on the well.

The minimum desired yield at the K2 site is 150 gpm. At the Milk Ranch well, linear proportioning of the observed specific capacities indicates the specific capacity at 150 gpm is approximately 1.36 gpm/ft. This is another way of stating that if the Milk Ranch well were pumped at 150 gpm, the combined hydraulic performance of the well and the hydraulic properties of the aquifer would result in a drawdown of the water level in the well to about 110 feet below static water level.

Assuming the hydraulic properties of the Martin and Tapeats strata are the same at the K2 site as at the Milk Ranch well, the potential saturated thickness range of 277 to 327 feet should be adequate to support a pumping rate of 150 gpm and drawdown in the pumped well of 110 feet. It is assumed the drawdown in the aquifer outside the effective hydraulic radius of the well will be negligible compared to the drawdown in the well, since most of the drawdown is head loss in the formation near the well.

If the hydraulic properties of the Martin and Tapeats strata at the K2 site are not as good as those at the Milk Ranch well, the above analysis is merely a frolic in mathematics. Accordingly, the question becomes that of if there is anything at the K2 site that suggests the hydraulic properties of the rocks may be similar to those penetrated by the Milk Ranch well or, for that matter, similar to those at the nearby Strawberry Hollow well that reportedly obtained a reasonable yield during testing.
The principal similarity is that a well at the K2 site will penetrate the same strata as the Strawberry Hollow and Milk Ranch wells. However, the Milk Ranch well is located near a fault identified by Mike Ploughe. The Milk Ranch well encountered a fault zone filled with impervious fault gouge at a depth of 1,045 feet that might be the subsurface expression of the fault recognized at the surface north of the well. Considerable problems were encountered with loss of circulation into voids above the groundwater depth as the well was drilled, indicating considerable fracturing of the formations, and likely enlargement of fractures in the carbonate units such as the Redwall and Martin by solution. Nearby outcrops of the Redwall at the south edge of Pine contain solution-enlarged fractures as well as a small cavern.

Likewise, the Strawberry Hollow well is located near to a probable fault zone identified by Clay Conway during fieldwork for the MRWRMS project. Loss of circulation into large fractures and voids was a significant problem during drilling of the Strawberry Hollow well.

All of these observations indicate the rock strata, including the Redwall and probably the Martin at the latter two sites, offered enhanced hydraulic properties due to fracturing of the rock and, probably, solution enlargement of the fractures. Is a well at the K2 site likely to penetrate similar conditions?

The Strawberry Borehole, approximately 1.5 miles west of the proposed K2 site, penetrated the same fractured rock conditions as encountered in the Strawberry Hollow and Milk Ranch wells southeast of the proposed K2 site. Fossil Springs, a location of major discharge from the R-aquifer, is associated with huge deposits of travertine, a spring deposit where calcium carbonate dissolved from the limestone in the Redwall by groundwater was precipitated out of the water after it discharged from the spring. The travertine deposits are geologically old and indicate significant development of solution openings in the Redwall, and potentially to a lesser extent in the Martin, in the geologic past. Moreover, the Redwall and its lateral equivalents such as the Leadville Limestone and the Madison Limestone are well known by spelunkers (and well drillers) for their cavernous nature throughout the Rocky Mountain region from Alberta to Mexico. The Martin Formation is less susceptible to solution than the Redwall; however, it is possible that the Martin has experienced fracture enlargement by solution, similar to the Naco which is known to contain considerable voids in the Pine/Strawberry area.

The proximity of the K2 site to three wells that penetrated enhanced permeability conditions in the Redwall, Martin, and overlying strata including the Naco and Supai, and its location between two of the wells is therefore favorable to finding those conditions at the K2 site. In other words, it is not unreasonable to expect that a well at the K2 site will penetrate rock strata with similar hydraulic properties to those at the other three wells. Based on the foregoing considerations, it is at least possible that a well at the K2 site can yield 150 gpm. For example, with 277 feet of saturated thickness or more, a properly constructed well would not require the specific capacity of 1.36 gpm/ft used above to obtain a yield of 150 gpm.

Fractured Rock Influences

Open fractures may greatly enhance the hydraulic properties of an aquifer. In some rocks, the only storage and movement of groundwater may be in fractures in otherwise impervious rock.

A number of successful groundwater exploration projects that I have accomplished over the years have depended on identification of fractures to select sites for successful wells. In the fine-grained Arikara sands in southwestern South Dakota, maximum well yields of 5 to 8 gpm are typical in some areas with many dry holes drilled. By drilling wells on lineaments identified by terrain analysis, I was able to penetrate subvertical joints that produced well yields ranging from 40 to 120 gpm.

On a project at Bridger Bowl, Montana, more than 80 domestic wells had been drilled into the tight shale, mudstone, and sandstone of the Billman Creek Formation to depths of 400-500 feet with many dry holes produced and typical yields of less than 10 gpm in most of the successful wells. By conducting a lineament study, I was successful in identifying large shear zones that bounded large structural blocks of the Billman Creek. The shear zones act as a drainage system for the mountain watersheds on the east side of the Bridger Mountains and wells sited on the shear zones produced yields ranging from 60 to 300 gpm.

The Bridger Batholith is a 120-mile long by 50-mile wide by and estimated 12-mile thick massive intrusion of igneous quartz monzonite rock into the local sedimentary strata. Quartz monzonite looks like granite and offers the same capacity to store and transmit groundwater as a concrete sidewalk. By preparing small-scale topographic maps and conducting lineament studies of terrain on the Boulder Batholith, I have obtained yields from wells penetrating joints in the igneous rock ranging from 70 to 200 gpm.

On two different projects in Wyoming, highly productive groundwater wells were found by siting them on large fractures identified by lineament studies or geologic mapping. On one study, a lineament extending about 25 miles from the flank of the Bighorn Mountains westward under soft sediments in the Bighorn Basin was identified by satellite imagery interpretation. A 3,660-foot well sited on the lineament penetrated the top of the Madison Limestone (an equivalent to the Redwall) at 2,215 feet, penetrated through the Bighorn Dolomite (an equivalent of the Martin), and provided an undiminished artesian flow of 1,280 gpm during a 20-day flow test. A nearby well to the same depth offset from the lineament produced a flow of only 120 gpm. In another project south of Glenrock, Wyoming, we used geologic mapping to identify a fault-cored anticline. A well drilled through the fractured rock along the fault produced a pumped yield from the Madison Limestone of 2,000 gpm with only 60 feet of drawdown. The State of Wyoming later tested the well with a larger pump at 2,600 gpm for 40 days.

These examples are provided to give you some idea of my background and experience in using lineament studies and geologic mapping of faults and joints to successfully identify sites where fractures have enhanced the hydraulic properties of the rock.

Identifying these features have enabled me to successfully site wells where we could obtain well yields from nearly impervious rocks where the only groundwater available was in the discontinuities in the rock caused by the fractures. In other cases, particularly in the Madison Limestone where a certain amount of well yield is generally assured, locating the wells on lineaments and/or mapped faults allowed us to obtain unusually large well yields relative to most wells in those aquifers.

In addition, I have considerable experience in testing fractured rock aquifers and working with their peculiar hydraulic characteristics. My following comments about the portions of the HWR report regarding lineaments and faults in the Pine/Strawberry area are based on considerable practical experience with the subject as well as my former experience in evaluating the hydraulic performance of the wells in the fractured rocks in the uppermost aquifers in the Pine/Strawberry area, as described in my August 2003 report.

I therefore recognize the value of attempting to site wells at locations where fractures have enhanced the hydraulic properties of the rock aquifers as well as provided preferred paths for groundwater flow through low permeability rock materials, a fundamental concept in the HWR report about the K2 site. Mike Ploughe, as an employee of the City of Payson, has worked on a large and successful water well project that depended on locating wells on known fault zones to obtain acceptable yields. Payson is located in an area where the underlying rock strata do not offer a great deal of intrinsic permeability to transmit groundwater or porosity to store groundwater. However, a number of successful wells have been completed for the municipality by locating them where they penetrate large fault zones. The sheared and broken rock along the faults offers sufficient groundwater storage and permeability in the fracture openings to transmit significant yields of groundwater to wells. The HWR report applies the latter concepts and experience to locating favorable sites for wells in the Pine/Strawberry area.

However, there are differences between the geology of the Pine/Strawberry area and the locations of the wells in the faults near Payson. The rock strata in the subsurface of the Payson area would not generally provide sufficient yields for municipal wells if the rocks were not fractured by large, regional faults. The R-aquifer strata in the Pine/Strawberry area offer potential to yield groundwater with or without large regional faults, and therefore, are a much more attractive target than the rock strata at Payson. Accordingly, the presence of the R-aquifer strata under Pine and Strawberry offer potentially more favorable conditions for development of groundwater than do the rock strata at Payson.

The faults at Payson are large, regional faults that formed when the part of Arizona south of the Mogollon Rim broke into a series of fault blocks referred to as the "basin and range" structural province of southern Arizona. These faults exhibit large vertical offsets measured in hundreds of feet. Shattering and fracturing and secondary faulting of the rock bordering such large shear zones is therefore considerable. The enhancement of porosity and permeability associated with the fractures enable the rock along the fault zones to store and transmit significant amounts of groundwater, a fact exploited by the locating of the Payson municipal wells on the faults. Large regional faults of this nature have not been identified directly under Pine or Strawberry.

The forthcoming MRWRMS study reportedly projects a regional fault into the Pine Creek valley under the community of Pine. Maps prepared by HWR independently or the MRWRMS study show a number of faults in both Pine and Strawberry, including a number of faults not shown on the MRWRMS maps, a fact revealed by my conversations with both Clay Conway, who prepared the MRWRMS maps, and Mike Ploughe, who stated to me that he used aerial photo interpretation to identify additional faults not shown on the MRWRMS maps. The important thing to recognize about both of the latter investigations, is that they are highly interpretive, based on study of linear features evident on aerial photographs. Such alignments of features are referred to as "lineaments" and may represent either faults with offset and sheared rock or joints with no offset and less enhancement of the rock by fracture openings than compared to the faults.

The majority of the "fault lineaments" (Ploughe's term) identified by Clay Conway for the MRWRMS investigation and Mike Ploughe for the HWR investigations may therefore represent relatively minor structural features and include a number of joints with no offset or small faults with very little offset as compared to the faults in the Payson area that are large regional features. In my discussion of this with Clay Conway, Clay stated that he and his assistant spent about 50 days each, field mapping the Pine/Strawberry area. Based on this discussion, I believe that features shown as definitely identified faults on the MRWRMS maps are likely correct; however, offsets associated with most of those faults are very small, often less than 10 feet. Features identified as lineaments may not offer offset of the strata or the degree of fracturing of the rock often associated with a fault.

In my investigations of the Pine/Strawberry area in the period leading up to my August 2003 report, I used precision GPS surveys to map the elevation at the base of the Fort Apache Limestone which comprises the prominent white cliff midway up the side of the Pine Creek valley and Strawberry Mesa. The survey extended through Pine and Strawberry north into Calf Pen Canyon. The survey revealed that only a few faults provide significant visible offset of the strata under Pine and Strawberry. One fault is located at the south end of Pine and brings the Redwall to the land surface. A small fault is exposed in the east side of Strawberry Mesa.

The Strawberry Hollow area may contain one of the larger faults in the Pine/Strawberry area; however, the evidence for this fault is not conclusive. HWR shows a "fault lineament" aligned directly with Strawberry Hollow with the northeast side of the fault dropped down relative to the southwest side. It is unlikely that a fault is present at this location for two reasons. I have carefully walked and inspected the outcrop of the Fort Apache Limestone at the top of Strawberry Hollow and found the outcrop to be continuous and unaffected by a fault in this area, including the outcrops on both sides of Highway 87. In addition, the Strawberry Hollow well is located on or near the trace of the fault lineament; however, the log of the well provided by Mike Ploughe fits perfectly on my structural map (based on the precision GPS survey), a fact that could not be possible if a fault with significant offset were present in Strawberry Hollow.

In early work performed by a student who later mapped in the area for the USGS, the Fort Apache Limestone is mapped from the north side of Pine, where it is crossed by Pine Creek, southward along the west or northwest side of Pine, where a series of knobby hills are supported by a layer of limestone near the bottom of the valley wall. If the layer of limestone supporting the line of hills is the Fort Apache Limestone, there is a fault with at least 200 feet of offset located parallel to and north of Highway 87, as indicated by the difference in elevation of the furthest southwest extent of the latter layer of limestone and the elevation of the last visible location of the Fort Apache Limestone I inspected at the top of Strawberry Hollow.

Although the layer of limestone supporting the knobby hills along the west or northwest side of the Pine Valley was mapped by the thesis student as Fort Apache Limestone, the subsequent USGS published map did not make that distinction and the fault was not shown. In my investigation of the area, I noted that a second layer of limestone is present below the Fort Apache Limestone and there is a possibility that this lower layer of limestone has been mistakenly mapped as Fort Apache Limestone, thus creating the false impression that a major fault is present in this area. In my report, I concluded this was the case and did not show the fault. However, I had limited time and resources to try to distinguish between the two layers of limestone. The outcrops in the area are heavily covered with overburden, a factor contributing to the difficulty of determining which limestone layer supports the hills. Therefore, I concluded that the possibility still exists that a significant fault is present along the north side of Strawberry Hollow, but did not include it on my map because I was not positive about it and it had no immediate bearing on the problem I was hired to solve.

I discussed these observations at length with Clay Conway, a former USGS geologist who had considerably more time to work on this problem than I had, and who is the principal investigator of the structural geology for the MRWRMS report. Clay concluded that a fault is present and that the knobby hills are supported by Fort Apache Limestone, not the lower limestone bed. He did not have his maps at hand because they are under review, so he could not identify for me exactly where he placed the fault.

The point of presenting this issue herein is to indicate that although the Strawberry Hollow well is not located directly on a major fault as suggested by the HWR map of Pine, it is very likely that the well is located near a fault that is north of Strawberry Hollow and parallels the hollow. In addition, I did identify a small fault in the east side of Strawberry Mesa, as did Clay Conway. These facts combined with the loss of circulation during drilling of the Strawberry Hollow well, starting in the Naco at 260 feet, suggest the rock strata in the subsurface of Strawberry Hollow may be influenced by the effects of fractures caused by a nearby fault. If so, this location is similar to the Milk Ranch well which is near a fault identified by Mike Ploughe.

The foregoing discussion of the probable fault in the Strawberry Hollow area also demonstrates the difficulty of positively identifying faults in the Pine/Strawberry area due to the similarities of various strata within the Supai and Schnebly Hill Formations and due to the large amount of overburden covering the bedrocks. With the exception of the aforementioned faults and a few other visible faults of small offset in upper Pine Creek and on the south end of Milk Ranch Point, my detailed and careful inspection and GPS survey of the local structure did not discover any large faults. Likewise the structural projections between the surveyed elevations on the base of the Fort Apache Limestone did not require the hypothesis of any major faults to explain the measured structural elevations and patterns.

Therefore, it must be concluded that the "fault lineaments" shown in the Pine and Strawberry area on the MRWRMS maps, which are not yet available for examination, and the HWR maps, which I have examined, are simply features identified by interpretation of terrain and patterns on aerial photographs or faults with very small offsets identified by Clay Conway and his assistant during mapping for the MRWRMS project. New faults identified by Clay Conway's work include one through the Dripping Springs on the east side of Pine and another fault just north of Dripping Springs. I recognized the possibility of a fault at both of these locations during my work but could not see enough offset to be comfortable with mapping them as such. Clay's more detailed effort convinced him there are faults at these locations, but with very small offsets, just enough to influence groundwater to discharge through a spring at the Dripping Spring location. A similar situation is offered by Puller Springs at the east end of Strawberry, where I again believe there is either joint or fault control of the spring but could not identify any offset of the strata.

Another factor must be considered when interpreting lineament features on aerial photographs and maps. Fractures can consist of joints or faults. Joints do not offset the fractured strata and simply provide openings where tension has caused the rock to crack and open. Faults are fractures that offset the geologic strata due to shear. In a detailed assessment of the regional aquifer north of the Pine/Strawberry area, the U.S. Geological Survey (Bills et al., 2000; p. 28) describe the potential effects of faults on groundwater flow as follows:

> " **In general, fractures formed under compressional stress tend to remain fairly tight and closed, which results in little if any increase in ground-water flow. Fractures formed under tensional stress tend to be more open, which results in increases in ground-water flow in places. In some cases, the blocks on either side of a fault can grind the sedimentary rock into a fine powder that fills the fault zone and substantially reduces ground-water flow. Information on the displacement of faults also is necessary to determine the continuity of water-bearing zones and confining layers."**

On page 30 of the same paper, the authors go on to state that in the area north of Pine and Strawberry, both tensional and compressional fractures may enhance groundwater flow because some of the compressional features were reactivated under tension:

> " **These researchers** (Bill et al., 2000; pg. 30) **found that (1) north-to north-eastward-striking fractures originate from compressional stress, (2) north- to northwestward-striking fractures originate from and are related to tensional stresses, and (3) some northeastward-striking fractures are related to reactivation of deep-seated faults caused by regional extension. . . . Northeastward-striking fractures generally parallel the direction of ground-water flow and surface drainage. Surface drainage may be better developed along these older structural features, and dissolution of formational material may have increased ground-water flow along these structures."**

In my investigation of the Pine/Strawberry area, I found that the major surface drainage features conformed reasonably well to the above pattern of northeastward-striking fractures, although there was no offset along the fractures. In addition to the above relationship, another factor is present at Pine and Strawberry. That factor is a number of tensional joints evidently related to the down-dropping of the basin and range structures to the south with respect to the southern margin of the Colorado Plateau, now referred to as the Mogollon Rim. The tensional joints and a few faults previously mentioned are generally east-west aligned features, essentially parallel to the Mogollon Rim and/or its ancestral expression.

My review of aquifer pumping tests in the Pine and Strawberry area found that the aquifer response in the wells in the Schnebly Hills and Supai strata in this area was universally that of flow to the pumped wells along linear fractures penetrated by the wells. In the Pine area, the rock hosting the fractures did not yield groundwater storage to the fractures. In the Strawberry area, the Schnebly Hill strata hosting the fractures did yield groundwater storage to the fractures. In discussions with Chris Miller, a local well driller from Payson, Chris indicated that wells drilled between the top and the toe of the Mogollon rim typically penetrate quite a few open fractures and "broken" zones. Most of these wells are not located on recognized faults or lineaments, a fact that suggests that open joints in the strata on the slope below the Mogollon rim may be related to tensional extension of the entire slope, not necessarily related to any particular individual fault or lineament.

It is with the foregoing background that the HWR report for the K2 well site is reviewed.

K2 WELL SITE

The presence of the R-aquifer strata, their depth, and potential groundwater depth and elevation are previously described above. Likewise, the foregoing narrative regarding solution enhancement of joint-controlled flow paths within the R-aquifer concluded it is very possible that such enhancement of the hydraulic properties of the aquifer may exist under the K2 site, with or without the presence of major faults. However, it was also demonstrated that the R-aquifer and deeper strata at the Strawberry Hollow and Milk Ranch wells are probably influenced by nearby faults. Are similar faults near the K2 site?

The K2 site is located near several lineament features shown on the map in the subject HWR report. Conversations with Clay Conway and Mike Ploughe revealed that the lineament aligned down the east-west axis of Strawberry Valley and passing just north of the K2 site was identified by Conway during the MRWRMS investigations. Conway believed that other smaller lineaments shown on the HWR map were probably identified by Ploughe and not shown on the MRWRMS map, but again could not verify this recollection because his maps were not available.

One of the interesting questions about Strawberry is why the Strawberry Valley exists. The east-west alignment of the Strawberry Valley is anomalous to the northeast-southwest alignment of most of the drainages in the area that are believed to have developed along major structural joints. Accordingly, there has been considerable speculation that the valley is aligned along a fault. Prior to writing my August 2003 report for the PSWID, I examined the Strawberry Valley very carefully. A prominent marker bed, the Fort Apache Limestone is exposed along part of the north side of the valley as a continuation of exposures on Strawberry Mesa southeast of the valley. I could not identify any conclusive evidence of an offset of the Fort Apache Limestone from one side of the valley to the other and concluded that the valley formed for reasons other than a fault. My conclusion was that the basalt capping Strawberry Mesa, which poured off the ancestral Mogollon Rim, blocked the flow of water off the rim as it receded to its present location by headward erosion. Accordingly, the flow of water to the east and west ends of the block eroded the valley in its present location. This is a simplification of a more complex situation that involves other ancestral drainages, but it is the gist of an alternative explanation to a fault. It is just as possible; however, that the erosion I hypothesize could have been influenced by a small fault or a major joint.

I have discussed this conclusion at length with Clay Conway. Clay mapped the lineament shown in the subject HWR report, aligned along the east-west axis of Strawberry Valley, and projecting through Puller Springs. I agree with Clay that this is a prominent and obvious alignment and it is consistent with joint control of the location of Puller Springs. Clay stated that evidence for offset of the strata between the north and south sides of Strawberry Valley was "subtle", but he believes it exists. I agree that this is possible, but the offset, if any, is so small it is not evident at Puller Springs and was not revealed by a change in the gradient of the structural contours constructed from my GPS survey data. This does not mean there is no offset or no fault, but if there is any offset, it is so small as to be nearly undetectable. Accordingly, the lineament along the axis of the Strawberry Valley is a much different and smaller feature than the faults near the Strawberry Hollow and Milk Ranch wells and tremendously smaller than the faults penetrated by the Payson wells. It may simply be a major joint that developed under tension along the alignment of the ancestral Mogollon Rim.

The smaller lineaments identified by Ploughe in his investigations for the K2 site are likewise good lineaments, but associated with structural features that are likely joints with little or no shear and fracturing of the surrounding rock. However, the significance of such features should not be downplayed. All of the pumping test data from wells penetrating the Schnebly Hill strata in Strawberry exhibited an aquifer response that indicated flow to the pumped well was controlled by single, planar fractures contained in a slowly pervious host rock that yielded water to the fractures. It is likely these features are tensional openings in the rock associated with the formation of the Mogollon Rim escarpment by regional fault movements. Therefore, the lineament traces identified by Conway and Ploughe are likely to be indications of the locations of larger joints in the overall fracture pattern. As described above, I have had good success in locating wells on such features.

Although the fracture pattern in the R-aquifer may not match that in the overlying softer strata of the Supai and Schnebly Hill, the larger lineaments on the MRWRMS and HWR maps may delineate deeper features that extend into the R-aquifer. It may be significant that the Strawberry Borehole, which encountered a high degree of fracturing and probably solution cavities from the top of the Naco on down, as well as some lost circulation in the higher Supai, is located nearly directly on the trace of the Strawberry Valley lineament.

As shown on the HWR map, the K2 site is not located directly on any of the mapped lineaments. However, it is very close to the east-west lineament down the axis of the valley; about the same distance from the Strawberry Valley lineament as the Strawberry Borehole. It is also reasonably close to a north-northwest by south-southeast lineament that crosses the main Strawberry Valley lineament. The presence of these lineaments and the proximity of the K2 site to an intersection between two lineaments is a very favorable condition that increases the probability of success in obtaining the desired well yield at the K2 site.

CONCLUSIONS

Taking all of the foregoing factors into consideration, the K2 site appears to be a reasonable site to drill a well into the R-aquifer and deeper strata.

It is impossible to know what a well drilled into the R-aquifer at the K2 site will yield. However, there are favorable conditions at the site that suggest it may provide similar yields to the Strawberry Hollow and Milk Ranch wells completed in the R-aquifer and deeper strata. Those yields equal and exceed 150 gpm.

As discussed in detail above, the science implicit in the HWR report, stated or unstated, supports the conclusion that the K2 site is a good site to drill a well into the R-aquifer and deeper strata.

In your instructions to me, you ask if the deep aquifer source is better, or worse, in Strawberry than Pine. My answer is that the Strawberry Hollow well and the more recent Milk Ranch well at the southern end of Pine indicate that baseline yields of 150 gpm may be available from the deep aquifer in all of this area, both Pine and Strawberry. Drilling depths to the R-aquifer will be less in Pine than in Strawberry, a fact noted by the subject HWR report.

The concept that groundwater availability from the deep aquifer may be better in Strawberry than in Pine probably started with my August 2003 report for the PSWID. There were two aspects of my report that could be interpreted that way. One was the fact that I found that wells producing from the Schnebly Hill in the Strawberry area were marginally more reliable than wells producing from the Supai in Pine. The difference between these two areas is that the wells in Strawberry produce from fractures that obtain groundwater out of storage in the surrounding fine-grained sandstone of the Schnebly Hill. This is indicated by the response of the aquifer to tests of those wells. In Pine; however, the wells produce from fractures where all of the production is from water stored in the fractures with no indication of inflow from the rock hosting the fractures, as determined by the aquifer response to pumping. Accordingly, wells in both communities may loose yield during the summer, but those in Pine run out of water much faster than those in Strawberry. My discussion of these factors definitely indicated more favorable conditions for wells in Strawberry than in Pine; however, that concept applied only to the Schnebly Hill and Supai strata, not the deeper R-aquifer system.

A second aspect of my August 2003 report that would be interpreted to indicate better conditions for a well in the R-aquifer in Strawberry than in Pine was my recommendation for a well site and the subsequent championing of that site by some members of the PSWID Board. In that report, I indicated that the most favorable location for a deep well into the R-aquifer is at the northwest corner of Strawberry. However, this conclusion must be put into the context of the goal set for me by the PSWID Board. That goal was to identify, if possible, a site where a design yield of 500 gpm or more could be obtained from the R-aquifer. In my view, and it has not changed, a 500-gpm yield could be obtained only from a confined portion of the aquifer. My analysis of the geologic structure and the groundwater levels in the area determined that the only part of the R-aquifer system where confined aquifer conditions are likely present was under the area identified at the northwest corner of Strawberry. The elevation of the R-aquifer strata and the water levels in the aquifer indicated the R-aquifer is likely unconfined in the remainder of those two communities.

The HWR report suggesting a site for a well drilled in the unconfined part of the aquifer, at K2, is a change in the paradigm used for my August 2003 report. It presents an alternative paradigm where a water supply is developed from one or more deep wells into the unconfined part of the R-aquifer, producing yields of 150 gpm plus or minus. I am not uncomfortable with this approach; however, it raises another issue, that of sustainability.

In the work I did for the PSWID and reported in my August 2003 report, a major concern was sustainability of the well yield. As you know from experience, wells that initially provide good yields can rapidly decline in yield. My work for the PSWID was calculated to reduce the risk that such a decline would happen. Simplistically, our concern was that wells completed in the higher elevations of the R-aquifer, i.e., Pine and the southern part of Pine, might abstract groundwater that is perched on the base of the aquifer above the elevation of the groundwater in the regional R-aquifer to the north. If this was the case, the only sustainable yield of such a well would be the amount of water that it could capture from the flow of water down the dip of the strata toward the confined portion of the aquifer to the north. Under those circumstances, pumping rates in excess of the natural groundwater flow rates past the well would begin to mine water from storage in the aquifer. Mining of groundwater storage would cause water levels around the well to decline and the yield of the well would decrease. Accordingly, the pumping rate would not be sustainable.

The sustainable yield of any well is ultimately limited to the amount of groundwater discharge that it can capture away from a natural discharge area. In the case of the Pine/Strawberry area, the source of groundwater for capture is the flow of recharge water through the area under the communities towards the discharge area, where ever it may be. The area within which capture can take place is limited to the area influenced by the well when it is pumped.

If a well pumps more water than the amount it can capture from a natural discharge area, it will begin to mine groundwater with the consequences of ensuing loss of yield described above. Recognizing that any desirable design yield for a well penetrating the R-aquifer in the Pine and Strawberry areas might exceed the amount of flow to natural discharge areas captured within the zone of influence around the well, particularly at pumping rates up to 500 gpm as mandated for the PSWID study, I tried to place the well in a location where a large amount of groundwater storage was available to tap for mining of groundwater. That meant the well had to produce from an area below the elevation of the water surface in the regional aquifer and from a location with a confined groundwater system. The goal of the investigation published in August 2003 was to find such a spot, if it existed, and fortunately such a spot was found in the northwest corner of Strawberry. Thus, my limiting the location for a well into the R-aquifer system was highly constricted by the foregoing considerations. It was not the only location at which a well could produce groundwater from the R-aquifer under Pine or Strawberry.

Under this new paradigm, there is probably more of a question about sustainability of a pumping rate at the K2 site than at the confined aquifer site I recommended in 2003. However, Mike Ploughe described a couple of conditions at both the Milk Ranch and Strawberry Hollow wells that are quite interesting.

Ploughe told me that when they drilled the Milk Ranch well, they did not penetrate a significant water-bearing zone until a depth of 615 to 620 feet. After they penetrated a water-bearing zone at this depth, the water came up the borehole to the present static level of about 515 feet BTOC (still in the Martin). This indicates that the zone penetrated by the Milk Ranch well at 615 feet, which places the top of the water-bearing zone about 35 feet above the base of the Martin Formation, is probably confined. I say probably, because he may have drilled through a block of rock into a system that is open to the atmosphere through surrounding fractures. The only way to make a diagnostic determination of confined versus unconfined conditions would be to simultaneously monitor water levels in the aquifer and barometric pressure. If the aquifer is confined, it will respond to fluctuations in barometric pressure; if it is unconfined it will not.

Ploughe also stated that he observed abrupt rises in the water level in the Milk Ranch well from the static of 515 feet to 474 feet in just a day or two. The higher water level gradually returned to the former level of 515 feet during the course of a week or so. Ploughe further stated that the water levels in the Strawberry Hollow well exhibit similar fluctuations. The water level in the Strawberry Borehole, which is monitored with a continuous recorder, does not exhibit these types of fluctuations, as far as I know.

This matter deserves more consideration and investigation; however, my first thought is that the transient fluctuations may represent the effect of local recharge events with rapid flow of the recharge water through enlarged fractures or solution channels independent of a larger confined or semiconfined aquifer system contained in a regional system of fractures in the deeper strata, including the quartzite. The fact that the Milk Ranch well produces in part from the quartzite may be significant, i.e., regional fractures through the quartzite and overlying strata may connect the groundwater in the fracture system to the massive volume of water stored in the R-aquifer system to the north. At this time, the sparse groundwater elevation data from the Pine/Strawberry area appear to indicate that the hydraulic gradient is from south to north, i.e., the groundwater storage in the R-aquifer north of the Mogollon Rim does not appear to be draining towards Pine, but is draining toward Fossil Springs.

I am suggesting that the transient fluctuations are superimposed over a more stable long-term groundwater level in the system. A long-term stable water level at this elevation in the aquifer can exist only if there is a large amount of groundwater storage to attenuate the transient flows of water into the aquifer. The only potential source of such storage is the R-aquifer and overlying regional aquifer to the north. The only way the aquifer at this elevation can be connected to that storage, with the observed groundwater elevations showing a hydraulic gradient from the south side of Pine northward toward the Mogollon Rim, is for deep fractures to make a hydraulic connection to the groundwater storage to the north through the basement rocks.

The fact that the groundwater level in the Strawberry Borehole, to the best of my knowledge, has not exhibited the large fluctuations observed in the other two wells indicates the water level at the Strawberry Borehole responds mostly to the storage in the aquifer to the north with very little response to transient events. I think it would be important to obtain and review the water level record from the logger in the Strawberry Borehole to verify these ideas, as well as review any water level data HWR can provide for the other two wells.

If these preliminary ideas are correct, they would indicate that the K2 site is potentially better located to pump from the regional aquifer storage than I would have believed in August of 2003. This would greatly enhance the sustainability of yield from a well at the K2 site.

In summary, the K2 site recommended in the HWR report appears to be a reasonable location to attempt a production well from the deeper aquifer. It is not without risk; however, the deep R-aquifer and deeper strata are the only remaining potential source of water for the Pine/Strawberry communities that have not been fully explored. The results of the Strawberry Hollow and Milk Ranch wells do not approach the 500-gpm production I was tasked to investigate by the PWSID Board in my study, but they are highly encouraging regarding the potential for lower capacity wells in the R-aquifer throughout the Pine/Strawberry area. The K2 site is better than some of the other sites recommended, although the potential for an interconnection of the regional systems through deep-seated fractures may lend more reliability to wells into the R-aquifer and deeper strata at Pine than I formerly believed. The latter ideas are mostly speculative at this time and, unfortunately, the only way to learn more about the deep groundwater system is to drill more wells into it.

Final comments include endorsement of Mike Ploughe's idea that drilling into the R-aquifer in Pine, rather than Strawberry, may defuse some of the concern that a well might affect Fossil Springs. The K2 site is a compromise site in this regards. I believe your chances of success are probably better at the K2 site than at Pine; however, some of the lineaments mapped by Clay Conway in Pine combined with the Milk Ranch well experience indicate there is a better chance of getting good production there than I originally thought; assuming the Milk Ranch well is not a fluke. I do not believe it is.

Another thought is that Mike Ploughe was associated with the evidently successful efforts by Payson to locate drilling sites on faults covered with thick overburden by applying deep resistivity geophysical methods. I am curious why Mike did not recommend this for Pine and Strawberry and forgot to ask him about that. He may not have recommended it since there would be no point to it if you are restricted to drilling on your existing property.

One final thought is that you should avoid the mistakes that were made in the Strawberry Borehole project, namely using a 4-inch test well to try to verify aquifer conditions prior to drilling a production well. The largest pump and motor that can fit down a 4-inch nominal diameter casing is a 4-inch nominal diameter pump and motor. With a static water level at an estimated 1,478 feet or greater, the yield of a 4-inch pump and motor will be too small to determine anything but the water quality and nothing about potential well yield. For example, a 4-inch Grundfos 10S50-58DS with 5 hp will provide 6 gpm with 1,500 feet total dynamic head (TDH). Other manufacturer's pumps will perform similarly, assuming the pump, pump column, and motor cable can be installed down a 4-inch casing without rubbing a hole through the insulation in the motor cable and shorting out the motor. Accordingly, there is little merit to a 4-inch or 6-inch test well into the aquifer at the K2 site where water quality is well known, the static water level projection is reasonably reliable, and the only question at hand is the potential yield of the well. A 4-inch or 6-inch test well will not answer any questions about yield.

For example, assuming 110 feet of drawdown and a static water level of 1,478 feet, the elevation lift out of a well at the K2 site will be 1,588 feet. This elevation lift, not considering pump column loss, will require 75 horsepower and a 6-inch minimum diameter pump. The minimum diameter of a 75-horsepower submersible motor is 8-inches nominal. Friction loss in 1,600 feet of 3-inch pump column will be 129 feet, increasing the total dynamic head on the pump to 1,717 feet. This exceeds the performance of most 6-inch pumps and will require a jump to a 100-hp motor. Increasing the pump column to 4-inch pipe reduces pump column loss to 32 feet, providing a TDH of 1,620 feet. Again, this is at the limit of most 6-inch pumps and an 8-inch diameter, 100-hp motor will be required. Considering the use of a 4-inch pump column, MCM 300 copper wire size motor cable required for a 1600-foot plus motor cable, and the certainty that a well this deep will not be perfectly straight and plumb, a well casing diameter of 12 inches is recommended for such a well. The minimum well casing diameter that will accept the 8-inch nominal diameter 75- or 100-hp motor is 10-inch nominal diameter casing; however, reducing the casing to 10-inch diameter will greatly increase the risk that the pump motor cable will be repeatedly damaged each time the pump is installed in the well. Repeatedly replacing burned out motors and motor cable from 1,600 feet will be both tedious and expensive and can be avoided if a larger casing diameter is used.

I think the considerations discussed above indicate the K2 site selected by Ploughe and HWR is as reasonable a spot to drill as you will find in the Strawberry area. The K1 site mentioned in the HWR report appears to be equally favorable and is crossed by three lineaments, a fact that might make it more attractive than the K1 site. I assume these sites are presently based on locations where you have access to the land.

Please call me with any questions this report does not address or any help you need with my review comments herein.

Sincerely,

Morrison-Maierle, Inc.

Michael B Kaczmarek /SL

Michael B. Kaczmarek
Chief Geologist