ATTACHMENT 1A

(Supplemental Documentation to the: Mogollon Rim Water Resource, Management Study Report of Findings)

Geology and Structural Controls of Groundwater, Mogollon Rim Water Resources Management Study by Gaeaorama, Inc., July, 2006

GEOLOGY AND STRUCTURAL CONTROLS OF GROUNDWATER, MOGOLLON RIM WATER RESOURCES MANAGEMENT STUDY

Prepared for the

Bureau of Reclamation

GÆAORAMA, INC.
Blanding, Utah

DRAFT FOR REVIEW
22 July 2006

CONTENTS

EXECUTIVE SUMMARY

As part of the Mogollon Rim Water Resources Management Study (MRWRMS), Gæaorama has produced a geologic map of the entire MRWRMS area and has done a geologic structural analysis to evaluate structural controls on groundwater. All data – geology, springs, wells, water chemistry sites, private property boundaries – have been compiled in Geographic Information Systems (GIS), utilizing ArcGIS software by Environmental Systems Research Institute (ESRI). The data can be utilized at any scale either on-screen or by hard-copy prints. Map data can be viewed or printed on any desired base, including 7.5 minute or 30 x 60 minute topographic maps or on DEM shaded relief or remote imagery.

A large amount of new mapping was done for this study in the central to northwestern parts of the area. The emphasis was on extending the Diamond Rim fault system from just north of Payson to the Fossil Springs area on Fossil Creek. Extensive new mapping and integration with earlier mapping was done in the Pine-Strawberry area. The upper drainage basin region of the East Verde River was mapping in reconnaissance. Compilation of mapping from many sources, including recent mapping for the Town of Payson, was utilized for the compilation. This work involved correlation of map units across the area and creating a customized set of geologic units for the study. Comprehensive descriptions of these map units are given as a section in the report; those units underlying areas of greatest groundwater interest for this study were given considerably more attention than other units and their descriptions include details in lithologic and stratigraphic variation and in thickness changes.

Faults in the region are primarily of Early Proterozoic (~1.65 billion years) or late Tertiary age (mostly younger than about 12 million years). The older faults, which trend mostly northeasterly are largely sealed due to formation deep in the earth under great pressure or to vein-filling during hydrothermal events. They are not conducive to water production. Tertiary faults of several trends but mostly northwesterly, on the other hand, commonly contain open space, thus providing secondary porosity and permeability, and can provide excellent targets for groundwater. Some Tertiary faults are in line with northeast-trending Proterozoic faults and in a few cases appear to have formed through reactivation of the old faults.

Fossil Springs lie at the intersection of the Diamond Rim fault and the Fossil Springs fault, the latter apparently being a reactivation of the Proterozoic Moore Gulch fault. The northeast-trending Fossil Springs fault is apparently a conduit for the spring water, whereas the Diamond Rim fault is a dam and has been for perhaps a few million years as evidenced by the enormous dissected travertine dam 400 feet above the canyon bottom. Fossil Springs and other large springs of the area derive their water almost entirely from the deep regional aquifer up-gradient beneath the Mogollon Rim. Some faults serve as barriers to groundwater passage, many do not. It can be argued, for instance, that spring water from Tonto Bridge spring and Webber spring have flowed across/through the Diamond Rim fault.

Most of the 124 springs in the study area are small, intermittent, and derive their water from perched tables containing mostly local recharge. Only very few springs in the region can be reliably used to created any sort of a meaningful water elevation map. Actually only one such map could be drawn anyway – the water elevation map for the deep regional aquifer. And at this point it can only be very tentatively created only locally because there are so few data points (wells and deep regional aquifer springs) in the northern MRWRMS area.

The water levels in the few deep wells (>1000 feet) in the region and the elevations of some large springs suggest the presence of a pervasive deep regional aquifer. In the Pine-Strawberry region this water table (about 4,400' - 4,600' elevation) is a matter of only about 50 to 200 feet higher in elevation than Fossil Springs and at about the same elevation as Tonto Bridge spring and Webber spring. The elevation of the deep regional aquifer in the north part of the Town of Payson is about 4,300 feet, based on 'old' water encountered at that elevation in the Goat Camp # 1 well.

We put forward as a conceptual model - as a working hypothesis - that the water of the deep regional aquifer in the structurally disrupted region in the northeastern part of the Verde graben (basically from the Mogollon Rim to the valley bottoms) has no specific lithologic host and has no effective confining layers. This aquifer is basically an unconfined fractured system reservoir that crosses many lithologic boundaries from the higher Paleozoic rocks down into the Proterozoic crystalline rocks. The standard aquifer systems of the Colorado Plateau country to the north - the C aquifer and the 'limestone' aquifer – break down in this highly fractured region which also has terrific topographic relief. The main control on the groundwater elevation of this deep regional aquifer is surface elevation. The water table roughly follows the surface form but ranges from perhaps 1500 feet to 0 feet (at springs) from the surface – 500 feet to 1200 feet is probably common.

Numerous Tertiary faults in the region, and particularly fault intersections can no doubt be profitably explored at these depths to obtain water from the practically limitless supply (relative to very few inhabitants) of water in the deep regional aquifer. Many of these faults are in or close to county subdivisions and thus feasibly are immediate water sources for these communities. The numerous faults and fracture systems in Pine and Strawberry, in particular, are inviting targets for water production in those water-starved communities.

INTRODUCTION

Gæaorama, or its principle, Clay Conway, working earlier for Southwest Ground-water Consultants, produced a number of reports (Southwest Ground-water Consultants, 1997, 1998; Gæaorama, 1999, 2003) in support of Payson's groundwater exploration program over the past 8 years. Each of these has involved geologic mapping, analysis of geologic structural controls on groundwater, and an assessment of groundwater potential. The Town of Payson has drilled numerous wells, and has discovered significant new groundwater resources, based in part on these studies. In particular, these studies have concentrated on an area in and near the Town, on the upper Rye Valley area southwest of the Town, and on an area beneath the Diamond Rim northeast of the Town. Numerous wellsites in the latter area were recommended to the Town but none have yet been drilled.

There is much in these reports on the local and regional geology, with an emphasis on hydrogeology, that is pertinent to the present study. The reader is therefore referred to these reports; it is not the purpose of the present report to repeat or to review the findings of these earlier reports. Rather it is the primary objective of this report to present a comprehensive portrayal of the hydrogeology of northernmost Gila County – the area defined by the Bureau of Reclamation for the Mogollon Rim Water Resources Management Study (MRWRMS), of which this report is a part. This portrayal is primarily through the creation of a geological spatial database using GIS software.

For the present study, the above mapping as well as other published and unpublished mapping (none previously digitized) in the MRWRMS study area was all integrated geologically and digitally to create the comprehensive geological spatial database as described in the next section.

Much of the study area was previously unmapped, or mapped in reconnaissance fashion. In particular, the area of greatest interest, a belt extending from Payson northwestward to the area of Fossil Springs, was at the outset of this study very poorly known. Likewise much of the area north of Payson to the Mogollon Rim was unmapped. It was therefore a necessary and most important part of this study to conduct new geologic mapping in these regions. Mapping by Gæaorama for this study occupied 48 field days, mostly in the fall of 2004. Mapping was done on aerial photographs and GPS was utilized. Hand compilation of the new mapping data was done on 1:24,000 topographic maps. This was then scanned and digitized in ArcGIS. The office and computer work related to the new mapping occupied many months of time.

As the new mapping and compilation progressed, pre-existing mapping, published and unpublished was scanned and digitized. This covered most of the area, with a few conspicuous gaps. Once mapping for the entire MRWRMS study was digitized, the challenging tasks of correlating and systematizing geologic units across the entire area and ‘blending’ the mapping at map area boundaries was undertaken. This was a huge job which relied both on the many years of field study in the region by C. Conway and also on extensive study of the geologic literature of the region. Many months were also consumed in this work.

Geologic structural analysis of the Fossil Creek-Strawberry-Pine (FSP) area was also a major undertaking of this study and involved painstaking, tightly-controlled construction of five geologic cross-sections (Plate 4). Hand construction and CAD rendering of these cross-sections also occupied several months time. A number of new faults were discovered and mapped in the FSP area in the course of the new mapping. Additionally, several faults were hypothesized from photolineaments, alignments of springs, or other geological considerations. Constraints from the construction of the ‘correlated’ cross-sections actually demonstrated the presence of several of these faults, notably the LoMia fault. By ‘correlated’ cross-sections is meant that the sections are drawn to agree with one another at their numerous intersections. Drawing involves, most importantly, precise rendering of topographic profiles, careful placement of mapped contacts and faults, and utilization of depths of formational contacts as determined in well logging. Numerous uncertainties remained, however, and many of these were gradually worked out in the iterative, trial-and-error correlative construction of the sections. Ultimately revealed through the mutual constraints of the various intersecting sections were such things as variations in unit thickness, variations in dispositions of beds (strike and dip), and even the existence and sense of offset of some faults. Understanding the structural geology, notably the fault locations and dispositions, will be important to future groundwater exploration (siting of wells).

One objective of this study was to complete the mapping of the Diamond Rim fault system, *the* major northeastern break in that part of the Verde graben that passes through the MRWRMS study area (Plate 2). This objective was met, primarily in the mapping of the belt of interest between Payson and Fossil Creek. We now know that understanding this fault is one key to understanding the groundwater regime in the MRWRMS study area. Until this study, the lateral extent of this fault, the magnitude of its vertical throw, and the fact that it controls the location of Fossil Springs were not known, although they had been anticipated for some years by C. M. Conway, as expressed to Mike Ploughe, Town of Payson, and others. Fault segments of the complex Diamond Rim fault system are key sites for groundwater potential. The numerous sites recommended for drilling (Gæaorama, 2003) beneath the Diamond Rim, northeast of Payson, are all on various strands of this fault system.

Regarding the actual deliverables to the MRWRMS project, the two most important products of Gæaorama's study are the GIS Database (explained in the next section), from which the maps of this report were prepared, and the Description of Map Units (DMU) which constitutes the major portion of this textual report. The DMU is a comprehensive 'geologic shorthand' description of the geologic units of the study area. It relies not only on the original field observations of the current study, and on observations and writings of C. M. Conway made in numerous studies in the MRWRMS area since 1976, but it also relies heavily on the extensively published and unpublished mapped and written information on the geology of the study area and surrounding regions. In previous studies made by Conway for the Town of Payson, reports have relied largely on personal knowledge and on field observations made in the course of the study at hand. In a departure from this, the DMU for the current study includes information gained from an extensive and careful excursion into the literature of the region. The DMU, however, is not in scientific balance. Much more careful attention was paid to geologic units in areas of greatest hydrogeological interest. Thus, for example, the Paleozoic units, of importance in the FSP area, have much more extensive descriptions in the DMU than various Proterozoic units in southwestern and southeastern parts of the study area (much in Wilderness areas) where there is little current practical interest in hydrogeology. The actual detailed descriptions of the geologic units, along with extensive reference to the literature, provide a fundamental lithologic framework for understanding the hydrogeology of the region.

The DMU further represents an attempt to make geological correlations within the region of study. This aspect of the DMU, in itself, required extensive study and analysis of descriptions of lithologies, facies, stratigraphy, and structure provided by the various authors and made at various stages in the scientific studies of the region over the past 7 decades. It has led in this study, for example, to a first-ever attempt to correlate, describe, and define so-called 'rim gravels' in this region *beneath* 'the rim' (Mogollon Rim). We postulate, from extensive evidence, that the consistently oldest Tertiary unit throughout the MRWRMS area, a basal gravel (Toc, Tertiary older conglomerate) is equivalent to the so-called 'rim gravel' of Mogollon Rim Formation (Potochnick, 1989) widespread on the Colorado Plateau in the Mogollon Rim region. This is important to aspects of the study relating to structural controls of groundwater.

Gæaorama's part of the MRWRMS project is a comprehensive study, incorporating the creation of a geospatial database, of the geology of the region with an emphasis on structural geology. It does not, in itself, focus on the hydrogeology although it clearly provides a strong foundation for the understanding of the hydrogeology. And, at this foundational stage, it leads directly to a number of important preliminary conclusions about groundwater, new questions regarding hydrogeology, and points to areas of groundwater potential in and near various subdivisions in Gila County. These are discussed in the report; directions are suggested for further hydrogeologic work and groundwater exploration that can be built on this foundation.

GIS DATABASE

Earlier studies by Gæaorama and Southwest Ground-water Consultants in the Payson area, first presented maps drafted by conventional means, then digital maps created in CANVAS, and finally maps created in ArcVIEW 3 and finalized in Adobe Illustrator for cartographic purposes. No other geologic mapping in the MRWRMS study area had been previously digitized.

The current study migrates previous digital products into a state-of-the-art geospatial database. Mapping of other authors has been digitized and incorporated into this regional database for the MRWRMS area. Gæaorama is currently doing this work in Environmental Science Research Institute's (ESRI) ArcGIS 9.1. We also make extensive use of Autodesk's AutodeskMAP which is AutoCAD with an added GIS module. The cross-sections of Plate 4 were done in AutoCAD.

The complete Geodatabase, including metadata, and a digital version of this text report are including in a CD with each printed and bound copy of the final report. The complete digital product standing alone on CD is available to any party on request to Gæaorama, to the Town of Payson, or to the Bureau of Reclamation. *(check to confirm this)*

At this stage, the geologic database of the MRWRMS area is deficient in that little of the extensive bedding, foliation, and joint attitude data has been incorporated due to time constraints. Extensive local use of this structural data (particularly in the FSP area) was made in evaluating structural geology for the current study, but time has not permitted digitization of the data. Otherwise the digital geology is nearly complete. The database can be expanded and improved in other ways. For example, descriptions of map units, tables of water chemistry, or photographs could be integrated digitally so they can be individually viewed by clicking on a polygon, data point, or waypoint of interest.

This digital geologic database provide a foundation for the region. It can be built upon geologically, it can be integrated with other GIS data, and it will prove to be useful not only for future hydrogeologic work in the region, but for purposes relating to geologic hazards, environmental studies, natural resources, engineering, etc. It should prove useful to various governmental agencies and private industry as well.

There is currently great interest in Fossil Creek as a result of the recent decommisioning of the two APS hydropower plants and the return of full stream flow into the drainage below Fossil Springs. There are studies underway pertaining to the environment and the habitat of Fossil Creek. This, and current attempts at deep groundwater development in the Pine-

Strawberry area, have brought considerable interest to Fossil Springs itself, which has never been subject to much hydrogeologic investigation. The new findings of this report regarding the localization of the springs on the Diamond Rim fault and particularly the geospatial database of this study will be integrated into a study underway at Northern Arizona University under the direction of Professor Abe Springer. Gæaorama is collaborating with Springer and his student Megan Green for integration of our geodatabase into a three-dimensional digital model intended to illustrate the geology and hydrogeology of the greater Fossil Creek area.

FAULTS AND FAULT SYSTEMS

Geologic structures, mainly faults, of three distinct ages are present in the MRWRMS study area: Early Proterozoic, late Cretaceous to Paleocene (Laramide), and Miocene to possibly Pliocene. These will be referred to in this report respectively as Proterozoic, Laramide, and Tertiary structures. There are numerous Proterozoic and Tertiary faults but very few Laramide faults and monoclines. The overall characteristics of these types of structures and their pertinent geologic histories in the central Arizona region are discussed extensively in Appendix A of Southwest Ground-water Consultants, 1998, and details will not be reviewed here.

In this report, the minor Laramide structures will be mentioned only incidentally. Regionally, the faults are readily categorized as Proterozoic and Tertiary (Figure 2). On Plate 2, where more detail can be shown, the faults are further subdivided into four classes:

1. Proterozoic faults
2. Re-activated Proterozoic faults
3. Post-Paleozoic faults of likely Proterozoic inheritance
4. Tertiary faults

Proterozoic Faults

These are north- to northeast-trending faults that occur only in Proterozoic rocks and which themselves are about 1.65 million years old. They originated mostly or entirely in an Early Proterozoic tectonic event called the Mazatzal orogeny. These are shown in blue in Figure 2 and in Plate 2 in southerly parts of the study area. They trend northeast to north and tend to be arcuate, swinging from northeasterly to northerly. The motion on these faults was largely left-lateral with variable vertical components of movement. Two of the faults, the Agate Mountain fault and The Buttes fault, are thrust faults. All formed in a compressional tectonic regime at considerable depth in the earth's crust; deformation was largely ductile but locally brittle especially in the thrust faults. Hydrothermal solutions moving along the faults in both Proterozoic and Tertiary time have extensively cemented these faults, largely with silica, leaving them with very little porosity and permeability. Proterozoic faults, therefore, generally do not provide much passageway for the movement of groundwater and are poor targets for groundwater production. To a large extent they are sealed.

Re-activated Proterozoic faults

On several Proterozoic faults there has been re-activation that is likely of Tertiary age. The best example is the Rumsey Park fault (see Appendix A, Southwest Ground-water

Consultants, 1998) which passes northeastward through western and northern parts of the Town of Payson. Re-activation on this Proterozoic fault has resulted in creation of open space in fault breccia. Some of Payson's best wells, including Woodland # 1 and Goat Camp # 1, occur at intersections of this fault with northwest-trending Tertiary faults.

An un-named re-activated Proterozoic fault lies immediately south of Pine. It is the western of two northeast-trending faults within quartzite of the Mazatzal Group. Its reactivation is demonstrated by offset of lower Paleozoic strata.

Time of re-activation of these faults is constrained from field relations to be younger than Tapeats Sandstone for the Rumsey Park fault and younger than Redwall Formation for the fault south of Pine. The northeast trend of these faults suggests they belong to one of the systems of Tertiary faults (see below).

There is undoubtedly re-activation on other Proterozoic faults – either unrecognized at present or of little import to this study. For example, in the complex intersection of the Proterozoic Deadman Creek fault and the Verde fault in the northern Mazatzal Mountains, a strand of the Verde fault turns southward and appears to join a strand of the Deadman Creek fault. Clearly the Deadman Creek fault has exercised some control on fault topologies of the Verde fault system.

Post-Paleozoic faults of likely Proterozoic inheritance

Inheritance, or control, from Proterozoic faults can be argued for a number of northeast-trending faults (lavender on Plate 2) that are largely in Paleozoic strata. Re-activation is implied, as in the previous category, but for faults of this group there is no Proterozoic fault exposed nearby. In the case of the small Natural Bridge fault (at Tonto Natural Bridge State Park), the fault pre-dates overlying Eocene Tertiary gravel (Toc) and is therefore likely Laramide. Location of this fault could be controlled by re-activation along northward extensions of either the Houston Creek fault or the Deadman Creek fault system. This fault is important to the study because it is likely the conduit for the spring at Tonto Natural Bridge State Park.

The other faults in this category (see Plate 2) are likely faults of Tertiary age; some clearly cut Tertiary strata. Fossil Creek fault is the best example of this type of fault; it is on trend with the Proterozoic Moore Gulch fault to the southwest (Figure 2). It is almost surely a Tertiary reactivation of the buried northeast extension of the Moore Gulch fault, one of the greatest Proterozoic faults in Arizona (Conway and others, 1987). It is not likely a coincidence that the Fossil Creek fault and Fossil Canyon are directly on trend with the Moore Gulch fault. This Fossil Creek fault is also very important to the study because Fossil Springs appear to be structurally controlled by the intersection of Fossil Creek fault with the Diamond Rim fault.

A number of other northeast-trending faults in the northern part of the study area could possibly have of Proterozoic inheritance. They include the Dripping Spring fault, Bear Spring fault, Webber Creek fault, and Horton Campground fault, among others. These faults are sub-parallel and they have basically the same trend as the Proterozoic faults of the region. This suggests Proterozoic inheritance, although, unlike the Fossil Springs fault, they are not as readily tied to specific Proterozoic faults.

Tertiary fault systems

There are fundamentally three Tertiary fault systems – two older systems, one east- to northeast-trending and the other north-trending, and a younger system of generally northwest-trending but locally north-trending faults. The relative ages of the two older systems is not known, but faults of both these systems are cut by the younger northwest-trending faults. This youngest system consists of the numerous major and minor faults of the Verde graben which cuts across the study area and is more or less continuous with other basins for 250 miles northwest-southeast in Arizona's Transition Zone and into southwesternmost New Mexico.

The paucity of faults in the west-central part of the study area (between Deadman Mesa and Polles Mesa, Plates 1 and 2) is likely only apparent. Tertiary faults on all sides trend toward this area which is underlain entirely by thick basalt flows. Faults are likely as abundant here as in surrounding areas, but they are difficult to recognize and map with nothing but basalt on the mesas and in the canyon walls. The same is true of the basalt mesas north of Fossil Canyon.

The Tertiary fault systems all developed under tensional tectonic conditions. They are often complex in terms of bifurcatons, irregular surfaces, and variable dips, all of which lead at least locally to much broken ground and much open space. This is ideal for secondary porosity and secondary permeability, the latter being by far the most important for development of a high-production well.

Verde graben system

The Verde graben is a major structural system on the southwest margin of the Colorado Plateau and it results in profound complications to the regional groundwater regimes.

The graben is assymetrical. It has fewer faults and greater displacments on its southwest margin and many more faults and overall less displacement on the northeast margin. The northeast margin east of the Verde Valley (Figure 2) is a faulted hinge across which Paleozoic strata form an arch – dipping northeastward northeast of the hinge and dipping southwestward on the southwest side of the hinge. The faults on the northeast margin are mostly down-to-the-southwest, but there are also down-to-the-northeast faults; faults of opposing movement form numerous small grabens, and in some cases nested grabens, and scarce horsts. Southward from the Verde Valley into the MRWRMS area the scenario changes in that there is a major break – the Diamond Rim fault - on the northeast margin of the graben along with the numerous minor faults.

The graben is relatively simple and narrow between the lower East Verde River-Limestone Hills area and the Pine-Strawberry area – the major bounding breaks being the Verde fault and the Diamond Rim fault. Displacement in this stretch on the Diamond Rim fault varies from about 500 feet south of Pine to about 2000 feet in the vicinity of Fossil Springs. South and east of this, the graben widens dramatically; it is very complex and includes a number of minor grabens. East-side-down displacements on the northeast side of the graben are taken up by many faults and the Diamond Rim fault dies out just before it reaches the eastern margin of the MRWRMS area.

It would appear that the graben also widens and becomes more complex northwest of the narrow area discussed in the previous paragraph. The Diamond Rim fault was mapped in the current study as far northwest as Fossil Canyon. In Fossil Canyon it apparently begins to swing northward. We speculate that this swing is pronounced and that the two major strands in Fossil Canyon arc northward then northeastward and join faults mapped by Weir and others (1989) in the Sedona quadrangle (see Figure 2). The easternmost of these two faults is here given the name Apache Maid fault. Should it be demonstrated that the faults are actually continuous this name should probably be dropped in favor of Diamond Rim fault.

Numerous faults of the Verde graben system have been the subject of detailed structural analysis and groundwater targeting in the vicinity of Payson over the past 10 years. An excellent well, Goat Camp #1, was located on the Goat Camp fault (Plates 1 & 2) at its intersection with the Rumsey Park fault. These studies have shown that Payson's historically best wells occurred on or near northwest-trending Tertiary faults. As a result of these recent studies, and the discovery of large amounts of water at greater depths (700-800 feet) than previously encountered (or previously drilled), the Town of Payson deepened many old wells and thereby greatly increased water production in many of these wells.

In the complex Lion Springs graben, along the Diamond Rim fault about 5 miles northeast of Payson (Plate 2), more than 30 well sites were picked based on detailed structural mapping (Gæaorama, 2003) and on audio-frequency magnetotelluric (resistivity) surveys (Zonge Engineering, 2004). At this date no drilling has been done at these sites.

East- to northeast-trending system

In central to northern parts of the study area are a number of Tertiary faults that trend east to northeast, commonly arcing from eastward to northeastward. Some of the more prominent easterly faults are Mayberry Spring fault, Pyeatt Draw fault, Ash Creek fault, Shannon Gulch fault and Strawberry fault. This group would probably also include all or most of the northeasterly faults discussed earlier as having potential Proterozoic inheritance; most are likely Tertiary although, as discussed above, some are Laramide.

The Mayberry Spring fault is cut by northwesterly faults of the Lion Spring graben. It is likely that most of the east-west faulting predates the formation of the Verde graben system.

North-trending system

A number of faults, mostly in westerly parts of the MRWRMS area, trend northward. These include Canyon Creek, Tangle Peak and other faults to the southwest (Plate 2 and Figure 2) and a number of mostly minor faults in the upper Fossil Canyon region. It also includes the bounding faults of the Cedar Bench horst and the LF Ranch horst near the Verde fault on the East Verde River. These faults all appear to predate the Verde graben system. It is uncertain whether north-south faults (e.g. Snowstorm Mountain, Table Mountain, Pole Hollow) in the south-central part of the study area, actually belong to the north-trending system. They are in an area of complex nested north-south grabens where the Verde fault turns southward and they may just be part of the Verde graben system itself.

REGIONAL DISTRIBUTION OF PALEOZOIC STRATA

Paleozoic strata of the Mogollon Rim region dip generally northeastward as shown by structural contours at the base of the Fort Apache Limestone Member of the Supai Formation (Fig. 3). Faulting in the region of the Verde graben has disrupted what is otherwise a simple homoclinal pattern in the distribution of these strata. As discussed above, the northeast margin of the assymetrical Verde graben is basically a faulted hinge. Southwest of this hinge the strata are dropped down on faults and in places dip to the north, northwest, or west. There are irregular rotations of strata in the various blocks bounded by Tertiary faults. These disruptions are evident in the Fort Apache elevation data (Fig. 3) in the vicinity of Pine and Strawberry.

In the region of 'STRUCTURAL DISRUPTIONS' (Fig. 3), structural contour data could only be properly drawn if the faulting is taken into account; contours would be continuous and have closure only within individual fault blocks. The short black dashed contour lines in Figure 3 show how the 5000', 6000', and 6500' contour lines would be drawn ignoring faults, which would be incorrect. Faulting is so minor it can be ignored in the broad region of the red contour lines. The western limit of these red contour lines in Figure 3 is approximately the western limit to which the contour lines can be meaningfully drawn at the scale of figure 3 and without taking into account the faulting.

A point to be drawn from this discussion and from Figure 3 is that Paleozoic strata in the Pine-Strawberry area do not dip simply to the northwest toward Fossil Springs as shown by structural contour lines at the top of the Redwall Limestone in Figure 6-4 of Morrison Maierle (2003). The strata have variable dips in the various fault blocks and a given horizon drops down toward Fossil Springs by steps on the numerous Tertiary faults (Plates 3 & 4).

MOGOLLON RIM FORMATION – DISTRIBUTIONS AND IMPLICATIONS

Mogollon Rim Formation is the name given by Potochnik (1989) to Eocene gravels widespread on the plateau north of the Mogollon Rim and also on south slopes of the rim in the area between Show Low and the Salt River. These were long informally called 'rim gravels' (e.g. Peirce and others, 1979). The older conglomerate unit (Toc) of this study (Plate 1) is in part, and perhaps entirely, equivalent to the Mogollon Rim Formation. Thus in Figure 2 we show Toc, which is all south of the rim in the MRWRMS area, and conglomerate of the Mogollon Rim Formation in the Blue Ridge area as being equivalent (Tertiary conglomerate of Fig. 2). Previous studies of these units (Wrucke and Conway, 1987; Conway, 1990) show that certain distinctive clasts of Proterozoic rocks, from the New River Mountains/Mazatzal Mountains region are common to gravels of Toc and to the gravels in the Blue Ridge area.

These distinctive gravels are key to understanding the faulting on the Diamond Rim fault in Fossil Creek. They are present at canyon bottom on the western down-thrown side of the southwestern strand of the Diamond Rim fault (Plate 3). They also occur about three-fourths the way up the north and south canyon walls between the strands of the Diamond Rim fault (Plates 3 and 4). The gravels and a great deal of Paleozoic rock and Tertiary basalt have been eroded away on the east side of the Diamond Rim fault. It is not certain whether basalts capping high places (e.g. Nash Point) northeast of the fault are remnants of 'old' basalt on Eocene erosional surfaces where the gravel was not deposited or whether they are 'young' basalts deposited after gravel and 'old' basalts were eroded away in the late Tertiary. In any case, rim gravel and overlying ‘old’ basalt are not found northeast of the fault until the East Clear Creek area – a distance of about 15 miles. If the basalt capping Nash Peak is ‘old’ and sitting on an Eocene erosional surface, presumably in a site of non-deposition of the gravels, projecting this surface to the fault constrains displacement on the fault to be about 2000 feet.

Conglomerate of the Mogollon Rim Formation was not deposited continuously across the Eocene erosional surface in central to northern Arizona. In Fig. 2 where the unit ‘Tertiary sedimentary and volcanic rocks’ lies directly on Paleozoic or Early Proterozoic rocks, the Mogollon Rim Formation is missing. Either it was never deposited or was eroded away prior to the onset of basalt volcanism in the region about 15-20 Ma. The conglomerate may have been deposited in two broad northeast-trending belts – one in the northwestern corner of Fig. 2 and one extending between the Mazatzal Mountains and the E. Clear Creek/Blue Ridge reservoir area. Sediment transport direction was generally northeastward away from the Laramide Mogollon Highlands which occupied the area now underlain by the Basin and Range province in central to southwestern Arizona.

Mogollon Rim Formation is deposited in a very low angle unconformity across the region. It lies on Proterozoic rocks in the Mazatzal Mountains vicinity in southern parts of Figure 2. Northward it lies on succeedingly stratigraphically higher Paleozoic units until finally in the vicinity of Blue Ridge Reservoir it rests on Triassic Moenkopi Formation. In southerly parts clast are entirely of Proterozoic material, largely granite and rhyolite, with locally abundant quartzite. Northward, once the gravel rests on Paleozoic strata it begins to pick up pebbles and cobbles of sandstone and limestone. These clasts of sedimentary rock become increasingly more abundant northward and come from increasingly higher in the Paleozoic section. Still, even in the Blue Ridge area, Proteorozic clasts are far more abundant than Paleozoic clasts.

Strontium isotope studies show that water from the regional aquifer in the Flagstaff area (Bills and others, 2000) is much less radiogenic than from the Mogollon Rim region (C. Eastoe and M. Ploughe, MRWRMS report, in prep.; Parker and others, 2004). Among the potential reasons for the difference is the possibility that rain and snow recharge waters may pick up radiogenic strontium passing through the highly radiogenic felsic clastic rocks of the Mogollon Rim Formation which is present on the Mogollon Rim but not in the Flagstaff area. These gravels are up to several hundred feet thick.

RELATION OF SPRINGS TO FAULTS

Springs, wells, gaging stations, water tanks, and windmills plotted on Plate 2 are taken almost wholly from 7.5 minute quadrangle maps of the MRWRMS area and vicinity. This is a very nearly complete data set for spring locations, but probably a rather poor representation of wells, gaging stations, water tanks, and windmills. For example, there are a number of water tanks in the Town of Payson that are not shown. The spring locations are important to this section; the other data is incidental. Most of the spring locations are shown with a blue-circled ‘S’. A few (Fish Hatchery, Cold, Webber,Tonto Bridge, Fossil), for which chemical and isotopic data were obtained for this study, are located with a red star.

Associated with each spring location is the name of the spring, or the word Spring if un-named, and elevation of the spring in feet.

Shown on Plate 2 are the locations of 124 springs. Sixteen are outside the geologic map and cannot therefore be evaluated in the following discussion. Springs classified as 'near' a fault in the next few paragraphs are within 500 feet of the fault – an arbitrary classification.

Of the 108 springs that can be related to geology, only 3 springs lie on or near Proterozoic faults in the study area. These are Bootleg spring 5356 (to distinguish from Bootleg spring 4923) and Spring 5025 both on the Bear Flat fault in the far eastern part of the study area, and Spring 4881 on the Lousy Gulch fault one mile south of the Town of Payson. Bootleg spring 4923 is actually in Paleozoic rocks, likely in a break 'above' the fault suggesting that a reactivation has occurred on the Bear Flat fault. Likewise Lousy Gulch fault could have some reactivation; this is suggested by the presence of two small exposures of Tapeats Sandstone between two branches of the Lousy Gulch fault which may be preserved by downdrop in a little graben. Of the remaining 105 springs, 59 lie on or near Tertiary faults or pronounced lineaments that are either faults or joints. An additional 6 springs (between Gilmore and Brushy Basin springs) aligned east-west at the south-central border of the map are likely on a basin-bounding Tertiary fault(s). Many of the remaining springs are close to faults and could lie on unmapped breaks parallel to nearby faults. Faults commonly have closely-spaced allied breaks that are not all readily mappable.

It is clear that there is extensive structural control of groundwater by Tertiary faults, but not by Proterozoic faults. As discussed above, the Proterozoic faults are largely 'sealed' – they do not carry water – they could, however serve as water barriers or aquitards, but we see little evidence of that in the study area.

The Tertiary faults in the study area are largely and probably entirely normal faults; they are tensional in nature – that is they are basically pull-apart faults. Certainly all the faults related to the Verde graben are normal faults. Faults formed under tension tend to have relatively large amounts of open space in which water can reside and along which water can travel quite rapidly. Such open space provides for what is called secondary porosity and secondary permeability. This is enhanced porosity and permeability above that provided in normal pore space between grains in sandstones and between crystals in limestones.

However, there are heterogeneities in the Tertiary faults. They can in places have little or no permeability and porosity due largely to the presence of clay-rich fault gouge or to veins that have filled the fault. The presence or absence of clay-rich fault gouge is a function of both local fault topology and of rock type. Because fault geometries can be very complicated due to fault irregularities, not all parts of normal faults are purely pull-apart. Some can have compressional characterisitics thus yielding minimal open space. Hard quartz-, feldspar- and calcite-rich rocks tend to rupture brittlely preferentially yielding breccia with relatively more open space. Soft rocks, particularly clay-rich rocks (shales, shaly and silty sandstones) lend to the formation of fine-grained fault gouge with little porosity and permeability. Formation of clay and/or calcite upon chemical decomposition of fault wallrock may also result in impermeable fault zones. Basalt, common in the study area, is a rock type that would readily form clay and calcite.

Thus faults, or portions of faults, can be impervious, preventing water from either passing along the fault or passing through the fault. Many springs occur along faults whose trace is more or less parallel to contours on slopes (common in the margins of the Verde graben and nested grabens) where it is clear that water has been dammed thus raising the local water table and resulting in formation of a spring. [Such instances must be carefully evaluated before they are used in the formation of a regional water table map – they can represent local perched aquifers and not the regional water table of interest.]

With the exception of Fish Hatchery spring, all the major springs in the study area lie on Tertiary faults. This includes, from west to east, Fossil Springs, Tonto Bridge Spring, Webber Spring, Cold Springs, and Pieper Hatchery Spring. The structural geologic settings of some of these springs are discussed below.

Fossil Springs

Fossil Springs consists of several dozen individual orifices, with the great bulk of the discharge coming from about a half dozen. These are distributed over a distance of about 300 yards either in the bed of Fossil Creek or in the north ledgy wall of the east-west section of the creek. Five individual springs are shown on the USGS Strawberry 7.5' topographic map; these are all actually in the lower part of the spring array. The biggest spring is the furthest upstream; it and two other springs, one large and one small, apparently issue from the Fossil Springs fault. These three springs are disposed on a straight line having an azimuth of 72°, which is essentially identical to the strike of the mapped Fossil Springs fault, and they lie on the extrapolation of the fault into the alluvium of the drainage bottom.

The other springs, to the southwest and on the south side of the Fossil Springs fault, issue mostly from a single horizon in the Naco Formation – a shaly layer between massive limestone beds. Likely these springs are fed also from the Fossil Springs fault which is only a few hundred feet to the north. These Naco beds lie perhaps 30 to 80 feet stratigraphically above the contact with the underlying Redwall Limestone which is exposed in the vicinity of the dam only another quarter mile to the west. On the north side of the north-side-down Fossil Springs fault the Redwall would be perhaps another 50 to 100 feet deeper. Detailed mapping and some cross-section constructions in the vicinity could considerably further constrain the stratigraphic and structural relations.

It seems likely that the Fossil Springs fault serves as a conduit to bring groundwater from the east-northeast to Fossil Springs. It seems likely also that the channelway is more complex than simply open space in the fault. Given that the wallrock of the fault is limestone of the Naco Formation and, at very shallow depth, limestone of the Redwall Formation, it is possible that solution passageways in the limestones also play a role in the water transmission.

A complex nexus of the Fossil Springs fault, the Flume fault, and the three strands of the Diamond Rim fault lies about a quarter mile west of Fossil Springs and beneath a great travertine bench. This travertine mass, no doubt deposited by ancestral Fossil Springs, is ¾ mile by ½ mile in lateral dimension and up to perhaps 200 feet thick. The top of the ledge is approximately 400 feet up a shear cliff from the canyon bottom. This travertine deposit is found only on the north side of the creek. It post-dates the faults and the various geologic units – Naco Formation, Supai Formation, and Tertiary basalt – that are juxtaposed on the faults and which lie beneath it.

The canyon bottom has been deepened by at least 200 feet since the travertine bench was deposited. The bench is the remnant of a great travertine dam which stretched from wall to wall across Fossil Canyon. There is no radiometric date on the travertine, but the geomorphological relationships suggest that it may be on the order of hundreds of thousands to several million years old.

It would appear that the Diamond Rim fault has long served as a barrier, at this site, to groundwater draining generally westward to southwestward away from the deep regional aquifer groundwater divide about 20 miles to the east (Fig. 2). Clay minerals and calcite formed both mechanically and chemically along the fault, largely from breakdown of the Tertiary basalt, have likely caused the subterranean damming. The spring waters have historically been, and still are, oversaturated with $CaCO_3$ which resulted not only in subaerial precipitation of calcium carbonate in the form of travertine/tufa, but perhaps also in the build-up of calcite veins in the faults. Whether the latter is feasible from a purely chemical perspective is beyond the scope of this report. Empirically, however, spring position has migrated not only downward with deepening of the canyon, but also upstream implying eastward build-up of minerals (veining) in the Fossil Creek fault.

Tonto Bridge Spring

Tonto Bridge spring lies in a developed area at the eastern margin of a large meadow atop the travertine bridge at Tonto Natural Bridge State Park. Exposure at the spring is poor. It appears there are two possible structural controls on the spring – unconformity and fault. The spring lies on or near the northward projection of the unconformable contact of the Martin Formation resting on Proterozoic rhyolite porphyry (Xdrp, Plate 1). The Tapeats Formation is missing at this location. Also, the spring lies at or near the projected intersection of two faults (Plate 2) - the Natural Bridge fault and a minor northwest-trending fault. The northeasterly Natural Bridge fault appears to be overlain by rim gravels (Toc); thus it may be a Laramide fault.

The Tonto Bridge Spring has a number of things in common with Fossil Springs – build-up of huge travertine dam, downcutting of canyon since travertine dam formation, similar water geochemistry including Sr isotopes (C. Eastoe and M. Ploughe, MRWRMS report, in prep.; Parker and others, 2004; Hydro Systems Inc., MRWRMS report, in prep.), and a fairly consistent historical discharge rate. Differences between the two springs are a huge difference in discharge rate (Fossil ~20,000 gpm; Tonto Bridge ~800 gpm), and geologic setting. Whereas Fossil Springs discharge from the Naco, and presumably the upper Redwall, Tonto Bridge Spring discharges from the very base of the Paleozoic section and possibly right at the unconformity. Yet, the spring water at Tonto Bridge does not 'see' the Precambrian rocks isotopically. This has implications for the role of several faults in the area, as explained in following paragraph.

Parker and others (2004) found in doing strontium isotope analyses (entirely in the MRWRMS area) that in most cases $^{87}Sr/^{86}Sr$ values in spring water were extremely close to $^{87}Sr/^{86}Sr$ values in wall rocks of the spring. The Tonto Bridge Spring is a major exception. Tapeats Sandstone at Tonto Bridge (Parker and others, 2004, Table 11; there is uncertainty of unit sampled – perhaps a basal sandy facies of Martin) gives the most radiogenic value (.71233) of any rock or water sample in the region either from MRWRMS data or from Parker and others (2004). This value is likely a reflection of detritus from Proterozoic granite and rhyolite in the 'Tapeats' sample. Yet the Tonto Bridge spring water (.70912) is similar to values obtained from the Redwall, Naco, and Supai rocks and also from Fossil Springs. It is clear also that the Natural Bridge spring water is not 'seeing' either the rim gravels (highly radiogenic) or the Tertiary basalt (non-radiogenic) which combine to make a cap several hundred feet thick on Buckhead mesa immediately to the east of the Spring. It would appear that the source of the spring water at Tonto Bridge is the middle to lower part of the Paleozoic section of the Mogollon Rim and that the water has passed through the Diamond Rim fault (2 miles to the northeast) and under Buckhead Mesa.

On hydrogeologic grounds alone, one can readily make the argument that Tonto Bridge Spring must have a source north of Buckhead Mesa and therefore north of the Diamond Rim fault. This spring, with not too much variation in flow at around 800 gpm basically year-round, cannot have its source in re-charge to Buckhead Mesa south of the Diamond Rim fault, a rather small area of only 6-8 square miles immediately east of the spring. Similar, much larger mesas in the area, for example west of Pine Creek, contain only tiny springs and seeps.

The strontium isotopic data confirms what was ascertained from geological arguments and provides powerful evidence that the source of spring water at Fossil Springs and at Tonto Bridge Spring is the same – what we call in this report the deep regional aquifer. They are on opposite sides, however, of a secondary groundwater drainage divide which runs northeastward from about Strawberry Mountain to the regional drainage divide beneath the East Clear Creek area (see Fig. 2).

Whereas at Fossil Springs the Diamond Rim fault is fundamentally impenetrable by groundwater, at Buckhead Mesa the same fault permits an 800-gpm-flow-through which breaches the surface at Tonto Bridge Spring. The northeast-trending Natural Bridge fault may be the channelway for the flow beneath Buckhead Mesa; as such it would be the only known Laramide fault in the study area with from which a spring issues. Alternatively, and less likely, the water could be moving along the unconformity and just happen to emanate at the intersection of the two faults.

Weber Spring and Flowing Spring

Weber Springs and the two un-named springs (Spring 4654 and Spring 4650) at the Flowing Springs subdivision (Plate 2) are in an area of complex Tertiary faulting along the East Verde River about 4 miles north of Payson. They are also near the base of the Paleozoic section. The un-named springs are within and perhaps near the top of the Tapeats Sandstone (poor exposure). Webber Spring, ½ mile northeast of the un-named springs, issues from several horizons within the Martin Formation.

The two un-named springs are near the intersection of the north-trending Flowing Springs fault and an east-west fault extending eastward from the small Cherry Spring graben. The northern of these two springs flows well during wet seasons and stops flowing in dry times. It was not flowing when investigated in summer 2004. The other spring has a very small consistent flow and keeps a pond full on private property. Obviously these two springs, even though close, are controlled by separate channelways.

Weber Spring discharge rates have varied in three measurements from 1,570 gpm to 996 gpm (Parker and others, 2004). Chris Miller (pers. comm., summer 2004), who has lived in Fossil Springs subdivision for many years, reports marked variations in flow from dry to wet periods. This spring, which lies close to an small auxiliary fault of the Weber Spring fault, is dependant to a large extent on annual recharge for its water source. Its highly radiogenic $^{87}Sr/^{86}Sr$ (.71132) indicates, however, that a substantial portion of its water has equilibrated with Proterozoic granitic rocks. It is likely that much of its water has come from the north, across the Diamond Rim fault. Only 1-1/2 miles to the northeast, immediately on the north side of the fault, is a large mass of coarse porphyritic granite (unit XYg). It seems likely this granite and/or other high-potassium Proterozoic rocks buried just north of the Diamond Rim have imparted an isotopic character to water moving downslope in the deep regional aquifer which manifests itself in waters of Webber Spring.

As at Tonto Bridge Spring, spring water at Webber has surely passed through the Diamond Rim fault. Webber Spring is another point of discharge for the deep regional aquifer.

Cold Spring

Cold Spring is somewhat analogous in its setting to Tonto Bridge spring – it is on both a fault and the regional unconformity. The relations are more clear, however, at Cold Spring. The spring lies near the west end of the 9-mile-long east-west Ellison Creek fault. It would appear that the fault has served to at least partially dam the water and that the water has traveled westward down-gradient along the fault. It is somewhat puzzling that the spring did not form further west where the Ellison Creek fault drops down into the East Verde River drainage. An explanation may be that a change in rock type beneath the unconformity resulted, for some reason, in impermeable fault gouge. Thus water moved westward along the fault through Paleozoic rocks then discharged where the Precambrian basement became exposed on the fault.

Three discharge measurements from 1952 (Parker and others, 2004) give 830, 1,060, and 4,200 gpm. It now generally runs about 2,000 gpm (M. Ploughe, 2004, pers. comm.) but is strongly influenced by variations in precipitation. Moderately radiogenic strontium (.71057; E. Eastoe and M. Ploughe, MRWRMS report, in prep.) is similar to water and to Supai 'wall rock' at the Tonto Fish Hatchery Spring and is also similar to surface water at Blue Ridge Reservoir. It may be that surface water in this area might not be readily distinguished from groundwater equilibrated with middle to lower Paleozoic strata. The isotopic data suggests, however, that unlike Webber spring, the water of Cold Spring has not pickup up significant radiogenic strontium from passage through Proterozoic basement. This is consistent with the observation in the previous paragraph that water was not able to move down along the fault into the Proterozoic rocks.

Thus it appears that Cold Sring is fault controlled and also unconformity controlled. Ellison Creek fault dammed the water to a certain extent and provided passage for the water. How leakey this 'dam' was cannot be ascertained at this point.

FOSSIL CANYON-STRAWBERRY-PINE AREA

A geologic map (Plate 3) and geologic cross-sections (Plate 4) provide details at 1:24,000 scale) of the structure and stratigraphy of the Fossil Canyon-Strawberry-Pine area. Through extensive new mapping, the current study adds considerably to previously published maps – notably in identification of new faults and particularly in extending the Diamond Rim fault from Pine Creek northwestward to Fossil Creek.

The Diamond Rim fault at Pine Creek has a south-side-down displacement of about 500 feet (cross-section A-A'). Displacement in the northeast margin of the Verde graben in this area is partly distributed to faults further south along Pine Creek. Northwest from Pine Creek, the fault bifurcates so that there are three strands in Fossil Creek. As discussed earlier, in the section on the Mogollon Rim Formation, there is approximately 2,000 feet of total displacement on the fault in Fossil Creek.

Strata of the Supai Formation on the Hardscrabble road southwest of Pine have highly variable dips due to much minor faulting on the northeast side of the Diamond Rim fault. But a rough average dip is gently to moderately to the northeast. From this and other structural data, it appears that the Paleozoic beds have been somewhat upturned in the vicinity of Strawberry Mountain. The Fort Apache Limestone was truncated by erosion, presumably in the Laramide orogeny, under southern Strawberry Mountain and also at Nash Pasture Tank at the west end of Strawberry valley. The line of truncation parallels the Diamond Rim fault immediately off the fault to the northeast. This may suggest that 1) this was a zone of Laramide uplift with a possible monocline trending northwestward and dipping northeastward, and 2) that the local position of the Diamond Rim fault may be controlled by the Laramide structure. In other words, the Diamond Rim fault could be a re-activated Laramide structure, with the opposite sense of movement.

The east-west Strawberry valley owes its presence largely to preferential erosion along the Strawberry fault. The Strawberry fault could actually consist of a number of parallel breaks even though it is shown on Plate 3 as being a single fault. The fault appears to bifurcate on its eastern end (Plate 3). Several generally north-trending faults were also mapped in this study across Strawberry valley. These are part of the same north-south fault system mapped by Weir and Beard (1997) crossing Calf Pen Canyon and Sandrock Canyon to the north of Strawberry. Offsets on these faults range from perhaps 25' to 100' and are mostly down to the west (cross-section B-B'. Preferential erosion on parts of these faults has resulted in roughly north-south drainages and divides in the higher terrain north and south of Strawberry valley.

Similarly, the basin occupied by the village of Pine owes its existence to preferential erosion along faults, primarily the LoMia fault and the Strawberry Hollow fault. The water courses of Pine Creek and Strawberry Hollow closely follow these two faults. The upper part of The Narrows through which Pine Creek leaves the Pine basin is also structurally controlled; the drainage follows the Strawberry Hollow fault for more than half a mile. Dripping Spring fault is down to the north as determined primarily by the offset of a thin, probably discontinuous limestone unit (Psll) in the lower part of the Supai Formation in the Hardscrabble road area.

Dripping Springs on the west face of Milk Ranch Point lie on the Dripping Springs fault and owe their presence to water being carried down along the fault zone from recharge areas atop Milk Ranch Point. They are an example of a perched aquifer, dependant entirely upon annual recharge for replenishment.

Preferential erosion along the various faults in Pine and Strawberry is instructive. It indicates that the fault zones are soft zones, that they are not occupied by resistant vein material. They are soft zones, easily weathered and eroded, because they contain broken-up material. This material may be as small as clay-rich fault gouge or as coarse as blocky fault breccia with individual clasts and open space as large as inches to perhaps locally feet. This bodes well for the presence of groundwater in these zones and for the potential in these zones of excellent secondary permeability. A nexus of faults in the south part of Pine provides a superior target area for groundwater.

On the south margin of the Pine basin is a resistant somewhat high-standing mass of quartzite; this quartzite belongs to the regionally widespread Early Proterozoic Mazatzal Group. This rock is almost pure quartz and is exceedingly hard. Mapping shows that this quartzite exposure, like a number of others in the central Arizona region was a monadnock on a regional peneplane when shallow seas flooded the continent and Paleozoic sedimentation began. When the area was covered with shallow early Paleozoic seas it may have stood emergent as an island. From all directions the lower Paleozoic units lapped out against this resistant quartzite mass. Tapeats Sandstone is entirely missing near the quartzite. Overlying Paleozoic Formations, as high as the Naco rest directly on the quartzite. This relationship is shown best in cross-section E-E' but also in cross-sections A-A' and B-B.' Redwall Limestone rests on the quartzite in the south Part of Pine (Plate 3) and Naco Formation rests on the quartzite at the southernmost end of cross-section A-A' just south across the Diamond Rim fault. The steep westward dip of the base of the quartzite (near Hwy 87) and distribution of attitudes within the quartzite suggest it is distributed in a syncline as shown in cross-section B-B.' Note that a well penetrates the quartzite giving some control in the construction of this part of cross-section B-B.' The well in the southern part of cross-section E-E,' which bottoms in Martin Formation constrains the northern paleoslope away from the quartzite prominence to be quite steep. Proterozoic units Xe (East Verde River Formation) and Xu (Undivided) are best guesses at what type of Proterozoic rock might lie beneath the cross sections of the Pine-Strawberry area. It is unlikely that quartzite will be encountered by drilling except in southernmost parts of Pine.

Thicknesses of Paleozoic units as shown in the cross-sections (Plate 4) are probably accurate in most places to ±20 feet and relatively minor lateral changes in thickness as shown are for the most part real. Some of these thickness changes are described in the Description of Map Units. The unusually wavy contact line between the Naco Formation and the Redwall Formation is intended to reflect the irregular nature of this contact in space. The irregularity is due to a karst topography which developed on the surface of the Redwall prior to deposition of the Naco. Because of this, thicknesses of the Redwall and Naco are quite unpredictable; again see the Description of Map Units for details. The total thickness of the Redwall plus Naco is better controlled and this was used for construction of the cross-sections.

Logs of four wells were extremely useful in constraining the cross-sections. These are logs for the Strawberry borehole of the Northern Gila County Water Plan Alliance (Corkhill, 2000); for the Strawberry Hollow well (M. Ploughe, 2004, pers. comm., ADWR Application No. 22-401908); for a preliminary 740-foot boring in southcentral Pine (Highland Water Resources Consulting, 2005; ADWR Application No. 55-205322); and for a boring that bottomed in quartzite (need to locate file on this). Schematics of these wells, with formational boundaries and depth to water table, are shown in various cross-sections of Plate 4. Plate 4 also contains an explanation of the well schematics.

The numerous cross-sections drawn through Pine closely constrain the actual attitudes and thicknesses of the various units and also the offsets on the faults. There is a huge amount of information and spatial data in these carefully constructed sections which could never be fully or properly explained by tens of hundreds of pages of text, but which can visualized, understood, and appreciated to a great extent by thorough study of the cross-sections and maps in tandem.

SPECULATIONS ON AQUIFER SYSTEMS

Except in a small area of thin basin-fill sand and gravel a few miles southwest of Payson, groundwater in the MRWRMS area is hosted in bedrock; the only significant water resources are in bedrock. The bedrock groundwater systems are exceedingly complex because the physiography and geology are complex.

The study area contains the great escarpment of the Mogollon Rim. Elevations range from 7,500 feet on the rim down to almost 3,500 feet on Tonto Creek in the southern part of the area. The topography is rugged, resulting in numerous minor surface drainage divides. The area contains parts of three regional drainage basins: Little Colorado River north of the Mogollon Rim; Salt River including Tonto Creek and its tributaries; and Verde River including Verde River, East Verde River and their tributaries. Groundwater divides mimic the surface divides. Groundwater gradients are locally very steep (see Fig 2).

Rain and snowmelt recharge waters percolate down, variably, through Tertiary volcanic and sedimentary rocks, Tertiary gravels of the Mogollon Rim Formation, sandstone and limestone of the Paleozoic section, and through Proterozoic rocks such as granite, gabbro, and metamorphic rocks (see Figure 2). Inherent porosities and permeabilities are highly variable in these rocks; superimposed on that are the strong controls on groundwater of the Proterozoic and Tertiary fault systems in the area. The classic notion of an aquifer as a distinct sedimentary layer or group of layers having relatively high porosity and permeability is of very limited applicability in the study area. The best known and simplest of the aquifers, the C aquifer, consisting of the Coconino Sandstone and the Supai Formation, really loses its definition where these formations are exposed in the slopes beneath the Mogollon Rim.

Likewise, the concept of a limited recharge area - where the strata of an aquifer are exposed - also has very limited applicability. Certainly the exposures of Coconino Sandstone and Supai Formation on the slopes beneath the Mogollon Rim provide *no* recharge to the C aquifer extending northward beneath the Little Colorado River region. Recharge received in these formations in the study area either remains shallow and issues as springs not far downslope or it percolates down to the water table in lower Paleozoic strata or Proterozoic rocks. Recharge occurs throughout the area although it is far more effective in some rocks than others. For example, in the Payson area, Payson Granite readily accepts recharge whereas the gabbro/diorite of the Gibson Creek Intrusive Suite does not (see Appendix A, Southwest Ground-water Consultants, 1998).

What appears to be emerging from the limited 'deep' drilling in the area and from isotopic data is that below a certain depth, the rocks (of whatever rock formation) are saturated with mostly 'old' water that has moved southward to westward from the drainage divide of the deep regional aquifer (see Fig. 2). Currently, if this water is in the Coconino or Supai Formations it is said to be in the C aquifer; if it is in the Redwall or Martin formations it is said to be in the 'limestone aquifer;' if it is in Proterozoic rocks it is said to be in the X aquifer. We suggest this is all quite meaningless in the current study area and we present the following conceptual model for a deep regional aquifer. This is modeled somewhat after Bills and others (2000) who use the term regional aquifer basically for the C aquifer but modify it to include important variations such as local 'mounds' of water up into the Kaibab Limestone.

We suggest that throughout much of the study area a certain fraction of the recharge water moves virtually unimpeaded downward through the extensive Tertiary fracture and fault systems of the region to a deep regional aquifer. There is much greater precipitation and much greater recharge from the plateau country north of the Mogollon Rim. The relatively continuous groundwater surface in this aquifer lies generally at depths on the order of, perhaps, 500 feet to 2000 feet; depth from place to place is highly variable because of locally great topographic relief. Beneath this level the rocks are everywhere saturated. This groundwater surface mimics the earth surface to a certain extent, being, for example, very steep beneath the steep slopes below the Mogollon Rim. This is not a potentiometric surface because there is no real confining layer, although, locally, unusual conditions may cause water to rise under a hydrostatic head to a level in a well above the regional water table. This deep regional aquifer is not defined by rock type – it is defined fundamentally by distance from the earth's surface, and its geometric properties are permitted by the extensive fractures in the region. The fractures are the key. Structural disruptions on the northeast margin of the Verde graben (see Fig. 2, 3) permit ready downward percolation almost everywhere and make this system an unconfined aquifer. We call it the deep regional aquifer. We argue it is pointless to attempt division of this deep regional aquifer in the study area into other aquifers such as C aquifer, 'limestone' aquifer, or X aquifer. Northeast of the Verde graben, however, the deep regional aquifer changes into the different classical bedrock aquifers of the southernmost Colorado Plateau.

Above this deep regional aquifer are countless more or less perched tiny to fairly large 'aquifers.' These are controlled by rock type and by faults. They are more common along faults. In places they exist on slopes as water dammed behind impermeable faults. The great majority of springs in the region are from these highly variable perched aquifers. Because of this it is quite meaningless to use spring elevations in an attempt to draw a groundwater elevation map. There is little or no continuity between these perched aquifers. The only groundwater elevation map that can have any meaning must be drawn on the deep regional aquifer and it can only be drawn from well data and from the few, generally large, springs that can be demonstrated to have their origin from the deep regional aquifer.

GROUNDWATER POTENTIAL

It is not the purpose of this report to actually determine specific sites for water well drilling. Nevertheless, a number of potential target areas have become obvious and merit discussion in this report. Loosely, these target areas are faults or fault intersections in or near tracts of unincorporated private property – county subdivisions. Payson will not be discussed in this section as it has been the subject of an earlier report (Southwest Ground-water Consultants, 1998)

The thesis underlying the groundwater potential here discussed is that significant to pronounced secondary permeability may be encountered in faults and fractures. The objective would be to drill into such zones of secondary permeability within the deep regional aquifer which can typically be reached at about 1000 feet, in many places shallower. The idea would be to construct relatively large-capacity wells to provide for subdivisions. This report should not be taken as a guide for drilling on individual private parcels. For these small parcels, low-budget shallow wells might better target perched aquifers away from faults. Fault and fracture systems at shallow depths might be dry because the water could readily drain down to the deep regional aquifer.

Ideally, detailed exploration should be undertaken to determine optimal drill sites. This could involve more detailed geologic structural analysis to better locate the faults and could also involve geophysical techniques to image the subsurface. Audio-magnetotellurics (AMT, a resistivity method) has been employed with considerable success in recent years in Arizona. For example, the drilling of a deep well (>2,000 feet) into a fault zone in the Supai Formation in the Belmont area west of Flagstaff (Gary Small, Hydro Systems, Inc., pers. comm., 2005) was guided by AMT. Two previous unsuccessful wells (11 and 23 gpm) failed to intercept the fault. Two wells guided by AMT did encounter the fault zone and produced 73 and 371 gpm. One of the successful locations was only 300 feet from one of the first, unsuccessful, wells (Norm Carlson, Zonge Engineering, written comm., 2006). Optimal well siting and then carefully controlled penetration of fractures beneath the water table are absolutely essential to ensure successful drilling.

Pine-Strawberry area

Strawberry valley is traversed by an east-west fault system and numerous north-south faults. Thus there are a number of potential targets; fault intersections should be given top priority. Wells will ideally be drilled to depths of 1800 to 2000 feet and the water level will be about 1400 feet, based on the one deep well drilled so far (Corkhill, 2000). A number of faults traverse Pine; they, and particularly their intersections, present a number of targets within the community. They are advantageous compared to Strawberry targets in that the water table will be at about 600-800 feet and the wells need be drilled only to about 1200-1400 feet. Locally, the Redwall Limestone may be partly beneath the water table (see cross-sections, Plate 4). Wells sited in such places would have a possible added advantage in that cavernous areas within the Redwall could be intercepted, providing potentially huge secondary permeability. This should not be a primary consideration, however, in siting the wells. Water can potentially be produced in large quantities from any rock unit, including granites and other rock types of the Proterozoic basement, provided fault systems are properly intercepted within the deep regional aquifer.

Geronimo Estates

The Webber Creek fault passes through a considerable part of the Geronimo Estates subdivision along its southeast margin. This normal fault dips to the northwest, beneath the subdivision, thus providing excellent potential drill sites within the subdivision. Shannon Gulch fault also passes through the subdivision and it has an intersection within the subdivision with a minor fault. This fault, and particularly the fault intersection, present good groundwater possibilities.

Whispering Pines

The Dude Creek fault and the Brody Hills fault intersect in the northernmost part of the Whispering Pines subdivision. Production of water from this point would be ideal as it could be gravity fed downhill to the rest of the subdivision. Displacements on these two faults, particularly the Dude Creek fault, may be small, however, and so open space in the fault might not be so well developed. The Willow Spring fault, with considerably more displacement (several hundred feet), lies only one-quarter mile west of the subdivision. Its intersections with the Dude Creek fault and the Brody Hills fault are also potential target areas for the Whispering Pines subdivision.

Other subdivisions

The Mayfield Canyon fault cuts across the southwestern part of Dealer's Choice and the Diamond Point Shadows fault cuts across the northern part of Diamond Point Shadows. These faults offer excellent opportunities for groundwater from the deep regional aquifer.

Star Valley is transected by a number of faults and contains several fault intersections.

Mead Ranch subdivision is transected by the east-west Ellison Creek fault.

A number of small subdivisions in the Kohls Ranch area are transected by faults or are close to faults.

DESCRIPTION OF MAP UNITS

(For Plates 1-3)

Quaternary Sediments and Sedimentary Rocks

Qa1 **Alluvium (Holocene)**—Unconsolidated clay, silt, sand, and gravel. Mapped chiefly along major drainages. Locally includes terrace deposits at higher levels than drainage bottoms. Includes fine-grained materials, including moderately developed soils, in large flats. Includes extensive granite grus where underlain by Payson Granite.

Qc **Colluvium (Holocene)**—Veneer of unconsolidated materials, generally containing large amounts of silt, sand, and fine angular gravel on slopes. Deposited largely by masswasting processes. Shown as mapped widely by Weir and Beard (1997) in Fossil Creek as well as locally elsewhere on the map.

Q1 **Landslide deposits (Holocene and Pleistocene?)**—Broken and dislocated slump masses and debris flows. Common on steep walls of canyons and steep slopes of mesas where Tertiary basalt caps softer sedimentary strata. Locally consists of glide blocks of broken but stratigraphically coherent Paleozoic strata. Includes some talus.

Qt **Talus deposits (Holocene and Pleistocene?)**—Blocky rubble on steep slopes. Generally contains small amounts of clay-, silt-, and sand-size particles.

Qtc **Talus and colluvium (Pleistocene)**—Widely varying unconsolidated material, primarily immediately west of the Snowstorm Mountain fault. Ranges from pre-fault to post-fault deposits.

Qg **Gravel (Pleistocene)**—Unconsolidated and weakly consolidated gravel, sand, and silt in terrace deposits along drainages, and poorly sorted pebble to cobble and locally boulder alluvium in isolated patches and old fan deposits. Highly variable. Commonly dissected. Some could be Tertiary.

Qtr **Travertine and tufa (Holocene, Pleistocene and possibly Pliocene)**—Generally light- to medium-gray to yellowish-gray, dense to porous carbonate deposited by springs; in part cavernous. Main occurrences are the deposits of the huge travertine bench above Fossil Springs in Fossil Creek (Weir and Beard, 1997), and the travertine bridge at Tonto Natural Bridge State Park in Pine Creek (Wrucke and Conway, 1987). A number of smaller deposits in the area commonly associated with springs. Woody plant material and angular talus rocks commonly imbedded in the calcareous deposits.

Travertine at Fossil Springs as much as 120 feet thick; forms conspicuous bench about 0.7 mi wide and 1 mile long (Weir and Beard, 1997).

Qp **Pediment alluvium (Pleistocene or Pliocene)**—Loosely consolidated sand and gravel on pediment surfaces. Primarily in upper Rye Creek drainage basin and on knobs in the northern parts of community of Pine.

Tertiary Sedimentary and Volcanic Rocks

Tg **Gravel (Miocene)**—Weakly consolidated, poorly sorted, crudely stratified pebble to boulder alluvium locally containing thin beds and lenses of pebbly sandstone. Deeply dissected. Forms cliffs and gentle to steep slopes strewn with pebbles and cobbles. Mapped chiefly on ridges in the vicinity of the confluence of Pine Creek and the East Verde River and in the Lion Spring graben under the Diamond Rim and in the Houston Pocket area. In the latter area clasts tend to be coarse and angular and are derived from Proterozoic and Paleozoic outcrops to the north. In general, rocks of this unit were derived as a result of latest faulting and basin subsidence in the region. Could be roughly equivalent to Tyc, but is likely younger. Thickness up to perhaps several hundred feet.

Tls **Limestone (Pliocene of Miocene)**—Light-gray to yellow-gray, thick-bedded massive limestone that rests on basalt (Tb) on Polles Mesa and Whiterock Mesa in west-central part of map area. Contains abundant irregular vugs 1-10 mm across, partly lined with secondary calcite. Closely resembles limestone of the Tertiary gravel and limestone unit (Tgl), with which it is likely correlative. Weathers medium gray. Maximum thickness about 120 feet.

Tgl **Tertiary gravel and limestone (Miocene)**—Gravel, sandstone, and interbedded limestone primarily in the upper Rye Creek area; smaller isolated deposits near Payson and eastward. Deposited on a middle Tertiary erosional surface having local relief up to several hundred feet. Deposited in closed basin prior to downdropping of graben between the Snowstorm Mountain fault and the Verde fault.

In Rye Creek, heavily cemented with calcite in lower parts that are well consolidated; otherwise poorly cemented and weakly to moderately consolidated. Abundant breccia in lower parts composed largely of diorite and gabbro derived locally from unit Xgc. In thicker parts to the west, upper half of section contains quartzite and rhyolite clasts derived from the Mazatzal Mountains nearby to the west and coarse porphyritic granite possibly from regions to the south. Lacustrine limestone beds in upper parts of the thicker western section south of the Verde River contain plant fossils. These pale orange, medium-gray weathering limestone are in beds up to 10 feet. Upper gravel beds in northerly exposures south of East Verde River possibly equivalent to gravel of unit Tg. More than 600 feet thick in boreholes near the Baby Doll ranch (Town of Payson Water Department, 2004).

Unit includes 'gray gravels' (Tgg, Gæaorama, 2003) of the Lion Springs graben that contain abundant limestone, dolomite and sandstone clasts from the Paleozoic strata of the Diamond Rim. These gray gravels contain widespread abundant carbonate cement but no continuous limestone layers; they contain minor clasts derived from underlying older conglomerate (Toc).

Tst **Siliceous tuff (Miocene)**—White to tan tuff and tuff breccia interbedded with Tertiary basalt (Tb) at Fossil Creek, Hardscrabble Creek, Squaw Butte, and further south along the Verde River. Notable for soft white pumice fragments and for angular lithic clasts; latter are Tertiary silicic volcanics. Single bed about 50 feet thick in Fossil Creek near Fossil Springs. Two closely spaced beds in lower Fossil Creek and Hardscrabble Creek. Age at Black Ridge (west of study area 1.5 miles northwest of confluence of Verde River and Fossil Creek) as dated by K-Ar methods is 11.0 ± 0.6 Ma (Wrucke and Conway, 1987).

Ttg **Tuffaceous gravel (Miocene)**—White to light gray gravel interbedded with basalt (Tg) about a mile downstream from Fossil Springs along flume road. Distinctly different from siliceous tuff (Tst) higher in the basalt section. Contains light-colored pumice fragments, light-gray obsidian, and other Tertiary volcanic fragments including basalt (up to 6 inches). Also contains up to 5% fragments of Proterozoic rock types – primarily hornblende-biotite-granodiorite. Thickness perhaps about 50 feet.

Tb **Basalt (Miocene)**—Medium- to dark-gray mostly olivine basalt throughout the study area north of the Limestone Hills (basically, north of the Verde fault) and east of the Mazatzal Mountains. Includes Tbu of Wrucke and Conway (1987). Probably largely equivalent to older basalt (Tob) of the area south of the East Verde River gorge in the Mazatzal Wilderness, but may locally contain equivalent of younger basalt (Tyb). Consists of flows 5 to 100 feet thick that contain olivine phenocrysts 1-2 mm long, commonly altered to iddingsite and, in some flows, conspicuous phenocrysts of a dark-green pyroxene, in an intergranular groundmass. Flows high in the unit capping the eastern parts of Polles Mesa and parts of Hardscrabble Mesa contain abundant prominent augite phenocrysts 2-6 mm in size. Deeply embayed quartz phenocrysts and large blocky plagioclase crystals locally are abundant in flows of the lower third of the unit. Vesicles are common and locally are partly lined with a zeolite; calcite amygdules and veins are abundant. Contains locally conspicuous interbeds of basaltic sand and scoria.

Forms cliffs and steep slopes commonly mantled with talus and landslide deposits. Great thicknesses exposed in deep gorges of East Verde River, Hardscrabble Creek, and Fossil Creek. Caps Buckhead Mesa and smaller mesas east of Buckhead Mesa. Thin scattered basalt remnants in central to eastern parts of map area. Also caps parts of the Mogollon Rim where it lies on a gently southward dipping erosional surface. Source of most of the basalt is likely at or near the northwestern margin of the study area, perhaps in the volcanic complex of the Hackberry Mountains area (Lewis, 1983; Scott, 1974). Section thins from more than 1,200 feet to less than 100 feet from western parts to the central part of the study area.

K-Ar ages on basalts of unit Tb (Tbu of Wrucke and Conway, 1987) in the Mazatzal Wilderness range from 9.9 ± 0.5 Ma in the Limestone Hills to 13.4 ± 0.8 Ma at the base of the unit on the East Verde River, 2.5 km east of the confluence with the Verde River (Wrucke and Conway, 1987). Peirce and others (1979) report whole-rock K-Ar ages of 12.1 ± 0.4 Ma for basalt of Buckhead Mesa and 11.4 ± 0.27 Ma for basalt of Bakers Butte on the Mogollon Rim just north of Milk Ranch Point. Peirce and others (1979) also determined K-Ar whole-rock ages of 9.30 ± 0.40 and 10.16 ± 0.22 Ma for uppermost flows of Fossil Creek. Weisman and Weir (1990) report: "A feldspar-groundmass concentrate from a sample of basalt from the base of the topmost flow on the south end of Milk Ranch Point yielded a K-Ar date of 14.25 ± 0.74 Ma (Sample number UAKA 77-79, Muhammad Shafiqullah, Laboratory of Isotope Geochemistry, University of Arizona, and H. Wesley Peirce, Geologist, Arizona Bureau of Geology and Mineral Technology, oral and written communs., 1988)."

Ta **Andesite (Miocene)**—Small occurrences along upper Tonto Creek above Kohls Ranch. Taken from mapping by Satterthwaite (1951). Not examined in this study. Age relation to other volcanic rocks unknown.

Tcb **Conglomerate and basalt (Miocene)**—Gray to brown conglomerate and sandstone and interlayered basalt in the valley of the Verde River south of Squaw Butte (Wrucke and Conway, 1987). The sedimentary deposits are equivalent to the younger conglomerate (Tyc) and the basalt is equivalent to the younger basalt (Tyb). Rests on younger conglomerate, silicious tuff (Tst), and older basalt (Toc). Maximum preserved thickness about 360 feet.

Tyb **Younger basalt (Miocene)**—Dark-gray to dark greenish-brown, massive to vesicular flows in the valley of the Verde (Wrucke and Conway, 1987). Consists mostly of olivine basalt but contains minor amounts of andesite. Vesicular basalt is common and generally is light- to medium-gray and deuterically altered. Olivine phenocrysts are ubiquitous but are mostly converted to iddingsite in the lighter-colored rocks. Pyroxene phenocrysts are rare. Red scoriaceous basaltic sands form rare but conspicuous interbeds. Commonly forms steep slopes and cliffs in which individual flows are fairly distinct. Separated from older basalt (Tob) by younger conglomerate (Tyc). Highest flow identified, several miles south of the study area, dated by K-Ar methods as 8.3±2.6 Ma (Wrucke and Conway, 1987). Maximum thickness about 330 feet.

Tyc **Younger conglomerate (Miocene)**—Weakly to moderately consolidated medium-gray pebble to cobble conglomerate along the valley of the Verde River (Wrucke and Conway, 1987). Clasts are 80-90 percent gray to black Tertiary olivine basalt, 0-5 percent red basalt scoria, 0-3 percent Tertiary volcanic rocks of intermediate composition, and locally 5-10 percent Proterozoic granite, granophyre, rhyolite quartzite and a few Paleozoic rocks. Most clasts are pebbles, but cobbles are common. The matrix is poorly sorted, fine- to coarse- grained, sandy volcanic debris. May contain basalt flows. Maximum thickness 750 feet south of study area (Wrucke and Conway, 1987) but probably less than 200 feet within study area.

Tvs **Volcanic sandstone (Miocene)**—Minor beds of mostly fine reworkd volcanic sands interbedded in Tob in far southwestern corner of map area.

Tob **Older basalt (Miocene)**—Light to dark-gray and dark-brown massive to vesicular flows of olivine basalt exposed from the Mazatzal Mountains west to the Verde River (Wrucke and Conway, 1987). Has abundant olivine phenocrysts mostly converted to iddingsite. Pyroxene phenocrysts are present in most flows and are abundant in some. Contains sparse bytownite phenocrysts and rare partly resorbed quartz phenocrysts. Calcite amygdules and veins abundant in upper parts of the unit. Has conspicuous subordinate interbeds of red-brown to yellow-brown scoriaceous basaltic debris containing crystals of green pyroxene. Unit may include andesitic rocks. Commonly forms gentle to steep slopes in which individual flows are difficult to identify.

K-Ar ages for this unit south of the study area range from 12.3 ± 0.8 Ma to 16.1 ± 0.15 Ma. Maximum thickness at least 1200 feet.

Toc **Older conglomerate (Eocene)**—Moderately consolidated cobble to pebble conglomerate and sandstone. Interlayered fine- to coarse-grained, thin- to medium-bedded sandstone containing lenses and beds of arkosic grit and fine pebbles forms as much as three-fourths of the unit. Clasts are principally of Proterozoic rocks, the main types being quartzite, rhyolite, granophyre, and granite. Clast types and proportions vary widely across the study area, depending on the source area which is generally to the south to southwest relative to a given locality. In Lion Spring graben area, clasts are primarily from Green Valley Hills Granophyre and Hells Gate Rhyolite to the southeast. Elsewhere clasts from quartzite of the Mazatzal Group and Payson Granite are common. In western exposures, there are also black rhyolite clasts from the New River Mountains. Locally there are also clasts of the Tapeats Sandstone, a distinctive trachyte porphyry (unit Tit), or other local distinct rock types from source areas. Deposited on irregular surface carved in Paleozoic and Proterozoic rocks. Thickness up to about 400 feet.

Unit includes 'red gravels' (Tgr, Gæaorama, 2003) of the Lion Springs graben area.

Occurs in areas east and north of Payson beneath the Diamond Rim, in the Buckhead Mesa/Pine Creek area, in the Limestone Hills, and in Fossil Creek. Also occurs north of the study area at various places north of the Mogollon Rim (Conway, 1990). These conglomerates are equivalent to the so-called 'rim gravels' of Cooley and Davidson (1963). The 'rim gravels' east of the study area between Young and Showlow were extensively studied by Potochnik (1989) who assigned to them the informal name Mogollon Rim formation. Two air-fall biotite tuff samples from the upper part of the Mogollon Rim formation yielded K-Ar ages of 37.6 ± 0.8 and 37.5 ± 0.8 Ma (Potochnik, 1989).

Tertiary Intrusive Rocks

Tis **Siliceous plugs and dikes (Miocene)**—Gray to tan and dark-brown, dacite to rhyodacite porphyry (Wrucke and Conway, 1987). The unit forms plugs into basalt (Tb) in western Hardscrabble Mesa and at Squaw Butte at southwestern edge of map area. Also forms dikes on the Ikes Backbone about 1.5 miles west of study area. Consists of plagioclase and subordinate hornblende and biotite plenocrysts in a matrix of devitrified glass and rarely of glass. Plagioclase phenocrysts are blocky euhedral to subhedral crystals and broken fragments of complexly twinned and, in some rocks, oscillatory zoned andesine and subordinate oligoclase. Plagioclase in a few rocks is spongy because of included myriad blebs of glass. Hornblende consists of brown prisms that locally enclose biotite, which also occurs separately as equant books. Hornblende and biotite exhibit varying stages of alteration. Accessory minerals are magnetite, apatite, and zircon. [Above petrographic description may not wholly apply; it was written to include plugs at Lion Mountain, many miles south of the study area.] Mostly massive but locally flow banded. As dated by the K-Ar method, the plug at Squaw butte is 8.9 ± 0.6 Ma (Wrucke and Conway, 1987).

Tib **Basalt plugs and dikes (Miocene)**—Basalt plugs, dikes, and sills. Sills and dikes in Tapeats Sandstone and Martin Formation in the western part of the Limestone Hills are greenish-black, fine-grained, olivine basalt comprising euhedral olivine in crystals as large as 1mm long in an intergranular matrix of calcic plagioclase, augite, and accessory biotite with late albite and zeolites concentrated in scattered pools 1-3 mm across (Conway and Wrucke, 1987). Sills and dikes intrude older basalt (Tob) south of the study area in the Mazatzal Wilderness (Wrucke and Conway, 1987). Occurs as plugs in Proterozoic gneissic granitoids (Xn) in northern Star Valley area and as a sill in Martin Formation on the eastern margin of Walnut Flat. Generally poorly exposed. Dike and sill width 2-30 feet.

Tit **Trachyte sill (Tertiary?)**—Brown, massive trachyte porphyry (Conway and Wrucke, 1987). Contains alkali feldspar phenocrysts 5-10 mm long in an aphanitic to phaneritic groundmass. Small vugs containing black and green alteration products common in the groundmass and particularly in the feldspar phenocrysts. Forms sill 600 feet thick in Tapeats Sandstone (Ct) in southwestern part of study area. Found only here and as dikes further south on the west side of the Verde River (Wrucke and Conway, 1987). This unusual and rare rock type is not demonstrably Tertiary. It could be as old as early Paleozoic. Presence of this distinctive rock type in older conglomerate (Toc) in the Fossil Creek area and in gravels atop the Mogollon Rim clearly reveals the provenance of the gravel as being south to southwest of depositional sites.

Paleozoic Sedimentary Rocks

Pk **Kaibab Formation (Lower Permian)**—Limestone, dolomite, and sandstone. Limestone and dolomite are yellowish-gray to light-gray, very fine- to fine-grained and locally sandy; commonly contain irregular nodules, about 1 in. across of reddish-brown and medium-gray chert. Fossils are sparse to common, in part silicified, in part as casts and molds, and consist mostly of whole and fragmented brachiopods, crinoid columnals, and fragments of sponges, bryozoans, and gastropods.

Sandstone is light-brown to pinkish-gray, calcareous, and spotted with limonite. Occurs at base of formation as a 2-foot-thick bed, and higher in section as thinner beds interlayered with dolomite and limestone. Stratification generally obscure because of bioturbation; composed of well-sorted, very fine to fine grains of subangular quartz and minor amounts of microcline, plagioclase, hornblende, and muscovite.

Formation weathers to a sandy residuum of chert and silicified fossils. Base, generally covered by colluvial chert, is a regional unconformity commonly having relief of less than 3 feet in 300 feet. Attains greatest thickness of about 350 feet in the north-central part of Pine quadrangle.

The Kaibab Formation is a shallow marine limestone commonly containing abundant shelly fossils.

Found only on top of Mogollon Rim and not closely examined in this study. Above description modified from Weisman and Weir (1990).

Pc **Coconino Sandstone (Lower Permian)**—Well-indurated sandstone, very light grayish-orange to pale-orange; generally weathers grayish orange. Composed mostly of very fine to fine grains of quartz and trace amounts of feldspar, chert, and mica; moderately well cemented by silica. In planar and more rarely in trough sets, commonly about 4 feet thick, of low- to high-angle crossbeds interstratified with a few thin horizontal beds. Rare straight, flat-topped ripple marks on crossbed surfaces. Wind-blown sand deposit having its origin as a vast sand sea (erg) in a Permian desert environment.

Steep cliff-forming unit at or near the top of the Mogollon Rim across the northern boundary of the study area and in upper parts of Fossil Creek canyon. Contact with underlying Supai Formation generally marked by a sharp break in slope; softer Supai Formation weathers to form a much gentler slope. At basal contact, for up to 100 feet, sandstone of Coconino is interlayered with silty redbeds of the Supai. Sharp break in slope mapped as the contact in this study.

Thickness ranges from about 1000 feet in northern parts (vicinity of Calf Pen Canyon) to as little as 800 feet in southern exposures. Coconino is entirely cut out on the pre-basalt erosional surface at the south end of Milk Ranch Point (Weisman and Weir, 1990).

Cliffs yield abundant debris of sandstone that commonly form a thick talus or colluvial cover on underlying formations beneath the steep cliffs of the Mogollon Rim or canyons that cut into the Rim. Locally, this material forms more distal fluvial gravel deposits, some of which are mapped as unit Qg.

Not examined closely in this study. Above description modified from Weisman and Weir (1990) and Weir and Beard (1997).

Supai Formation (Lower Permian and Upper Pennsylvanian)—In this report, all strata between the Coconino Sandstone and the Naco Formation belong to the Supai Formation. As a matter of practicality, for mapping purposes, this report divides the Supai into an upper member, the Fort Apache Member, and the lower member. This report follows the usage of Weisman and Weir (1990), Weir and Beard (1997), Ostrander (1950), and Satterthwaite (1951) which is similar to that of Huddle and Dobrovolny (1945).   Blakey (1990) proposed the name Schnebly Hill Formation which encompasses the upper member, the Fort Apache Member, and the upper part of the lower member of the Supai as mapped in this study.   We agree with Weir and Beard (1997) that: “Comparison of the units proposed by Blakey (1990, Fig. 2) with the units in this quadrangle (Strawberry 7.5’ quad) shows large differences.” The main difficulty would be to locate and map the base of the Schnebly Hill within the lower member. The lower member, as used in this study, is not amenable to division for mapping purposes; there is no readily discernible lithologic break to mark the base of the Schnebly Hill.   Though not a study of stratigraphy, the current mapping and structural work nevertheless suggests that some of the units of the Schnebly Hill, as proposed by Blakey (1990) are simply not readily mappable, if mappable at all, in the study area.   Likewise, the formational subdivisions of Peirce (1989) for his Supai Group do not lend themselves to mapping in the study area. Controversies of the Pennsylvanian-Permian stratigraphy of the region continue to the present and are beyond the scope of this study.

Overall, the Supai Formation is a classical Permian ‘red bed’ sequence.   It is composed almost entirely of highly oxidized fine-grained sediments that were deposited in a warm continental environment primarily by fluvial processes, but with intermittent and local marine and eolian conditions.

Supai Formation exposed continuously beneath the Mogollon Rim across the northern part of the study area from Promontory Butte on the east to the canyon of

Fossil Creek on the west. According to Ostrander (1950) and Satterthwaite (1951), the overall Supai Formation thins eastward from uppermost East Verde River area (~1900 feet) to the west side of Promontory Butte (~1400 feet). Thicknesses for members in the Strawberry-Pine-Fossil Creek area given below.

Descriptions below from field observations in this study and from modifications of Weisman and Weir (1990), Weir and Beard (1997), Ostrander (1950), and Satterthwaite (1951).

Ps **Supai, undivided (Permian)**—In fault slices within the Diamond Rim fault zone in Fossil Canyon. Could also include some Naco Formation.

Psu **Upper Member (Lower Permian)**—Siltstone, shale, sandstone, and minor limestone. Siltstone, shale, and sandstone are all reddish-brown, varying to brownish-gray and grayish-orange. Siltstone, shale, and sandstone are irregularly interbedded throughout. Siltstone and shale clayey to very fine sandy, in laminated to thin-bedded layers commonly 0.5 to 5 feet thick; form slopes. Sandstone very fine- to medium-grained, micaceous, well-cemented by calcite and iron oxides. Sandstone mostly in thin-bedded layers 1 to 10 feet thick, but near top of section includes layers with high-angle crossbeds similar to Coconino Sandstone; forms weak, discontinuous ledges.

Limestone in one or more thin (1-20 feet), discontinuous layers in the lower part of the section; rarely in the upper part of the section. Limestone constitutes perhaps 1-2% of the upper member. Locally a relatively continuous limestone ledge in lower part of unit is nearly half as thick as the Fort Apache Member. Light to medium tan or gray, fine-grained, and thin-bedded; locally ledge forming. Silicified mollusks and other fossils give a Leonardian (Early Permian) age (Weisman and Weir, 1990; Weir and Beard, 1997).

Thickness increases eastward from about 220 feet west of Strawberry in the vicinity of Nash Point to as much as 340 feet on Milk Ranch Point. Thickness not determined east of Milk Ranch Point.

Generally poorly exposed due to cover by colluvium and talus derived from overlying Coconino Sandstone.

Psuf **Upper member and Fort Apache Member (Lower Permian)**—These two members form one map unit where Fort Apache was not mapped in the current study – basically east of Pine Canyon. Fort Apache not mapped as a separate unit by previous workers.

Psf **Fort Apache Member (Lower Permian)**—Mostly limestone; medium to light tan to gray, locally silty to sandy, and micro- to fine-grained. Locally dolomitic. Wavy tabular beds 0.5 to 5 feet thick with pale red siltstone partings common between the beds. Kaolinite most abundant clay mineral; illite and mixed layer illite-smectite are common (Weisman, 1984).

Fossils in eastern Arizona (Winters, 1963, p. 15) and conodonts in central part of study area (Wardlaw cited by Peirce, 1989) yield early to middle Leonardian (early Permian) age. Ostrander (1950) reports scattered altered brachipods in northeastern part of study area.

Named by Stoyanow (1936) for section in the Fort Apache Indian Reservation more than 100 feet thick. Thins east to west across study area; about 60 feet on east margin and as little as 30 feet in far western parts. In Pine-Strawberry area typically 40-50 feet thick.

Forms striking 'white' intermittent cliffs on moderately steep reddish Supai slopes; largely covered with colluvium, especially on more gentle slopes.

Psl **Lower Member (Lower Permian and upper and middle Pennsylvanian)**—Siltstone, shale, sandstone, conglomerate, dolomite, limestone, and carbonaceous rocks. Siltstone, shale, and sandstone are red beds similar in character to clastic rocks in the upper member; occur irregularly interbedded throughout the lower member. Commonly calcareous.

Dolomite, mostly reddish brown, very fine-grained and locally silty, found in 1-foot discontinuous beds near top and base. Rare, tan to light-gray, 1-20-foot limestone beds found both high and low in the member across the study area. One such limestone bed mapped separately (Psll, see below). Limestones similar to that of Fort Apache Member.

Conglomerates composed of carbonate clasts near the bottom of section. In Pine area, conglomerates consist chiefly of clasts up to 8 inches of sandy limestone or limy siltstone in a matrix of similar composition; generally in lenses 1-15 feet thick, up to a hundred feet in length, with up to 7 lenses in vertical sequence (Weisman and Weir, 1990). Conglomerates layers less abundant in eastern part of study area. In vicinity of Kohls Ranch, single persistent 6-foot marker bed of conglomerate about 70 feet from base of section (Gæaorama, 1998). Ostrander (1950, p. 48) reported a basal conglomerate 6-32 feet thick.

Thin coaly beds and gray beds with plant fragments occur regionally, but sporadically, in the lower part of the lower member and are commonly associated with conglomerate (Peirce and others, 1977). Uranium and copper mineralization associated with these beds; largest uranium prospect in the region beneath Promontory Butte near Christopher Creek about 900 feet beneath the Fort Apache Member (Peirce and others, 1977; McGoon, 1962; Blazey, 1971). Satterthwaite (1951, p. 103) reported plant fragments in sandstones about 350 feet from base of section. Similar occurrence of carbonaceous siltstone and shale with coaly fragments and impressions of plant material and with uranium and copper minerals in southeast wall of Fossil Creek Canyon (Peirce and others, 1977; McGoon, 1962). Fossils late Pennsylvanian to early Permian in age (Peirce and others, 1977).

About 1120 feet thick on the rim of Fossil Creek canyon in vicinity of Nash Point. Thins eastward through Strawberry and Pine areas to about 950 feet in vicinity of Milk Ranch Point.

Lower member in the study area divided into two or three units by earlier workers doing stratigraphy; these units never actually mapped. Weir and Beard (1997) state that lower member in Strawberry quadrangle is naturally divisible into two parts, but cannot be mapped because of poor exposure and because of irregularly intergrading and intertonguing.

Psll **Limestone in lower member (Pennsylvanian)**—Buff limestone bed up to about 20 feet thick within lower member of Supai southwest of Pine. Caps ridge (named Limestone Point in this report) about 2 miles southwest of 'downtown' Pine and crops out along road from Pine to Hardscrabble Mesa. Key unit in determining direction and amount of displacement on Dripping Springs fault.

Pn **Naco Formation (Pennsylvanian)**—Limestone, dolomite, shale/mudstone, siltstone, sandstone, and conglomerate. Limestone much more abundant than dolomite; minor sandstone and conglomerate. Characterized by interbedding of primarily gray to light red-brown mudstone and siltstone with gray to reddish-gray commonly mottled limestone; detailed stratigraphy in vicinity of Kohls Ranch given in Gæaorama (1998). Also characterized by unusual and distinctive red-brown to orange chert in upper one-third to upper two-thirds of section, depending on locality. Chert occurs as scattered irregular nodules and lenses in limestone layers and as partial to complete replacement of shelly fossils in limestone layers. Two semi-continuous 1-5-foot layers of chert as lenses, nodules, and beads (resembling sandstones) in Kohls Ranch area (Gæaorama, 1998). Commonly contains one or more thin carbonate-clast conglomerate beds at (Gæaorama, 1998) or near (Satterthwaite, 1951) the base of the formation.

Generally highly fossiliferous, though Weisman and Weir (1990) found only a few broken ostracode tests and unidentifiable comminute shelly material in the Pine quadrangle. Fossils include foraminifers, brachiopods, crinoids, bryozoans, and sharks teeth. A gray shaly bed near Kohls Ranch contains abundant hard calciferous brachiopods, bryozoans, crinoids stems, and sharks teeth that weather out whole (Gæaorama, 1998). Brew (1965) determined from fusilinid forаmininfers that the Naco in central Arizona is Desmoinesian (late Middle Pennsylvanian) in age.

Contact with overlying Supai Formation in most places readily mapped within about 20 stratigraphic feet. In Kohls Ranch area, gray mudstone and limestone characteristic of Naco and red beds characteristic of Supai are interbedded over an interval of 20 to 40 feet (Gæaorama, 1998). Contact in this study mapped as being about midway in this transitional interval.

Ostrander (1950) and Satterthwaite (1951) report variable thicknesses for the Naco between 400 and 530 feet in the area between Promontory Butte and Dude Creek beneath the Mogollon Rim and each report gives one measured section. Gæaorama (1998), however, measured the section at only 250 feet in the Kohls Ranch area; relative thinness may be due to proximity to the Christopher Mountain paleohigh. According to Weismann and Weir (1990), thickness in the Pine quadrangle varies between 200 and 300 feet, but Weir and Beard (1997) give 360 feet for the thickness in the adjoining Strawberry quadrangle. From our mapping and cross-section construction in the Pine-Strawberry area, the thickness of the Naco and Redwall combined is quite constant between about 550 and 600 feet. We estimate thickness of the Naco in this area to range between about 300 and 450 feet, the variation due primarily to the relief on the Pre-Naco karsted surface. Thicknesses given by other workers, above, include terra rossa breccia beneath the formation; our thicknesses do not (see description of Redwall Limestone).

Naco formation distributed across the northern part of the area in lower slopes beneath the Mogollon Rim as far west as Pine. Exposed also in Fossil Creek canyon in the vicinity of Fossil Springs. Numerous springs there issue largely from a single horizon in the lowermost part of the Naco Formation.

Redwall Limestone (Mississippian)—Thick-bedded massive limestone in lower part of section; terra rossa breccia/conglomerate in upper part of section.

Terra rossa unit should, ideally, be a formation separate from either Naco or Redwall, in the manner of the Surprise Canyon Formation which lies between the Redwall and the Naco in the Grand Canyon (Billingsley and Beus, 1986; Beus, 1990). This unique unit in the Paleozoic section of the Mogollon Rim region formed as a result of terrestrial karstification during an approximately 30 million year period between the end of the deposition of the Redwall and the beginning of the deposition of the Naco

With the inclusion of the terra rossa/breccia in the Redwall, there is still considerable relief on the pre-Naco surface; inclusion of the terra rossa in the Naco would result in pronounced relief and mapping the contact would be a formidable task indeed. Terra rossa complex typically on the order of 10 to 40 feet thick; ranges up to about 150 feet; rarely, is missing. Total thickness of Redwall in Pine-Strawberry area from 100 feet to 300 feet, probably generally 200 to 250 feet. Redwall south of Pine laps out against paleohigh underlain by quartzite of the Mazatzal Group. Lower limestone 189 feet thick along Highway 87 from 3.7 to 11 miles north of the bridge over the East Verde River (Huddle and Dobrovolny,1952). Thickness from cross-section construction in Kohls Ranch area about 100 feet (Gæaorama (1998, Plate 2); as with Naco, thinness may be due to proximity to Christopher Mountain paleohigh. Laps out against this paleohigh on steep north slopes of Christopher Mountain.

Distributed in semi-continuous east-west belt between Christopher Creek and central Pine Creek, mostly north of Diamond Rim fault. Exposures in Buckhead Mesa area south of Diamond Rim fault. Small exposures in Fossil Creek on west side of Diamond Rim fault.

Mrt **Terra Rossa upper part of Redwall Limestone**—Thick section mapped separately, southwest corner of Buckhead Mesa (Conway, 1980). It is mappable in most places at 1:24,000 or larger scale, but such mapping was only done locally in this study and only shown on Buckhead Mesa.

Terra rossa breccia/conglomerate consists of generally angular fragments of limestone and chert in a matrix of red-brown locally formed clay-silt-sandstone detritus. Much of this highly oxidized detritus is residue from the solution and removal of probably hundreds of feet of limestone. In lower chaotic parts, limestone blocks are abundant; they decrease upward, giving way to chert and the terra rossa 'soil.' Uppermost parts become stratified and clasts become somewhat rounded clearly indicating fluvial activity on the karst surface. Commonly at the very top of the section, highly indurated chert pebble conglomerate beds are present. Chert-rich uppermost parts of terra rossa member locally mined for road metal. Many gravel pits along Control Road between Highway 260 and Highway 87.

Terra rossa/breccia genetically and lithologically distinct from either the underlying limestone of the Redwall or the overlying marine mudstones and limestones of the Naco. Some workers include the terra rossa in the Naco Formation; we include it in the Redwall for several reasons: 1) its fragments are derived entirely from the physical and chemical breakdown of the limestone, 2) terra rossa commonly grades down into less and less modified limestone, and 3) it is far easier to map the terra rossa as part of the Redwall than as part of the Naco.

Mr **Limestone lower part of Redwall Limestone**—Limestone light gray to rarely pinkish gray; upper parts commonly yellowish, particularly in association with terra rossa material, either the upper terra rossa member or irregular red sandy masses within the limestone. Yellow tints clearly distinguish Redwall from limestone of the Naco which is never yellowish. Limestone fine- to coarse-grained. Irregular chert nodules, more abundant in upper parts, are typically reddish- to dark-gray and commonly somewhat mottled; vary in color to brown and locally a yellow color similar to that of yellowed limestone. Irregular masses of dark red-brown unsorted siltstone/sandstone, locally common in upper parts, within limestone. These masses related to karsting processes wherein solutioning created openings (sometimes cavernous) into which fine terra rossa clastic particles fell. Sparse to locally concentrated fossils include horn corals, colonial corals, brachiopods, and fusulinid foraminifers. Latter indicate an Osagean (Early Mississippian) age (Skip, 1969, p. 179, 181). Outcrops near Pine quadrangle (Weisman and Weir, 1990) assigned to Mooney Falls Member of Redwall by McKee and Gutschick (1969).

Limestone locally cavernous. Hix (1978) describes 18” crevice in the Redwall on east side of the highway just south of Pine (from Morrison Maierle, 2003). Modern sinkholes several miles west of Kohls Ranch (Gæaorama,1998) where15-foot cavern discovered in borings for highway construction (Ken Ricker, RAM Associates, 1999, oral communication). Cavernous character important for groundwater considerations where below water table (Morrison Maierle, 2003).

Tan unsorted sandstone in basal parts where formation laps out against Pine Creek paleohigh; south margins of town of Pine and near highway just north of Buckhead Mesa and elsewhere. Thickness few feet to perhaps 30 feet.

As mentioned above, this map unit throughout most of the area also includes the terra rossa member, which ideally should be mapped separately.

Dm **Martin Formation (Upper and Middle? Devonian)**—Consists of upper Jerome and lower Beckers Butte members named by Teichert (1965) for type sections in Jerome and in Salt River Canyon. Both members widespread in central Arizona, including study area. Much variation in facies, particularly near Pine Creek and Christopher Mountain paleohighs. Entire formation laps out against the two paleohighs. Several of Teichert’s (1965) measured sections in the study area. The two members not mapped separately in this study, except that in some places the Beckers Butte Member is mapped with the Tapeats Sandstone (see below).

Jerome Member (Upper Devonian)—Dolomite, sandy dolomite, subordinate limestone and sandstone. Medium- to pinkish-gray, fine- to medium-grained, thin- to medium-bedded, commonly laminated dolomite and subordinate limestone. Sandy dolomite layers sparse to locally abundant; contain fine to coarse, clear to clouded quartz grains. Dolomitic sandstone also present locally. Brown thin-bedded limy dolomite beds (~25 feet) at or near base of unit emit petroliferous odor when broken. Gray to white chert nodules occur throughout the member and are particularly common in the lower half. Abundant bryozoans, corals and brachiopods locally in upper part of the member. Forms ledgy slopes, rarely cliffy.

Fairly consistent in character through middle parts of study area – roughly between Tonto Village on the east and Webber Creek on the west. West and east of this central area, section becomes much sandier (mostly sandy dolomites) approaching the Pine Creek and Christopher Mountain paleohighs. Brown unsorted sandstone common at base of section resting on Precambrian rocks of paleohighs, as with Redwall Limestone. Pronounced lithologic changes in section near Christopher Mountain paleohigh (Conway, 1980; Gæaorama, 1998). Lower half of section near Control Road turnoff from Highway 260 (Thompson Wash area) mostly sandstone with minor siltstone, mudstone, marly sandstone, dolomite and limestone; includes 85-foot-interval of medium-grained tan clean quartz sandstone (Gæaorama, 1998); lowermost fetid unit not recognized. Ostrander (1950) and Satterthwaite (1951) report that Martin in northeastern parts of study area is entirely limestone and that there are sinkholes in the area. These northeastern strata are certainly mostly dolomite and the existence of sinkholes is questionable. Extensive mapping of the Martin in the region (this study; Gæaorama, 1998, 2003; Wrucke and Conway, 1987) has revealed no sinkholes.

Jerome Member subdivided into three mappable sub-units on south slopes of Buckhead Mesa (Dml, Dmm, Dmu; Conway, 1980) and in Thompson Wash area (Gæaorama, 1998). But the units are different in these two areas, and in neither case do they correspond to Teichert's (1965) three units of the Jerome Member. Extensive facies changes, particularly near the paleohighs, and discontinuity of lenses would likely preclude continuous mapping of any subunits across the study area.

Beckers Butte Member (Upper and Middle? Devonian)—Lower parts mostly soft calcareous sandstone and minor sandy dolomite; minor local medium-gray aphanitic dolomite in uppermost parts. Commonly mottled pale red-purple to pale red, locally reddish brownish-orange; colorations distinctive and consistent. Sandstone is fine- to medium-grained, commonly containing 5-20 percent scattered rounded quartz grains 1-2 mm across. Bedding poorly expressed but generally thin locally emphasized by lenticular laminations of very coarse quartz grains and chert fragments. Pebble conglomerate (~8 feet) at base in Limestone Hills contains clasts of rhyolite, quartzite, and chert (Wrucke and Conway, 1989). Light-gray, medium-grained, well indurated sandstone as much as 1.2 m thick occurs at top of sandstone part of the member.

Beckers Butte poorly exposed slope forming unit 0 to 35 feet thick. Fairly persistent in thickness and character throughout much of central part of study area. Not recognized by Teichert (1965) or Gæaorama (1998) in Thompson Wash area.

Total thickness of Martin 350 to 190 feet in northeastern part of study area (Ostrander, 1950; Satterthwaite, 1951). At Thompson Wash Teichert (1965) measured 282 feet, in which he included Tapeats Sandstone, whereas, from detailed mapping and cross-section construction, Gæaorama (1998) measured 380 feet excluding 60 feet of Tapeats. At five places between Diamond Point and Tonto Natural Bridge Teichert measured 448, 437, 437, 467, and 389 feet; his Beckers Butte, which mistakenly included Tapeats Sandstone in the first four, measured 90, 84, 68, and 65 feet. At the fifth section, at Natural Bridge, the Tapeats and Beckers Butte are missing. Incomplete section in Limestone Hills up to about 200 feet. Martin in Pine-Strawberry area from limited drilling data may be about 300 feet thick (see cross-sections E-E' and B-B'). Thins to 0 feet against Pine Creek and Christopher Mountains paleohighs.

Martin Formation widespread in central to eastern parts of study area both north and south of Diamond Rim fault system. Intermittent exposures in Limestone Hills in southwestern part of study area.

Ct **Tapeats Sandstone (Middle? Cambrian)**—Generally reddish-purple to reddish-brown, coarse-grained, cross-stratified arkosic sandstone to granular and pebble conglomerate. Forms prominent cliffs and steep slopes.

Tapeats is basal formation of Tonto Group of Grand Canyon, extended into central Arizona as far south as Roosevelt Lake (Middleton, 1989). Teichert (1965) included the Tapeats of the study area in his Beckers Butte Member of the Martin, but Hereford (1977) demonstrated its equivalence to Tapeats northwest of the study area in the Pine Mountain and Black Hills areas.

Mapped unit in places includes Beckers Butte Member of Martin Formation with upper contact at change in slope from soft Beckers Butte to hard ledgy fetid dolomite. Together, Tapeats and Beckers Butte (both sandstones) make logical map unit given that Tapeats commonly forms single vertical cliff difficult to represent on a topographic map.

Basal resistant unit of Paleozoic section; deposited on generally very smoothly peneplaned Early Proterozoic rocks (about 1.7 Ga). Throughout most of area maintains fairly consistent thickness of 90 to 110 feet, but laps out against Pine Creek and Christopher Mountain paleohighs. Near paleohighs contains coarser sediment, notably one or more pebble-cobble conglomerate layers.

Section measured by R. Hereford (Wrucke and Conway, 1987) in central Limestone Hills: upper 12 feet white, coarse-grained, cross-bedded, arkosic sandstone containing scattered lenses of pebbles and cobbles of granite, argillite, and quartzite; next 51 feet reddish-purple, generally very coarse-grained, cross-bedded arkosic sandstone to fine-pebble conglomerate in beds 50-120 cm thick, commonly showing scour relations to one another; basal 33 feet reddish-purple granule to small-pebble conglomerate in beds 8 feet thick separated by thinner beds of very coarse-grained arkosic sandstone. Only the lower unit is preserved at most localities.

Sixty-foot section in Thompson Wash, from surface mapping and drill core (Gæaorama, 1998) divided into five units: basal conglomeratic arkose (0-10 feet); pebble-cobble conglomerate containing mostly quartzite of the Mazatzal Group (10-25 feet); coarse-grained arkosic sandstone characteristic of Tapeats regionally (~20 feet), dark red-brown siltstone (~20 feet); pebble-cobble conglomerate similar to lower conglomerate (~5 feet).

Crops out across central part of area from Thompson Wash on east to Webber Creek and Pine Creek on the west; also in Limestone Hills, southwestern part of study area. Locally caps broad mesas, with or without generally thin mantle of Martin Formation, e.g. on Houston Mesa north of Payson. Caps knobs south and southwest of Payson, remnants on early Tertiary erosional surface.

Ctc **Conglomerate member**—Pebble to cobble conglomerate and fine- to medium-grained, medium-bedded arkose; clasts from Proterozoic metamorphic and granitic rocks. Abundant iron oxides give red, brown and purple hues. Small exposures. Beneath Martin Formation north of East Verde River and west of Polles Mesa; beneath normal Tapeats in eastern Limestone Hills. Thickness up to 75 feet.

Middle Proterozoic Rocks

Yd **Diabase**—Small masses of gabbro that intrude intrude Payson Granite beneath the Diamond Rim. Distinctive ophitic texture suggests these bodies belong to the widespread diabase of the Southwest that intrudes as sills in the Apache Group (Shride, 1967) and as dikes in Proterozoic crystalline rocks (Conway and Gonzales, 1995).

Apache Group—Siltstone, conglomerate, and arkosic sandstone capping Christopher Mountain, far eastern part of the study area, mapped by Satterthwaite (1951) as lower Pioneer Shale, and the Barnes Conglomerate Member and Arkose member of the overlying Dripping Springs Quartzite. Total thickness perhaps on order of 200 feet.

From implications of publications (Gastil, 1958; Shride, 1967; Granger and Raup, 1964) following that of Satterthwaite (1951), it is questionable that Pioneer Shale and Barnes Conglomerate Member actually exist atop Christopher Mountain. Satterthwaite's mapping is nevertheless followed for the current map. Following general unit descriptions abbreviated from Shride (1967).

Dripping Springs Quartzite

Yad **Arkose middle member and/or siltstone upper member**—Arkose member: Thin- to thick-bedded massive-cropping arkose and feldspathic quartzite. Crossbedding characteristic but obscure. Siltstone member: Thin-parting feldspathic siltstone and subordinate quartzitic arkose.

Yab **Barnes Conglomerate Member**—Mainly quartzite pebbles in arkosic matrix.

Yap **Pioneer Shale**—Mostly grayish-red tuffaceous siltstone or silty mudstone.

Early or Middle Proterozoic Rocks

XYg **Granite**—Coarse-grained porphyritic granite in vicinity of ‘First Crossing’ on East Verde River (just north of Beaver Valley Estates). Potassium feldspar phenocrysts up to ~1 inch. Apparently massive and unfoliated. Presumably intrudes gneissic granitoids (Xn). Probably one of regional ~1.4-Ga granites with which it has lithologic affinity. Less likely is ~1.7-Ga granite. Nearest known granites of this character are Ruin Granite (Globe-Roosevelt Lake region) and Sunflower Granite (southern Mazatzal Mountains).

Early Proterozoic Rocks

Southern parts of the study area are underlain by representatives of several regionally important lithostratigraphic and lithodemic groupings (North American Commission of Stratigraphic Nomenclature, 1983) of Early Proterozoic rocks (Conway and Silver, 1989; Conway and others, 1987; Anderson, 1989; Karlstrom, 1991). These rocks are widely exposed in the overall Tonto Basin-Mazatzal Mountains (TBMM) region. [Tonto Basin in TBMM refers to the upper Tonto Creek drainage basin including the major tributaries Christopher Creek, Haigler Creek, Spring Creek, Green Valley Creek and Houston Creek.]

Strata of the Tonto Basin Supergroup rest unconformably on the East Verde River Formation (Wrucke and Conway, 1987; Conway, 1995). Intrusive rocks of the Diamond Rim Intrusive Suite are broadly coeval with strata of the central part of the Tonto Basin Supergroup; basically they are the hypabyssal equivalents of the rhyolites of the Red Rock Group (Conway, 1976; Conway and Silver, 1989). East Verde River Formation overlies the Gibson Creek Intrusive Suite (Dann, 1992, 1997; Conway, 1995). Mafic plutonic rocks and sheeted dikes of the Gibson Creek Intrusive Suite along with overlying pillow lavas at the base of the East Verde River Formation are interpreted by Dann (1992, 1997) and Dann and Bowring (1996) to be parts of their Payson ophiolite. The gneissic granitoids unit is undated and its physical relation to the other units remains uncertain except that it is intruded by Payson Granite of the Diamond Rim Intrusive Suite. Based on pervasive foliation gneissic granitoids is likely older than the only very weakly foliated Gibson Creek Intrusive Suite.

Early Proterozoic rocks of the region are generally metamorphosed in the greenschist facies but, with one exception, metamorphic terminology is not used in this report (i.e. rhyolite used instead of meta-rhyolite, etc.). The exception is the use of quartzite which has been historically used for metamorphosed quartz sandstone (meta-quartzite) of the Mazatzal Group, earlier formally known as Mazatzal Quartzite. Metamorphism is more readily detected in the mafic rocks, by the presence of epidote, chlorite, albite and secondary amphibole, than in the felsic rocks which are little changed mineralogically. Metamorphism is accompanied by weak to strong foliation in softer strata, but by little to no foliation in large massive resistant bodies of quartzite, rhyolite, and plutonic rocks.

Tonto Basin Supergroup—Volcanic and sedimentary strata approximately 1710-1700 Ma in the TBMM region (Conway and Silver, 1989; Silver and others, 1986; Conway, 1976; Wrucke and Conway, 1987). Sedimentary, volcaniclastic, and volcanic strata in lowermost Alder Group; mostly ash-flow rhyolite, but with minor mafic volcanics in middle Red Rock Group; mostly quartz arenite, but with minor shale and with a few rhyolite flows near the base in the Mazatzal Group.

Red Rock Group, up to 9,000 feet thick, *conformably* overlies a comparable thickness of the Alder Group in southern parts of the TBMM area. Northward, however, into the current study area, Alder Formation is missing or very thin (southwestern part of study area) and a relatively thin section of the Red Rock *unconformably* overlies the East Verde River Formation in the Limestone Hills and perhaps in the Pine Creek area, where there is also massive rhyolite beneath the unconformity. In the vicinity of North Peak, both the Alder Group and the Red Rock Group are missing and the Mazatzal Group rests unconformably on folded strata of the East Verde River Formation.

Mazatzal Group—Thick quartzite sequences with minor siltstone, shale and conglomerate underlying central parts of Pine Creek, Christopher Mountain, and North Peak area of the Mazatzal Mountains. Divided into Mazatzal Peak Quartzite, Maverick Shale, and Deadman Quartzite (Wilson, 1939; Anderson and Wirth, 1981; Wrucke and Conway, 1987;) in the Mazatzal Mountains; descriptions of these formations largely from Wrucke and Conway (1987). Uppermost Hopi Springs Shale (Doe and Karlstrom, 1991) occurs south of study area in the Mazatzal Mountains. Total thickness on the order of 3,500 feet.

Quartzite of the Mazatzal Group is quartz sandstone widely cemented with quartz and somewhat recrystallized metamorphically. Consisting almost entirely of quartz, this quartzite is by far the most resistant rock type in the study area. Prior to the deposition of Paleozoic formations, the Proterozoic rocks of the region were beveled by erosion to a smooth peneplain, the exception being that quartzite masses stood as erosional remnants, or monadnocks, on this plain. Such monadnocks stood at Pine Creek, at Christopher Mountain, and almost certainly at Mazatzal Mountains. Paleozoic strata, up through the Naco Formation, lapped out against these ancient monadnocks.

Mazatzal Peak Quartzite—Contains in descending order: White quartzite member and Red quartzite member

Xmpw **White quartzite member**—Light-gray or pinkish to white, commonly medium- to coarse-grained, locally gritty, crossbedded quartzite in beds generally 1.5-3 feet thick. Crops out in cliffs and steep slopes in high parts of the Mazatzal Mountains. Thickness up to 1,050 feet.

Xmpr **Red quartzite member**—Pale-brown to reddish-brown, fine- to coarse-grained quartzite commonly with a distinctive purplish hue. Beds planar to cross stratified, locally ripple marked, and are a few inches to 6 feet thick. Contains minor amount of interbedded red-brown, silty shale. Exposed in highest parts of the Mazatzal Mountains where it forms jagged cliffs and steep ledgy slopes. Thickness 600-1,000 feet.

Xmm **Maverick Shale**—Greenish-gray to reddish brown, silty and sandy shale and minor sandstone exposed on the flanks of North Peak. Shale consists of 25-40 percent quartz grains, 0.03-0.1 mm in size, in a matrix of very fine grained white mica and black to red-brown iron oxides in laminated, thin, hard, weakly fissile beds. Some beds ripple marked. Locally has weak cleavage. Sandstone in planar to cross-laminated beds 1-24 inches thick forms less than 5 percent of the unit. Thickness 390-750 feet.

Xmd **Deadman Quartzite**—Grayish red-purple to reddish-brown, fine- to medium-grained, crossbedded quartzite containing minor amounts of hematitic shale and argillaceous sandstone. Local basal conglomerate up to 20 feet thick (thickens to 300 feet at Cactus Ridge south of the study area) consists of angular and subangular pebbles, chiefly of red-brown rhyolite. Thickness in North Peak area up to about 200 feet.

Xmq **Quartzite, siltstone, conglomerate**—Rocks of the Mazatzal Group at Pine Creek and Christopher Mountain. Light to dark purplish red-brown, medium- to coarse-grained, and locally pebbly; in all essential characteristics similar to red quartzite of Mazatzal Peak or upper part of Deadman. Very minor silty, shaly, or conglomeratic beds; clasts in latter grit to small pebble size. Has thin interbedded rhyolite flow (Xrr) near base of section at Pine Creek; U-Pb zircon age same as for rhyolites of Red Rock Group (Silver and others, 1986; Conway and Silver, 1989).

Xms **Silty quartzite**—Reddish-brown to tan and grayish-green, thin-bedded, fine-grained sandstone, siltstone and minor shale as a single layer within lower part of quartzite (Xm) in Pine Creek area. Possibly equivalent to Maverick Shale, but much thinner and considerably different in facies. Thickness about 150 feet.

Xmc **Conglomerate**—Pebble to boulder conglomerate at base of Mazatzal Group in Pine Creek near Natural Bridge. Grades upward into lithic-rich sandstone which in turn grades into quartz sandstone of unit Xm. Consists entirely of rhyolite clasts probably derived from Red Rock Group. Equivalent to conglomerate at base of Deadman Quartzite.

Red Rock Group—Light to dark reddish-brown rhyolite ash-flow tuff, flows, tuff and breccia. From area to area contains variable, but generally very small, amounts of intermediate and mafic volcanic rocks, sandstone, shale and conglomerate. Clastic rocks are virtually all volcanogenic. Major exposures of Red Rock Group, containing formational subdivisions, are out of study area in central Mazatzal Mountains (Wilson, 1939; Ludwig, 1974; Wrucke and Conway, 1987) and in Tonto Basin (Gastil, 1958; Conway, 1976). Regional correlations are proposed for strata of the Red Rock Group in Conway and Silver (1989).

It is uncertain how proposed Red Rock strata (Wrucke and Conway, 1989) in the Limestone Hills (Xrab, Xry, Xra, and Xrh), southwestern part of the current study area, and at Pine Creek (Xrr) correlate with major Red Rock formations elsewhere. The Limestone Hills section has an unusually high proportion of mafic flows and an overwhelming amount of conglomerate. The units (Xrr, Xrm and Xrs) along Tonto Creek in the eastern part of the area are likely part of the Haigler Formation (Conway, 1976; Conway and Silver, 1989).

Xrr **Rhyolite**—Variable rhyolite and minor other volcanic and volcanogenic rocks. May include rhyolite flows, ash-flows, breccias and tuffs. Quartz, potassium feldspar, and albite occur as phenocrysts in varying amounts and sizes. Typically extensive oxidized. Locally has abundant lithophysae. Includes a thin (~50 feet) rhyolite ash flow in lower part of Mazatzal quartzite (Xm) at Pine Creek and a thin rhyolite section beneath this quartzite. Also includes rhyolite in fault slice in far eastern part of study area.

Xrm **Mafic volcanic rocks**—Small bodies associated with Xrr in far eastern part of study area.

Xrs **Sedimentary rocks**—Small exposure north of Kohls Ranch (Satterthwaite, 1951).

Following four units in Limestone Hills in stratigraphic order, top to bottom (descriptions from Wrucke and Conway, 1989). Probably part of Red Rock Group; less likely an up-section continuation of East Verde River Formation.

Xrab **Andesitic basalt**—Grayish-red and dark greenish-gray, porphyritic and nonporphyritic flows along East Verde River north of Limestone Hills. Consists of plagioclase laths (altered to albite) 0.1-0.4 mm long in a completely altered matrix of chlorite, calcite, iron oxides, and minor quartz. Porphyritic rocks have abundant euhedral plagioclase phenocrysts 1-2 mm long, commonly arranged in clusters. Has amygdules filled with chlorite, quartz, calcite, and epidote. Unconformable on rhyolite ash-flow tuff (Xry). Variable thickness up to 275 feet.

Xry **Rhyolite ash-flow tuff**—Welded ash-flow tuff exposed along the East Verde River north of Limestone Hills. Consists of massive to finely laminated tuffs. Locally has abundant lithophysae a few millimeters to a few centimeters in diameter. Interlayered with rhyolite and andesite unit (Xra) and hematitic rhyolite conglomerate (Xrh). Thickness about 450 feet.

Xra **Rhyolite and andesite**—Dark grayish-brown to very dark-gray andesite flows interlayered with lesser amounts of dark brownish-gray rhyolite ash-flow tuff. Andesite is aphanitic, largely metamorphic, intergrowth of albite, white mica, chlorite, quartz, and opaque iron oxides showing little original texture other than locally preserved fine groundmass plagioclase needles and sparse plagioclase phenocrysts (now partly sericitized albite) 3 mm or less in length. The interlayered tuffs are densely welded and closely resemble rocks in the overlying rhyolite ash-flow tuff (Xry). Thickness 80-110 feet.

Xrh **Hematitic rhyolite conglomerate**—Grayish-red, reddish-purple, and brownish-red conglomerate, lithic sandstone, siltstone, grit, and rhyolite. Conglomerate consists of subangular to rounded pebbles and sparse cobbles of rhyolite, argillite, and jasper in a hematite-rich matrix of lithic, commonly gritty sandstone composed of the same rock types as the pebbles. Beds many feet thick and poorly defined. Interlayered with thin to medium-thick beds of lithic sandstone in sequences as thick as 60 feet and with unmapped rhyolite of the rhyolite ash-flow tuff (Xry). Rests in apparent slight angular unconformity on upper graywacke unit (Xeug) of the East Verde River Formation. Thickness about 2000 feet.

Alder Group(?)—Sedimentary rocks in the far southwestern part of the study area which have lithologic affinity to strata of the Alder Group in the central Mazatzal Mountains.

Xaq **Quartzite**—Gray to tan, medium- to coarse- grained, crossbedded quartz sandstone and dark-gray to brown, medium-bedded lithic sandstone south of Squaw Butte. Probably part of Alder Group. Thickness about 900 feet.

Diamond Rim Intrusive Suite—Granite, granophyre, rhyolite and minor mafic rocks intruded at 1705-1695 Ma (Conway and Silver, 1989; Silver and others, 1986; Conway, 1976). Hypabyssal equivalents of overlying volcanics of the Red Rock Group formed in caldera ash-flow events. Generally leucocratic high-silica, high-alkali rocks of anorogenic character. In gently southeastward to southwestward dipping sheets between Payson and Christopher Mountain. This great sill complex intrusive into strata of Tonto Basin Supergroup and between the Supergroup and planar upper surface of gneissic granitoids unit (Xn). In sub-horizontal sheets between the northern Mazatzal Mountains and the Verde River in the southwestern part of the study area; sheets intrude East Verde River Formation at high angle to stratification.

Xdb **Bear Flat Alaskite**—Tan to reddish-brown, fine- to medium-grained, biotite alkali granite containing accessory opaque oxides, fluorite, and zircon. Biotite strongly to totally altered to hematite and muscovite; rare trace of amphibole in least altered parts. Feldspars albite and perthite (K-feldspar with exsolved albite lamellae). Locally porphyritic and micrographic along upper contacts. Forms sills along southern margins of the Payson Granite between the Green Valley Hills and Bear Flat in Tonto Creek and along Gibson Rim south of Payson. Occurs also as plugs in Payson Granite east of Payson. Intrudes Payson Granite, Green Valley Hills Granophyre, and Gibson Creek batholith (Conway, 1976).

Xdt **Tourmaline granite**—Biotite alkali granite similar to Bear Flat Alaskite (included in Bear Flat Alaskite by Conway and Silver, 1989) except for its widespread, locally abundant tourmaline pods and stringers and common pale pea-green color of albite.

Sheet intrusive into upper part of Payson Granite in vicinity of Mud Spring in Green Valley Creek.

Xdtp **Tourmaline-bearing porphyry**—Tan to white porphyritic rhyolite in dike 12 feet wide in upper Clover Creek, located on the south side of Limestone Hills (Wrucke and Conway, 1987). Has bursts and clots of black tourmaline and conspicuous 5-6-mm-long quartz phenocrysts. Broken into large float blocks north of Clover Creek.

Xdg **Green Valley Hills Granophyre**—Classical 'red-rock granophyre;' pervasively highly oxidized with almost all iron as hematite. Feldspars commonly brick red from hematite 'dust' throughout the crystals. Porphyritic, commonly miarolitic, and micrographic to spherulitic; in deeper bodies coarsens to granular texture. Phenocryst and groundmass sodic pyroxene and amphibole preserved only in rare gray or grayish-red rocks. Phenocrysts are resorbed quartz and mesoperthite which serve as substrate to micrographic or spherulitic domains of intergrown quartz and feldspar. Accessory minerals are fluorite, sphene, zircon, allanite(?), and garnet(?). Minor, mostly secondary minerals (from oxidation of rocks) are hematite, magnetite, muscovite, biotite, and rare albite. Secondary minerals commonly found in miarolitic cavities.

Commonly lies as irregular sills between Payson Granite or Bear Flat Alaskite and structurally overlying units, including Hells Gate Rhyolite and Gibson Creek batholith in Tonto Basin region (Conway, 1976) and East Verde River Formation in the northern Mazatzal Wilderness (Conway, 1995, p. 28). Sheets intrude Payson Granite and overlying units. Numerous plugs and irregular masses in Payson Granite (likely much more than mapped) between Star Valley and Green Valley Creek likely feeders to sills at roof of Payson Granite. Small mass near North Peak.

Consists of Mescal Ridge, Thompson Wash and King Ridge sills and aplite selvages in Tonto Basin, described below; shown as map unit Xdg where not subdivided. Not mapped separately in Mazatzal Wilderness, but included with Payson Granite as unit Xdpg.

Composite thickness of intrusive sheets a few hundred feet to as much as 6,000 feet.

Xdgt **Thompson Wash sill**—Granophyre sheet extending from Bear Mountain fault on east to McDonald Mountain fault on west (in eastern part of study area). Generally about 900 to 1,200 feet thick, but nearly pinches out on west end. Contains 5-10% 1-3 mm alkali feldspar phenocrysts and about 2% quartz phenocyrsts less an 1 mm. Intrudes both overlying King Ridge sill and underlying Mescal Ridge sill.

Xdgk **King Ridge sill**—Apparently bulbous sill on either side of Tonto Creek in King Ridge area in east-central part of study area; up to 3,000 feet thick. Consisting of granophyre in lower parts grading upward into spherulitic rhyolite in uppermost parts. Intrudes Salt Lick Canyon sill of Hells Gate Rhyolite; intrudes rhyolite of Red Rock Group. Two distinctive phenocryst generations of alkali feldspar, plagioclase, and quartz persist throughout the sill.

Xdgm **Mescal Ridge sill**—Granophyre sheet extending from Bear Mountain fault on east to Green Valley Creek fault on west; from 300 to 3,000 feet thick, generally around 1,800 feet. Intrudes Payson Granite. Intrudes Blue Dog Ridge sill of Hells Gate Rhyolite. Most coarse-grained phase of Green Valley Hills Granophyre; 5-10% each of 2-3 mm roundish quartz and alkali feldspar phenocrysts; micrographic texture coarsens with depth into sub-equigranular texture locally at base.

Xdga **Aplite phase**—Aplite selvages (small sheets) at upper contact of Mescal Ridge sill. Locally gradational into granophyre of Mescal Ridge sill; probably represents magma, without phenocrysts and micrograhic domains, differentiated from the Mescal Ridge granophyre.

Hells Gate Rhyolite—Intrusive rhyolite occupying a large area mostly between the Green Valley Hills and Tonto Creek in the southeastern part of the study area (Conway, 1976). Two closely related irregular sills, one with abundant mafic xenoliths, of generally massive, columnar jointed rhyolite porphyry. Both sills contain 10-15% phenocrysts of partially resorbed quartz (1-3 mm) and mesoperthitic alkali feldspar (2-4 mm) in approximately equal amounts. Pyroxene phenocrysts rarely preserved; usually altered to pseudomorphic clots of opaque minerals, chlorite(?), and calcite. Rocks oxidized and thereby reddened with ubiquitous hematite, but generally not as strongly as Green Valley Hills Granophyre.

Cumulative thicknesses from 1,500 feet to 7,500 feet, but highly irregular. Intruded complexly and semi-concordantly into Haigler Formation of the Red Rock Group and quartzite of the Mazatzal Group east and southeast of the study area (see cross-sections in Conway, 1976). Columnar joints pass continuously across contacts of the two phases, indicating the two sills probably cooled together.

Xdhb **Blue Dog Ridge sill**—Extensively contaminated sill with two kinds of mafic inclusions: 1) gabbro or diorite xenoliths rarely up to a foot in diameter, generally only an inch or two, and as small as clusters of several phagioclase and hornblende crystals, and 2) mafite porphyry (Conway, 1976) which is basically a fine-grained basaltic porphyry with plagioclase megacrysts up to 1.5 inches. Mafite porphyry xenoliths range in size from 0.5 inches to 3 feet. Intrudes overlying Salt Lick Canyon sill. Very fine-grained matrix (0.1-0.3 mm) in upper parts, but coarsens in lower parts to 0.3 mm and becomes micrographic to vermicular near lower contacts.

Xdhs **Salt Lick Canyon sill**—Generally uncontaminated to locally only slightly contaminated sill. Uppermost and thinnest of the two sills; complexly intruded into extrusive rhyolite of the Red Rock Group. Weakly flow-banded near uppermost margins. Contaminated parts contain xenoliths up to a foot in length of mafite porphyry as described above under Blue Dog Ridge sill; plagioclase megacrysts very rare. Inclusions are commonly platy to swirled; they may represent small amounts of mafic magma mixed into the rhyolitic magma.

Xdrp **Rhyolite porphyry**—Red-brown massive to rarely flow-foliated rhyolite porphyry in vicinity of Natural Bridge in Pine Creek. Quartz, plagioclase, and K-feldspar phenocrysts and very fine-grained mafic clots, all about 3-8 mm in size, total 25-35% percent of the rock. Western exposures along Pine Creek where overlain by rhyolite (Xrr) of Red Rock Group extensively altered. Relatively unaltered and weakly columnar jointed in eastern exposures on south slope of Buckhead Mesa. Possibly intrusive into siltstone of upper graywacke (Xeug) of East Verde River Formation. Includes dike on northeast part of Buckhead Mesa immediately north of Diamond Rim fault.

Xdp **Payson Granite**—Reddish-brown to tan, medium- to coarse-grained, hypidiomorphic granular alkali biotite-amphibole granite widespread between Payson and Kohls Ranch areas (Conway, 1976; Southwest Ground-water Consultants, 1998). Constitutes a gently (10° to 30°) southward-dipping mega-sill; upper southern contacts described by Conway (1976); northern basal contact, between lower Mayfield Canyon and southern Houston Mesa, described by Southwest Ground-water Consultants (1998) and Gæaorama (2003). Sill about 5,000 feet thick between Gibson Rim and Star Valley; could be two to three times thicker in areas eastward.

Superficially homogeneous, but with subtle changes from base to roof (Conway, 1976). Uppermost leucocratic parts, similar to Bear Flat Alaskite, are biotite alkali granite in which biotite is commonly altered to hematite and muscovite. Amphibole (probably ferrohastingsite) in trace amounts in upper parts and increasing to several percent in lower parts. Plagioclase/K-feldspar ratio increases with depth in the body and plagioclase (albite to sodic oligoclase in upper parts) becomes more calcic (intermediate oligoclase in lower parts). K-feldspar in upper parts usually coarsely perthitic microcline; at depth is clear, weakly exsolved orthoclase with rims of coarsely exsolved microcline or orthoclase. Uppermost parts extensively altered deuterically and/or hydrothermally.

Slightly to well developed rapakivi texture (plagioclase mantling K-feldspar) pervasive in middle to lower parts; absent in uppermost parts. Textural variants in uppermost parts: seriate porphyritic, porphyritic, miarolitic, rare micrographic.

Deeply weathered mechanically; very little weathered chemically. Common loose mantle (grus) of mostly quartz and alkali feldspar crystals with very little clay. Generally poorly exposed in areas of little relief. Local bold bedrock in drainages and on steep slopes; good rocky exposures in southeastern parts of area in deeply incised tributaries to Tonto Creek. Unweathered, really hard, hammer-ringing rock extremely rare.

Three major lithologic types within the Payson Granite: 1) Granophyre plugs and irregular bodies. Discussed above under Green Valley Hills Granophyre. 2) Irregular masses of leucocratic granite virtually free of mafic minerals and plagioclase; form resistant ridges and knobs. Relatively small masses generally in upper parts of the mega-sill. Probably a late highly differentiated, cross-cutting phase of the Payson Granite. Not mapped separately. 3) Variable generally dark masses of mostly intermediate to mafic plutonic rocks and very minor metamorphosed strata; commonly foliated. Found mostly in lower parts of mega-sill. Interpreted as screens (large inclusions) incorporated from gneissic granitoids unit (Xn); a few masses mapped immediately south of Diamond Point.

Sparse dikes of Payson Granite (a few mapped) intrude gneissic granitoids unit (Xn). Texturally variable felsic dikes (unmapped) above the megasill in the Gibson Creek batholith (Xgc) are likely from Payson Granite and from Green Valley Hills Granophyre.

Texturally homogeneous; foliated (or brecciated) only in near vicinity of major Proterozoic faults (e.g. Green Valley Hills fault; Agate Mountain thrust fault) and along base where foliation is parallel to sub-planar contact with gneissic granitoids unit (Xn). In both cases foliation is due to shearing related to fault movement (Conway, 1976; Gæaorama, 2003).

Xdpq **Pegmatite and/or quartz vein**—Small masses on far eastern Diamond Rim just west of Thompson Wash (Satterthwaite, 1951). Probably related to Payson Granite or to post-granite faulting.

Xdpg **Payson Granite and Green Valley Hills Granophyre**—Widespread granite and less abundant granophyre in northern part of Mazatzal Wilderness south of the East Verde River (Wrucke and Conway, 1987). Lithologically similar to Payson Granite and Green Valley Hills Granophyre in central to eastern part of study area. Granophyre occurs as one or more sheets lying structurally above the granite; sub-horizontal contacts particularly well-exposed in Wet Bottom Creek (Wrucke and Conway, 1987). Structural relation entirely analogous to the sill-above-sill-relationship in the area east of Payson.

Xddg **Diorite and gabbro (Early Proterozoic)**—Brownish-green to gray, fine- to coarse-grained, massive hornblende diorite and pyroxene-hornblende gabbro in vicinity of Limestone Hills and Squaw Butte, southwestern part of study area. Gabbro locally has igneous laminations. Intrudes East Verde River Formation and rocks as young as hematitic rhyolite conglomerate (Xrh) of Tonto Basin Supergroup.

Xds **Syenite**—Massive intrusive rock in Limestone Hills similar to associated diorite and gabbro in overall character, but with much more abundant K-feldspar.

East Verde River Formation—Very thick section (minimum 25,000 feet) of lower mafic volcanic rocks, central thin sequence of siltstone/shale and rhyodacite/jasper, and upper classical turbidite graywacke (Wrucke and Conway, 1987; Conway and others, 1987). Section appears to be entirely submarine. Group status warranted because of great thickness and lithologic variability, but would require more work to define constituent formations and their type sections.

Entire west-dipping and mostly west-facing sequence exposed between North Peak and the western Limestone Hills; central to lower parts of sequence exposed also on slopes of Buckhead Mesa/Crackerjack Mesa and locally northeastward into south slopes of the Diamond Rim in the vicinity of Webber Creek and eastward.

Tuff beds in lower part of graywacke section dated by U-Pb zircon methods at about 1710 Ma (Dann, 1997; Dann and others, 1989).

Xeug **Upper graywacke**—Gray to maroon, unfoliated, thin- to thick- bedded, fine-to coarse-grained graywacke, maroon siltstone, and conglomerate on south side of East Verde River. Graded graywacke beds contain more quartz than lower graywacke unit (Xelg). Siltstone is similar to siltstone units (Xeus and Xels). Conglomerate near the top of the unit contains dacite pebbles, cobbles, and boulders. Thickness about 3,500 feet.

Xeus **Upper Siltstone—**Dark bluish-gray, thin-bedded siltstone and minor sandstone. Thickness about 200 feet.

Xec **Conglomerate**—Gray to green, unfoliated, granule to boulder conglomerate, breccia, and gray to tan graywacke and siltstone. Conglomerate clasts are mostly graywacke but also consist of jasper and various types of volcanic rocks. Many breccia beds are composed only of chaotic ripped-up clasts of graywacke of all Bouma cycle lithologies. Tan graywacke is richer in quartz and felsic volcanic material than gray graywacke. Thickness about 1,900 feet.

Xels **Lower siltstone**—Dark bluish-gray, thin-bedded siltstone and subordinate sandstone. Siltstone similar to fine-grained tops of graded sequences in graywacke units (Xeug and Xelg). Unit incompletely studied and may be more heterogeneous then described. Thickness about 2,600 feet.

Xelg **Lower graywacke**—Bluish–gray to maroon and brown graywacke, siltstone, and pebble conglomerate exposed in Bull Spring Mesa area on south slopes of East Verde River canyon and on northern and eastern slopes of North Peak. Thin- to thick-bedded and massive. Unfoliated to weakly foliated. Bluish-gray graywacke predominates. Reddish-brown rocks occur mostly at base of the unit. Consists of innumerable turbidite graded-bed cycles from a few inches up to about ten feet thick. Graded beds range from pebble to medium-grained sandstone at the base and from fine-grained sandstone to siltstone at the top. Coarse basal portions of beds commonly contain ripped-up, dark-gray siltstone fragments from the top of the underlying bed. Graywacke usually consists of 10-15 percent quartz, 30-60 percent clouded sericitized plagioclase, and 10-50 percent lithic clasts. Lithic clasts are graywacke, jasper, and felsic to mafic volcanic rocks. Groundmass minerals are quartz, feldspar, sericite, magnetite, hematite, epidote, chlorite, blue-green amphibole, and rare zircon. Sericite, epidote, chlorite, and amphibole are metamorphic minerals. Mafic clasts are difficult to identify because of metamorphic modification. Thickness about 8000 feet.

Xes **Siltstone and shale**—Red, maroon, tan, and green thin-bedded siltstone and shale and minor thin, resistant beds of fine-to medium-grained green to tan basaltic to rhyodacitic tuff and tuffaceous quartz-bearing sandstone. Small-scale, low-angle crossbeds occur in some siltstone beds. Sparse graded beds occur in silty to sandy layers. Main exposures in lower City Creek and vicinity approximately equivalent to City Creek series of Wilson (1939); here and in Buckhead Canyon area thickness as much as 600 feet. Much thinner section (~70 feet) south of East Verde River in Houston Creek-Bullfrog Canyon area.

Xerj **Rhyodacite and jasper**—Gray to greenish-gray rhyodacite or dacite pumice breccia and massive to laminated jasper in same exposure areas as given above for Xes but also on lower eastern slopes of North Peak area. Has slightly flattened and irregularly oriented pumice clasts of granule to cobble size. Jasper lenses as much as 60 feet thick. At City Creek unit also has massive brown rhyolite or rhyodacite flows(?) that contain elongate quartz amygdules, interlayered conglomerate, and brown to maroon siltstone. Felsic volcanic rocks all contain plagioclase phenocrysts; no quartz phenocrysts identified. Clasts in the conglomerate are of amygdaloidal and pumice breccia rocks of the unit. Forms distinctive marker unit in the East Verde River Formation. Thickness from about 75 to 500 feet.

Xem **Mafic volcanic rocks**—Andesite and basalt flows, pyroclastics, and epiclastics and felsic volcanic and sedimentary rocks. Mafic volcanic rocks are mostly green to greenish-brown and consist of pillow flows, massive amygdaloidal flows, agglomerate, breccia, conglomerate, and volcanic sandstone and graywacke. Andesite containing abundant plagioclase and or pyroxene phenocrysts probably more abundant than basalt. Jasper common as lenses and irregular masses in the flows and as clasts in the clastic rocks. Light greenish-gray, massive andesite or dacite containing completely sericitized plagioclase phenocrysts and a percent of two each of quartz and clinopyroxene phenocrysts crops out extensively in lower Boardinghouse Canyon. Unit includes rare tan to gray or green rhyolite to dacite tuffs. Gray to green, thin-bedded siliceous shale and shaly chert locally interbedded with mafic detrital rocks. Flows probably constitute less than one-half of the unit. Much of the unit is massive and poorly bedded. Finer detrital material commonly well bedded and contains internal sedimentary structures. Primary textures are moderately well preserved in the mafic rocks, but in general only the greenschist facies minerals albite, chlorite, epidote, actinolite-tremolite, sericite, calcite, and magnetite are present. Generally unfoliated except near major faults. Variations in attitude suggest the presence of folds in the large mass west of City Creek.

Thickness uncertain but may be from 10,000 to 20,000 feet.

Main exposures on eastern and northern lower slopes of the North Peak area, including area west of confluence of Pine Creek and East Verde River, thence westward on south slopes of East Verde River canyon to Bullfrog Canyon. Widely exposed also on south slopes of Crackerjack Mesa, immediately north of Buckhead Mesa, and in area between confluence of Shannon Gulch with Webber Creek and Hells Half Acre.

Descriptions above from Wrucke and Conway (1987) for exposures in the northern Mazatzal Mountains-East Verde River area, but likely have general application to the northerly exposures where reconnaissance mapping was done for this study.

Lowermost exposures of mafic section (Xem) on east flank of the northern Mazatzal Mountains found by Dann (1992, 1997) to consist almost entirely of sheeted dikes perpendicular to layering of mafic strata. These dikes, also present eastward into plutons of the Gibson Creek Intrusive Suite, are key to Dann's definition of the Payson ophiolite.

Xeft **Felsic tuff**—Light-tan to olive-gray sequence of incompletely mapped felsic tuff within the mafic volcanics (Xem) about 3 miles northwest of North Peak. With or without sparse 0.1-0.6-mm quartz and plagioclase phenocrysts in weakly laminated aggregate of shards recrystallized to very fine-grained mass of white mica, quartz, and feldspar. Thickness about 300 feet.

Gibson Creek Intrusive Suite and Gneissic Granitoids—Mafic plutonic complex south and southwest of Payson comprises the Gibson Creek Intrusive Suite, a name here used to replace Gibson Creek batholith (Conway and others, 1987). Batholith may not be appropriate name for this plutonic complex for two reasons: 1) According to Dann's (1992, 1997) ophiolite model, the Gibson Creek may be part of an arc-rift complex; batholiths are generally huge plutonic complexes emplaced in continental crust, commonly above subduction zones. 2) The Gibson Creek has a very small exposure area (<80 square miles) compared to typically huge batholithic terrains (e.g. Sierra Nevada batholith, Idaho batholith).

U-Pb zircon ages of the Gibson Creek range from about 1710 to 1735 Ma (Dann and others, 1989, 1993, 1996; Conway and others, 1987).

The various phases of Gibson Creek combined with the lower mafic volcanic section of the East Verde River Formation constitute the Payson ophiolite (Dann, 1991, 1992, 1997).

Gneissic granitoids an interim informal name for a distinct body of rocks found between Town of Payson and Diamond Rim. May correlate with screens of granitic rocks and strata found within the Gibson Creek Intrusive Suite. Granite of the screens dated at 1751 ± 3 Ma (Dann and others, 1989).

The Gibson Creek and gneissic granitoids units only briefly described in this report, compared with other map units. Gibson Creek contains a number of map units (Dann, 1992) which could be added to the map and descriptions for these units derived from Dann's thesis and publications. Much additional work would be required to properly describe the various units within the gneissic granitoid unit and to make comparisons and possible correlations with screens of granitoids and metamorphic rock mapped by Dann (1992) within the Gibson Creek Intrusive Suite.

Xgc **Gibson Creek Intrusive Suite**—Mostly mafic plutonic rocks and sheeted dikes studied extensively by Dann (1991, 1992, 1997), Dann and Bowring (1996), and Dann and others (1989, 1993). Lowermost parts layered pyroxene gabbro and hornblende gabbro and diorite in general area between Payson and Oxbow Hill (Conway, 1976). Diorite and granophyric tonalite present in uppermost parts between lower Oxbow Hill and East Verde River 4-5 miles west of Payson. Central to uppermost parts cut by west- to northwest-striking dikes which westward become mutually intrusive sheeted dikes overlain orthogonally by mafic volcanics of the East Verde River Formation on the east flank of the Mazatzal Mountains. Dikes of highly variable intermediate to mafic composition. Dikes cut by a late gabbro body.

Contains numerous distinct intrusive bodies. Slightly to locally moderately foliated. Contains extensive veins, many in fault zones, of quartz, epidote and local gold-bearing sulfide minerals. Structurally overlies Payson Granite and is intruded by the Payson Granite. Locally contains granite/granophyre dikes probably derived from the Payson Granite or Green Valley Hills Granophyre.

Gibson Creek rocks mapped by Southwest Ground-water Consultants (1997, 1998) but not subdivided for mapping purposes. Additional general descriptions in these reports.

Xgg **Granodiorite**—Sphene-bearing weakly foliated granodiorite along the East Verde River between East Verde Park and Crackerjack Mine area. May or may not be properly included with the Gibson Creek Intrusive Suite. Dated by L. T. Silver at 1709 Ma (Conway and others, 1987).

Xn **Gneissic granitoids**—Primarily granodiorite, but also granite, diorite, and minor gabbro with probably small amounts of stratified rock. Pervasive weak to strong foliation; foliation locally strongly contorted. Gneissic in many places; augen gneiss present. Intruded by small sheets and plugs of Payson Granite mostly near the contact with Payson Granite. Generally deeply weathered and poorly exposed.

Crops out in a belt bounded by Diamond Rim and the Diamond Rim fault (Gæaorama, 2003); also north of Star Valley between Payson Granite and Houston Mesa/Walnut Flat (Southwest Ground-water Consultants, 1998;Gæaorama, 1999). Additional descriptive material in these reports.

May be equivalent to small pendants/screens of granitoids and stratified rocks within Gibson Creek Intrusive Suite. These stratified rocks, consisting primarily of intermediate to felsic volcanics and volcaniclastics, given the name Larson Spring Formation by Dann (1992).

Following two units small bodies within gneissic granitoids 0.5-1 mile east of Beaver Valley Estates (Gæaorama, 2003).

Xnl **Leucogranite**—Small mass of boldly cropping leucogranite.

Xnd **Diorite**—Small mass of melanocratic diorite and granodiorite

Xpe **Pendant**—Small pendant of volcanic and volcaniclastic rocks within Gibson Creek Intrusive Suite near Gisela, south-central part of map area (Conway, 1976). Dann (1997) includes these strata in his Larson Spring Formation.

REFERENCES CITED

Anderson, P., 1989, Stratigraphic framework, volcanic-plutonic evolution, and vertical deformation of the Proterozoic volcanic belts of central Arizona, *in* Jenny, J. P., and Reynolds, S. J., eds., Geologic Evolution of Arizona: Arizona Geological Society Digest 17, p. 57-147.

Anderson, P., and Wirth, K. R., 1981, Uranium potential in Precambrian conglomerates of the central Arizona arch, Final Report: U.S. Department of Energy Open-File Report GJBX-33(81), 122 p.

Beus, S. S., 1989, Devonian and Mississippian geology of Arizona, *in* Jenney, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological society Digest 17, p. 287-311.

Beus, S. S., 1990, Redwall Limestone and Surprise Canyon Formation, *in* Beus, S. S., and Morales, Michael, eds. Grand Canyon Geology: Oxford and New York, Oxford and University Press, and Flagstaff, Museum of Northern Arizona Press, p. 119-145.

Billingsley, G. H., and Beus, S. S., 1986, The Surprise Canyon Formation—an Upper Mississippian and Lower Pennsylvanian(?) rock unit in the Grand Canyon of Arizona: U.S. Geological Survey Bulletin 1605-A, p. 27-33.

Bills, D. J., Truini, M., Flynn, M. E., Pierce, H. E., Catchings, R. D., and Rymer, M. J., 2000, Hydrogeology of the regional aquifer near Flagstaff, Arizona, 1994-1997: U.S. Geological Survey Water-Resources Investigations Report 00-4122, 103 p., 4 map plates.

Blakey, R. C., 1990, Stratigraphy and geologic history of Pennsylvanian and Permian rocks, Mogollon Rim region, central Arizona and vicinity: Geological Society of America Bulletin, v. 102, p. 1189-1217.

Blazey, E. B., 1971, Fossil flora of the Mogollon Rim, Arizona State University, Ph.D. thesis, 169 p.

Brew, D. C., 1965, Stratigraphy of the Naco Formation (Pennsylvanian) in central Arizona: Ithaca, New York, Cornell University, Ph.D. thesis, 201 p.

Cooley, M. E., and Davidson, E. S., 1963, The Mogollon highlands—their influence on Mesozoic and Cenozoic erosion and sedimentation: Arizona Geological Society Digest, v. 6, p. 7-35.

Conway, C. M., 1976, Petrology, structure, and evolution of a Precambrian volcanic and plutonic complex, Tonto Basin, Gila County, Arizona: Pasadena, California Institute of Technology, Ph.D. thesis, 460 p.

Conway, C. M., 1980, Unpublished geologic mapping, vicinity of Camp Tontozona (Kohls Ranch) and vicinity of Tonto Natural Bridge: Mapping done for Arizona State University Geology Department in connection with teaching Summer Field Camp, scale 1:24,000.

Conway, C. M., 1990, Provenance of Mesozoic and Tertiary conglomerates in the Mogollon Rim and Little Colorado River region: Flagstaff, Museum of Northern Arizona, Abstracts of the Symposium on Southwestern Geology and Paleontology, 1990, p. 4.

Conway, C. M., 1995, An overview of Proterozoic metallogenesis in southwestern North America, *in* Metallogeny of Proterozoic Basins, Mineral Deposits Research Unit Short Course 19: Vancouver, University of British Columbia, 48 p.

Conway, C. M., and Gonzales, D. M., 1995, Grenvillian tectonic setting of the 1.1-Ga diabase province in the southwestern United States, *in* Leon T. Silver 70th Birthday Symposium and Celebration: Pasadena, California Institute of Technology, p. 185-190.

Conway, C. M., and Silver, L. T., 1989, Early Proterozoic rocks (1710-1615-Ma) in central to southeastern Arizona, *in* Jenny, J. P., and Reynolds, S. J., eds., Geologic Evolution of Arizona: Arizona Geological Society Digest 17, p. 165-186.

Conway, C. M., Karlstrom, K. E., Wrucke, C. T., and Silver, L. T., 1987, Tectonic and magmatic contrasts across a two-province boundary in central Arizona, *in* Davis, G. H., and VandenDolder, E. M., eds., Geologic diversity of Arizona and its margins: Excursions to choice areas (Field-trip guidebook, 100th annual meeting, Geological Society of America): Arizona Bureau of Geology and Mineral Technology Special Paper 5, p. 158-175.

Corkhill, F., 2000, Report on the drilling of an exploratory borehole near Strawberry, Arizona (May 18-June 2, 2000)—A hydrogeologic investigation for the Northern Gila County Water Plan Alliance: Arizona Department of Water Resources, Hydrology Division, unpubished report (August 9, 2000), 33 p.

Dann, J. C., 1991, Early Proterozoic ophiolite, central Arizona: Geology, v. 19, p. 590-593.

Dann, J. C., 1992, Origin and emplacement of the Early Proterozoic Payson ophiolite, central Arizona: St. Louis, Washington University, Ph.D. thesis, 340 p.

Dann, J. C., 1997, Pseudostratigraphy and origin of the Early Proterozoic Payson ophiolite, central Arizona: Geological Society of America Bulletin, v. 109, p. 347-365.

Dann, J. C., Chamberlain, K. R., and Bowring, S. A., 1989, An Early Proterozoic ophiolite, central Arizona: U-Pb constraints on its structure and development: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A23.

Dann, J. C., Bowring, S. A., and Coleman, D. S., 1993, Geochronologic, isotopic, and structural constraints on the evolution of an Early Proterozoic intra-arc basin, central Arizona: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 237.

Dann, J. C., and Bowring, S. A., 1996, The Early Proterozoic Payson ophiolite and the Yavapai-Mazatzal orogenic belt, central Arizona, *in* de Wit, M. J., and Ashwall, L., eds., Greenstone belts: Oxford, United Kingdom, Oxford Monograph on Geology and Geophysics, No. 35, p. 781-790.

Doe, M. F., and Karlstrom, K. E., 1991, Structural geology of an Early Proterozoic foreland thrust belt, Mazatzal Mountains, Arizona, *in* Karlstrom, K. E., ed., Proterozoic geology and ore deposits of Arizona: Arizona Geological Society Digest 19, p. 181-192.

Feth, J. H., and Hem, J. D., 1962, Springs along the Mogollon Rim in Arizona: New Mexico Geological Society Thirteenth Field Conference, p. 129-134.

Gæaorama, 1998, Geologic mapping of the Kohls Ranch segment, ADOT realignment of Highway 260—Final report on the geology of map sheets 1-5: Flagstaff, Arizona, Gæaorama, Inc., report to Ricker, Atkinson, McBee and Associates, 10 June 1998, 37 p., appendices, 5 map plates scale 1:2,400 (1" = 200').

Gæaorama, 1999, Preliminary report on the structural geology and groundwater potential of the north Payson Area: Flagstaff, Arizona, Gæaorama, Inc., report to Town of Payson, 24 March 1999, 6 pages, map plate 1:24,000.

Gæaorama, 2003, Structural geology and groundwater potential, Diamond Rim study area, Gila County, Arizona: Blanding, Utah, Gæaorama, Inc., report to Town of Payson, 1 August 2003, 47 pages, 1 map plate scale 1:24,000.

Gastil, R. G., 1958, Older Precambrian rocks of the Diamond Butte quadrangle, Gila County, Arizona: Geological Society of America Bulletin, v. 69, p. 1495-1514.

Granger, H. C., and Raup, R. B., 1964, Stratigraphy of the Dripping Spring Quartzite, southeastern Arizona: U.S. Geological Survey Bulletin 1168, 119 p.

Hart, R. J., Ward, J. J., Bills, D. J., and Flynn, M. E., 2002, Generalized hydrogeology and ground-water budget for the C aquifer, Little Colorado River Basin and parts of the Verde and Salt River Basins, Arizona and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 02-4026, 47 p.,

Highland Water Resources Consulting Inc., 2005, Hydrogeological study for the demonstration of an adequate water suply for Strawberry Hollow, Pine, Arizona: Payson, Arizona, Highland Water Resources Consulting Inc., report to Strawberry Hollow Domestic Water Improvement District, pages, plates?

Hix, G. L., 1978, A hydrogeologic investigation of the Pine-Strawberry area, Arizona: G. L., Hix, Consulting geologist, report to E & R Water Company under the supervision of John S. Summer.

Hereford, R., 1977, Deposition of the Tapeats Sandstone (Cambrian) in central Arizona: Geological Society of America Bulletin, v. 88, p. 199-211.

Hobbs, W. H., 1982, The geology of the City Creek area, Gila County, Arizona: Flagstaff, Northern Arizona University, M.S. thesis, 94 p.

Huddle, J. W., and Dobrovolny, E., 1945, Late Paleozoic stratigraphy and oil and gas possibilities of central and northeastern Arizona: U.S. Geological Survey Oil and Gas Investigations Preliminary Chart 10.

Karlstrom, K. E., ed., 1991, Proterozoic Geology and ore deposits of Arizona: Arizona Geological Society Digest 19, 332 p.

Lewis, R. E., 1983, Geology of the Hackberry Mountains volcanic center, Yavapai County, Arizona: Pasadena, California Institute of Technology, Ph.D. dissertation, 297 p.

Ludwig, K. R., 1974, Precambrian geology of the central Mazatzal Mountains, Arizona (Part I), and lead isotope heterogeneity in Precambrian igneous feldspars (Part II): Pasadena, California Institute of Technology, Ph.D. thesis, 363 p.

Martin, 1990, (incomplete – mapping in Tonto Basin)

Martinsen, R. S., 1975, Geology of a part of the East Verde River canyon near Payson, Arizona: Flagstaff, Northern Arizona University, M.S. thesis, 117 p.

McKee, E. D., and Gutschick, R. C., 1969, The Redwall faunas, *in* McKee, E. D., and Gutschick, R. C., History of the Redwall Limestone of northern Arizona: Geological Society of America Memoir 114, p. 125-172.

McGoon, D. O., 1962, Occurrences of Paleozoic carbonaceous deposits in the Mogollon Rim region: New Mexico Geological Society Guidebook 13th Field Conference, p. 89-91.

Middleton, L. T., 1989, Cambrian and Ordovician depositional systems in Arizona, *in* Jenney, J. P., and Reynolds, S. J., Geologic evolution of Arizona: Tucson, Arizona Geological Society Digest 17, p. 273-286.

Moore, R. T., unpublished mapping upper Tonto Creek area: Arizona Geological Survey files, 1:62,500.

Morrison Maierle, 2003, Investigation of groundwater availability for the Pine/Strawberry Water Improvement District: Helena, Morrison Maierle, Inc., report to Pine/Strawberry Water Improvement District, July, 2003, 148 p., appendices, map plates scale not given.

North American Commission on Stratigraphic Nomenclature, 1981, North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841-875.

Ostrander, R. E., 1950, Geology of the west-central portion of the Promontory Butte quadrangle, Arizona: Iowa City, University of Iowa, M.S. thesis, 184 p.

Parker, J. T. C., Steinkampf, W. C., and Flynn, M. R., 2004, Hydrogeology of the Mogollon Highlands, central Arizona: U.S. Geological Survey Scientific Investigations Report 2004-5294, 87 p.

Pedersen, E. P., 1969, Sedimentology and stratigraphy of basin-fill sediments of the Payson Basin, Gila County, Arizona: Tempe, Arizona State University, M.S. thesis, 136 p.

Peirce, H. W., unpublished mapping Payson-East Verde River area: Arizona Geological Survey files, 1:48,000.

Peirce, H. W., 1989, Correlation problems of Pennsylvanian-Permian strata of the Colorado Plateau of Arizona, *in* Jenney, J. P., and Reynolds, S. J., Geologic evolution of Arizona: Tucson, Arizona Geological Society Digest 17, p. 349-368.

Peirce, H. W., Jones, N., and Rogers, R., 1977, A survey of uranium favorability of Paleozoic rocks in the Mogollon Rim and slope region – east central Arizona: Bureau of Geology and Mineral Technology Circular 19, 60 p., appendices.

Peirce, H. W., Damon, P. E., and Shafiqullah, M., 1979, An Oligocene(?) Colorado Plateau edge in Arizona: Tectonophysics, v. 61, p. 1-24.

Potochnik, A. R., 1989, Depositional style and tectonic implications of the Mogollon Rim formation (Eocene), east-central Arizona: New Mexico Geological Society Guidebook, 40th Field Conference, Southeastern Colorado Plateau, p. 107-118.

Satterthwaite, L. C., 1951, Geology of the east-central part of Promontory Butte quadrangle, Arizona: Iowa City, University of Iowa, M.S. thesis, 184 p.

Scott, G. S., 1974, Geology, petrology, Sr-isotopes, and paleomagnetism of the Thirteenmile Rock volcanics, central Arizona: Dallas, University of Texas at Dallas, M.S. thesis, 70 p.

Shride, A. F., 1967, Younger Precambrian geology in southern Arizona: U.S. Geological Survey Professional Paper 566, 89 p.

Silver, L. T., Conway, C. M., and Ludwig, K. R., 1986, Implications of a precise chronology for Early Proterozoic crustal evolution and caldera formation in the Tonto Basin-Mazatzal Mountains region, Arizona: Geological Society of America Abstracts with Programs, v. 18, p. 413.

Skip, B., 1969, Foraminifera, *in* McKee, E. D., and Gutschick, R. C., History of the Redwall Limestone of northern Arizona: Geological Society of America Memoir 114, p. 173-225.

Stoyanow, A. A., 1936, Correlation of Arizona Paleozoic Formations: Geological Society of America Bulletin, v. 47, p. 459-540.

Southwest Ground-water Consultants, 1997, Structural geology and hydrogeology of the Rye Creek Graben, Gila County, Arizona: Phoenix, Arizona, Southwest Ground-water Consultants, Inc., report to Town of Payson, 28 May 1997, 19 pages, map plate 1:24,000 scale.

Southwest Ground-water Consultants, 1998, Long-term management program of the Town of Payson's water resources - Appendix A, Geology of the Town of Payson: Phoenix, Arizona, Southwest Ground-water Consultants, Inc., report to Town of Payson, 1 June 1998, 28 p. with figures, tables, appendices

Teichert, C., 1965, Devonian rocks and paleogeography of central Arizona: U.S. Geological Survey Professional Paper 464, 181 p.

Titley, S. R., 1962, Geology along the Diamond Rim and adjoining areas, Gila and Navajo Counties, Arizona: New Mexico Geological Society Thirteenth Field Conference, p. 123-128.

Town of Payson Water Department, 2004, Results of preliminary water resources investigations at Baby Doll Ranch: Payson, Arizona, Town of Payson Water Department, 8 pages, appendices (borehole logs, geophysical logs, other).

Weir, G. W., and Beard, L. S., 1997, Preliminary geologic map of the Strawberry Quadrangle, Yavapai, Gila, and Coconino Counties, Arizona: U.S. Geological Survey Open-File Report 94-265, scale 1:24,000.

Weisman, M. K., 1984, Geology of the Pine and northern Buckhead Mesa quadrangles, Mogollon Rim region, central Arizona: Flagstaff, Arizona, University of Northern Arizona, M.S. thesis, 126 p., Appendices A, B.

Weisman, M. K., and Weir, G. W., 1990, Geologic map of the Pine 7.5' quadrangle, Coconino and Gila Counties, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-2123.

Wilson, E. D., unpublished mapping Payson-Mazatzal Mountains area: Arizona Geological Survey files, 1:62,500.

Wilson, E. D., 1939, Pre-Cambrian Mazatzal Revolution in central Arizona: Geological Society of America Bulletin, v. 50, p. 1113-1164.

Wilson, E. D., Moore, R. T., and Peirce, H. W., 1959, Geologic map of Gila County, Arizona: Arizona Bureau of Mines map, scale 1:375,000.

Winters, S. S., 1963, Supai Formation (Permian) of eastern Arizona: Geological Society of America Memoir 89, 99 p.

Wrucke, C. T., and Conway, C. M., 1987, Geologic map of the Mazatzal Wilderness and contiguous roadless areas, Gila, Maricopa, and Yavapai Counties, Arizona: U.S. Geological Survey Open-File Report 87-664, scale 1:48,000.

Zonge Engineering, 2004, Payson Diamond Rim Project Geophysical Survey, Gila County, Arizona: Tucson, Arizona, Zonge Engineering & Research Organization, Inc., report to Town of Payson and HydroSystems, Inc., 15 March 2004, 20 p., map plates, various scales.

ADDITIONAL REFERENCES

AGRA Earth & Environmental, 1998a, Summary report for evaluation of groundwater resource, RV/Borrow Pits site, Payson-Heber highway (SR 260), Gila County, Arizona: Report to Parsons Brinkerhoff Quade & Douglas, Inc., 23 December 1998, 10 pages with accompanying figures and tables.

AGRA Earth & Environmental, 1998b, Phase III work plan for evaluation of groundwater resource, RV/Borrow Pits site, Payson-Heber highway (SR 260), Gila County, Arizona: Report to Parsons Brinkerhoff Quade & Douglas, Inc. 16 pages with accompanying figures, tables, and appendices.

Blakey, R. C., and Knepp, R., 1989, Pennsylvanian and Permian geology of Arizona, *in* Jenney, J. P., and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 313-347.

Brumbaugh, D. S., 1985, Geometric and chronologic evolution of the Verde and Payson Basins of central Arizona and possible relationships to detachment faulting, *in* Conference on heat and detachment in crustal extension on continents and planets: Houston, Lunar and Planetary Institute, p. 22-24.

Canney, F. C., Lehmbeck, W. L., and Williams, F. E., 1967, Mineral resources of the Pine Mountain primitive area, Arizona: U.S. Geological Survey Bulletin 1230-J, 45 p., scale 1:31,680.

Conway, C. M., McColly, R. A., Marsh, S. P., Kulik, D. M., Martin, R. A., and Kilburn, J. E., 1983, Mineral resource potential for the Hells Gate Roadless Area, Gila County, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1644-A, scale 1:48,000.

Conway, C. M., and Wrucke, C. T., 1986, Proterozoic geology of the Sierra Ancha-Tonto Basin-Mazatzal Mountains region, road log and field guide: Arizona Geological Society Digest, v. XVI, p. 227-247.

Crossey, L. J., Newell, D. L., Karlstrom, K. E., and Fischer, T. P., 2005, Travertine-depositing systems of the western U.S.: Regional links between Cenozoic tectonism and water quality: Geological Society of America Abstracts with Programs, v. 37, no. 6, p. 16.

Feth, J. H., and Hem, J. D., 1963, Reconnaissance of headwater springs in the Gila River drainage basin, Arizona: U.S. Geological Survey Water-Supply Paper 1619-H, 54 p.

Hereford, R., 1975, Chino Valley Formation (Cambrian?) in northwestern Arizona: Geological Society of America Bulletin, v. 86, p. 677-682.

Huddle, J. W., and Dobrovolny, E., 1950, Devonian and Mississippian rocks of central Arizona: U.S. Geological Survey Professional Paper 233-D, p. 66-112.

Karlstrom, K.E., and Bowring, S.A., 1993, Proterozoic orogenic history of Arizona, *in* Reed, J.C.J., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 188-211.

Kottlowski, F. E., and Havenor, K. C., 1962, Pennsylvanian rocks of the Mogollon Rim area, Arizona: New Mexico Geological Society Thirteenth Field Conference, p. 77-83.

Levings, G. W., 1980, Water resources in the Sedona area, Yavapai and Coconino Counties, Arizona: Arizona Water Commission Bulletin 11, 37 p., 3 map plates, various scales.

McGavock, E. H., Anderson, T. W., Moosburner, O., and Mann, L. J., 1986, Water Resources of southern Coconino County, Arizona: Arizona Department of Water Resources Bulletin 4, 53 p., map plates.

Montgomery, 1993, Hydrogeologic investigations to identify and evaluate potential groundwater development areas in the vicinity of the Town of Payson, Gila County, Arizona: Tucson, Arizona, Errol L. Montgomery and Associates, report to Town of Payson, 28 June 1993, 45 pages with accompanying tables and illustrations.

Moore, R. T., Wilson, E. D., and O'Haire, R. T., 1960, Geologic map of Coconino County, Arizona: Arizona Bureau of Mines, scale 1:375,000.

Muehlberger, E. W., year & complete title……….Payson Basin, Gila County, Arizona: Flagstaff, Northern Arizona University, M.S. thesis, pages

Navarro, Nicolas, 2005, Incorporating $\delta^{18}O$ values of past waters in the calibration of radiocarbon dating: Geology v. 33, no. 5, p. 425-428.

Owen-Joyce, S. J., 1984, Hydrology of a stream-aquifer system in the Camp Verde area, Yavapai County, Arizona: Arizona Department of Water Resources Bulletin 3, 60 p., 3 plates, 1:24,000.

Owen-Joyce, S. J., and Bell, C. K., 1983, Appraisal of water resources in the upper Verde River area, Yavapai and Coconino Counties, Arizona: Arizona Department of Water Resources Bulletin 2, 219 p., map plates.

Parker, J. T. C., Steinkampf, W. C., and Flynn, M. E., 2004, Hydrogeology of the Mogollon highlands, central Arizona: U.S. Geological Survey Scientific Investigations Report 2004-5294, 87 p.

Ploughe, M.D. and Conway, C.M., 2002, Finding water in the cracks: Extended abstract for Arizona Hydrological Symposium, Flagstaff, September 2002.

Remick, W. H., 1987, Bibliography of selected reports on groundwater in Arizona: Arizona Department of Water Resources Open-File Report No. 4, 39 p.

Schwab, K. J., 1995, Maps showing groundwater conditions in the Big Chino Sub-basin of the Verde River Basin, Coconino and Yavapai Counties, Arizona—1992: Arizona Department of Water Resources Hydrologic Map Series Report Number 28, scale 1:250,000.

Town of Payson, 2000, North Payson area - hydrogeological investigation results: Town of Payson, Groundwater Exploration Program, 29 September 2000, 9 pages plus figures and appendices.

Town of Payson, 2004, Results of preliminary water resources investigations at Baby Doll ranch: Town of Payson, Groundwater Exploration Program, 13 February 2004, 8 pages plus figures and appendices.

Town of Payson 2001, Town of Payson Ground-Water Management 2001 Status Report, 12 April 2001, 13 pages plus figures, tables, and supporting data.

Twenter, F. R., 1962, Rocks and water in Verde Valley, Arizona: New Mexico Geological Society Thirteenth Field Conference, p. 135-139.

Twenter, F. R., 1962, The significance of the volcanic rocks in the Fossil Creek area, Arizona: New Mexico Geological Society Thirteenth Field Conference, p. 107-108.

Twenter, F. R., and Metzger, D. G., 1963, Geology and ground water in Verde Valley—the Mogollon Rim region, Arizona: U.S. Geological Survey Bulletin 1177, 132 p., 1:62,500-scale geologic map plate.

Vance, R., 1983, Geology of the Hardt Creek-Tonto Creek area, Gila County, Arizona: Flagstaff, Northern Arizona University, M.S. thesis, 99 p.

Wang, M., Kulatilake, P. H. S. W., Panda, B. B., and Rucker, M. L., 2001, Groundwater resources evaluation case study via discrete fracture flow modeling: Engineering Geology, v. 62, p. 267-291.

Weir, G. W., 1997, Preliminary geologic map of the Blue Ridge Reservoir quadrangle, Coconino County, Arizona: U.S. Geological Survey Open-File Report 94-271, scale 1:24,000.

Weir, G. W., Ulrich, G. E., and Nealey, L. D., 1989, Geologic map of the Sedona 30’ X 60’ quadrangle, Yavapai and Coconino Counties, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1896, scale 1:100,000.

Weir, G. W., and Beard, L. S., 1984, Geologic map of the Fossil Springs Roadless Area: U.S. Geological Survey Miscellaneous Field Studies Map MF-1568-C, scale 1:24,000.

Weitzman, M., 2002, Geology and hydrology of the Payson-Strawberry-Diamond rim area, Gila and Coconino Counties, central Arizona: Arizona Geological Survey Contributed Report CR-02-B, 15 p., 2 map plates, scale 1:62,500.

Wilson, E. D., Moore, R. T., and Cooper, J. R., 1969, Geologic map of Arizona: Arizona Bureau of Mines and U.S. Geological Survey, scale 1:500,000.

Winters, S. S., 1962, Lithology and stratigraphy of the Supai Formation, Fort Apache Indian Reservation: New Mexico Geological Society Thirteenth Field Conference, p. 87-88.

Wolfe, E. W., 1983, Geologic map of the Arnold Mesa Roadless Area, Yavapai County, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1577-B, scale 1:24,000.

Wrucke, C. T., Marsh, S. P., Conway, C. M., Ellis, C. E., Kulik, D. M., Moss, C. K., and Raines, G. L., 1983, Mineral resource potential of the Mazatzal Wilderness and contiguous roadless areas, Gila, Maricopa, and Yavapai Counties, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1573-A, scale 1:48,000

Young, R.A., and Hartman, J.H., 1984, Early Eocene fluviolacustrine sediments near Grand Canyon, Arizona: evidence for Laramide drainage across northern Arizona into southern Utah: Geological Society of America, Abstracts with Programs, v. 16, p. 703.