Hydrogeologic Framework

By Laurie Wirt, Ed DeWitt, and V.E. Langenheim

Chapter D

Geologic Framework of Aquifer Units and Ground-Water Flowpaths, Verde River Headwaters, North-Central Arizona

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Abstract

The upper Verde River watershed drains the northwestern Transition Zone and southwestern Colorado Plateau geologic provinces. Proterozoic igneous rocks largely define the basin geometry and boundaries of the Big and Little Chino basin-fill aquifers. Big and Little Chino Valleys contain gently sloping reservoirs of ground water that drain toward large springs near their basin outlets. The ground-water flow direction of basin-fill aquifers is from the basin margins and tributaries toward the basin center and then down the major axes of the valleys. Spring flow in the river canyon emerges from Paleozoic carbonate rocks downstream from the confluence of the Big and Little Chino basin-fill aquifers.

In Little Chino Valley, a complex sequence of alluvial and volcanic deposits forms a highly productive aquifer having confined and unconfined ground-water conditions. Artesian flow near the town of Chino Valley can be produced from (a) trachyandesite overlying small pockets of irregularly distributed sediment, (b) volcanic-clastic sequences within the lati-andesite, (c) lati-andesite over sedimentary rock or alluvium, (d) permeable basalt beneath strongly cemented alluvium, and (e) unconsolidated alluvium beneath strongly cemented alluvium. Buried plugs of lati-andesite increase in abundance north of Del Rio Springs. The narrow basin outlet and low permeability of the plugs restrict northern movement of ground water, contributing to discharge at Del Rio Springs. From Del Rio Springs, the most reasonable flowpath is northeast through faulted Paleozoic rock and lati-andesite toward spring-fed Stillman Lake and Lower Granite Spring.

In Big Chino Valley, ground-water flowpaths and rates of flow are influenced by the heterogeneous distribution of alluvial deposits (including a fine-grained playa deposit) and buried basalt flows. At the ground-water outlet near Paulden, a highly permeable basalt flow straddles both sides of the basin margin, and a moderately permeable carbonate aquifer shallowly underlies the basin-fill deposits. The Big Chino basin-fill aquifer and the carbonate aquifer north of the upper Verde River are hydraulically connected, as indicated by a water-level gradient of less than 10 ft per mi across the basin boundary. The regional ground-water flow direction between Paulden and Hell Canyon is east or southeast, consistent with the Big Chino aquifer as the major source of discharge to upper Verde River springs. Potential contributions from carbonate units to the Big Chino basin-fill aquifer, if any, are most likely to occur (a) beneath the Big Chino basin-fill aquifer, (b) through alluvial fans along the base of Big Black Mesa, or (c) near the outlet of the basin-fill aquifer along fractures parallel to the northwest-striking Big Chino Fault.

Introduction

Three major aquifers in the headwaters study area contribute base flow to the upper Verde River. They are the Big and Little Chino basin-fill aquifers and the adjoining carbonate aquifer. This chapter describes the geologic setting, aquifer boundary conditions, water-bearing characteristics, and regional water-level gradients. Local heterogeneities within each major subbasin or aquifer are described, including differences in permeability of rock types, water-bearing characteristics of aquifer units, stratigraphic relations, and structures that control local movement of ground water. The objective of this chapter is to provide a conceptual hydrogeologic framework for ground-water flowpaths in the upper Verde River headwaters region.

Geologic Setting

Big and Little Chino Valleys are part of the Transition Zone, a physiographic and tectonic transition between the relatively undeformed Colorado Plateau province to the northeast, and the severely faulted Basin and Range province to the southeast (Pierce, 1985; Ostenaa and others, 1993). The Verde River watershed drains nearly equal parts of the Transition Zone and the southwestern edge of the Colorado Plateau (fig. D1). The Transition Zone developed in response to tectonic uplift, rifting, and extensional movements that formed the Basin and Range province during the Tertiary period. These profound structural changes had little effect on the flat-lying rocks of Colorado Plateau (Lucchitta, 1989). Big and Little Chino Valleys (and Verde Valley to the east) are among the first in a series of alluvial basins extending outward from the eroded southwestern margin of the Colorado Plateau. Transition Zone basins tend to be smaller and shallower than Basin and Range basins farther south and west. Their average elevation is intermediate between the plateau rim and the southern desert basins.

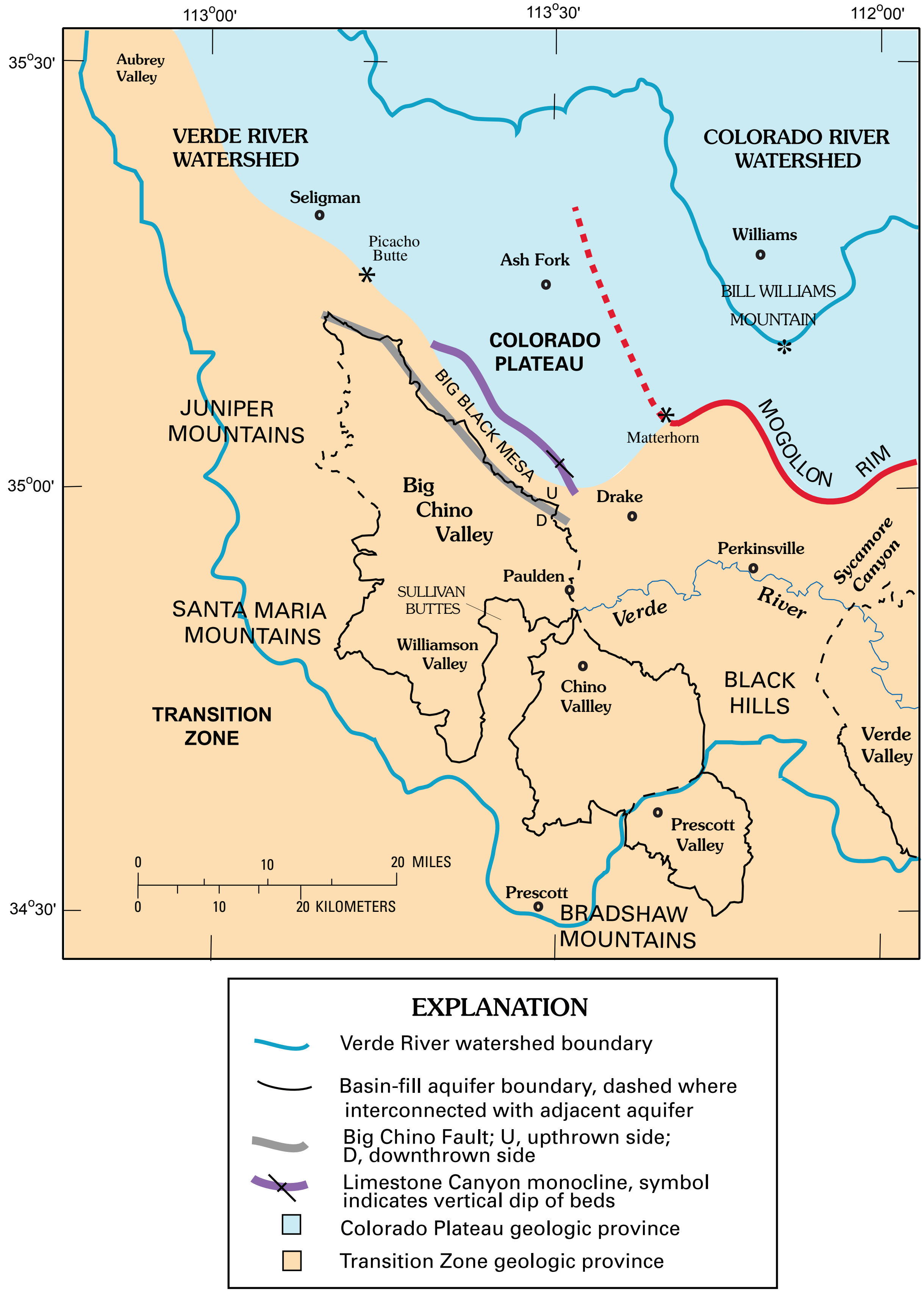


Figure D1. Schematic diagram of Colorado Plateau and Transition Zone geologic provinces and prominent geographical features, upper Verde River watershed. Base is from U.S. Geological Survey digital data 1:100,000.

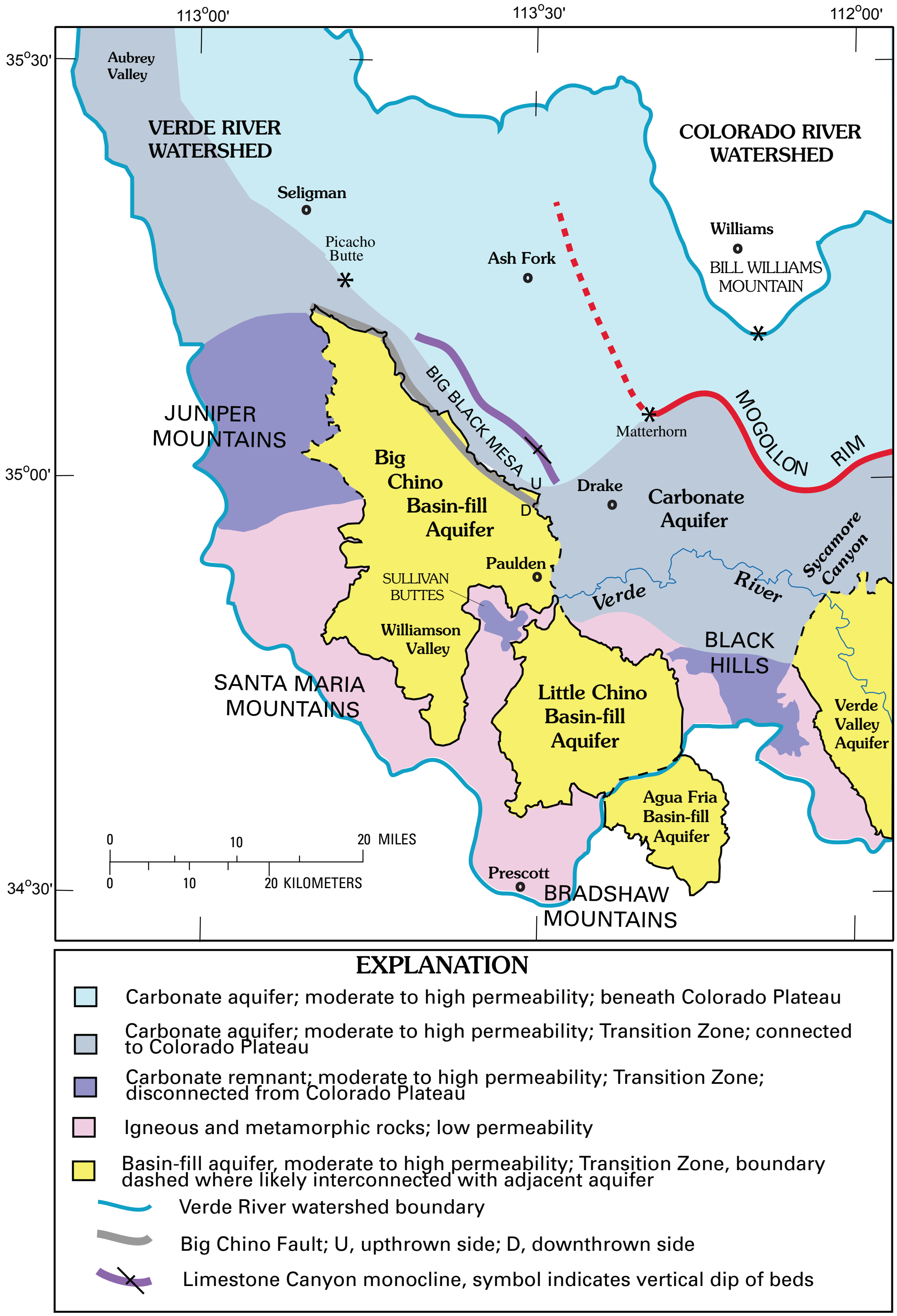


Figure D2. Schematic diagram of basin-fill aquifer boundaries in relation to geologic provinces and different parts of the regional carbonate aquifer, upper Verde River watershed. Base is from U.S. Geological Survey digital data 1:100,000.

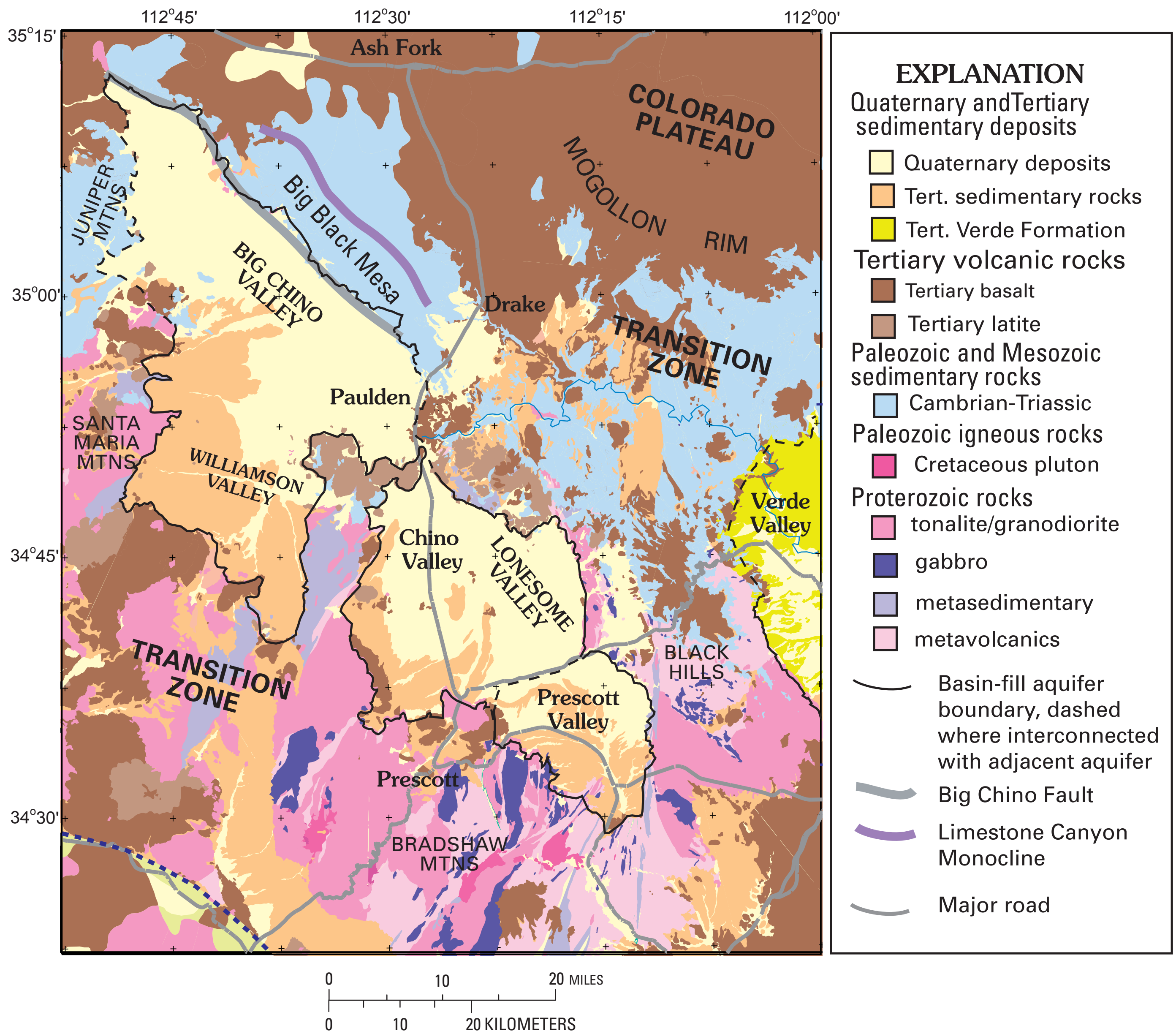
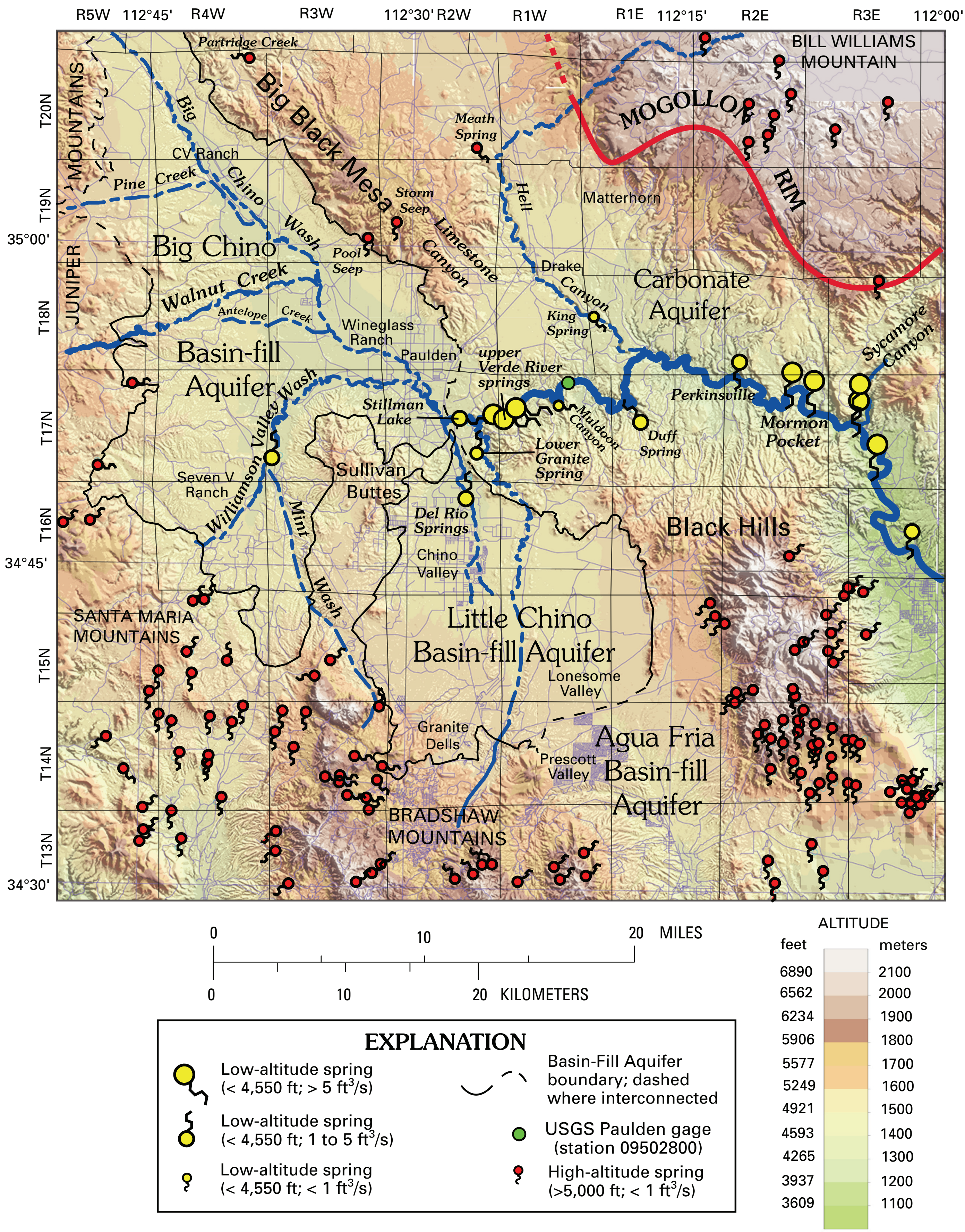


Figure D3. Geologic map of the Verde River headwaters study area (simplified from DeWitt and others, in press). Geology outside of thick dotted blue line is abridged from Reynolds (1988) and Richard and Kneale (1993). Base is from U.S. Geological Survey digital data 1:100,000.

Figure D4 (facing page). Shaded elevation map showing basin-fill aquifer boundaries and the location of high-altitude (red) and low-altitude (yellow) springs. Aquifer boundaries are dashed where likely interconnected with adjacent aquifer. Base is from 1:100,000 U.S. Geological Survey digital data.


R5W
112°45'
R4W
R3W
112°30'
R2W
R1W
R1E
112°15'
R2E
R3E
112°00'
T20N
T19N
35°00'
T18N
T17N
T16N
34°45'
T15N
T14N
T13N
34°30'
Partridge Creek
Big Black Mesa
BILL WILLIAMS MOUNTAIN
MOGOLLON
RIM
Meath Spring
Hell
Matterhorn
JUNIPER
MOUNTAINS
Big
CV Ranch
Pine Creek
Chino
Wash
Storm Seep
Limestone
Canyon
Big Chino
Pool Seep
Walnut Creek
Antelope Creek
Wineglass Ranch
Drake
Canyon
Carbonate Aquifer
King Spring
Basin-fill Aquifer
Paulden
upper Verde River springs
Sycamore Canyon
Williamson Valley Wash
Stillman Lake
Muldoon Canyon
Perkinsville
Mormon Pocket
Duff Spring
Lower Granite Spring
Seven V Ranch
Sullivan Buttes
Mint
Wash
Del Rio Springs
Black Hills
Chino Valley
SANTA MARIA MOUNTAINS
Little Chino Basin-fill Aquifer
Lonesome Valley
Granite Dells
Agua Fria Basin-fill Aquifer
Prescott Valley
BRADSHAW MOUNTAINS
0
10
20
MILES
0
10
20
KILOMETERS
ALTITUDE
feet
meters
6890 2100
6562 2000
6234 1900
5906 1800
5577 1700
5249 1600
4921 1500
4593 1400
4265 1300
3937 1200
3609 1100
EXPLANATION
Low-altitude spring (< 4,550 ft; > 5 ft³/s)
Low-altitude spring (< 4,550 ft; 1 to 5 ft³/s)
Low-altitude spring (< 4,550 ft; < 1 ft³/s)
Basin-Fill Aquifer boundary; dashed where interconnected
USGS Paulden gage (station 09502800)
High-altitude spring (>5,000 ft; < 1 ft³/s)

All basins and ranges south and west of the margin of the Colorado Plateau are in the Transition Zone (Pierce, 1985). Within the study area, the southern boundary of the Colorado Plateau is defined, in part, by the erosional scarp of the Mogollon Rim (figs. D1–D4). The Mogollon Rim is well-defined near the Matterhorn, a prominent topographic feature northeast of Drake. The Rim is a steep escarpment east of the Matterhorn in Sycamore Canyon and north of Verde Valley. West of the Matterhorn, the Rim extends northward toward Ash Fork, where it is partially to completely buried by Tertiary basalt flows (DeWitt and others, in press), and lacking in topographic definition. The southern boundary of the Colorado Plateau west of Drake is defined by the crest of Big Black Mesa north of Big Chino Valley. North of Drake, the southern boundary of the Colorado Plateau is offset between the Matterhorn and the anticlinal crest of Big Black Mesa. Thus, the southern and western boundary of the Colorado Plateau within the study area is defined by Big Chino Valley and the crest of Big Black Mesa, which define the northern boundary of fault-bounded basins of middle Tertiary age.

As evidenced by the extremely rugged topography of canyons, cliffs, and buttes, the upper Verde River is actively eroding the southern margin of the Colorado Plateau. Given enough geologic time and the right conditions, the rim of the Colorado Plateau predictably will recede farther north toward the Grand Canyon. Sycamore Canyon, Hell Canyon, and Partridge Creek are among the largest of many deeply incised canyons eroding the edge of the plateau within the Verde River watershed (fig. D4). Prominent head cuts occur at the confluence of Big and Little Chino Valleys at Sullivan Lake and in Hell Canyon north of Drake. Erosion along Partridge Creek and Limestone Canyon has nearly severed Big Black Mesa from the rest of the Colorado Plateau. Other erosional remnants of Paleozoic strata that were once connected to the Colorado Plateau are located in the Juniper Mountains, Sullivan Buttes, and in the Black Hills (fig. D2).

Basement rocks in the Transition Zone have undergone regional Basin and Range extensional faulting. Mountain ranges are the uplifted blocks, and the down-dropped basins form grabens. Proterozoic igneous and metamorphic rocks are presumed to underlie Paleozoic sedimentary rocks beneath the basin-fill material in most of Big and Little Chino basins (fig. D3). Where Proterozoic rocks are exposed in the bottoms of canyons, they display irregular relief beneath the Paleozoic strata.

The three major aquifers in the study area—the Big and Little Chino basin-fill aquifers and the adjoining carbonate aquifer—have aquifer characteristics intermediate to those of the Colorado Plateau and the Basin and Range. The two basin-fill aquifers contain alluvial sediments and Tertiary volcanic rocks that resulted from Basin and Range faulting and extension. The regional carbonate aquifer is partly capped by Tertiary basalt, which in some areas has filled incised paleochannels. The Big and Little Chino basin-fill aquifers have the large storage capacity of typical Basin and Range basin-fill aquifers and deliver steady, reliable discharge to their outlets. The carbonate aquifer in the Transition Zone north of Big Chino Valley and the upper Verde River is the broken and eroded margin of a large regional carbonate aquifer that lies more than 3,000 ft beneath much of the southwestern Colorado Plateau. Karst plays an important role in ground water movement not only for the carbonate aquifer north of the upper Verde River, but underneath and along the margins of the Big Chino basin-fill aquifer where it is shallowly underlain by carbonate rocks.

Permeability of Rock Units

Permeability is the capacity of a porous rock or sediment to transmit fluid. Overall permeability of rock types in the study area is a function of primary and secondary porosity. Primary porosity is the percentage of pore space in a rock or sediment at the time of deposition or following cementation. Secondary porosity develops after emplacement of a stratigraphic unit through processes such as fracturing or dissolution. Secondary porosity greatly increases the overall permeability because of the presence of fractures, joints, karst features, and other structures, such as faults, which are likely to be connected and allow fluid flow.

Proterozoic Rocks

Most Proterozoic rocks types of igneous and metamorphic origin have low to very low porosity (table D1). Such rocks lack pore space because of their crystalline nature and include granodiorite (units Xpr, Xwv), aplite-pegmatite (unit Xap), and gabbro (unit Xgb). The Mazatzal Group consists of quartzite that is strongly cemented by secondary quartz, thereby destroying any primary porosity that the sandstone had prior to metamorphism. All these rock units and similar granite and granodiorite to the west, beneath Big Chino Valley, contain few fractures, joints, and faults, and have low permeability.

Strongly foliated rock units such as metabasalt (unit Xb), metatuff (unit Xt), and metamorphosed pelitic sediments (unit Xp) have an increased secondary porosity due their prominent northeast-striking foliation, which creates zones of weakness along which joints and fractures locally form. At some places, these rocks have been deeply weathered before deposition of the Tapeats Sandstone, and their overall permeability may be markedly increased. Some water wells southeast of Sullivan Lake report yields of 50–100 gallons per minute (gpm) from zones within metatuff (Arizona Department of Water Resources, 2002).

Paleozoic Rocks

Most Paleozoic rocks have moderate permeability (table D1). Only the Tapeats Sandstone (unit Ct) has low permeability, due to its strongly cemented nature. The Bright Angel Shale and the Chino Valley Formation, found

Table D1. Relative porosity and permeability of stratigraphic units.

Period	Map unit	Stratigraphic unit	Primary porosity	Secondary porosity	Overall permeability
Quaternary	Qal	alluvium	high		high
	Qf	fanglomerate	high		high
	Qt	gravel	high		moderate
	Qg	gravel	high		high
	Qs	undivided sediment	moderate		moderate
	QTf	fanglomerate	moderate		moderate
	QTs	undivided sediment	moderate		moderate
Tertiary	Taby	alkali basalt	low	high	high
	Tby	basalt	low	high	high
	Tcy	cinders	high		high
	Tsy	conglomerate	high		high
	Tabo	alkali basalt	low	high	moderate
	Tso	conglomerate	high		high
	Thb	basalt	low	high	moderate
	Tha	trachyandesite	low	moderate	moderate
	Ths	conglomerate	high		high
	Tlau	upper lati-andesite	low	moderate	moderate
	Tlal	lower lati-andesite	low	moderate	moderate
	Tla	undivided lati-andesite	low	moderate	moderate
	Tla	lati-andesite intrusive centers	low	low	low
	Tla	breccia	moderate		moderate
	Tla	cinders	moderate		moderate
	Tos	conglomerate	high		high
Permian	Ps	sandstone	moderate		moderate
Mississippian	Mr	limestone	moderate	high	high
Devonian	Dm	dolomite	moderate	moderate	moderate
Cambrian	Ct	sandstone	low		low
Proterozoic	Xq	quartzite	very low		very low
	Xpr	granodiorite	very low		very low
	Xap	aplite-pegmatite	very low		very low
	Xwv	granodiorite	very low		very low
	Xp	pelitic schist	very low	moderate	low
	Xgb	gabbro	very low		very low
	Xb	metabasalt	low	moderate	low
	Xt	metatuff	very low	moderate	moderate

above the Tapeats, are inferred to have low porosity owing to the clay origin of shale. The Martin Formation contains abundant northwest-striking high-angle joints near its base, thereby enhancing its overall permeability. Locally, the base of the Martin includes dissolution cavities and other small karst features. The middle part of the Redwall Limestone is strongly modified by karst solution, creating connected caves and collapse features. Hence, its overall permeability is among the highest of any rock type for the study area (table D1). Sandstone in the Supai Formation is poorly cemented, giving it moderate overall permeability.

The Tapeats, due to its low overall porosity, forms a resistive layer to vertical movement beneath the overlying Paleozoic units. For this reason, springs such as those along the upper Verde River are preferentially localized at the base of the Martin. Productive water wells near Drake (Southwest Groundwater Consultants; 2002) and in the carbonate aquifer north of Paulden (Water Resources Associates, 1990) attest to the moderate permeability of the lower part of the Martin.

Tertiary Rocks and Sediment

Conglomerate beneath lati-andesite (unit Tso) contains poorly lithified and cemented gravel and sandstone, all of which have high primary porosity and high permeability (table D1). Overlying lati-andesite flows (units Tla, Tlal, and Tlau) have low primary porosity due to their igneous nature, but interbedded breccia and cinders have an increased permeability. Lati-andesite flows contain intersecting cooling fractures and joints that give the lati-andesite a moderate overall permeability. Strongly cemented lati-andesite may form a confining layer in the central part of Little Chino Valley. Intrusive centers of lati-andesite have very low permeability.

Conglomerate beneath flows in the Hickey Formation (unit Ths) contains poorly cemented and lithified gravel and sandstone, all of which of have high secondary porosity and permeability (table D1). Overlying basalt flows (unit Tby) contain abundant intersection columnar joints which give the basalt a moderate overall permeability. Trachyandesite in the Hickey (unit Tha) contains fewer columnar joints, and a somewhat lower overall permeability, but a classification of moderate is assigned (table D1). Because the trachyandesite in the Hickey contains fewer columnar joints than basalt, it may form a confining layer between the town of Chino Valley and outcrops in the Sullivan Buttes to the west.

Conglomerate beneath highly magnetic basalt flows (unit Tso) is poorly sorted and lithified and has high permeability. Underlying highly magnetic alkali basalt (unit Tabo) is presumed to have high secondary porosity and overall moderate permeability similar to flows in the Hickey Formation.

Basalt flows derived from the Colorado Plateau or erupted within the study area (units Taby and Tby) have high overall permeability (table D1), due in large part to extensive intersecting columnar joints. Highly productive water wells near Paulden, some yielding thousands of gpm (Water Resource Associates, 1989, 1990), attest to the high permeability of the basalt flows. Interbedded deposits of cinders (unit Tcy) have high permeability, as shown by driller's logs of water wells located south and west of Paulden (Arizona Department of Water Resources, 2002). Conglomeratic sediment interbedded with the basalt flows (unit Tsy) has a high permeability due to the uncemented nature of the sediment.

Tertiary and Quaternary sedimentary rocks and sediments in Big and Little Chino Valleys have moderate to high primary porosity and overall permeability (table D1). High permeability is indicated for alluvium (unit Qal), fanglomerate along the southwestern face of Big Black Mesa (unit Qf), and well-sorted gravel (units Qg and Qt). Distal deposits of fanglomerate, near the center of Big Chino Valley, should have reduced permeability compared to proximal deposits near Big Black Mesa. Moderate permeability is estimated for mixed types of sedimentary rocks and sediments (units Qs, QTs) and fanglomerate that surrounds Sullivan Buttes (unit QTf). This fanglomerate is locally strongly cemented in layers tens-of-ft thick, unlike fanglomerate along the southwestern face of Big Black Mesa. The strongly cemented fanglomerate may form a local confining layer in the northern part of Little Chino Valley.

Playa deposits in Big Chino Valley (time equivalent of unit Tsy and Tso) in all likelihood have a lower overall permeability than most surficial units (Qal, Qf, Qt and Qg), but an accurate estimation is difficult due to a lack of representative samples. Most cuttings of playa materials are contaminated with drilling mud and probably represent the most resistant rock types in the playa; the softer and water-soluble material was destroyed during drilling. Representative core samples of the playa deposit would be needed to determine its overall permeability.

Basement Geometry and Aquifer Boundaries

Proterozoic basement rocks define the basin geometry and areal extent of basin-fill aquifers in the Verde River headwaters region (fig. D3). The basin-fill deposits and Paleozoic sedimentary rock overlie an irregular topography of Proterozoic igneous and metamorphic rocks. The most common basement rocks are granite, gabbro, metavolcanic and metasedimentary schist, in decreasing order of abundance. Water yields in such rocks generally are poor and depend on the presence, if any, of fractures and their degree of inteconnection. These rocks play an important role hydrologically, because they define the low permeability boundaries of the basins and increase runoff potential in upland areas where they are exposed. They also provide a source of solutes and detrital minerals to alluvium and soil.

Aquifer boundaries (figs. D1– D4) are drawn as solid lines where the basin-fill deposits abut Proterozoic basement rocks having low permeability. Dashed lines indicate potential connections between the basin-fill aquifers and adjoining carbonate or basin-fill aquifers. Dashed boundaries occur in four locations. First, the northwest boundary of the Big Chino aquifer along the Juniper Mountains is in contact with an erosional remnant of the carbonate aquifer. Second, the Big Chino aquifer north of Paulden is in contact with carbonate rock along part of the Big Chino fault, where there is little vertical displacement. Displacement along the fault increases to the northwest, where basin-fill sediments are in faulted contact with relatively impermeable Proterozoic rock (DeWitt and others, Chapter B, this volume), indicated by a solid-line boundary. Third, the southeast boundary of the Little Chino basin-fill aquifer adjoins the Agua Fria basin-fill aquifer. And fourth, the northeastern boundary of the Little Chino aquifer (north of Del Rio Springs) adjoins the carbonate aquifer near Stillman Lake and lower Granite Creek. In all four cases where aquifer boundaries are dashed, the adjoining aquifers are interpreted as connected, indicating that ground water can potentially move between one aquifer and the other. The basin-fill aquifer boundaries presented here are largely consistent with those interpreted by Robson and Banta (1995) at the 1:100,000 scale.

Recharge Areas and Spring Locations

Recharge from snowmelt and rainfall runoff is conveyed by gravity from upland areas to basin-fill aquifers and then through connected bedrock openings to reach springs near the topographic outlets of Big and Little Chino Valleys. The size and location of springs depend on many factors, including climate, the nature and relation of permeable and impermeable strata, the extent of upland drainage areas, and the position of the water-level gradient relative to the land surface. Springs identified from USGS 1:24,000 scale maps (fig. D4) in this study have been broadly subdivided into two groups—high-altitude springs (in red) and low-altitude springs (in yellow). These groupings will be conceptually useful in the forthcoming discussion of water chemistry (Wirt and DeWitt, Chapter E; this volume).

High-altitude springs are defined here as springs in bedrock areas at elevations greater than 5,000 ft above sea level. These springs are not part of a large aquifer system and generally discharge small volumes relative to low-altitude springs (defined here as springs at elevations below 4,550 ft above sea level). Ground water supplying high-altitude springs is stored in small-volume secondary openings, such as fractures, catchments of colluvium, or pockets of stream alluvium. High-altitude springs tend to respond more quickly to temporal changes in precipitation than low-altitude springs. Having limited storage capacity, they are more likely to dry up during extended periods of drought. Despite their smaller volume, high-altitude springs sustain intermittent and perennial stream segments in Mint Wash, Williamson Valley Wash, Walnut Creek, Pine Creek, and their tributaries.

Streams and washes in Big and Little Chino Valleys are predominantly ephemeral except where the ground-water table is shallow and intercepted by the land surface, such as near the topographic outlets of the valleys. These low-altitude springs often create cienagas, or spring-fed marshes. The largest low-altitude spring in Little Chino Valley is Del Rio Springs. A 4-mi reach of lower Williamson Valley Wash is supplied by ground water, or spring fed, as are reaches of Walnut Creek, lower Granite Creek, and lower Sycamore Creek. The largest spring network downstream from the Verde River/Granite Creek confluence (upper Verde River springs) lies below the topographical outlets of both Big and Little Chino valleys. Ground water in the Paleozoic carbonate aquifer usually discharges to the base of incised limestone canyons, such as upper Verde River springs, Stillman Lake, and King Spring in Hell Canyon (fig. D5). Ground water travels preferentially through networks of fractures and solution zones in limestone, although seepage from limestone beneath streambed alluvium will appear diffuse.

Within the Transition Zone, the Paleozoic sedimentary rocks that form the carbonate aquifer typically are incised, with as much as 2,000 ft of vertical relief north of the upper

Figure D5. Photograph of King Spring in Hell Canyon. View is north. Rocks are Supai Formation capped with Tertiary basalt. The spring discharges from the carbonate aquifer where the land surface intersects the water table. (Photograph by L. Wirt, U.S. Geological Survey.)

Verde River and along Big Black Mesa. Because the topography is so irregular, the depth of the water table beneath the land surface is highly variable. For example, the land surface intersects the water table at King Spring, a permanent spring in the bottom of Hell Canyon about 2 mi southeast of Drake (fig. D4). At the base of the vertical walled canyon between Drake and King Spring, the saturated zone is between 0 and about 25 ft beneath the stream channel. Perpendicular to this reach in either direction, the aquifer is overlain by 400 ft of unsaturated rock. Artesian conditions have been encountered near Drake, indicating the aquifer is confined, at least locally.

The amount of surface-water runoff and ground-water recharge at any location is a function of precipitation, vegetation, slope, and the capacity of water-bearing rock and sediment units to absorb, store, and transmit water. High-altitude springs are most numerous where precipitation is great and rocks are relatively impermeable, particularly in the granite and gneissic rocks of the Bradshaw, Santa Maria, and Juniper Mountains, and the Black Hills (fig. D4). Only four small springs are present around the perimeter of Big Black Mesa, which is attributed in part to lesser amounts of precipitation and in part to the greater permeablility of the carbonate rocks. Ground-water recharge is very efficient in karst terrain because precipitation readily infiltrates secondary rock openings that intersect the land surface (Winter and others, 1999; p. 50). Volcanic rocks also have a high degree of secondary porosity caused by uneven cooling fractures and unconformities. High-altitude springs are relatively common draining from basalt south of Bill Williams Mountain and in the headwaters of Sycamore Canyon. These high areas receive some of the greatest amounts of precipitation in the study area (Chapter A; fig. A9).

In a study of southern Coconino County, McGavock and others (1986, p. 13) found the least amount of surface-water runoff (and greatest recharge potential) where permeable volcanic cinders were exposed at land surface. Infiltration also tended to be higher at lower altitudes, such as in relatively flat parts of Cataract Canyon and Little Colorado River drainages. Runoff was greatest where topography was steep and rocks were least permeable, such as igneous rocks and schist. Based on these findings it is expected that infiltration in the study area is greatest for Paleozoic carbonate rocks and Tertiary volcanic rocks. Recharge also is expected to be high for low-gradient runoff flowing over alluvium. In addition, recharge occurs as seepage losses beneath losing reaches of major tributaries.

Water-Bearing Characteristics of Major Aquifer Units

Water-bearing units range from Paleozoic to Quaternary in age and are presented in ascending order from oldest to youngest. At any given location, an aquifer may consist of one or more water-bearing units, spanning a broad range in age (fig. D5). Not all units are available in all locations. The carbonate aquifer is comprised of several Paleozoic sedimentary units, ranging in age from Cambrian to Permian. The carbonate aquifer is locally overlain by thick Tertiary basalt flows and sediments, which can fill incised paleochannels to depths that extend below the water table. Similarly, the Big and Little Chino basin-fill aquifers, which are predominantly comprised of Tertiary and Quaternary sediment, commonly include Tertiary basalt, lati-andesite, and conglomerate facies.

Carbonate Aquifer

Nearly the entire region north of the Big Chino Fault and the upper Verde River (in the Transition Zone and extending beneath the Colorado Plateau) is comprised of a continuous expanse of Paleozoic sedimentary rocks, overlain in some areas by Tertiary basalt flows. In addition, eroded remnants of Paleozoic rocks south of the Big Chino Fault are concealed beneath Big Chino Valley and part of northern Little Chino Valley (DeWitt and others, Chapter B, this volume). Southward, the carbonate rocks are uplifted and exposed in the Juniper Mountains, Sullivan Buttes, and Black Hills (fig. D2). Paleozoic remnants beneath the basins and in mountain ranges to the south are mostly separated from carbonate rocks beneath the Colorado Plateau by faulting and erosion. Thus, some Transition Zone carbonate rocks are stratigraphically continuous with the carbonate rocks beneath the Colorado Plateau, and some are not. In the northwestern part of Big Chino Valley, the basin-fill aquifer north of Walnut Creek is bounded by carbonate rocks that are partly capped with basalt. These carbonate rocks are considered an erosional remnant of the Colorado Plateau (fig. D2), because they are stratigraphically discontinuous. Little hydrologic information is available for the Juniper Mountain area adjoining the Big Chino basin-fill aquifer.

The carbonate aquifer consists of several hydraulically connected limestone, dolomite, sandstone, and shale formations. The formations, in ascending order, include the Tapeats Sandstone and Bright Angel Shale of Cambrian age; the Martin Formation of Devonian age; the Redwall Limestone of Mississippian age; and the Supai Formation of Pennsylvanian and Permian age. The primary water-bearing unit in the study area is the Martin, followed to a lesser degree by the Redwall. Together these units are known as the regional carbonate aquifer.

Owing to variations in uplift and erosion, not all Paleozoic units are preserved at all locations in the study area. In the southern and western parts of the area where Paleozoic units are exposed, the Martin usually is the uppermost unit. On Big Black Mesa and north of the upper Verde River (toward Drake and east of Hell Canyon), the Redwall is the uppermost unit. Although exposed in just a few locations in Hell Canyon and along the upper Verde River canyon, the Supai is an important unit in the regional aquifer farther east in Verde Valley (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983).

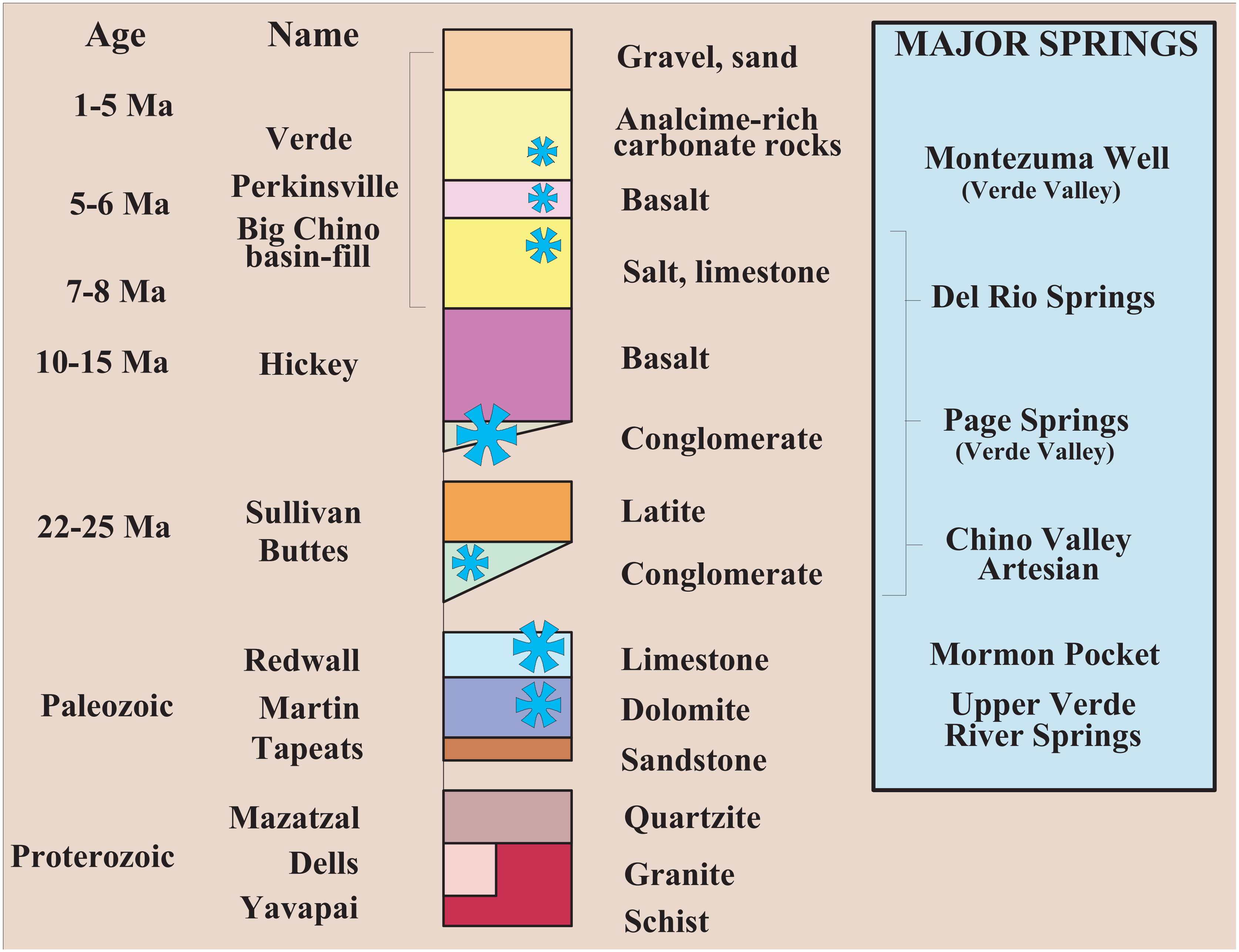


Figure D6. Columnar section of Verde River headwaters region, north-central Arizona. Water-bearing units that host springs are indicated by blue asterisks. Source of water may be different than host unit.

The Tapeats Sandstone is the basal aquifer unit, consisting of medium-to-coarse grained feldspathic sandstone ranging in thickness from 0 to 300 ft. This formation is exposed along the base of Big Black Mesa and the Juniper Mountains and in lower Granite Creek. In the northwestern part of Big Chino Valley, the Tapeats Sandstone is overlain by the Bright Angel Shale. In the southeastern part Big Chino Valley and near the mouth of Granite Creek, the Tapeats is overlain by interbedded carbonate and clastic rocks of unknown age known as the Chino Valley Formation (shown in fig. A8, Chapter A; Hereford, 1975; Beus, 1989). Three facies are recognized in the Chino Valley Formation—a lithic sandstone, a pebble conglomerate, and a red shaley dolomite.

The overlying Martin Formation is composed predominantly of dolomite, followed by minor limestone, interbedded shale and sandstone, and minor amounts of limey siltsone and sandstone. It is easily distinguished by its gray color and evenly-bedded, step-like outcrops (Krieger, 1965). Within the study area, the Martin ranges in thickness from 300 to 400 ft. The Martin crops out on Big Black Mesa, in the Juniper Mountains, and throughout much of the upper Verde River canyon between Stillman Lake and the Paulden gauge. The Martin contains fractures and solution features, which are evident in Verde River canyon exposures near upper Verde River springs (Knauth and Greenbie, 1997).

The Martin is unconformably overlain by the Mississippian Redwall Limestone, except where eroded near the surface. The Redwall Limestone, which has a thickness of about 200 ft in the study area, is a massive, cliff-forming unit (fig. D7). In the Grand Canyon region it is well known for its large caverns, collapse features, and extensive caves and springs (Stanton's Cave, Redwall Cavern, and Vasey's Paradise, for example).

Large springs at Mormon Pocket and Summers Spring in Sycamore Canyon emerge through the Redwall near its lower contact with underlying Martin. Earlier studies recognized that the water-bearing Paleozoic rock formations are hydraulically connected laterally and vertically by connected fractures and dissolution cavities (Twenter and Metzger; 1963; Owen-Joyce and Bell, 1983). Dissolution openings, known as karst, offer the potential for water to travel rapidly through the subsurface (White, 1969, 1988, 1999; Ford, 1999; Ford and Williams,

Figure D7. Photograph of large solution features in Redwall Limestone in upper Verde River canyon. (Photograph by L. Wirt, U.S. Geological Survey.)

1989). Solution channels and saturated caverns are capable of storing and transmitting large amounts of water.

The irregular distribution of fractures can produce confined aquifer conditions. This concept is demonstrated by a 700-ft well at Drake (fig. D8 and D9; SB0001; B-19-01 33cca), which was drilled through unsaturated basalt, Redwall, and Martin into what is probably the Chino Valley Formation or upper Tapeats. Upon penetrating the lower Martin, the water level rose nearly 300 ft within the borehole (Southwest Groundwater Consultants, 2002; William G. Wellendorf, written commun., 2002). Subsequent inspection with a down-hole camera showed a pronounced increase in the number of fractures and solution features near the base of the Martin relative to the overlying units. The static water level of the well (4,244 ft; table D3; Southwest Groundwater Consultants, written commun., 2004) is about the same as the stream elevation in nearby Hell Canyon.

The lower Martin Formation is host to several prominent springs in the Verde River watershed, including upper Verde River springs and spring-fed Stillman Lake near Paulden, Haskell Spring near Cottonwood (Thiele, 1961), and Allen Springs on Mingus Mountain, which are the water supply for the town of Jerome (Paul Lindberg, oral commun., 2002). The Martin is similar in composition and thickness to the Cambrian Muav Limestone that is host to many springs in the Grand Canyon. In the Grand Canyon, most springs in the lower Paleozoic section generally discharge above the Bright Angel Shale, which is a relatively impermeable rock unit. A small quantity of water evidently penetrates the shale, as evidenced by smaller springs in the shale and underlying rock. The Bright Angel Shale is recognized for its properties in retarding the downward percolation of ground water (Metzger, 1961; Twenter, 1962; Huntoon, 1977; Myers, 1987). The shale in the Bright Angel and the highly-cemented sandstone layers in the Tapeats impede downward movement and cause ground water to move laterally above the contact. This accounts for the accumulation of ground water in the overlying formation, the Muav Limestone. In the Verde River watershed, the relation between the Martin and the underlying Chino Valley Formation and Tapeats Sandstone units is hydrologically analogous to the relation between the Muav Limestone and the Bright Angel Shale.

Carbonate Aquifer Underlying Basin-Fill Deposits

Some of the highest-yield water wells in Big Chino Valley are located along the base of Big Black Mesa north of Paulden where the basin-fill deposits are thin. These wells penetrate Paleozoic limestone beneath 50 to 400 ft of Tertiary basin-fill sediment (fig. B11; DeWitt and others, Chapter B, this volume). The "Weber Well" north of Paulden (B-18-02-28abb) is an example of such a well, reportedly yielding as much as 5,000 gpm (Water Resources Associates, 1990). This well is 385 ft in depth. Although few wells fully penetrate the basin-fill deposits to produce from the carbonate aquifer, Paleozoic rocks are presumed to underlie most or all of the Big Chino basin-fill aquifer (Ostenna and others, 1993; DeWitt and others, Chapter B, this volume). In earlier studies, water-level contour maps did not distinguish among wells producing from carbonate rocks underlying the basin-fill versus those producing from Tertiary basin-fill sediment or volcanic rocks (fig. D8; Wallace and Laney, 1976; Schwab, 1995). Water-levels for the carbonate aquifer near Paulden are not substantially different from those in alluvium or basalt in the basin-fill aquifer, suggesting that the "upper" basin-fill aquifer and "lower" carbonate aquifer are strongly connected in the basin outlet region. Additional work is needed to better understand the interrelation between the upper and lower aquifers.

Carbonate Aquifer North of Upper Verde River

The depth of wells in the carbonate aquifer north of the Verde River ranges from 480 to 720 ft (table D3). Based on the small number of well logs, reported water yields are highly variable. A few wells are productive, and some are not. Dry holes north of the Bar Hart Ranch have been drilled as deep as 700 ft, and well drilling in this region is considered risky (Don Varner and David Gipe, local ranchers, oral commun., 2002).

A highly productive well near Drake (SB0001; B-19-01 33cca), discussed earlier, is completed in the lower Martin near the contact of the Chino Valley or Tapeats (Southwest Groundwater Consultants, 2002). This stratigraphic interval was observed to have a pronounced increase in the number of fractures and solution features relative to overlying units. The same stratigraphic interval is exposed at the base of the upper Verde River canyon where there is spring discharge; at river mi 2.3 (upper Verde River springs), and at river mi 8.0 (unnamed spring near Muldoon Canyon).[1] The well log of a 620-ft stock well 2 mi south of Drake at B-18-01 17aa is fairly similar to well SB0001. The borehole penetrated unsaturated basalt in the near surface (from 96 to 138 ft), which is underlain by conglomerate and limestone. A 720-ft stock well 2 mi northeast of Drake at B-19-01 16acb is completed almost entirely in basalt. Both stock wells typically are pumped at a rate of about 10 gpm (Don Varner and David Gipe, local ranchers, oral commun., 2002). No aquifer tests are available for any of the wells in the carbonate aquifer near Drake.

A second highly productive well (HR-2 in fig. D9) in the carbonate aquifer is located just outside of the Big Chino basin, 1.5-mi north of upper Verde River springs and the Verde River. At this location, the well penetrates a basalt-filled paleochannel that is cut into Paleozoic rock (DeWitt and others, this volume). The driller's log indicates that the HR-2 borehole initially penetrated 200 ft of basalt, lost circulation for 265 ft, and bottomed in what was described as sand, sandstone, or limestone. The lowermost part of the log is interpreted as penetrating buried Tertiary alluvium,

[1] Locations along Verde River in river miles shown in fig. A2 and listed in Table A1, Chapter A, this volume.

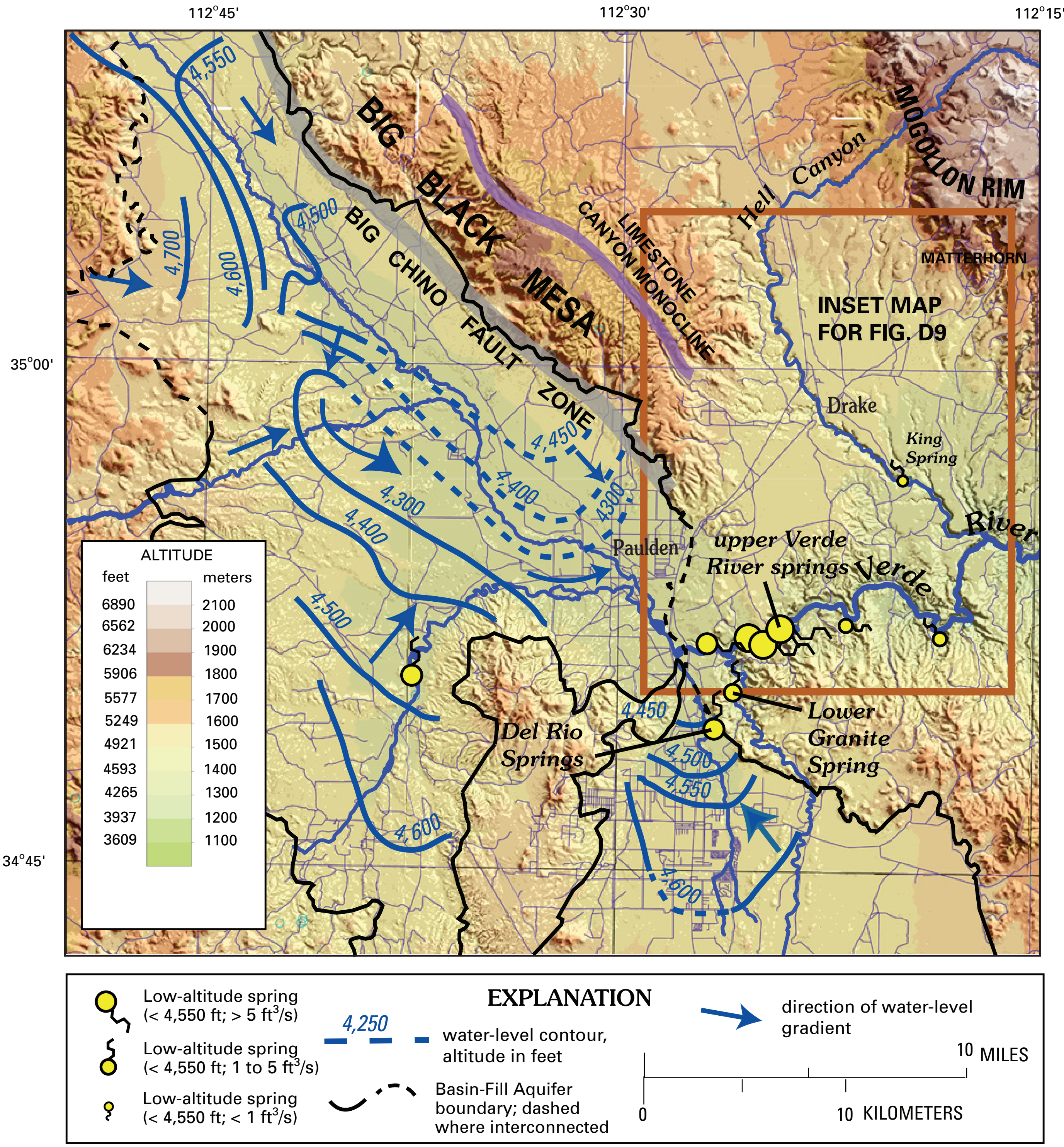


Figure D8. Compilation of water-level contours in the Verde River headwaters area (after Schwab, 1995; Corkhill and Mason, 1995). Dashed contours and arrows are the author's interpretation. Low-altitude springs shown as yellow circles, water-level contour elevations given in feet.

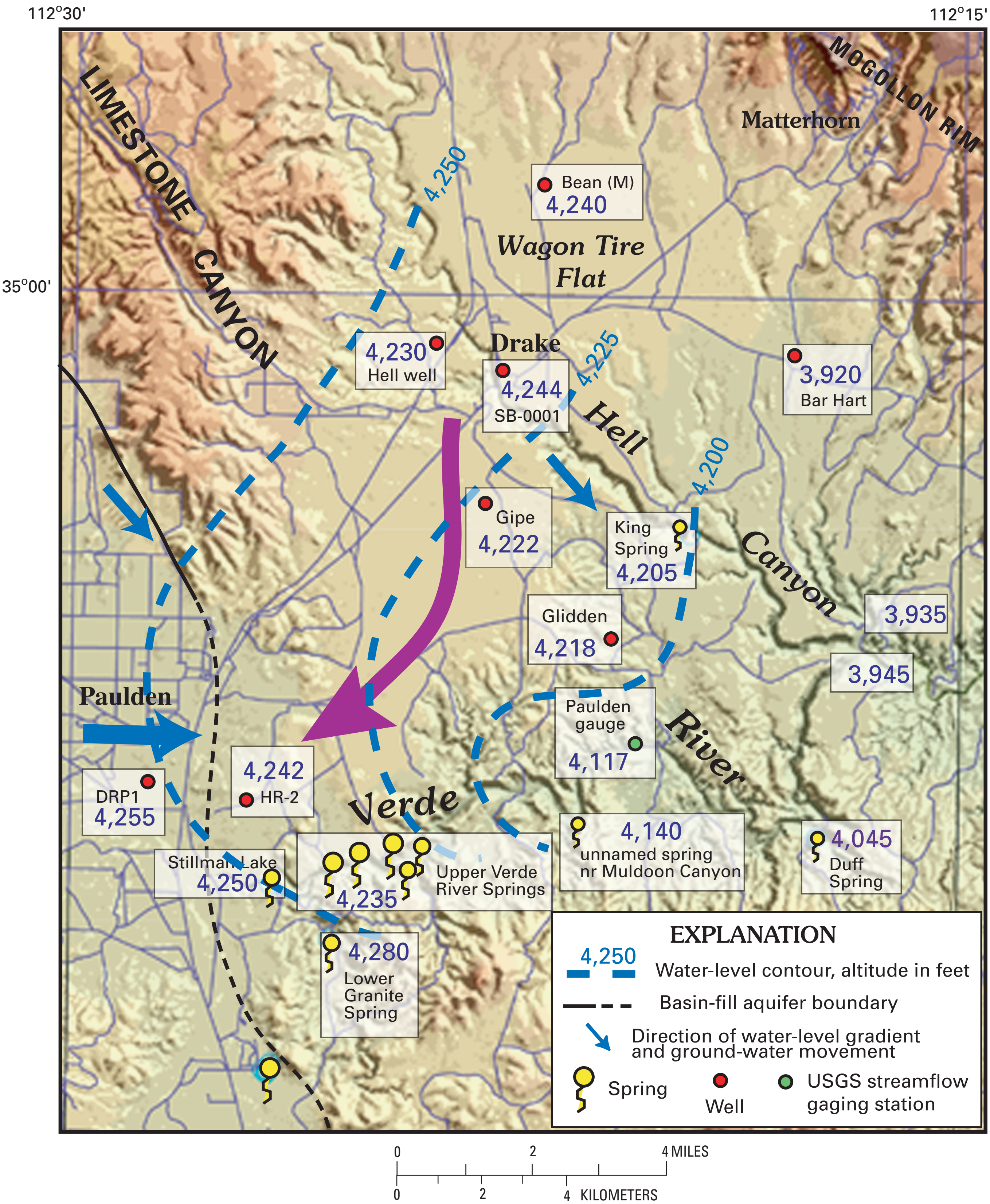


Figure D9. Water-level contour map for carbonate aquifer north of upper Verde River. Blue arrows indicate direction of ground-water movement. Two-sigma accuracy of water-level data within 20 ft (data in table D3). Purple arrow is approximate location of buried basalt-filled paleochannel (DeWitt and others, Chapter B, this volume). Base is from U.S. Geological Survey digital data 1:100,00.

Table D3. Water-level measurements for wells north of the upper Verde River. Well locations shown on fig. D9.

[ADWR = Arizona Department of Water Resources (2002), USGS = U.S. Geological Survey (Bills and Flynn, 2002), SGC = Southwest Groundwater Consultants (2002), WRA = Water Resources Associates (1990, 1991)]

Local ID	Well Name	Data Source	Registration No./Name	Land Surface Altitude	Well Depth	Water Level Date	Water Level Depth (feet)	Water Level Altitude (feet)
B-19-01 16aca	Bean	ADWR	55-645843	4790	720	8/4/1994	552.8	4237
	"	ADWR				3/19/1996	552.8	4237
	"	ADWR				11/1/1996	553.1	4237
	"	ADWR				10/17/1997	553.4	4237
	"	ADWR				10/23/1998	553.0	4237
	"	ADWR				5/21/1999	553.6	4236
	"	ADWR				10/22/1999	553.8	4236
	"	ADWR				3/28/2001	553.7	4236
A-19-01 33bbd	Bar Hart	ADWR		4460	585	7/26/1994	533.6	3926
	" "	ADWR				5/19/1999	540.1	3920
B-19-01 33ccc	SB-0001/Drake	SGC	55-586901	4650	700	7/1/2001	400.0	4244
B-18-01 06aba	Hells well	ADWR	55-631892	4631	460	2/22/2001	401.0	4230
B-18-01 17aaa	Gipe	ADWR	55-511557	4643	620	4/6/1993	420.6	4222
	" "	ADWR				4/12/1994	420.0	4223
	" "	ADWR				10/4/1995	419.8	4223
	" "	ADWR				3/19/1996	420.1	4223
	" "	ADWR				11/1/1996	420.7	4222
	" "	ADWR				10/17/1997	421.2	4222
	" "	ADWR				10/23/1998	421.1	4222
	" "	ADWR				4/19/1999	422.1	4221
	" "	ADWR				10/22/1999	422.2	4221
	" "	ADWR				3/28/2001	422.6	4220
B-18-01 27abc	Glidden	ADWR	55-631886	4407		4/12/1994	189.0	4218
	"	ADWR				4/19/1999	189.3	4218
B-17-02W02dcc1	HR-2	WRA	55-527679	4565.33	500	7/13/1990	323.3	4242
	"	ADWR		4570		6/12/2001	325.1	4245
	"	ADWR				10/15/2001	325.1	4245
B-17-02W02dcc2	HR-1	ADWR		4565	397	6/12/2001	319.0	4246
	"	ADWR				10/10/2001	318.9	4246
B-17-2 04cda	DRP1	WRA		4457	400	8/11/1989	102.0	4255
B-21-02 14bcc	Ash Fork #1, AF-06	USGS		5110	1700	12/1/1974	1000	4110
	" "	USGS				5/1/1984	999	4111
	" "	USGS				2/7/1986	1000	4110
	" "	USGS				2/13/1987	988	4122
	" "	USGS				1/27/1988	999	4111
	" "	USGS				10/17/1997	997	4113

or Martin, Chino Valley, or Tapeats at the bottom of the paleochannel (DeWitt and others, this volume). Any of these units typically would have maximum hydraulic conductivities comparable to fractured basalt, ranging from $1x10^2$ to $1x10^3$ (table D2). An aquifer test was conducted for 2 days at approximately 600 gpm, with 3.04 ft of drawdown (Water Resource Associates, 1991). Transmissivity was estimated to be 122,800 gallons per day per foot (gpd/ft) by the Theis type-curve method. The large transmissivity at well HR-2 is thought here to indicate a line source or boundary condition at constant head, such as recharge from a perennial stream (Lohman, 1979; p. 58-61; Theis, 1941), which in this case would be the nearby Verde River.

In short, well yields in the carbonate aquifer tend to be improved where the well intercepts basalt-filled drainages or the base of the Martin, or both. The Martin/Chino Valley/Tapeats stratigraphic interval is host to most of the springs in this region.

Table D2. Range in hydraulic conductivity of sediment and rock types found in Big and Little Chino basins (after Ewing and others, 1993).

Rock Type	Hydraulic conductivity (feet per day)	
	minimum	maximum
unfractured limestone	$5*10^{-4}$	$5*10^{0}$
fractured limestone	$5*10^{-3}$	$5*10^{2}$
unfractured basalt	$1*10^{-8}$	$1*10^{-4}$
fractured basalt	$1*10^{-2}$	$1*10^{3}$
unfractured sandstone	$1*10^{-3}$	$1*10^{2}$
coarse sand and gravel	$1*10^{3}$	$1*10^{5}$
medium sand	$1*10^{2}$	$1*10^{4}$
fine sand	$1*10^{-1}$	$1*10^{2}$
playa deposits	$1*10^{-6}$	$1*10^{-2}$

Basin-fill Deposits

Principal water-bearing units within Big and Little Chino basin-fill deposits consist of Tertiary volcanic rock and Quaternary and Tertiary sediment.

Tertiary deposits include alluvial fans, floodplain or playa sediments, basalt flows, lati-andesite flows, and intrusive lati-andesite. Tertiary sediment varies in particle size from clay to gravel depending on the environment of deposition and may be poorly consolidated. Floodplain and playa deposits near the center of the basins are fine-grained and difficult to distinguish from one another. The mineralogy of basin sediment varies substantially according to source area. Big Black Mesa and Juniper Mountains supply predominantly carbonate minerals, whereas the Bradshaw and Santa Maria mountain ranges and Sullivan Buttes provide predominantly silicate minerals.

Quaternary deposits include alluvial fans, colluvium covering hill slopes, floodplain terraces, and stream gravels. In the center of the basins, these young Quaternary surface deposits are commonly less than 50-ft thick. Thick alluvial-fan deposits are prevalent along the valley margins. Some of the largest fans along Big Black Mesa were initiated in the Late Tertiary and extend at least 500-ft deep (Bureau of Reclamation borehole CV-DH-3; in Ostenaa and others, 1993, and shown in Chapter B, fig. B3).

All of the stratigraphic facies described above are unevenly distributed, creating a heterogeneous aquifer. For example, buried Tertiary basalt flows facilitate movement of ground water in northwest and southeast Big ChinoValley. The presence of lati-andesite intrusives in Little Chino Valley may confine older sediment, creating artesian conditions. Paleozoic carbonate rocks may be hydrologically connected with alluvial sediments and Tertiary basalt flows in areas where they underlie and adjoin the basins. The hydraulic conductivity of different rock types and alluvium varies greatly within each major aquifer.

Table D2 lists hydraulic conductivity values compiled from the literature by Ewing and others (1994) for the Big Chino basin-fill aquifer and adjoining carbonate aquifer. The hydraulic conductivity, reported in feet per day (ft/d), is the rate at which a rock or sediment unit transmits water. These values span more than ten orders of magnitude. Within the Verde headwaters, the hydraulic conductivity may be as high as $1x10^3$ ft/d (basalt) or $5x10^2$ ft/d (limestone). Hydraulic conductivity for coarse sand and gravel ranges from $1x10^3$ ft/d to $1x10^5$ ft/d. Tertiary basalt ranges in texture from unfractured and relatively impermeable, to columnar and extremely fractured. Karst solution features are commonly observed in Paleozoic limestone and dolomite. Secondary porosity in the limestone and basalt accounts for several high-yielding wells in the Paulden area.

Big Chino Basin-Fill Aquifer

Big Chino Valley is an elongate, fault-bounded basin that is at least 2,300 ft deep in the center and shallower around the northwest, southeast, and southwestern margins (Langenheim and others, Chapter C, this volume). Big Chino Valley owes its long, narrow configuration to the northwesterly strike of the Big Chino Fault. Displacement along the fault places basin deposits against granitic basement rock, creating a relatively impermeable basin boundary along most of Big Black Mesa, except where there is little displacement against Paleozoic carbonate rocks north of Paulden. Extensive fine-grained carbonate in the center of Big Chino Valley is interpreted as having formed in a lacustrine playa (DeWitt and others, this volume). Williamson Valley, the largest tributary subbasin, is at least 1,500 ft deep in the center and shallower near its edges (Langenheim and others, Chapter C, this volume). Depth to water in both Big Chino and Williamson Valleys is typically between a few ft and 200 ft below land surface (Wallace and Laney, 1976; Schwab, 1995). The Big Chino basin-fill aquifer is capable of storing large amounts of ground water (Krieger, 1965; Water Resource Associates, 1990; Ostenaa and others, 1993; Ewing and others, 1994).

The major lithological units within the Big Chino basin-fill aquifer include (a) buried basalt flows in the northwest and southeast parts of the basin, (b) thick fine-grained playa sediment in the basin center, and (c) other basin-fill sediment. These are discussed in greater detail next.

Tertiary Basalt Flows

Basalt flows in southeast Big Chino Valley originated north of Paulden or east of Sullivan Lake (DeWitt and others, this volume). Three flows are exposed east of Sullivan Lake in the modern Verde River canyon. A 4.5-Ma basalt flowed down a paleochannel (penetrated by well HR-2) in the carbonate aquifer. The basalt is as much as 400-ft thick within a narrow paleochannel about 1 mi north of the upper Verde River. The basalt flows widened and thinned as they flowed into Big Chino Valley and were subsequently buried by younger Tertiary alluvium (DeWitt and others, this volume, fig. B8). Basalt can be traced in well logs sloping toward the center of the basin, to a depth greater than 500-ft west of Wineglass Ranch. The basalt thins to less than 90 ft where last detected. Basalt flows reached the Sullivan Buttes latiandesite on the south and the Paleozoic rock along the Big Chino Fault to the north.

Wells that penetrate the basalt flow in southeast Big Chino Valley are capable of very large yields, as demonstrated by a 400-ft uncased supply well (known as the Dugan well or DRP1) located inside the basin about 1 mi northeast of Sullivan Lake at (B-17-02) 04cda (fig. D9 and table D3). Water Resources Associates (1990) conducted an aquifer test of DRP1 with a pumping rate of 5,000 gpm for 7 days that resulted in 3.31 ft of total drawdown. The calculated rate of transmissivity and specific yield are 220,000 gpd/ft and 0.29, respectively (Water Resource Associates, 1990; phase IV, v. V, p. 14), which makes this well one of the highest yielding in Big Chino Valley.

The hydrogeologic setting for DRP1 is best interpreted from the deeper monitoring well (DRM2) at the site that was drilled to a depth of 600 ft. The borehole encountered alluvium from land surface to 125 ft, followed by an upper and a lower basalt flow between 125 and 350 ft, underlain by Tertiary alluvium from 350 to 600 ft. From 185 to 285 ft the driller lost circulation in a reddish-brown basalt layer. Lost circulation is often an indication of openings, such as columnar fractures or rubbles zones. The three piezometers that were nested inside the monitoring well casing were screened in the upper basalt, lower basalt, and underlying alluvium, respectively. During the aquifer test, the difference in water levels for the three stratigraphic units was slight (< 0.52 ft), and amount of the drawdown for each well was similar in response to pumping stress (Water Resources Associates, 1990), an indication that the upper and lower basalt flows are hydrologically connected with one another, as well as with the underlying Tertiary alluvium.

The DRP1 and HR-2 supply wells are interpreted as penetrating the same sequence of basalt flows, although DRP1 is completed within the basin-fill aquifer, and HR-2 penetrates a basalt-filled paleochannel in the carbonate aquifer north of the Verde River. Both are highly productive wells that lost circulation at approximately the same elevation during drilling and produce water predominantly from fractured basalt. At both locations, the small amount of drawdown during aquifer testing is an indication that the basalt units are hydrologically connected with adjoining carbonate or sediment units.

Buried basalt also is present in northwestern Big Chino Valley. The basalt originated either in the Partridge Creek or Juniper Mountain areas and flowed into Big Chino Valley, where it subsequently has been buried by younger alluvial deposits (DeWitt and others, this volume). In upper Big Chino Valley, there are no drillers' logs for wells that fully penetrate or produce directly from the buried basalt. At (B-19-04)03bcd on CV Ranch, a well intercepted basalt at about 730-ft below land surface. The well is screened in the overlying alluvium, thus little can be said about the water-bearing characteristics of the basalt at this location.

Playa Deposit

The center of the basin contains a thick sequence of fine-grained carbonate sediment formed in a playa environment (Ostenaa and others, 1993; DeWitt and others, Chapter B, this volume). The center of the basin is thought to contain at least 2,300 ft of sediment, but basin thickness (and inferred playa thickness) diminishes toward the margins of the basin. The fine-grained carbonate sediment is composed of as much as 80 percent calcite, dolomite, and analcime, and <15 percent quartz, feldspar, illite, and bloedite(?) (DeWitt and others, this volume). Bloedite is a sulfate mineral that forms under evaporative conditions. A lack of halite and gypsum in the sediment suggests less saline conditions than those that formed the closed-basin playa in Verde Valley during deposition of the Verde Formation, however, mineralogical analyses have been completed only for selected cuttings from three Bureau of Reclamation deep boreholes.

The playa has a lower hydraulic conductivity than other alluvial deposits (table D2) but does not extend far enough across the valley to create a barrier to ground-water movement, either down the axis of Big Chino Valley or across the outlet of Williamson Valley (Ostenaa and others, 1993; Ewing and others, 1994; p. 28). Coarser-grained material was found above latite in the bottom of borehole CVDH-3 penetrating the playa (Chapter B, this volume), suggesting more permeable sediment may be present beneath the playa. In addition, the playa deposit presumably is underlain by Paleozoic carbonate rock in some places, and thus movement of water beneath the playa through karst openings is possible. The lack of change in the slope of water levels between northwest and southeast Big Chino Valley (Wallace and Laney, 1976; Schwab, 1995; fig. D8) is considered compelling evidence that the playa does not form an impassable barrier between these areas.

Other Basin-Fill Alluvium

With the exception of the playa deposit, other types of alluvial basin-fill deposits in the Big Chino aquifer are fairly heterogeneous with respect to grain size, ranging from clay to boulders. Williamson Valley supplies mostly silicate minerals (quartz) and feldspar from the granites, gneisses, and volcanic rocks in the Santa Maria Mountains, Mint Wash, and Sullivan Buttes areas. Physical and chemical weathering of quartz and feldspar tends to produce relatively sandy, permeable sediment. Partridge Creek and the Juniper Mountains contribute both carbonate detritus and basalt to upper Big Chino Wash. Big Black Mesa is the largest source of carbonate sediment. In general, carbonate rocks dissolve to produce finer-grained, relatively less permeable sediment than sediment derived from silicate sources. Grain size also is related to other factors, however, such as the length of time and intensity of surficial weathering and the distance the particle has been physically transported from its source area. Stream sediment in southeast Big Chino Wash is an integrated mixture of granitic, volcanic, and carbonate debris from upland source areas.

Hydraulic conductivity of unconsolidated sand and gravel may span five orders of magnitude, ranging from 0.1 to 10,000 ft/day (table D2). Alluvial fans, colluvium covering hill slopes, stream gravels, and flood-plain terraces are common along major stream drainages. Quaternary surface deposits are commonly less than 50-ft thick. Most driller's logs that would be described as "alluvial wells" typically penetrate the shallow surfacial deposits to produce from underlying Tertiary sediments. Substantial quantities of ground water may be produced from wells completed in these deposits.

Large diameter production wells near Big Chino Wash in upper Big Chino Valley commonly produce between 1,000 and 4,000 gpm (Water Resources Associates, 1990). Many of these irrigation wells are old and lack driller's logs. In general, most of these wells are less than 700 ft in depth. The wells probably are screened in alluvial deposits above the buried basalt units (where present), but some wells may intercept basalt layers in the part of the valley upgradient from the confluence of Pine Creek and Big Chino Wash. Water Resources Associates (1990) drilled a monitoring well and conducted an aquifer test on a relatively deep supply well on the CV Ranch at (B-19-04)03bcd. This aquifer test provides some of the best descriptions regarding water-bearing characteristics of alluvial wells in upper Big Chino Valley.

A 7-day aquifer test of production well CVP1 was conducted at a rate of 3,000 gpm and resulted in 63.12 ft of drawdown. The calculated rate of transmissivity and specific yield are 157,000 gpd/ft and 0.36 (dimensionless), respectively (Water Resource Associates, 1990; p. 13 phase IV, v. V). The 700-ft production well is 55 ft north of the monitor well (CVM1). CVP1 has a screened interval from 107 to 698 ft, and a saturated thickness of 638 ft. CVM1 was drilled to a total depth of 744 ft, penetrating basalt at 730 ft (Water Resources Associates, 1990). The upper 710 ft of sediment were mostly described as "silty clay" or "clayey silt." The basalt is overlain by 20 ft of "granitic and basaltic sand and gravel." The monitoring well was completed at a bottom depth of 700 ft, and is screened from 612 to 697 ft below land surface. Although both wells are screened in mostly fine-grained alluvium, it is not clear whether the high well yield should be entirely attributed to the fine-grained sediment. Some of the high yield could be derived from underlying coarse-grained basalt gravels or possibly from high secondary porosity in basalt.

Little is known about the extensive basin-fill deposits below about 700 ft in Big Chino Valley, including grain size, degree of consolidation, and degree of hydraulic confinement, if any. Nor is much known about the extent of interfingering between the playa deposit and basin-fill alluvium, or the full occurrence of the buried basalt flows. Less is directly known about a presumed hydraulic connection with the underlying carbonate aquifer at the base of the basin-fill deposits. Most wells are relatively shallow compared to total basin depth, and no wells fully penetrate the center of the playa or the basalt flows in middle and northwestern Big Chino Valley.

Little Chino Basin-Fill Aquifer

In general, the Little Chino basin-fill aquifer is not as deep or narrow as Big Chino Valley. Thickness of the aquifer increases from southwest to northeast, with its greatest thickness locally in excess of about 700 ft near Del Rio Springs (Langenheim and others, Chapter C; fig. C3). Many drillers' logs are available surrounding the town of Chino Valley (ADWR, 2002); however, the subsurface geology is quite complex owing to the irregular distribution of buried volcanic extrusive rocks, volcanic-clastic sedimentary rocks, and basalt flows (DeWitt and others, Chapter B, this volume).

Ground-water movement across the basin-fill aquifer boundary is known to occur in two locations where basement rock is absent. Along the southeastern aquifer boundary, the interface between the Little Chino and Agua Fria basin-fill aquifers consists of about 700-ft of predominantly sedimentary deposits. Overpumping in the Chino Valley and Prescott Valley areas may be shifting the ground-water divide between these two aquifers. The second location of ground-water movement across the basin-fill aquifer boundary is the groundwater outlet northeast of Del Rio Springs and Little Chino Creek. Not all ground water discharges at Del Rio Springs; some underflow continues north. The northeastern boundary of the basin-fill aquifer with the carbonate aquifer consists of moderately permeable rocks that are exposed along Stillman Lake and Lower Granite Creek (DeWitt and others, Chapter B, this volume; figure B8; see also Chapter A, figs. A8 and A15).

Depth to water ranges from land surface at Del Rio Springs (elevation 4,450 ft) to about 100 ft (elevation 4,550 ft) beneath the town of Chino Valley (Corkhill and Mason, 1995, *their* fig. 17). The main artesian zone beneath Chino Valley extends north to Del Rio Springs for a distance of at least 6.5 mi and has a width of about 4 mi (Schwalen, 1967). The artesian part of the aquifer is highly productive, with many wells discharging 1,000 to 3,000 gpm (Corkhill and Mason, 1995).

In the northern part of Little Chino Valley, water from artesian wells used to flow at the land surface. Remick (1983) reported seven flowing wells in the winter of 1981–82. Historically, hydraulic head in the main artesian zone has been approximately 100 ft higher than the shallow unconfined part of the aquifer near the town of Chino Valley, although water levels have been steadily declining (Arizona Department of Water Resources, 2000).

A correlation has been observed between pumping from wells in the artesian zone and discharge at Del Rio Springs. Schwalen (1967) describes a lag time of 6 hours between pumping of deep wells near Del Rio Springs and a 0.74 ft^3/s reduction in streamflow near the present-day USGS gauge (09502900; see Chapter A, table A3; shown on fig. A6). In addition, Allen, Stephenson & Associates (2001) evaluated USGS gauge data, metered wells, recorded irrigation activities, and a series of aquifer tests to assess whether water pumped from the confined aquifer on other parts of the Del Rio Ranch had a direct relation with flow at Del Rio Springs. Their study concluded that pumping in the northern part of the basin had a “direct, immediate, and quantifiable impact” on the discharge at the gauge.

Corkhill and Mason (1995) divided the Little Chino basin-fill deposits into an upper alluvial unit and a lower volcanic unit. The upper unit was considered a water-table aquifer, and the lower aquifer unit was considered hydrologically distinct and artesian. DeWitt and others (this volume) have identified confining conditions in shallow alluvium, as well as in underlying volcanic and sedimentary rock units. These confining conditions are irregularly distributed and discontinuous. Therefore, the shallow alluvium and underlying stratigraphic units are presumed hydrologically connected, and the single aquifer system is complex. Depending on location, ground water within the basin-fill aquifer is under either confined or unconfined conditions. Artesian flow can be produced from several different geologic settings. These settings include (a) trachyandesite overlying small pockets of irregularly distributed sediment, (b) volcanic-clastic sequences within the lati-andesite, (c) lati-andesite over sedimentary rock or alluvium, (d) permeable basalt beneath strongly cemented alluvium, and (e) unconsolidated alluvium beneath cemented alluvium. The Little Chino basin-fill deposits are discussed in detail next, in order from oldest to youngest formation.

Paleozoic Rocks

Few wells penetrate Paleozoic rocks in the northern part of Little Chino Valley, and regional interpretation by DeWitt and others (in press) indicates that only minor thicknesses (less than 100 ft) of Paleozoic rocks should be found in the subsurface of far northern Little Chino Valley. South of the town of Chino Valley, and extending to Prescott, Paleozoic rocks are unknown in southern Little Chino Valley and in Lonesome Valley.

Older Sedimentary Rocks

A paleochannel 4-mi wide and as much as 230 ft thick underlies lati-andesite in outcrop east and north of Del Rio Springs, outside the basin boundary (DeWitt and others, this volume; fig B2 unit Tos). The channel is filled with poorly-sorted to well-sorted conglomerate, gravel, and finer-grained sediment derived from the southwest. The paleochannel is vertically offset by faulting at the basin boundary. Within the basin, the paleochannel extends southwest beneath northern Little Chino Valley and the town of Chino Valley. Its full extent farther southwest is unknown because of cover by younger rock units. Sediment in the paleovalley is poorly and moderately cemented and is interpreted to have high permeability. In southern Little Chino Valley, these sediments are thought to be hydrologically connected to overlying sediment in the Hickey Formation, which extends south to Prescott and the Bradshaw Mountains.

Lati-andesite

Flows, breccias, and intrusive centers of 24-Ma lati-andesite underlie much of northern Little Chino Valley at depth, below the Hickey Formation. Locally, rocks of the Hickey may be absent where topographic highs related to intrusive centers of lati-andesite are present. Thickness of lati-andesite is highly variable, but is greatest (~650 ft) near intrusive centers that are resistant to erosion. Breccias, deposits of cinders, and tuffaceous rocks of lati-andesite composition are moderately permeable and are interbedded with flows that are much less permeable. Intrusive centers are interpreted to have low permeability, due to their unfractured nature. Very few wells go completely through the lati-andesite. Impermeable lati-andesite probably confines the underlying older Tertiary sedimentary rocks. Intrusive centers form impermeable plugs that divert water flow up and away from underlying Tertiary sedimentary rocks and from deposits of breccia, cinders, and tuffaceous rocks. Some of the central artesian field near the town of Chino Valley probably is created by barriers of unfractured lati-andesite.

Hickey Formation Volcanic and Sedimentary Deposits

Flows of basalt and trachyandesite underlie the alluvial deposits in parts of the basin. In the southwestern part of the basin, southwest of the town of Chino Valley, a trachyandesite flow can be traced from outcrop in the Sullivan Buttes to the southern limit of the artesian field (DeWitt and others, Chapter B, this volume, fig. B7). The 130-ft thick flow appears to have been derived from a northwest-striking, high-angle feeder dike. Trachyandesite does not contain as many cooling cracks and through-going fractures as basalt, so the flow serves as a local confining layer to uncemented sediment in the Hickey Formation beneath the flow. Farther south, a basalt flow extends, at the surface, from near Table Mountain to highway 89. The flow is as much as 330 ft thick and overlies sediment in the Hickey. Some deep wells south of Del Rio

Springs penetrate as much as 150 ft of basalt in paleovalleys cut into the underlying lati-andesite. This basalt could be Hickey in age or it could be 8–10 Ma. Alluvial deposits within the Hickey were deposited in sinuous, narrow valleys whose locations are difficult to map. Sediment thickness varies from 30 to 100 ft.

Thin lenses of poorly sorted sediment probably underlie Hickey trachyandesite in the southern part of Little Chino Valley. The trachyandesite may form a confining layer above this sediment and above volcaniclastic sediments associated with lati-andesite. Many of the shallowest artesian wells in middle Little Chino Valley appear to have penetrated the trachyandesite and produced water from pockets of alluvium and lati-andesite below. These volcanic units are irregularly distributed, and there are not enough deep drillers' logs to make detailed interpretations in these areas.

Quaternary to Late Tertiary Alluvial Deposits

Diverse sedimentary units in northern Little Chino Valley above the youngest Tertiary volcanic units include proximal and distal fanglomerate, fine-grained clastic valley fill, and local alluvium distributed along old stream courses. Thickness of the sedimentary units is highly variable due to the underlying volcanic field of Hickey basalt and lati-andesite (DeWitt and others, Chapter B, fig. B12) and varies from less than 100 ft southwest of the town of Chino Valley to more than 650 ft near Del Rio Springs. Much of the fine-grained sedimentary fill is poorly lithified and cemented and is inferred to have moderate or higher permeability. Fanglomerates derived from the Sullivan Buttes west of Del Rio Springs are locally highly cemented in discontinuous zones as much as 30 ft thick on the northwestern side of northern Little Chino Valley. These highly cemented units form locally confining layers above clastic sediment of late Tertiary age. Wells in (B-17-02)34 and (B-16-02)3 produce from sediment beneath the cemented fanglomerate.

Most wells completed in the shallow alluvium are used for domestic and stock purposes, and well yields cannot be determined (Allen, Stephenson & Associates, 2001). Estimated hydraulic conductivities range from 1 to 200 ft/day and average 9 ft/day (Corkhill and Mason, 1995). Historically, the shallow alluvium has received recharge from irrigation return flows (Schwalen, 1967).

Water-Level Gradients of Major Aquifers

Water-level gradients provide an indication of the directions of ground-water flow in an aquifer. Water-level contour maps of the Big and Little Chino basin-fill aquifers that were constructed in the early 1990s are represented in fig. D8. Water-level data are sparse for the carbonate aquifer north of the upper Verde River, shown within the area of the inset map rectangle (Levings and Mann, 1980; Owen-Joyce and Bell, 1983). In the following section, available water-level data and gradients are evaluated in relation to the hydrogeologic framework of the major aquifers, as presented thus far in this chapter.

Big Chino Basin-fill Aquifer

Ground-water movement in Big Chino Valley follows a curved axis from northwest to southeast (fig. D8). From an elevation of about 4,525 ft near the mouth of Partridge Creek to 4,255 ft near Paulden (Schwab, 1995; Water Resources Associates, 1990), the water-level gradient is gentle, dropping about 270 ft in 22 mi or an average of 12 ft/mi. In Williamson Valley, the gradient drops from 4,600 ft near the northeast flank of Granite Mountain to 4,455 ft at the USGS gauge on Williamson Valley Wash, or an average of 28 ft/mi in 5 mi. The depth to ground water in Big Chino Valley, Williamson Valley, and Walnut Creek ranges from the surface to 250 ft below land surface (Schwab, 1995). Depth to water is largely dependent on topography and, therefore, is shallow near the center and increases towards the basin margins. Ground water typically is less than 25 ft below land surface beneath Big Chino Wash from its confluence with Pine Creek to Antelope Creek, and beneath Williamson Valley Wash from the Seven V Ranch to the USGS streamflow gauging station 09502800 (Schwab, 1995). The direction of ground-water movement is perpendicular to water-level contours, as indicated by the arrow directions in fig. D8. Around the perimeter of Big Chino Valley, ground-water flowpaths generally follow major surface-water inflows (such as Williamson Valley and Pine Creek) from the margins toward the valley center. In the center of the basin, ground water travels above, around, and possibly beneath the playa deposit.

Large alluvial fans along Big Black Mesa overlie the playa deposit in the center of the basin. The fans extend basinward from Big Black Mesa for 2.4 mi (DeWitt and others, this volume). Alluvial fans overlie the playa deposit from a depth of less than 30 ft in the center of the basin to as much as 500 ft along the Big Chino Fault (Ostenaa and others, 1993). Most of the wells on the alluvial fans are relatively shallow and produce from above the playa deposit. Depth to water in the alluvial fan area overlying the playa is relatively shallow, ranging from 11 to 170 ft below land surface (Schwab, 1995). Ground-water contours approximately follow the topography of the coalescing fans, sloping away from Big Black Mesa toward Big Chino Wash.

On the southwest side of Big Chino Valley, the sandier sediments across the wide outlet of Williamson Valley provide greater permeability and a faster rate of ground-water flow than would a direct route through the center of the playa. Here, the main ground-water flowpath down the axis of the valley is west of Big Chino Wash and the edge of the playa. Few data are available to demonstrate whether a secondary component of ground-water movement occurs through Tertiary volcanic rocks and Paleozoic sedimentary rocks that underlie the playa, or through alluvial fan deposits along the down-dropped side of the Big Chino Fault.

The main ground-water flowpath approximately underlies Big Chino Wash in the upper part of the basin but deviates from Big Chino Wash in the center and southeastern part of the basin. Ground-water contours curve gently south and west of Big Chino Wash from its confluence with Pine Creek to Antelope Creek, where the main axis of flow again curves back towards the valley center. There is a narrow low-lying region, or saddle, in the water table trending from southwest to northeast between Wineglass Ranch and Paulden, possibly caused by well pumping. The saddle is too small to show with 100 ft contour intervals (fig. D8), but is defined by eight wells with measured water levels < 4,260 ft (Schwab, 1995).

The lowest point of the water table is in the southeastern part of the basin north of Paulden where basalt and carbonate rocks are concealed by alluvium (DeWitt and others, this volume; fig. B8). In addition to buried basalt, ground-water movement down the valley is probably influenced by eastward thinning of the basin-fill deposits, and by the shallow underlying carbonate aquifer (DeWitt and others, this volume; fig. B8). North of Paulden along the horsetail splays that mark the terminus of the Big Chino Fault, the thickness of basin-fill deposits overlying the carbonate aquifer is less than 400 ft.

The Big Chino basin-fill aquifer drains through the carbonate aquifer north and east of Paulden, rather than southeast beneath the surface-water outlet at Sullivan Lake. The flowpath may be diverted northward by mounding of the water table beneath Sullivan Lake (Water Resource Associates, 1990). The mounding is caused by from recharge of impounded surface-water runoff from Big and Little Chino Valleys. Proterozoic basement is relatively shallow south of Sullivan Lake (DeWitt and others, Chapter D, this volume) and is thought to block much of the northward flow from the Little Chino basin-fill aquifer. The water-level elevation for the Big Chino basin-fill aquifer near Paulden is about 4,255±10 ft, (for a well at (B-17-02)04cda; Water Resource Associates, 1990; table D3); which is about 20 ft higher than the altitude of upper Verde River springs (4,235±1; river mi 2.3).

The elevation of first perennial flow at upper Verde River springs that is used in this report is 4,235±1 ft as determined by a high-vertical resolution, or "survey grade" global positioning survey (Maurice Tatlow, Arizona Department of Water Resources, written commun., 1999). This compares favorably with a measured elevation of 4,233±1 for the water surface of the upper Verde River on April 29, 1991 with a level and rod survey, at an imprecise location described as below the confluence of Granite Creek at river mi 2.5 (Water Resources Associates, 1991). The elevation of the largest spring, located against the north canyon wall, is a few ft higher than the water surface of the river indicating artesian conditions. The water-level gradient between the Big Chino basin-fill aquifer and upper Verde River springs is less than 10 ft/mi.

Little Chino Basin-fill Aquifer

Granite Creek is the major surface-water drainage, and the largest potential source of ground-water recharge to the Little Chino basin-fill aquifer. The main ground-water flowpath is from south to north beneath Granite Creek in the central part of the alluvial basin (4,600 ft contour; fig. D8). Northward movement is blocked by rugged outcrops of Proterozoic rocks along lower Granite Creek, including Mazatzal Quartzite and Tertiary lati-andesite (Wirt, this volume; fig. A8). Ground water travels northwest towards Chino Valley, and then north toward Del Rio Springs (4,425 ft), a gradient of about 175 ft in 3 mi, or about 58 ft/mi. Del Rio Springs and Little Chino Creek are the discharge zone for both the artesian and unconfined aquifer units, with hydraulic head in the artesian parts of aquifer higher than that under water-table conditions (Schwalen, 1967; Matlock and others, 1973; Corkhill and Mason, 1995; Allen, Stephenson & Associates, 2001). During predevelopment conditions, the hydraulic head in the deepest part of the aquifer was as much as 100 ft greater than the head in shallow part of the aquifer (Corkhill and Mason, 1995; Remick, 1983). The difference in head indicates that deeper water-bearing units receive recharge at higher altitudes, which is consistent with a major recharge area beneath the ephemeral reach of Granite Creek southeast of the town of Chino Valley.

Buried plugs of lati-andesite increase in abundance north of Del Rio Springs. The lower permeability of these intrusive rocks restricts subsurface movement of ground water in the lati-andesite and paleochannel conglomerate, partly accounting for discharge at Del Rio Springs. In addition, there is an abrupt decrease in the width and thickness of the aquifer system. The occurrence of younger alluvium north of Del Rio Springs is limited to a narrow neck of shallow alluvium along Little Chino Creek, underlain by lati-andesite and shallow basement. The least restrictive ground-water flowpath is northeast of Del Rio Springs (elevation 4,425) toward moderately permeable Paleozoic rock and lati-andesite exposed along Stillman Lake and lower Granite Spring (at elevations 4,250 and 4,280 ft, respectively). The beginning of the spring-fed reach in lower Granite Creek coincides with the location of two small northeast-striking faults in Paleozoic rocks shown at the 1:48,000 scale by Krieger (1965). Between Del Rio Springs and springs in lower Granite Creek and Sullivan Lake, the water table or potentiometric surface drops 145 ft over a distance of 1.5 to 2 mi, a gradient of 70 to 100 ft/mi.

Carbonate Aquifer

The regional carbonate aquifer north of the upper Verde River and Big Chino Valley straddles the Colorado Plateau and the Transition Zone provinces (fig. D2). North of the Transition Zone boundary, sedimentary rocks are relatively flat and unbroken, and movement of ground water is north or northeast toward Cataract Canyon and the Colorado River. South of the Transition Zone boundary, ground water in the carbonate aquifer is captured by the upper Verde River and Big Chino Valley. In comparison to the Colorado Plateau, carbonate rocks in the Transition Zone have undergone a greater intensity of faulting, folding, and erosion. Consequently, ground water within the aquifer is more likely to be compartmentalized or confined in some locations.

In northern Arizona, prominent northwest-striking fractures throughout the Colorado Plateau area tend to be open to fluid flow (Thorstenson and Beard 1998; L. S. Beard, oral commun., 1999). In the study area, the largest structures most likely to influence ground-water movement include the Big Chino Fault and Limestone Canyon Monocline—which roughly parallel one another and strike northwest. These structural flexures and faults have influenced topography and drainage patterns of the exposed sedimentary rocks within the Transition Zone. Stratigraphic contacts and bedding planes also may provide conduits for flow.

Secondary porosity from fractures and karst near the base of the Martin are recognized as an important pathway. The pattern of subsurface karst dissolution is nearly impossible to discern, however, except where large caves allow underground exploration, such as in nearby Grand Canyon (Huntoon, 1970). Karst often approximately follows major faults and dominant fracture patterns, which here include northwest-striking structures such as the Big Chino Fault and the Limestone Canyon Monocline. Alternately, some karst pathways may follow primary depositional features such as the collapse and rubbles zones in the Redwall Limestone. Preferential dissolution also could have occurred along segments of basalt-filled paleochannels that are exposed in the walls of Hell Canyon and noted in driller's logs north of the upper Verde River (DeWitt and others, this volume). Paleocanyon walls would have been weathered before the basalt was emplaced. In addition, permeability of the basalt is high (table D1). Any combination of these pathways through the carbonate aquifer is possible.

Ground water in a large carbonate aquifer typically will discharge to one or a few large springs. Within the study area, the carbonate aquifer discharges to the base of incised limestone canyons at Storm Seep on Big Black Mesa, upper Verde River springs, King Spring in Hell Canyon, Mormon Pocket, and Sycamore Canyon. Although the pattern of karst may seem random, the source area must be upgradient from the point of discharge. Ground-water flowpaths within the carbonate aquifer can be inferred in part from topography, geologic framework, well information, and the locations of springs.

Big Black Mesa and the Ground-Water Divide

The crest of Big Black Mesa is a ground-water divide for the carbonate aquifer between the Colorado Plateau and the Transition Zone. The location of the ground-water divide is inferred here on the basis of the geologic framework and limited water-level data. Relevant features important to the hydrogeologic framework include (a) northwest-striking faults, monclines, and fracture trends, (b) the stratigraphy and dip of the sedimentary rock units, and (c) karst dissolution openings.

Displacement along the Big Chino Fault places basin deposits against granitic basement rock, creating a relatively impermeable basin boundary along most of the base of Big Black Mesa except near Paulden. The large area north of the Big Black Mesa has the topographic and structural characteristics of the Colorado Plateau. Streams and washes flow toward Partridge Creek and upper Big Chino Wash, which are ephemeral (Myers, 1987). North of I-40, ground water follows the gentle northeast dip of the Paleozoic strata, more or less perpendicular to the regional strike (Twenter, 1962, p. 22; Myers, 1987; McGavock, 1986; Montgomery and Associates, 1996). This direction may be locally modified by karst or structural features. Surface-water runoff on the Colorado Plateau overlying the carbonate aquifer infrequently reaches Big Chino Valley. Little if any ground-water recharge to Big Chino Valley is likely north of the ground-water divide, which approximately follows the crest of Big Black Mesa.

High-altitude springs on Big Black Mesa may or may not be perched, but their presence above the floor of Big Chino Valley suggests that the water table or the potentiometric surface is mounded beneath topographic highs. Four high-altitude springs around the perimeter of Big Black Mesa range in elevation from 5,000 to 5,700 ft (fig. D4). There are no wells on Big Black Mesa, although water-level measurements from eight wells northwest of Big Black Mesa near Partridge Creek and Pichacho Butte range from 4,541 to 4,636 ft (Bills and Flynn, 2002). Water-level measurements from deep municipal wells along I-40 near the towns of Ash Fork (4,095 to 4,114 ft) and Williams (between 3,900 and 4,100 ft) (Arizona Department of Water Resources, 2002; Bills and Flynn, 2002; Pierce, 2003) are substantially lower than water-level altitudes ranging between 4,205 ft at King Spring and 4,230 to 4,244 ft near Drake (table D3).

In comparison, measured water levels throughout Big and Little Chino Valleys and in the carbonate aquifer north of the upper Verde River all exceed 4,235±1 ft in altitude—at least 100 ft greater than the elevation of measured water levels in the carbonate aquifer near Ash Fork and Williams. The ground-water divide between the Transition Zone and the Colorado Plateau is inferred to continue northeast of Big Black Mesa, toward the Matterhorn and Bill Williams Mountain, approximately following the northern boundary of the Transition Zone (figs. D1 and D2). The precise location of the ground-water divide between Drake and Ash Fork is uncertain, but is thought to approximately follow the northern Transition zone boundary for the carbonate aquifer (shown in fig. D2). This interpretation agrees with the northern aquifer boundary for the Big Chino basin-fill aquifer as depicted by Robson and Banta (1995). Water levels surrounding Bill Williams Mountain range from about 3,860 for the regional aquifer to 4,900 ft for perched conditions (Arizona Department of Water Resources, 2002; Bills and Flynn, 2002; Pierce, 2003).

Carbonate Aquifer North of Upper Verde River

In the Transition Zone north of the upper Verde River, the regional direction of ground-water movement in the carbonate aquifer is east or southeast, as inferred from water-level altitudes of gaining reaches of the upper Verde River (see fig. A14, Chapter A), springs, and wells in the carbonate aquifer north of the river (fig. D9 and table D3). New water-level measurements collected since 1993 include twice as many wells and spring locations for this area than in previous studies (Owen-Joyce and Bell, 1983; Levings and Mann, 1980). The vertical accuracy of most land-surface elevations was estimated from USGS 7.5-minute quadrangle maps having 20-ft topographic contours, and, therefore, individual water-level data are presumed accurate to within ±10 ft. Two of the new sites are index wells in the Arizona Department of Water Resources monitoring program, which are measured annually. The index measurements have changed little from year to year, varying less than 2.0 ft over an 8-year period.

Water-level elevations in the carbonate aquifer directly north of upper Verde River springs vary between 4,244 and 4,205 ft in elevation, a range of about 40±10 ft. This area, which lies between the 4,250 and 4,200 ft contours (fig. D9), extends from Paulden on the west to Drake on the north, and from King Spring on the east to the upper Verde River to the south. The small range in variability of the water-level measurements for this area is notable despite the fact that different parties collected to data in different years, using different methods and equipment, and in that topographic relief varies more than 400 ft (fig. D9 and table D3). From west to east along the gaining reach of the Verde River, the water-level gradient slopes from about 4,255 ft near Paulden to 4,130 ft near Muldoon Canyon, a gradient of about 25 ft/mi. From north to south, the water-level gradient changes less than 5 ft/mi between Drake and upper Verde River springs. Owing to little well control, the 4,250 ft contour could extend farther north of Drake, or farther northwest beneath Big Black Mesa, but is well constrained to the east and south.

Near Drake, the water-level gradient slopes southeast toward King Spring, parallel to Hell Canyon. King Spring is a local point of discharge for this part of the carbonate aquifer, with evapotranspiration and seepage losses to the shallow alluvium approximately equal to discharge. East of Hell Canyon, the water-level gradient declines abruptly by more than 300 ft in less than a mi. To the east from King Spring to Mormon Pocket and Sycamore Canyon (a distance about 20 mi) the total decline in the water-level gradient is about 500 ft or an average of 25 ft/mi. The major ground-water flow direction between the town of Paulden and Hell Canyon is west to east; or northwest to southeast—parallel to the northwest-striking faults, monoclines, and fracture patterns. Underflow from Big and Little Chino Valleys past the mouth of Hell Canyon is presumed to be insignificant (Freethey and Anderson, 1986). Proterozoic rocks with low permeability crop out at river level between the Paulden gauge and Hell Canyon, which may contribute to the lack of measurable ground-water inflow to the upper Verde River between Hell Canyon and Perkinsville (Wirt, Chapter A, this volume; fig. A14).

Ground water exits Big Chino Valley north and east of Paulden (figs. D8 and D9; Wallace and Laney, 1976; Owen-Joyce and Bell, 1983; Freethey and Anderson, 1986; Schwab, 1995), through Tertiary basalt, or Paleozoic sedimentary rocks, or both. The lack of an abrupt change in gradient across the basin boundary between the Big Chino basin-fill aquifer and the carbonate aquifer is a strong indication that these two aquifers are hydraulically connected. Less than a mi northwest of upper Verde River springs (4,235+1 ft), well HR-2 in the basalt paleochannel is 500-ft deep and has a water-level elevation of 4,242+1 ft (Water Resource Associates, 1991).

The water-level gradient along the first 8 mi of the upper Verde River (25 ft/mi) is about twice that of the gradient over Big Chino Valley (12 ft/mi). The regional gradient and flow direction are consistent with the Big Chino aquifer as the primary source of discharge to upper Verde Springs, although it is possible that a small fraction of base flow could be derived from the carbonate aquifer. This possibility will be addressed further in Chapters E and F (this volume). Based on the regional water-level gradients in the basin-fill and carbonate aquifers (figs. D8 and D9), all inflow is derived west or northwest of upper Verde River springs. As mentioned earlier, discharge from the carbonate aquifer, if any, could potentially contribute to upper Verde River springs from Paleozoic rocks (a) beneath the Big Chino basin-fill aquifer, (b) through alluvial fans along the base of Big Black Mesa, or (c) near the outlet of the basin-fill aquifer along joints parallel to the northwest-striking Big Chino Fault.

Ground water from the Big Chino aquifer passes through about 2 mi of basalt and carbonate rock before reaching upper Verde River springs. Some ground water discharges farther east near the confluence of Muldoon Canyon with the Verde River (river mi 8). On the basis of the regional ground-water gradient, the source of this seepage is from the west or northwest, which could include the Big Chino basin-fill aquifer, as well as the carbonate aquifer in the Drake area. An alternate possibility is that all or part of the seepage could be derived from the vicinity of Muldoon Canyon to the south, where little water-level information is available.

Summary and Conclusions

The Transition Zone geologic province within the Verde River headwaters region contains three major aquifers, the Big and Little basin-fill aquifers, and a compartmentalized carbonate aquifer. Basin and Range faulting created the down-dropped structural basins that contain large basin-fill aquifers in Big and Little Chino valleys. Tertiary volcanic rocks are an important component of the basin-fill material, particularly in Little Chino Valley. North of Big Chino Valley and the Verde River, essentially flat-lying Paleozoic carbonate rocks are considered part of the Colorado Plateau. Within the Transition Zone, Paleozoic carbonate rocks lack continuity, and have been faulted and in some areas folded. Carbonate rocks are present beneath Big Chino Valley and in northern Little Chino Valley and crop out as erosional remnants in mountain ranges to the south. North of the upper Verde River and in the Granite/Verde confluence area, sedimentary rock units are deeply incised and partly buried. Near the confluence area, at least two paleocanyons are concealed by Tertiary basalt flows, one east of Del Rio Springs and one northeast of Paulden.

Ground-water recharge to basin-fill aquifers in the Verde River headwaters is from mountain recharge and from direct stream runoff within the basins in areas having the greatest precipitation, favorable topography, and permeable rock or sediments. The water table is usually shallow beneath incised canyons, where recharge to the carbonate aquifer likely is greatest in areas having well-developed karst or fracture systems. Tertiary basalts also have a high degree of secondary porosity and recharge potential. In contrast, surface-water runoff is greatest in high-altitude areas underlain by relatively impermeable Proterozoic rocks.

Big and Little Chino Valleys contain gently sloping reservoirs of ground water that drain by gravity toward large springs near their outlets. The ground-water flow direction of basin-fill aquifers generally is from the basin margins and tributaries toward the center and down valley axes. In Big Chino Valley, ground-water conditions are typically unconfined. In Little Chino Valley ground water flows under both unconfined and a variety of confining conditions. Despite these complexities, each basin-fill aquifer is interpreted as a single, connected system.

Big Chino Valley owes its elongate, assymetric configuration to the northwesterly strike of the Big Chino Fault. Displacement along the fault places basin deposits against Proterozoic rocks, creating an impermeable boundary along most of Big Black Mesa. The fault ends in a series of horsetail splays north of Paulden, where Paleozoic carbonate rocks shallowly underlie and abut basin-fill sediments. Ground-water flowpaths and rates of flow are influenced by lateral and vertical changes in grain size of alluvial sediments (such as permeable stream gravels versus the fine-grained playa deposits) and buried basalt flows. High-yielding wells along Big Chino Wash have been developed from heterogeneous basin-fill sediments. In upper Big Chino Valley, high yielding wells in basin-fill alluvium are underlain by a basalt flow. At the basin outlet near Paulden, a basalt unit with high overall permeability straddles the basin-fill aquifer boundary, facilitating the movement of ground water into the carbonate aquifer. In addition, the lower Martin Formation shallowly underlies the basin-fill deposits north of Paulden (< 400 ft in depth). High-yielding supply wells near Paulden have been developed in Tertiary basalt and karst on both sides of the basin boundary.

Little Chino Valley is not as deep or elongate in any direction as Big Chino Valley. Alluvial and volcanic basin fill directly overlies Proterozoic basement rock and Paleozoic strata in the deepest part of the basin, forming a highly productive artesian aquifer. Buried plugs of lati-andesite increase in abundance north of Del Rio Springs. The narrowing of alluviul deposits toward the basin outlet and low permeability of the plugs restricts northern movement of ground water, which in part accounts for discharge at Del Rio Springs. From Del Rio Springs, the most reasonable ground-water flowpath is northeast through faulted Paleozoic rock and lati-andesite in the carbonate aquifer near Stillman Lake and Lower Granite Creek.

The crest of Big Black Mesa is interpreted as a groundwater divide separating the Big Chino basin-fill aquifer and the regional carbonate aquifer beneath the Colorado Plateau. A large part of the carbonate aquifer north of the divide (nearly half of the upper Verde River watershed) probably contributes little, if any, ground water tributary to Big Chino Valley or the Verde River. Between the Verde River and Drake, the regional ground-water flow direction in the carbonate aquifer is to the southeast, and appears to follow the dominant northwest-southeast structural orientation of Big Chino Valley and Big Black Mesa. On a more local scale, ground-water movement likely is influenced by the presence of basalt flows, faults and connected fractures, karst, stratigraphic contacts and bedding planes, and differences in the grain size of sediment. Fractures and karst near the base of the Martin Formation are important conduits.

The Big Chino basin-fill aquifer and the carbonate aquifer north of the upper Verde River are strongly connected near Paulden. This is evidenced by a gently sloping water-level gradient east of Paulden that extends north of Drake, and east as far as Hell Canyon. Gradient and flow direction are entirely consistent with the Big Chino aquifer providing the major source of discharge to upper Verde River springs, although it is possible that a minor fraction of inflow could be derived from the carbonate aquifer. Potential contributions from the carbonate aquifer to the Big Chino basin-fill aquifers are most likely from carbonate rocks (a) beneath the Big Chino basin-fill aquifer, (b) through alluvial fans along the base of Big Black Mesa, or (c) near the outlet of the basin-fill aquifer along solution-enhanced fractures parallel to the northwest-striking Big Chino Fault.

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