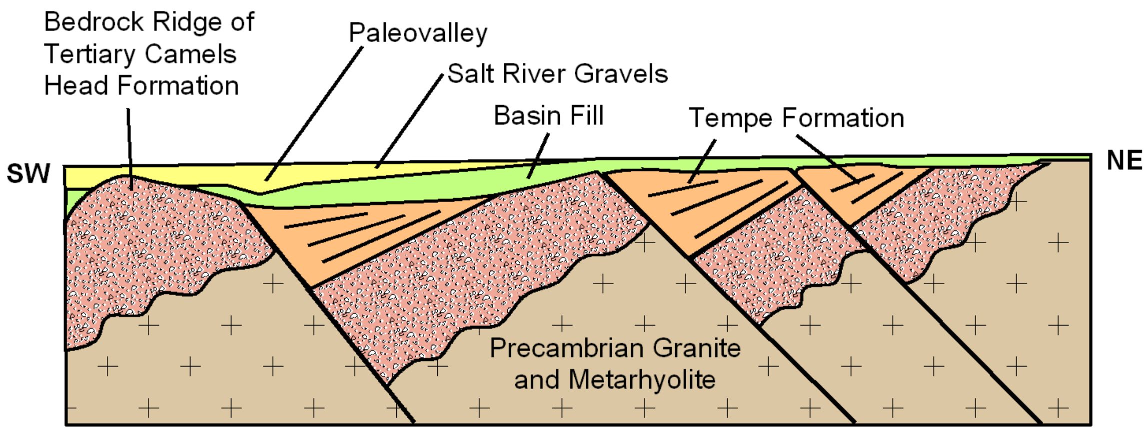
Subsurface geology of the easternmost Phoenix basin, Arizona: Implications for groundwater flow



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Abstract

Volatile organic compounds in groundwater have been the subject of various investigations in the easternmost part of the Phoenix basin near Sky Harbor Airport. Geologic and hydrogeologic data from hundreds of monitor wells provide an opportunity to investigate the subsurface geology and its influence on groundwater flow. The combination of numerous drill cores hundreds of feet into hard bedrock and new drilling techniques that yielded soft-sediment cores of overlying less consolidated sediments have enabled us to constrain the character, stratigraphy, and structure of the various units. These data provide an unprecedented look at the geology of the buried bedrock pediment that defines the eastern margin of the Phoenix basin. The bedrock pediment surface is exposed in Papago Park, but becomes buried to the west toward Sky Harbor Airport. The buried pediment is the most important geologic and hydrologic boundary, separating underlying tilted and faulted mid-Tertiary and Proterozoic rocks from overlying flat-lying, less consolidated Quaternary to late Tertiary alluvium and basin fill.

Below the pediment surface, hidden beneath approximately 50 to 200 feet of late Tertiary to Quaternary sediments, is an array of tilted fault blocks composed of middle Tertiary sedimentary and volcanic rocks and Proterozoic crystalline rocks. The Proterozoic rocks include metarhyolite and several types of granite, and are depositionally overlain by mid-Tertiary sedimentary rocks. The middle Tertiary section includes, from bottom to top, (1) coarse sedimentary breccias, conglomerate, and sandstone of the Camels Head Formation, (2) fine-grained clastic rocks of the Tempe Formation, and (3) Tertiary volcanic rocks and overlying fine-grained clastic rocks. Dips of the mid-Tertiary units average 30 to 40 degrees and, in several drill holes, increase downward

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from 15 to 30 degrees in the Tempe Formation to 30 to 50 degrees in the underlying Camels Head Formation. The basal contact of the volcanic rocks is locally an unconformity that cuts down section to the northeast, where in the subsurface the volcanic rocks rest directly on lower Camels Head Formation.

Based on exposures in Papago Park, detailed cross sections in areas of closely spaced drill holes, and structural relations typical for the region, the mid-Tertiary units are interpreted to strike northwest, dip southwest, and be cut by Tertiary normal faults that dip moderately to the northeast. The structurally complex Tertiary units were beveled by erosion that formed a broad, low-relief pediment prior to deposition of late Tertiary to Quaternary units. This buried pediment has a very gentle slope to the west, but contains two broad, low-relief features: a broad trough cut into less resistant Tempe Formation and a northwest-trending bedrock ridge (referred to herein as the "Bedrock Ridge") interpreted to represent an eroded strike ridge of Camels Head Formation.

The late Tertiary and Quaternary units above the buried pediment can be subdivided into three units: basin fill, Salt River Gravels, and uppermost alluvium. *Basin fill*, the lowest and oldest basin unit, was deposited on top of the beveled mid-Tertiary and Proterozoic units and consists of sandy and silty sediments, locally with small pebbles. Most of the pebbles are lithologies that match the local bedrock, and the unit is interpreted to be mostly locally derived. Basin fill is generally somewhat consolidated due to widespread calcite cement and minor compaction.

In the western half of the study area, basin fill is overlain by very coarse, unconsolidated gravels, consisting mostly of pebbles, cobbles, and boulders in a sandy matrix. This gravel unit includes clasts of rocks not found in the local mountains and represents deposits of the Salt River; it is formally named the *Salt River Gravels* in this report. The gravels have a more silty matrix in some areas, but lack any sandy or silty matrix in some very coarse channel deposits. Overall, the Salt River Gravels have a wedge-shaped geometry that thickens to the west and pinches out to the northeastward, reflecting the restriction of the gravels to the central, lower elevation part of the basin. The Salt River Gravels have infilled a paleovalley carved into underlying basin fill, and we interpret the gravels to be appreciably younger than, and unrelated to, basin fill.

The highest and youngest unit is *uppermost alluvium,* which consists of silt, sand, minor gravel, and construction fill. This unit is interpreted to mostly represent recent floodplain deposits, perhaps with minor eolian and locally derived components.

Groundwater in the area generally flows to the west, but is strongly influenced by the different lithologies, buried bedrock ridges, and pumping of large irrigation and water-supply wells. Proterozoic and mid-Tertiary units are hard, consolidated rocks, and have very low intrinsic permeabilities. Permeability in these units is largely controlled by faults and fractures, but many of these structures have been mineralized and sealed by mid-Tertiary fluids, so the units generally have a low overall permeability and hold little water. Buried ridges of these bedrock units locally approach or even protrude upward through the water table and act as barriers to groundwater flow, deflecting groundwater flow around the ridges. At the Bedrock Ridge north of Sky Harbor Airport, groundwater upgradient of the ridge flows to the southwest but is diverted to the northwest at the northwest end of the ridge and to the south at the southeast end of the ridge.

The overlying basin fill and Salt River Gravels have higher permeabilities and constitute the main aquifers for the area. The Salt River Gravels, due to their coarseness and general lack of silt and clay, generally have very high permeabilities. The westward thickening and wedge-shaped geometry of the Salt River Gravels result in greater hydraulic transmissivity in the western parts of the study area. Basin fill is finer grained and more consolidated and cemented than the Salt River Gravels, and has significantly lower permeabilities. It extends from bedrock to the land surface in the easternmost part of the basin, and these areas have less ability to transmit groundwater.

Introduction

Water is the lifeblood of the Southwest, and much of the region's water resources occur in the large sedimentary basins that underlie the modern valleys of the Basin and Range Province. One such basin encompasses most of the city of Phoenix in central Arizona (Figure 1). This subsurface basin, herein called the *Phoenix basin*, underlies the western part of the Salt River Valley; many hydrologists use the term *western Salt River Valley* synonymously with the Phoenix basin. In the geologic literature, *valley* refers to a modern physiographic feature, whereas *basin* refers to a subsurface feature. The Phoenix basin is a major source of groundwater for the large growing metropolitan area, and in some parts of the basin the groundwater contains municipal and industrial contaminants. To understand the directions and flow rates of the groundwater requires knowledge of the geometry of the basin, the internal stratigraphy of the basin-filling units, and the ability of these units to hold and transmit groundwater. It is within this context that the present study was undertaken.

The specific area examined is the eastern flank of the Phoenix basin, north of Sky Harbor Airport (Figure 2). This part of the basin is bounded by bedrock exposures in Papago Park to the east and the Phoenix Mountains to the north. The land surface decreases in elevation from northeast to southwest, toward the modern Salt River, which is located just south of Sky Harbor Airport. The Salt River flows westward across the valley. The area is highly urbanized, covered nearly entirely by houses, buildings, roads, and parking lots. Geologic studies of the area, therefore, must rely almost exclusively on subsurface information, such as drill holes and geophysics. Fortunately, more than 200 drill holes have been completed in this part of the basin as part of ongoing investigations of contaminants in groundwater. Drill holes and monitor wells (Figure 2), although widely distributed across the area, are concentrated near the 52nd Street facility, formerly owned by Motorola, and a facility owned by Honeywell just north of Sky Harbor Airport.

Volatile organic compounds (VOCs) in groundwater have been the subject of various investigations for the 52nd Street Superfund site since 1983. The site is located in the easternmost part of the Phoenix basin near Sky Harbor Airport. An area of VOC contamination from multiple sources has been delineated between the area of 52nd Street and McDowell Road to west of 7th Avenue between Washington and Roosevelt Streets. Since 1983, hundreds of monitor wells have been installed, logged, and sampled in this area (Table 1). The drilling methodology varied from well to well but included the mud rotary method, rock core drilling using diamond-impregnated drilling bits, various casing-advance methods (e.g., air rotary casing hammer and the "Becker" hammer methods), and sonic drilling methods. Each method had advantages and disadvantages and provided drill cuttings or core of varying quality for analysis. Excellent quality bedrock core was available from numerous borings and was used to investigate the bedrock geology and infer bedrock structure. Soft-sediment core was provided by the sonic drilling method, which was first used in the study area in the early- to mid-1990s. These soft-sediment cores provide an outstanding view of relatively undisturbed columns of alluvium and basin fill. Data and observations from bedrock and soft-sediment cores were given greater weight in our analysis than observations inferred from drill cuttings alone.

Hundreds of monitor wells used in the VOC investigation were reviewed for geologic and hydrogeologic subsurface data. As part of this investigation, we had access to data from nearly all of the wells drilled in the study area We scrutinized all drilling logs that were available and examined or relogged core and cuttings for many key drill holes. A summary of our observations and conclusions for key drill holes is included in Table 1, which also lists drill intercepts and bedding dips for each unit. For bedrock units, we focused on the overall lithologies, dips of bedding, and the geometry of faults. We compared what we observed in the drill holes with outcrop exposures of the same units in Papago Park and the Phoenix Mountains. For the sedimentary fill of the basin, we examined the grain size, maturity, and the degree of consolidation and cementation of the sediments. Another key aspect of the sedimentary fill is the provenance of the larger clasts: the sand, pebbles, cobbles, and boulders. Some clasts are rock types that could be derived from nearby bedrock exposures, whereas others are rock types that are only exposed in the mountains many miles to the east, being brought into the basin by the Salt River. Using these data, we constrained the thickness, lateral distribution, and correlation of units across this part of the basin. We present these correlations in a series of maps and cross sections. We also assessed the relative hydraulic conductivity of key units, based on grain size and sorting of the sediments and on available hydrologic tests.

The availability of this subsurface data has afforded an opportunity to investigate the bedrock geology buried beneath Quaternary and Tertiary basin fill sediments and to assess the influence of bedrock topography on local groundwater flow. The analysis of the soft sediment cores coupled with drill cuttings from other boreholes have contributed to a better understanding of the unconsolidated sediments overlying the bedrock pediment that defines the margins of the Phoenix basin. In this report, we first summarize the geologic setting of the region, based on our understanding of the local geology as well as regional relations observed across the Basin and Range of Arizona. We then describe the predominant rock units and structures for each of three time periods represented in the Phoenix basin: Proterozoic, middle Tertiary, and late Tertiary to Quaternary. We close with a discussion of the implications for the geologic evolution and hydrology of the area.

Geologic Setting

The geologic history of Phoenix spans over 1.7 billion years and has produced a complex array of rock types and geologic structures (Figure 3). The oldest rocks are Proterozoic metamorphic rocks, including metavolcanic rocks, metasedimentary rocks, and foliated to gneissic plutonic rocks. The metavolcanic rocks are mostly greenstone (metamorphosed basalts and andesites) and metarhyolite, and are most widely preserved in the Phoenix Mountains (Reynolds and DeWitt, 1991; Johnson, 2000) and near Papago Park (Péwé and others, 1986). The metasedimentary rocks are mostly exposed in the Phoenix Mountains and include slate, phyllite, schist, and quartzite (Jones, 1996; Johnson, 2000). Higher grade metamorphic rocks, consisting of gneiss, schist, and amphibolite, comprise parts of the ranges to the south and west of Phoenix, such as the White Tank Mountains, Sierra Estrella, and western part of the South Mountains (Reynolds and DeWitt, 1991). All of these rocks were metamorphosed and strongly deformed during the Proterozoic, at approximately 1.7 to 1.6 billion years ago (b.y.).

Intruding the metamorphic rocks are several distinct Proterozoic plutons, probably ranging in age from 1.7 to 1.4 b.y. A granodiorite-tonalite pluton is present in the western Phoenix Mountains (Johnson, 2000) and the more widespread *Camelback Granite* occupies the main mass of Camelback Mountain and the low areas of Papago Park (Cordy, 1978; Péwé and others, 1986). Another local pluton, called the *Tovrea Granite,* is exposed in a small area southwest of Papago Park (Péwé and others, 1986). Other Proterozoic plutons, most of which are strongly foliated to gneissic, are exposed in ranges to the south and west (Reynolds, 1988; Reynolds and DeWitt, 1991; Reynolds and Wood, 2001). Much younger plutons, including Late Cretaceous to early Tertiary granodiorite to granite, are exposed in the White Tank Mountains (Reynolds and Wood, 2001).

The next main sequence of rocks exposed in the Phoenix area consists of middle Tertiary sedimentary and volcanic rocks. Paleozoic and Mesozoic sedimentary rocks, such as those presently exposed on the Colorado Plateau and in southern and western Arizona, once covered the Phoenix area but were completely eroded away during one or more episodes of Mesozoic to early Tertiary uplift. As a consequence, the middle Tertiary rocks were deposited directly on Proterozoic basement rocks along an unconformity that represents nearly 1.6 billion years of missing geologic history. Middle Tertiary plutons of approximately the same age as the sedimentary and volcanic rocks are present in the eastern South Mountains (Reynolds, 1988) and western White Tank Mountains (Reynolds and Wood, 2001).

In the eastern potion of the Phoenix basin, there are three main mid-Tertiary rock units: Camels Head Formation, Tempe Formation (also called the *Tempe Beds*), and unnamed volcanic rocks (Cordy, 1978; Péwé and others, 1986). The Camels Head Formation is composed of coarse sedimentary breccia and conglomerate, with thin interbeds of conglomeratic sandstone. Most sedimentary breccias are debris-flow deposits, but some represent huge landslides and rock-avalanche deposits. The overlying Tempe Formation is finer grained, consisting mostly of siltstone and sandstone. Above the Tempe Formation are mafic to intermediate volcanic rocks, such as those exposed on Tempe Butte near Arizona State University. Fine-grained sediments referred to in this report as the "upper Tempe Formation", locally overlie the volcanic rocks and are exposed in outcrops in Papago Park and are encountered in drill holes to the west and southwest of Papago Park. All of the mid-Tertiary sediments were compacted and cemented into rock by burial and diagenesis in the mid-Tertiary basins (Roddy and others, 1988). These fluids also extensively affected the accompanying mid-Tertiary volcanic rocks (Leighty, 1997). The overall reddish color and hard character of the mid-Tertiary sedimentary rocks is regarded as being due in part to these fluids.

During formation of the mid-Tertiary rocks, the Basin and Range of southern Arizona experienced a profound episode of extreme crustal extension. This extension formed huge, gently-dipping normal faults, termed *detachment faults*, that have horizontal offsets of several tens of kilometers (Spencer and Reynolds, 1989a). Metamorphic and plutonic rocks in the footwall of the detachment faults were sheared and transported to the surface along the detachment fault, forming domal mountain ranges, termed *metamorphic core complexes*, such as the South Mountains and White Tank Mountains in the Phoenix area (Figure 3). Detachment faults are observed or interpreted to surround the South Mountains and White Tank Mountains metamorphic core complexes (Spencer and Reynolds, 1989a), and to dip gently to the northeast beneath the entire Phoenix basin, Phoenix Mountains, and Papago Park. Rocks in the South Mountains and White Tank Mountains are beneath the detachment fault and were extracted up and southwestward from beneath the Phoenix Basin and areas to the northeast (Figure 4).

Rocks above the detachment fault were broken into a series of fault blocks that were progressively tilted during displacement on the underlying detachment fault (Figure 4). In Papago Park, the exposed mid-Tertiary units dip to the southwest and the bounding normal faults dip to the northeast. Such orientations of layers and faults characterize a large area that stretches from the South Mountains northwestward to the Colorado River (Spencer and Reynolds, 1989a). Viewed within this broader context, mid-Tertiary units in the subsurface of the Phoenix basin are also likely to dip southwest and be bounded by northeast-dipping normal faults. This geometry is expressed in a seismic reflection line that extends eastward from the South Mountains (Frost and Okaya, 1986).

As the fault blocks tilted, sediment was eroded off the uplifted corners of the fault blocks and was deposited in half-graben basins formed in the down-dropped corners of the blocks (Figure 5). At times, a blanket of sediment covered the fault blocks, allowing some stratigraphic units to be continuous across multiple fault blocks. Sediment deposition was concurrent with tilting, so the earliest sediments deposited were tilted more than those deposited later. This is clearly expressed in some drill holes where the Camels Head Formation dips 40 to 50 degrees, whereas the overlying Tempe Formation dips 15 to 30 degrees. Such fanning of dips is common in mid-Tertiary sequences throughout Arizona, and is generally accompanied by local unconformities as younger units overstep the upturned and eroded edges of older units (Dickinson, 1991).

As the mid-Tertiary faulting waned, erosion beveled the fault blocks, beginning the formation of a major unconformity between middle and late Tertiary rocks (Eberly and Stanley, 1978). At about the same time, a new episode of normal faulting, termed the *Basin and Range*

Disturbance, began to break up the region into a series of broader and more northerly trending fault blocks (Figure 6). Some blocks were uplifted, becoming the present-day mountain ranges, and others were down-dropped, forming the basins between the mountain range blocks. Sediment was eroded from the range blocks and then deposited in the basins. The term *basin fill* is widely used in the geologic literature of Arizona for such sediment deposited in the Basin and Range basins and on the flanking pediments. Coarser basin fill, represented by tan conglomerate and sandstone, was deposited next to the ranges, and finer basin fill and salt accumulated in the center of the basins. Basin fill exposed at the surface was never deeply buried and was deposited after the mid-Tertiary fluid event, so basin fill is less consolidated and less red than the mid-Tertiary rocks. Regionally, basin fill is typically late Tertiary, mostly accumulating after 15 m.y. and before 4 m.y.

Erosion outlasted the Basin and Range Disturbance, reducing the mountain ranges to smaller, eroded remnants and carving broad, low-relief pediments along the embayed mountain fronts (Figure 6). Basin fill continued to accumulate in many basins, filling up the basin and being deposited over the pediments. After the basins became integrated into the regional drainage network, downcutting along the main rivers and tributaries incised the basin fill and locally exhuming parts of the once-buried pediments. Successive episodes of deposition and downcutting left behind a series of terraces along the rivers and smaller drainages, with the highest stranded terraces being the oldest (Péwé, 1978).

Proterozoic Crystalline Rocks

The oldest rocks near the Phoenix basin are Proterozoic metavolcanic and granitic rocks (Figure 7), which are encountered in the easternmost part of the area, just west of Papago Park. The metarhyolite is a gray, strongly foliated, fine-grained rock, commonly with small relict feldspar phenocrysts. This rock type occurs as a fairly intact (i.e., unshattered) basement below the mid-Tertiary units and as shattered landslide blocks within mid-Tertiary Camels Head Formation. Metarhyolite bedrock is exposed in small outcrops near the Salt River (Péwé and others, 1986) and north of the area in the Phoenix Mountains (Johnson, 2000). Across the region, the metavolcanic and metasedimentary rocks generally are 1.7 b.y. old and have steep, northeast-striking foliation and contacts. Exposures of metarhyolite in Papago Park, although mapped as bedrock by Péwé and others (1986), are highly shattered, encased in sedimentary breccias of the Camels Head Formation, and interpreted as landslide masses in the mid-Tertiary section (Reynolds and Lister, 1987).

Several varieties of Proterozoic granite are exposed in outcrop and displayed in drill holes. The Camelback Granite is exposed in Papago Park, where it is depositionally overlain by Camels Head Formation in a spectacular nonconformity, as at Hole in the Rock, a local landmark in Papago Park (Péwé and others, 1986). This granite is coarse grained, with local potassium feldspar phenocrysts and abundant biotite. The biotite is commonly altered to chlorite, imparting a greenish tint to the rock. Camelback Granite is largely unfoliated, but locally contains steep northeast-striking mylonitic fabric interpreted to be Proterozoic in age. A different pluton, called Tovrea Granite (Péwé and others, 1986), is exposed in outcrops southwest of Papago Park and is encountered in drill holes. The Tovrea Granite is also coarse grained, but contains less biotite and is lighter colored than Camelback Granite. The two granites both have intruded the metarhyolite, based on contacts in (1) drill core across the metarhyolite-granite contact and (2) outcrops of these Proterozoic rocks within mid-Tertiary landslide masses in Papago Park. In both settings, the granite-metarhyolite contact is very complex, with the two rock types alternating on a scale of several feet to several tens of feet, representing dikes of granite cutting metarhyolite or large inclusions of metarhyolite within granite. Some exposures that resemble metarhyolite may instead be fine-grained dikes that intruded Camelback Granite and were subsequently sheared.

Metarhyolite and granite are intact and unfractured in some drill holes, but are very fractured to highly shattered in others. There are two main styles of fracturing observed in drill core. The first consists of closely spaced fractures that are subparallel to each other and commonly associated with an adjacent fault. The second type consists of more randomly oriented fractures that are numerous, but short and discontinuous. These short factures bound discrete clasts, imparting to the rock an overall appearance of a breccia. Between the clasts there is commonly a reddish matrix of either crushed rock or reddish mud, but some drill-hole intervals lack any such matrix. In outcrop, this second type of fracturing occurs where the basement lithologies represent landslide masses within the mid-Tertiary section. We therefore interpret some of these fractured masses in drill holes to also be landslide masses in the Camels Head Formation. In other cases, especially where the breccia lacks red matrix, we interpret breccia to represent the top of the basement that has been shattered by incipient landslide development – the rocks began to slip downhill, but only enough to shatter, not enough to form a separate landslide block. In addition to these fractures, some basement rock is cut by reddish, brittle-ductile shear zones that have both brittle fracturing and ductile shear-zone fabrics.

Middle Tertiary Rocks and Structures

Overlying the Proterozoic rocks is a suite of mid-Tertiary sedimentary and volcanic rocks. There are three main units: Camels Head Formation, Tempe Formation, and Tertiary volcanic rocks (Figure 7). The geometry and depositional setting of these units are closely linked to numerous mid-Tertiary normal faults that were operating during deposition of the units (Figure 8). These units and faults are depicted in two northeast-southwest cross sections, one that extends across most of the study area (Figure 9) and another that is a more detailed view of the easternmost part of the study area (Figure 10).

Camels Head Formation and Granite-Camels Head Contact

The lowest mid-Tertiary unit is Camels Head Formation (Péwé and others, 1986), which is characterized by sedimentary breccia, with less abundant conglomerate and conglomeratic sandstone. It may be subdivided into upper and lower parts, with most of the formation being the lower part. The lower part consists of massive sedimentary breccia with abundant red matrix, but little or no preserved bedding or sandstone-siltstone interbeds. The clasts are angular to subangular and centimeters to over a meter in diameter. Most clasts are composed of granite, metarhyolite, and vein quartz, except in the westernmost drill holes where some schistose and gneissic clasts are also present. This lower part locally contains huge shattered blocks of granite and metarhyolite, some of which can be traced in outcrop for hundreds of meters, or longer. The lower part mostly represents mud- or sand-matrix debris flows, rock-avalanche deposits, and large, shattered landslide blocks. There are a few fluvial beds, especially near the base.

For this lower part of the Camels Head Formation, we do not apply the members defined by Péwé and others (1986). The stratigraphic position and relationship of these members are problematic because Péwé and others did not recognize that shattered metarhyolite and granite in Papago Park were tilted landslide masses *within* the formation, not Precambrian bedrock.

The upper part of the Camels Head Formation contains fluvial conglomerate, sandstone, and siltstone, in addition to sedimentary breccia. This part is tens of meters thick in outcrop and in key drill holes. It is equivalent to the Papago Park member of the Camels Head Formation as defined by Péwé and others (1986). Bedding and sandstone-siltstone interbeds are fairly common and increase in abundance upward as part of an overall fining-upward sequence.

The thickness of the Camels Head Formation is not well constrained, but evidently varies from approximately 300 feet (~100 m) in the eastern part of the area to over 1000 feet (>300 m) farther to the west. The base of the Camels Head Formation is very difficult to identify precisely in some drill holes, because it is interpreted to be between coarse Camels Head sedimentary breccia and brecciated granite basement. The sedimentary breccia typically contains clasts of different lithologies (e.g., granite and metarhyolite) and intervals with abundant red matrix, whereas brecciated basement is monolithologic and may contain little or no red matrix. The contact may even be completely gradational over tens of meters where sedimentary breccias and landslide blocks directly overlie granite that has also experienced some slippage during the faulting and tilting event.

The Camels Head Formation is a very hard, consolidated rock. The matrix, although originally muddy, has been hardened and presumably diagenetically altered by burial and mid-Tertiary fluids. The formation is the most erosionally resistant unit in Papago Park, and drilling rates drop dramatically once this unit is encountered.

The Camels Head is interpreted to have been deposited during mid-Tertiary faulting and block tilting, in mostly proximal environments, such as alluvial fans, close to mountain fronts. Active fault scarps and over-steepened tilt blocks provided steep slopes for debris flows, rock falls, rock avalanches, and mountain-stream deposits. Clasts were derived from the local mountains of granite and metarhyolite, with minor vein quartz, schist, and other rock types. With time, the steep relief became eroded away or buried, permitting more clear-water fluvial deposits to accumulate in the upper Camels Head Formation. The Camels Head Formation has a fairly consistent 40 ± 10 degree dip in drill core, but locally displays steeper dips down section, which is consistent with the unit being deposited during faulting and tilting.

Tempe Formation

The overlying Tempe Formation is characterized by finer grained rocks: siltstone, sandstone, mudstone, shale, and conglomeratic sandstone. It can be subdivided into a lower sequence of reddish sandstone and siltstone and an upper sequence of greenish, gray, and yellowish siltstone, shale, and sandstone, with local conglomerate beds. There are a few tuffaceous intervals, some of which are yellowish with contorted layering, as is observed in outcrops at Tempe Butte (Peters, 1979). Thin bedding planes or laminations are generally very obvious throughout the Tempe Formation in drill core. The formation is hard and well consolidated, but is softer than the underlying and overlying units. The Tempe Formation has been called the *Tempe Beds* in some reports, but we herein propose renaming the unit *Tempe Formation* to conform to modern stratigraphic usage and to better convey the character of the unit. The type section of the unit remains on the north flank of Tempe Butte near Arizona State University (Péwé and others, 1986).

The base of the formation is gradational downward into the underlying upper Camels Head Formation through an interval of interbedded reddish sandstone and conglomerate. This gradation is well exposed in Papago Park, south of Curry Road, and has been recognized and mapped across Papago Park (Péwé and others, 1986) and into Camelback Mountain (Cordy, 1978). The top of the formation is generally a sharp contact with the overlying Tertiary volcanic rocks. In outcrop at Tempe Butte, uppermost beds of Tempe Formation are baked along this contact, and inclusions of Tempe Formation are incorporated into the base of the overlying volcanic flow (Peters, 1979). In a few drill holes, fine-grained lithologies identical to Tempe Formation also occur *above* the Tertiary volcanic rocks. A similar relationship has been mapped in the westernmost outcrops of Papago Park (Péwé and others, 1986).

The Tempe Formation commonly dips less than the underlying Camels Head Formation, with 15 to 30 degree dips being most common (Figures 9 and 10). Dips progressively increase downward in the Tempe Formation and across the transition between the Tempe Formation and Camels Head Formation, in conjunction with the downward coarsening. This indicates that (1) faulting and rotation of fault blocks was occurring during deposition of the Tempe Formation and uppermost Camels Head Formation, (2) some rotation of the Camels Head Formation occurred prior to deposition of the Tempe Formation, probably during formation of the coarse lower Camels Head breccias; and (3) the Tempe Formation could locally overlie the Camels Head along an angular unconformity, although this was nowhere observed. Both formations were probably deposited in one or more half-grabens, but the lack of coarse clasts in the Tempe Formation implies that the entire area was subsiding rapidly enough so that fault-scarps were no longer contributing coarse detritus into the half graben by Tempe Formation time. The widespread and continuous nature of the Tempe Formation further implies that the unit was deposited in a broader basin that spanned several underlying fault blocks.

The Tempe Formation is probably at least 300 feet (~100 m) thick near the Grand Canal, but is absent in some areas to the east. Such variations in thickness could be due to (1) original depositional variations because the unit was deposited in half-grabens, and (2) erosional removal beneath an unconformity at the base of the volcanic rocks, as is observed in drill holes in the eastern part of the study area (Figure 10).

Tertiary Volcanic Rocks and Overlying Strata

The Tertiary volcanic unit consists of a lower mafic to intermediate unit and an upper altered, greenish volcaniclastic rock. The lower unit is dark gray to greenish gray, massive to amygdaloidal, and highly altered. It is interpreted to be one or more lava flows, such as that exposed at Tempe Butte (Péwé and others, 1986). The upper volcaniclastic unit is not exposed, but either represents weathering and erosion of the underlying flow or a more tuffaceous phase of volcanism. In a few drill holes, the volcanic rocks are overlain by a thin, uppermost sequence of fine-grained clastic rocks that are very similar to the Tempe Formation.

The volcanic unit is clearly tilted because it dips 30 to 45 degrees in outcrop, dips 20 to 30 degrees at its base in several drill holes, and is overlain by 30-degree-dipping sediments in one drill hole. The volcanic unit is probably at least locally unconformable across the underlying units, because in drill holes it (1) dips less steeply than the Camels Head Formation, (2) apparently cuts down-section across the Tempe Formation and Camels Head Formation toward the east, and (3) overlies various units, ranging from upper Tempe Formation near the Grand Canal to middle Camels Head Formation farther east. This unconformity accounts for the absence of Tempe Formation in drill holes to the east (Figure 10), where the volcanic rocks directly overlie the Camels Head Formation. The thickness of the volcanic unit is also poorly constrained, but is probably 150 to 300 feet (~50 to 100 m). The unit has been dated at 18 Ma at Tempe Butte, but the altered nature of this rock renders this age somewhat uncertain (Reynolds and others, 1986).

Mid-Tertiary Structures

Mid-Tertiary faults are exposed in Papago Park and have been intersected by some drill holes, but many more faults are required in the subsurface to account for the distribution of units. To understand the mid-Tertiary structural evolution, we studied the dips of Tertiary units, especially in drill holes that spanned the contacts between the Camels Head Formation, Tempe Formation, and volcanic rocks (Table 1). Determining the attitude of the volcanic rocks was especially important because these rocks could have been tilted concordantly with the underlying sedimentary units or could have unconformably overlain underlying formations. We also needed to constrain the number, location, orientation, and stratigraphic separation of Tertiary normal faults, a feat that is difficult in places where drill holes may be a half mile or more apart but the spacing of faults could be half that amount.

The primary means of assessing the location of faults was to draw two northeast-southwest-trending cross sections (Figures 9 and 10) across the inferred structural grain of the Tertiary units. The number of faults needed in the cross sections is governed by the interpreted thicknesses of the units, which are not well known because the units are thick compared to the depth of drilling. Also, the units are moderately dipping and extensively faulted so adjacent drill holes rarely encounter the same part of the stratigraphic section, unless the drill holes are very closely spaced. Fewer, more widely spaced faults are sufficient to explain the drill-hole data if the units are thicker than shown on the cross sections. Some faults were not encountered in drilling, but are suggested by the dips and thickness of units in adjacent drill holes. The precise location and even existence of such faults are unknown, considering the uncertainties in stratigraphic thicknesses. The position of such hypothetical faults is arbitrarily placed half way between adjacent drill holes, unless constrained by structural or stratigraphic data.

From the cross sections and all available drill-hole information, we constructed an interpretive geologic map of the bedrock geology exposed below the overlying late Tertiary and Quaternary units (Figure 11). The trend of mid-Tertiary units and faults is shown as being northwest based on available drill-hole data and on surface exposures. The precise position and trend of contacts and faults in the subsurface, however, is not resolvable with presently available data.

The Tertiary units are interpreted to strike northwest and dip moderately southwest beneath the entire area (Figure 11). This conclusion is based on the following:

- Widespread outcrops of southwest-dipping strata to the northeast and southeast, in Papago Park. Some of these units project along strike into the cross section and would be unlikely to change orientation without the presence of some major structure, which has not been found.
- Detailed cross sections in areas of closely spaced drilling (Figure 9 and other unpublished cross sections). For example, the basal contact of the Camels Head Formation was encountered in several nearby drill holes, yielding a southwest dip equal to the dip amounts observed in core.
- Several three-point solutions for the contact between the Camels Head and the volcanic rocks in the eastern part of the area.
- The relatively constant amount of dip of the Camels Head in all drill holes. This strongly suggests that the unit dips in the same direction across the entire cross section because a change in dip direction in normal-fault terrains generally takes place gradually, with a lessening of dip as the dip reversal is approached. The apparent absence of flat-lying rocks that might mark a reversal in dip direction supports a consistent southwest dip.

The area is interpreted to be cut by numerous northwest-trending normal faults and at least one northeast-trending "transverse" fault. Both types of faults are considered to be mid-Tertiary based on regional relations and on the fact that the normal faults cut the mid-Tertiary volcanic rocks but fail to cut overlying late Tertiary–Quaternary deposits. The northeast-trending fault was not encountered in the drilling, but seems required by the vast expanse of granite and metavolcanic rocks to the southeast, along strike of mid-Tertiary units located to the northwest. Smaller examples of this type of northeast-trending fault are exposed at Papago Park, and are clearly mid-Tertiary because they are sealed tight by hard, red material.

The normal faults are interpreted to dip moderately (25 to 50 degrees) to the northeast based on the following:

- Northeast-dipping faults exposed in Papago Park (Péwé and others, 1986);
- Southwest dip of bedding. Faults in normal-fault terrains generally dip in the direction opposite to bedding, as was observed in numerous places in the core. Dips in the Camels Head Formation are a fairly consistent 40 ± 10 degrees across the cross sections. This indicates that the major faults are mostly planar. If the fault were curved, such as a listric fault, the dip of bedding would change across the curved fault. Also, the faults most likely dip less than 50 degrees because bedding-fault angles are typically between 60 and 90 degrees in normal-fault terrains. The faults formed with initial dips of 60 to 90 degrees, but were rotated to more gentle dips by continued faulting and extension, while bedding simultaneously rotated to steeper dips (see Figures 4 and 5). Such faults would be expected to dip 20 to 50 degrees when bedding has been rotated to 40 degrees. Dips of the Tempe Formation and volcanic rocks cannot be used in this regard, because they clearly reflect only the last part of the faulting/rotation history.
- Detailed cross sections, where a fault observed in one drill hole projects up dip to the southwest directly into a fault observed in another drill hole. Based on the detailed cross section, these two fault surfaces are likely to be segments of the same fault.

The amount of offset on each of the larger faults is not well constrained, but probably varies from several hundred feet to over 3000 feet (~100 – 1000 m). Each fault is shown as a normal fault, with the northeast side (i.e., the hanging-wall block) dropped down. The faults are shown as planar, rather than curved (e.g., listric), because stratal dips generally are consistent from one block to another. The amount of displacement on the northeast-trending fault is unconstrained, but probably includes a lateral component as well as a southeast-side-up component.

A single north-trending fault is shown on the geologic map (Figure 11). This fault is inferred to account for (1) the apparently large expanse of Tempe Formation west of the fault, (2) the truncation of otherwise northwest-trending belts of mid-Tertiary and Proterozoic units located east of the fault, and (3) a north-trending gradient in the depth to bedrock (Figure 12). Based on the northerly trend of this fault and regional relations, the fault is interpreted to postdate the mid-Tertiary faulting event and be related instead to the Late Tertiary Basin and Range Disturbance. A similar, larger fault is probably present west of the study area to account for the rapid increase in the depth of the basin in that direction.

This type of geology, with southwest-dipping units and northeast-dipping normal faults, characterizes a huge region that extends from Phoenix westward to the Colorado River (Spencer and Reynolds, 1989a, b). Such structural relations are exposed in many mountain ranges in this region and are well documented in maps and detailed studies. Also, the South Mountain detachment fault projects under the eastern Phoenix basin, and normal faults in the upper plate of such faults generally dip in the same direction as the master detachment fault (Figure 4). Therefore, the geology depicted in the interpreted geologic map and cross sections of the Phoenix basin is drawn to be consistent with the observed local and regional geology.

Late Tertiary Erosion and Depths to Hard Bedrock

The complex middle Tertiary geology now lies beneath 50 to 200 feet of late Tertiary and Quaternary deposits, with remarkably little expression in the depth to bedrock or thickness of the overlying deposits. A map of the depth to hard bedrock (that is, top of mid-Tertiary and Proterozoic rocks) shows that bedrock overall becomes deeper from east to west (Figure 12). There are, however, several buried topographic features (Figure 9), including a broad, northwest-trending ridge, herein called the *Bedrock Ridge*. The Bedrock Ridge is 8,000 to 10,000 feet long, extending from north of Sky Harbor Airport northwestward toward the intersection of 24th Street and Roosevelt Street. It is a broad feature, typically 1,000 to 2,000 feet wide. The top of the ridge reaches elevations of 1050 to 1060 feet, which is only 50 to 60 feet below the land surface, and well above the present water table. In general, the top of the ridge is broad and remarkably constant in elevation. A series of five drill holes (BR1 to BR5) were drilled along the axis of the ridge spaced approximately 1,000 feet apart, and four of these holes encountered bedrock at elevations of 1054 to 1058 feet.

As the ridge apparently diminishes to the southeast, it becomes somewhat more irregular and less continuous. A shallow saddle, referred to in unpublished technical reports as the *southern saddle*, is present near the southeast end of the ridge, just north of Sky Harbor Airport. In this portion of the structure, the bedrock is approximately 30 to 50 feet lower than in areas on either side. A smaller, much narrower saddle, called the *central saddle*, is evidently present to the northwest of the southern saddle (Figure 12). Alternative interpretations of the bedrock geometry have been submitted to the Arizona Department of Environmental Quality showing a "northern" saddle. No evidence has been found to support this interpretation.

To assess the slopes of the bedrock ridge, we calculated the slopes between the tops of bedrock in adjacent drill holes. Calculated slopes are typically 0 to 3 degrees on the top of the ridge and 3 to 6 degrees on the flanks. These calculations show that the bedrock ridge, although impressive on the bedrock contour map, is a very broad feature with very gentle slopes. Steeper relief, on a scale of about 10 feet, locally occurs between some drill holes, but this is not common. Alternative interpretations submitted to the Arizona Department of Environmental Quality portray much greater local relief, but these interpretations are based largely on seismic data that are inconsistent with key drill holes and are therefore regarded as unreliable . If the entire ridge had such relief, it would be difficult to understand how the four previously mentioned drill holes, spaced so far apart, could all encounter bedrock within several feet elevation of one another.

Drilling indicates that the northwest-trending bedrock ridge is composed of coarse breccia of the Camels Head Formation. Tempe Formation is encountered both northeast and southeast of the ridge. We interpret the ridge to be a strike ridge that parallels the northwest strike of units and faults. With an inferred southwest dip of bedding, the contact with Tempe Formation on the *southwest* flank of the ridge is probably depositional (Figure 9). In contrast, the contact on the *northeast* flank of the ridge is interpreted to be a northeast-dipping normal fault that places Tempe Formation down against the strike ridge of Camels Head Formation (Figure 8).

East of the bedrock ridge is a broad, north- to northwest-trending trough that widens and becomes deeper to the northwest, along the area of the Grand Canal. The west flank of the trough is the bedrock ridge, and the east flank is the north-trending gradient in the bedrock contours that is inferred to parallel a north-trending Basin and Range fault. The trough is floored by fine-grained Tempe Formation, which is softer and more easily eroded than other mid-Tertiary units.

In spite of these subsidiary ridges and troughs, it is worth reiterating that the top of the Proterozoic and middle Tertiary rocks is a nearly featureless pediment, with very broad relief (Figure 9). This pediment was carved by erosion after mid-Tertiary faulting and was filled in by the overlying deposits. The top to bedrock is slightly deeper where there is nonresistant Tempe Formation, and is shallower over some exposures of erosionally resistant lower Camels Head Formation. But this very complex bedrock geology has surprisingly little expression in the shape of the bedrock surface, an expression of the significant amount of geologic time needed to erosionally bevel the geology nearly flat.

Late Tertiary and Quaternary Rocks and Deposits

The low-relief pediment surface that bevels across the mid-Tertiary units and structures generally is overlain by 50 feet to 200 feet of Late Tertiary to Quaternary sediments. These overlying sediments can be subdivided into three main units (from oldest to youngest): basin fill, Salt River Gravels, and uppermost alluvium (Figure 13). The three units have distinctive sedimentologic characteristics, distributions, depositional settings, and ages. These distinctions can be observed on the drilling logs and in drill cuttings and core, and have important implications for the hydrology of the area. The three units are shown on six cross sections (Figures 14 to 19), constructed from detailed study of core, cuttings, and logs.

The three units together fill a basin that deepens to the west, increasing in total thickness from zero at Papago Park to hundreds of feet along the western edge of the study area (Figures 14, 15, and 16). This overall westward increase in thickness is complicated by local thinning over the bedrock ridge and thickening in the trough east of the bedrock ridge. The specific geometries of basin fill and Salt River Gravels are quite distinct, reflecting differences in the ages and depositional settings of the two units.

Basin Fill

The oldest sediments deposited on top of the post-mid-Tertiary unconformity are variably consolidated sandy, silty, and pebbly units, herein grouped under the general term *basin fill*. There are four distinct facies of basin fill, varying from deposits that are nearly all silt to those that are sand with small, angular pebbles. The different facies are distributed in distinct patterns across the basin, and locally define a clear stratigraphy.

The most widespread type of basin fill is composed of sand, with variable amounts of silt and fine to very fine pebbles. This *sandy facies* is tan to light brown overall, and bedding is thick enough to be absent or ambiguous in cores. The sand grains generally have a limited range in colors: clear, cream, gray, and buff, with some rosy (light pink) and dark gray grains. Most sand is quartz, plagioclase, and potassium feldspar. The grains are fine to coarse grained, angular to subrounded, and poorly sorted to moderately well sorted. Flakes of fine-grained (0.5 to 1 mm), bronze-colored to yellowish mica make up less than several percent of the sand, but are generally conspicuous. The sand is commonly accompanied by tan silt, with minor amounts of clay, but some sandy units are well sorted and lack much silt.

The sandy facies commonly contains some fine to very fine pebbles (2 to 6 mm), which are mostly angular to subrounded. The pebbles are composed dominantly of quartz, feldspar, granite, metarhyolite, and some fine-grained greenish lithologies. All of these rock types are present in the local mountains (Papago Park, Camelback Mountain, and Phoenix Mountains), and we conclude that these pebbles and the associated sand are locally derived. We interpret the sandy facies to have been deposited mostly by small streams and alluvial fans draining south and west off the mountains and local bedrock highs. Relief must have been low enough, or the mountains far enough away, that no coarser debris flows and sediments were deposited.

The next most common facies of basin fill is dominantly silt and sand, with lesser clay and gravel. This *fine-grained facies* is tan, light brown, or reddish brown, and varies from nearly all silt and clay to more sand than silt. The sand grains have limited colors and most are very fine to medium grained. Mica is conspicuous, but a minor component. Bedding is surprisingly rare in drill cores. This facies is most common near the bedrock ridge, where it forms a discrete stratigraphic unit typically 10 to 30 feet thick at the top of basin fill. The depositional environment of this unit is uncertain, but must have been low energy, perhaps including lacustrine, eolian, and distal fluvial deposition. It could include some floodplain deposits, but generally lacks the multicolored sand characteristic of deposits of the Salt River.

The third facies of basin fill is a thin unit at the base of the unit. This *basal unit* is typically only several meters thick and consists of angular pebbles and gravel in a fine matrix of silt, clay, and sand. The matrix of this unit is finer grained than typical matrix of the sandy facies. The pebbles are lithologies, such as granite, metarhyolite, and coarse quartz, that could be locally derived. Some sedimentary clasts are clearly derived from mid-Tertiary units, such as Camels Head Formation and Tempe Formation, increasing the likelihood that some of the other clasts (e.g., granite and metarhyolite) are second-generation clasts that were originally clasts in Camels Head Formation. The unit is interpreted to represent (1) in-situ weathering of the underlying units, perhaps accounting for the silt- and clay-rich character, (2) very local redistribution of the clasts produced by such weathering, via alluvial or colluvial processes, or (3) locally derived alluvial fans.

The final facies of basin fill occurs as a thin lens of gravelly to conglomeratic material that is locally restricted to an area near the southern saddle of the bedrock ridge (Figures 18 and 19). This *conglomerate facies* forms a laterally discontinuous lens that underlies fine-grained basin fill and overlies the basal unit. Compared to other facies of basin fill, the conglomerate facies is distinctive in that it contains small, rounded pebbles of maroon quartzite, tan quartzite, red metarhyolite, diabase, and jasper. These lithologies are exotic to the local mountains and must have been brought into the Phoenix basin by an early version of the Salt River. In keeping with the varied assortment of pebbles, the sand in this facies is partly multicolored (clear, gray, cream, rosy, maroon, red, green, and black). The conglomerate facies is more consolidated than Salt River Gravels, but most cores contain some looser material. The conglomerate forms a lens that is generally only several meters thick and clearly pinches out to the north and east of the southern saddle, or is replaced laterally with more sand- and silt-rich units.

The conglomerate facies shares some characteristics with the Salt River Gravels, including multicolored sand and exotic clasts, but is clearly distinct because it (1) is more consolidated, (2) contains smaller clasts (gravel to small pebbles in the conglomerate, versus gravel, pebbles, cobbles, and boulders in Salt River Gravels), and (3) is separated from Salt River Gravels by fine-grained basin fill. Nevertheless, the thin lens of conglomerate documents that some form of the Salt River had formed by basin-fill time. The conglomerate lens likely was deposited by an influx of detritus northward into the southern saddle from an ancestral version of the Salt River to the south. This would help explain why the thin lens does not extend further north and east. The influx must have been a transient event, however, because it was followed by deposition of the fine-grained facies of basin fill in and around the southern saddle and continued deposition of sandy facies further to the north and east.

Basin fill is less consolidated than the mid-Tertiary units, but generally is significantly more consolidated than the overlying Salt River Gravels. The drilling logs commonly convey this consolidation with terms such as “dense”, “hard”, “stiff”, and “cemented”. Many samples in core and cuttings are too hard to break with bare hands. The sandy and basal units generally have a well-developed calcite cement, and such cement is also common in the fine-grained facies. Some intervals are called caliche in the logs, and we concur with this observation. Many of the samples are hard enough to be properly called sandstone, siltstone, mudstone, or conglomerate, and many logs use this terminology. The rocks are so indurated and cemented that many logs and industry reports call these units “weathered bedrock.” Such cemented and partially indurated deposits are present all the way to the surface in the eastern part of the study area, which implies that they were buried by other sediments that have been subsequently eroded away. That is, during basin fill time, the basin-fill sediments probably filled the basin to a higher level than they do today.

The lithology and degree of induration of these deposits are similar to *pre-Quaternary* basin-fill deposits of the region (Scarborough, 1989). These deposits are mostly late Miocene to Pliocene and represent infilling of interior basins that were created by late Tertiary Basin and Range faulting or mid-Tertiary extension. Most basin fill deposits predate establishment of the through-going, regional drainages, such as the Salt River. This is consistent with the predominance in basin fill of locally derived clasts over exotic clasts.

The facies of basin fill are broadly consistent with this interpretation. The basal unit represents very locally derived material that accumulated on or was transported across the pediment surface. The sandy facies contains locally derived sand and fine gravel and is the main basin-filling unit. It comprises nearly all of basin fill in the eastern part of the area, adjacent to the bedrock exposures from which it was derived. The clasts are apparently coarser and more angular toward the mountain front, although this has not been studied in detail. The fine-grained basin fill is further away from the mountain front, near the bedrock ridge. It may represent a locally ponded setting, perhaps caused by the bedrock ridge partially blocking local drainages. Alternatively, since it is the highest basin fill unit, it may record a more closed-basin setting late in the history of filling of the basin. The local conglomerate lens, with its exotic clasts, requires that an ancestral Salt River entered the basin, but it is unclear if it exited the basin.

Salt River Gravels

Basin fill is overlain by coarse river gravels composed of well-rounded gravel, cobbles, and boulders in a sandy matrix. The well-rounded clasts are mostly rock types that are not present in the local mountains around Phoenix. Instead, these clasts include distinctive rock types, such as red metarhyolite (Precambrian Red Rock Group) and maroon quartzite (Precambrian Mazatzal Quartzite), which are only exposed far upstream of the Phoenix basin along the Verde and Salt rivers (Reynolds, 1988). This coarse alluvium is identical in all aspects to the gravels seen in the modern channel of the Salt River; therefore we name these deposits the *Salt River Gravels*. We designate the type locality for this geologic unit to be the modern channel of the Salt River near the bridge at Priest Drive. There is conclusive evidence that these gravels were deposited by the Salt River, rather than in locally derived alluvial fans.

The Salt River Gravels are very coarse and sandy, generally with little or no finer grained material. Some core intervals have significant silt in the matrix, and may represent floodplain deposits. Other intervals have no matrix and are composed entirely of pebbles, cobbles, and boulders; these clearly represent main-channel deposits.

The gravels are consistently described in the drilling logs as gray and brown. The sands are multicolored, with clear, cream, gray, tan, red, green, black, and maroon grains. The Salt River Gravels are characteristically loose and unconsolidated, with no calcite cement. In a very few intervals, the grains adhere to one another and there is small amount of calcite cement.

The Salt River Gravels are widely distributed across the study area, except toward the northeast, where they are absent. In cross section, they appear as a wedge that thickens to the west and southwest and pinches out just northeast of the Grand Canal area (Figures 14 and 15). This pinch-out trends northwest across the area, and marks the northeastward, up-slope limit of former positions of the river. All areas to the southwest of this pinch-out were once sites of the Salt River. Coarse channel deposits are ubiquitous in these areas to the southwest, which indicates that one or more main channels of the Salt River once crossed these areas.

The contact between the Salt River Gravels and underlying basin fill is generally very sharp in the logs, cores, and cuttings. In the soft-sediment cores of the ASE-series of drill holes, the contact is very sharp, with coarse gravels directly overlying silt-dominated basin fill, with no gradation or intermixing of sediment types. Where drill holes are closely spaced, the contact has tens of feet of relief (Figures 17 to 19), although layers in the underlying basin fill are horizontal (Figure 19). We interpret this contact to be an erosion surface or unconformity, perhaps representing hundreds of thousands to millions of years of missing time. The contrasts in the depositional environments and the degree of cementation are evidence for a significant age difference between the two units. There is a surprising lack of soil development along the contact, which can be explained by (1) no large age difference between the two units, or (2) scouring of the contact by the Salt River prior to deposition of the lowest Salt River Gravels. Nevertheless, the contact appears to be an erosion surface, but of unknown duration. The age of the Salt River Gravels is unknown. The oldest, most deeply buried gravels could be hundreds of thousands to a million years old, whereas the highest, youngest ones are probably Holocene.

The Salt River Gravels display some interesting relations to underlying units near the bedrock ridge (Figures 14 to 19). Salt River Gravels directly overlie Camels Head Formation on the top and upper flanks of the bedrock ridge, but elsewhere basin fill intervenes between the gravels and the hard bedrock. The basal contact of the gravels shows considerable relief, as shown on a contour map in Figure 20. The base of the gravels is at an elevation of 1060 feet on the bedrock ridge, but is lower on both the east and west sides (Figures 14 and 16). On the east flank of the ridge, the base of the gravels is a notch cut into the underlying basin fill (Figures 14, 16, and 17). In view of the sharp contact between Salt River Gravels and basin fill, this feature is most easily interpreted as a paleovalley eroded into basin fill and then filled with Salt River Gravels. This interpretation is supported by the decrease in the preserved thickness of basin fill in the paleovalley compared to observations from drill holes east of the paleovalley (Figures 14 and 16). That is, more basin fill was eroded away to create the valley. The relief shown by this paleovalley is consistent with other evidence that an episode of erosion intervened between the basin fill and Salt River Gravels.

The paleovalley trends northwest on the east side of the bedrock ridge, and curves to the west around the north end of the ridge. As depicted on the contour map (Figure 20), the paleovalley is narrower near the southeast end of the ridge but becomes wider and deeper down slope to the northwest. The paleovalley may have several branches from the south, one through the southern saddle (Figure 18) and one farther to the east, where there are few data points.

After it was formed, the paleovalley was infilled by coarse channel facies of the Salt River Gravels. When the lowest and oldest Salt River Gravels were deposited in the paleovalley, the bedrock ridge was a topographic positive area west of the paleovalley. Seen in this context, the Salt River was flowing northwest, on the east side of the ridge, turning westward only after it had cleared the north end of the ridge (Figure 21). With time, the gravels filled the paleovalley and began to be deposited higher up the flanks of the bedrock ridge. With further deposition, the Salt River must have reached the level of the top of the ridge. At this point, the river was no longer trapped east of the ridge and could have flowed across the top of the ridge, depositing the coarse channel gravels observed in cores. Eventually, the gravel accumulations buried the bedrock ridge, permitting Salt River gravels to be deposited directly on bedrock along the top of the ridge.

The result of this evolution is that buried channels, with coarse material, probably form a network extending northwest along the northeast flank of the bedrock ridge. Similar northwest-trending channels are probably also present on the southwest side of the ridge, where the lowest and oldest Salt River Gravels are seen. Such channels could be of any orientation in gravels above the top of the bedrock ridge, because these were formed when the ridge no longer had any influence on depositional patterns.

It is important to view the bedrock ridge and the flanking older paleovalley in their proper context, not just in cross sections that are greatly vertically exaggerated. In each of the cross sections shown here (Figures 14 to 19), a nonexaggerated version is included. In this perspective, the paleovalley, bedrock ridge, and their flanks are revealed as broad, gentle features.

The history of successive infilling of the paleovalley and subsequent burial of the bedrock ridge may help explain why the top of the ridge appears to be so flat. As the level of the Salt River rose and the gravels infilled the valley, the river could by lateral migration begin to erode any bedrock hills that stood above the elevation of the river. Migration of the river laterally could have eroded away such hills resulting in a relatively flat-topped bedrock ridge.

Uppermost Alluvium

The youngest deposits in the area, except for those in the modern channel of the Salt River, are the *uppermost alluvium*. This unit consists of 2 to 20 feet of reddish-brown silt, clay, and sand, with only local gravels. The unit is mostly unconsolidated and is described in the logs as being loose or loose to moderately dense, with some carbonate cement. The silt and sand probably represent floodplain and eolian deposits, with the clay and carbonated soil representing modern soil deposits. Because of the heavily urbanized and industrialized nature of the area, there is commonly several feet of construction fill on top of the unit.

A Brief Geologic History of the Easternmost Phoenix Basin

After the Precambrian rocks were formed, uplifted, and exposed at the surface, mid-Tertiary extension formed sedimentary basins, into which the Camels Head Formation and Tempe Formation were deposited. Extension broke up the landscape into a series of tilted fault blocks, bounded by northwest-trending faults. Mid-Tertiary units in the fault blocks dip 30° to 50° to the southwest, with evidence of decreasing dips upward across the Camels Head – Tempe Formation interval. Tertiary volcanic rocks are also tilted and locally rest unconformably on Camels Head Formation, without any intervening Tempe Formation.

The fault blocks and units were beveled by erosion after the faulting and tilting, resulting in an extensive, low-relief pediment. On this pediment are the bedrock ridge, which is an eroded remnant of a tilted fault block of Camels Head Formation, and a broad northwest-trending trough cut into Tempe Formation east of the bedrock ridge. The broad trough was subsequently infilled by Late Tertiary (?) basin fill. The basal facies of basin fill was probably derived in place or was transported very locally. The sandy facies of basin fill was deposited across much of the basin, containing angular to subrounded clasts that were derived from the local bedrock exposures. Near the bedrock ridge, a thin unit of exotic-clast conglomerate and overlying fine-grained basin fill accumulated, probably to higher levels than are preserved today.

After the basin fill was deposited, buried, and partially indurated, a paleovalley was carved just east of the bedrock ridge. This paleovalley was subsequently infilled by channel deposits of the Salt River. These Salt River Gravels form an eastward-thinning wedge. A network of Salt River channels probably flowed to the northwest on both the northeast and southwest sides of the bedrock ridge. It was not until after this time that the bedrock ridge was finally covered with Salt River Gravels, preserving its broad, gentle topography. In the late Quaternary and Holocene, the Salt River incised its modern channel.

Hydrogeologic Implications

The complex subsurface geology of this part of the Phoenix basin poses some interesting challenges to those trying to understand the area's hydrogeology (Figure 22). Overall, groundwater flows to the west and southwest, from higher topography near Papago Park toward lower and deeper parts of the basin to the northwest, west, and southwest. But imposed on this general regime are complicating aspects, such as the bedrock ridge, the paleovalley, and the wedge-shaped geometry of the Salt River Gravels.

From a hydrologic viewpoint, there are three main units: hard bedrock, basin fill, and Salt River Gravels. Hard bedrock includes Proterozoic metarhyolite and granite, and the three mid-Tertiary units: Camels Head Formation, Tempe Formation, and the volcanic rocks. These units are hard, indurated rocks, with little intrinsic permeability. The main source of permeability is faults and other fractures. In outcrops at Papago Park and in many cores, however, many faults and fractures are filled, and at least partially sealed, with hard red material. In outcrop and in core, some fractures are not sealed. The most fractured rocks are the metarhyolite and granite landslide masses, which are encased within sedimentary breccias of the Camels Head Formation. The fractures in these landslide masses are mostly filled with red mud and other fine-grained matrix. Pumping tests in the Proterozoic crystalline rocks, whether representing intact basement or mid-Tertiary landslide deposits, yield low hydraulic conductivities, generally less than 0.01 feet/day (Dames & Moore, 1987). Proterozoic rocks are only important, from a hydrologic perspective, in the easternmost part of the study area where they are closest to the surface. Elsewhere, they evidently are structurally too deep to be of significance.

The mid-Tertiary units are also consolidated rocks with relatively low intrinsic permeabilities. The sedimentary breccias of the Camels Head Formation are very poorly sorted with red mud and silt occupying the matrix between the large angular clasts. Most of the Tempe Formation consists of fine-grained rocks, including siltstones, mudstones, and sandstones. These rocks commonly have a calcite cement further limiting their permeability. Hydrologic tests on the Camels Head Formation and Tempe Formation yielded hydraulic conductivities that range from 0.01 to 0.3 feet/day (Dames & Moore, 1987, 1992, 1993). The hydraulic conductivities of the basalts are less well known, but this unit has limited areal extent.

Numerous faults cut the Proterozoic and mid-Tertiary units, providing potential pathways for groundwater. The dominant faults dip northeast, opposite to the southwest direction of groundwater flow, and are therefore unlikely to act as major conduits of groundwater flow. The lithologic units, such as Camels Head Formation, in the fault blocks dip moderately to the southwest, but are truncated down dip by the northeast-dipping faults. This geometry does not favor southwest groundwater flow through the units to any large extent.

The erosion surface developed across the mid-Tertiary rocks and structures represents a profound hydrologic boundary, separating hard bedrock below from basin fill and Salt River Gravels above. The permeability of basin fill is likely to be variable, in concert with the grain-size variations in the unit. The sandy facies varies from poorly to well sorted, and has abundant calcite cement and silt. It has a moderate hydraulic conductivity based on a pumping test that yielded a hydraulic conductivity of 60 feet per day (Dames & Moore, 1992). In contrast, the fine-grained facies, being composed mostly of silt and fine sand, would have much lower hydraulic conductivities (perhaps 1-10 feet per day), but there are no pumping tests completed solely in this unit.

The Salt River Gravels by virtue of their very coarse grain size, well-rounded clasts, and general lack of silt and clay matrix, have much higher permeabilities. All but the upper 50 to 60 feet of this unit is saturated, making this unit an important aquifer. Measured hydraulic conductivities in this unit range from 200 to 450 feet/day (Dames & Moore, 1993; Conestoga-Rovers & Associates, 1999).

In addition to the permeabilities of these units, the hydrology is also strongly influenced by the *geometry* of the units. The top of hard bedrock decreases gradually in elevation from east to west, forming a broad westward-deepening basin that is filled with basin fill and Salt River Gravels. This basin is interrupted by the northwest-trending bedrock ridge, where hard bedrock protrudes above the present-day water table. This configuration, combined with low permeabilities typical for Camels Head Formation, provides a barrier to southwestward groundwater flow. Presently, west- and southwest-flowing groundwater is diverted around the north and south ends of the ridge, and through the southern saddle. Compared to the southern saddle, the central saddle is narrow and filled with low permeability lower basin fill sediments. Groundwater flow through the central saddle is therefore insignificant compared to the southern saddle.

Basin fill is thickest in the broad trough east of the bedrock ridge and to the west of the bedrock ridge. Basin fill laps out against the bedrock ridge, but extends into the southern saddle. Basin fill in the saddle is predominately the fine-grained facies, which should have lower permeabilities than sandier basin fill farther to the north and east. The thin conglomeratic lens in basin fill near the southern saddle is flanked laterally by hard bedrock and capped by fine-grained basin fill, so it may not be well connected hydrogeologically to more permeable units to the northeast and south.

The Salt River Gravels have a wedge-shaped geometry that pinches out to the northeast, restricting this very permeable unit to the southwestern parts of the study area. Further east, cemented and less permeable basin fill extends from hard bedrock all the way to the surface. Groundwater flowing southwest from the eastern part of this area would need to flow from one hydrologic unit (basin fill) into another (Salt River Gravels). Flow of groundwater from hard bedrock into basin fill would likewise represent an abrupt change in hydrogeologic unit, and would have to pass through the dominantly fine-grained basal unit of basin fill.

The Salt River Gravels are thin and presently unsaturated over the top of the bedrock ridge. Coarse channel deposits of the Salt River fill the paleovalley to the east of the bedrock ridge and extend up to within several feet of the present-day surface, blanketing the bedrock ridge and surrounding areas. The paleovalley, cut into less permeable fine-grained basin fill and flanked by hard bedrock of the bedrock ridge, provides a natural pathway for groundwater flow. There is likely to be a network of buried Salt River channels on both sides of the ridge, trending northwest.

From our analysis, we conclude that groundwater flow in the study area is strongly controlled by the relationship of bedrock topography and the geometry of key hydrogeologic units. The groundwater table currently lies below the elevation of the broad northwest-trending Bedrock Ridge north of Sky Harbor Airport. This fact, coupled with the relatively low permeability of the bedrock and overlying basin fill units and the high permeability of the Salt River Gravels make the Bedrock Ridge a major controlling feature of local groundwater flow.

Groundwater upgradient of the ridge flowing toward the southwest must be redirected both northwest and south of the bedrock ridge at the northwest and southeast ends of the ridge, respectively. As occurs today, groundwater probably flowed southwest through the southern saddle.

Historical changes in groundwater elevation could have resulted in changes in flow direction locally as the groundwater table either overtopped the bedrock ridge or dropped below it. Flow in the Salt River during flood events may also have compounded the influence of the Bedrock Ridge in driving groundwater flow to the northwest from the Sky Harbor Airport area.

The geologic control of groundwater flow has important implications for understanding the dispersal and containment of groundwater contamination, including volatile organic compounds (VOC), such as TCE. VOC contamination in this Superfund site arose from several known sources and is present in a broad area north of the Salt River. The dispersal of contamination would have been influenced by the subsurface geology, especially (1) the profound hydrologic boundary between hard bedrock and the overlying units, (2) the boundary between less permeable basin fill and more permeable Salt River Gravels, (3) the westward-thickening geometry of the Salt River Gravels and the absence of these gravels in the eastern part of the study area, (4) the bedrock ridge, which protrudes up into the permeable Salt River Gravels, and (5) the paleovalley east of the bedrock ridge, which is filled by coarse, channel-facies Salt River Gravels. The design remedies for containing this contamination need to consider each of these factors and how they influence the flow of contaminated groundwater.

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Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
A	Reverse Air Circulation Percussion Hammer	1118	108	95 (1023)	NE	0 – 10 10 – 95 95 – 108	Uppermost alluvium Salt River Gravels Camels Head Formation	L
B	Reverse Air Circulation Percussion Hammer	1122	130	105 (1017)	130 (992)	0 – 10 10 – 105 105 – 130 130	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Camels Head Formation	C
C	Reverse Air Circulation Percussion Hammer	1112	159	120 (992)	156 (956)	0 – 10 10 – 120 120 – 156 156 – 159	Uppermost alluvium Salt River Gravels Basin Fill (sandstone and breccia) Camels Head Formation	L
D	Reverse Air Circulation Percussion Hammer	1116	70	55 (1061)	NE	0 – 55 55 – 70	Salt River Gravels Camels Head Formation	L
F	Reverse Air Circulation Percussion Hammer	1113	59	54 (1059)	NE	0 – 10 10 – 54 54 – 59	Uppermost alluvium Salt River Gravels Weathered bedrock or Camels Head Formation	C
G	Reverse Air Circulation Percussion Hammer	1113	59	54 (1059)	NE	0 – 10 10 – 54 54 - 59	Uppermost alluvium Salt River Gravels Camels Head Formation	L
H	Reverse Air Circulation Percussion Hammer	1113	130	90 (1023)	NR	0 – 15 15 – 90 90 – 130	Uppermost alluvium Salt River Gravels Basin Fill (fine grained)	L, C
I	Reverse Air Circulation Percussion Hammer	1116	99	85 (1031)	NE	0 – 10 10 – 85 85 – 99	Uppermost alluvium Salt River Gravels Weathered bedrock and Camels Head Formation	L
J	Reverse Air Circulation Percussion Hammer	1118	76	75 (1043)	NE	0 – 10 10 – 75 75 – 76	Uppermost alluvium Salt River Gravels Camels Head Formation	L
K	Reverse Air Circulation Percussion Hammer	1108	122	115 (993)	NR	0 – 10 10 – 115 115 – 122	Uppermost alluvium Salt River Gravels Basin Fill (fine grained)?	L

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
L	Reverse Air Circulation Percussion Hammer	1117	100	90 (1027)	NR	0 – 90 90 – 100	Salt River Gravels Basin Fill (fine grained)	C
M	Reverse Air Circulation Percussion Hammer	1115	57.5	52 (1063)	NE	0 – 52 52 – 57.5	Salt River Gravels Camels Head Formation	L
ASE-19B	Rotosonic	1121	145	89 (1032)	135 (986)	0 – 9 9 – 89 89 – 115 115 – 125 125 – 135 135 – 145	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate) Basin Fill (sandstone) Tempe Formation: 30 – 40°	C
ASE-20B	Rotosonic	1121	144	98 (1023)	133 (988)	0 – 6 6 – 98 98 – 118 118 – 122 122 – 133 133 – 144	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate) Basin Fill (sandstone and breccia) Camels Head Formation: 30°	L, C
ASE-21C	Air Rotary	1123	174	80 (1043)	133 (990)	0 – 10 10 – 80 80 – 123 123 – 133 133 – 174	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (sandstone and breccia) or weathered bedrock Camels Head Formation	C
ASE-22B	Rotosonic	1115	143	116 (999)	133 (982)	0 – 7 7 – 83 83 – 116 116 – 128 128 – 133 133 – 143	Uppermost alluvium Salt River Gravels Salt River Gravels: weakly cemented Basin Fill (fine grained): conglomerate at 124 – 126' Basin Fill (sandstone and breccia) or weathered bedrock Camels Head Formation	C, L

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
ASE-23B	Rotosonic	1114	216	126 (988)	186 (928)	0 – 7.5 7.5 – 75 75 – 126 126 – 135 135 – 140 140 – 172 172 – 186 186 – 216	Uppermost alluvium Salt River Gravels Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate) Basin Fill (fine grained) Basin Fill (sandstone and breccia): caliche at 183 – 186' Camels Head Formation: 35 – 40° at 210'	C
ASE-24C	Air Rotary	1118	180	91 (1027)	127 (991)	0 – 5 5 – 91 91 – 100 100 – 103 103 – 115 115 - 120 120 – 127 127 – 180	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate)? Basin Fill (fine grained) Basin Fill (conglomerate) Basin Fill (sandstone) Camels Head Formation	C
ASE-25C	Air Rotary	1115	95	40 (1075)	NE	0 – 40 40 – 95	Salt River Gravels Camels Head Formation: 30 – 40°	L, C
ASE-26A	Rotosonic	1114	97	NR	NE	0 – 11 11 – 97	Uppermost alluvium Salt River Gravels	L
ASE-27A	Air Rotary	1114	94	NR	NE	0 – 7 7 – 40 40 – 63 63 – 94	Uppermost alluvium Salt River Gravels Salt River Gravels: silty Salt River Gravels: mostly fine grained	L, C
ASE-28A	Air Rotary	1108	90	NR	NE	0 – 5 5 – 90	Uppermost alluvium Salt River Gravels	L
ASE-29A	Air Rotary	1116	87	62 (1054)	86 (1030)	0 – 10 10 – 62 62 – 65 65 – 86 86 – 87	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (sandstone and breccia) Camels Head Formation	C
ASE-30A	Air Rotary	1111	87	NR	NE	0 – 3 3 – 87	Fill Salt River Gravels	L

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Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
ASE-31A	Air Rotary	1108	90	NR	NE	0 – 7 7 - 90	Uppermost alluvium Salt River Gravels	L, C
ASE-32A	Air Rotary	1112	92	NR	NE	0 – 10 10 – 92	Fill and uppermost alluvium Salt River Gravels	L, C
ASE-33A	Air Rotary	1113	93	NR	NE	0 – 93	Salt River Gravels: moderately cemented sandstone at 56' and 78'	L, C
ASE-34A	Air Rotary	1111	100	NR	NE	0 – 17 17 – 100	Uppermost alluvium Salt River Gravels	L, C
ASE-35A	Air Rotary	1109	100	NR	NE	0 – 7 7 – 100	Uppermost alluvium Salt River Gravels	L, C
ASE-37A	Air Rotary	1121	112	82 (1039)	108 (1013)	0 – 20 20 – 82 82 – 106 106 – 108 108 – 112	Fill and uppermost alluvium Salt River Gravels Basin Fill (fine grained and cemented sandstone) Basin Fill (sandstone and breccia): strongly cemented Camels Head Formation	C, L
ASE-38A	Rotosonic	1121	112	80 (1041)	110 (1011)	0 – 8 8 – 80 80 – 89 89 89 – 102 102 – 108 108 – 110 110 – 112	Uppermost alluvium Salt River Gravels: cemented 70 – 75' Basin Fill (fine grained) Basin Fill (conglomerate) Basin Fill (fine grained) Basin Fill (sandstone and breccia) Basin Fill (fine grained) and weathered bedrock Camels Head Formation	C
ASE-39A	Rotosonic	1121	105	85 (1036)	98 (1023)	0 – 6 6 – 78 78 – 85 85 – 93 93 – 98 98 – 105	Uppermost alluvium Salt River Gravels Salt River Gravels: cemented sandstone Basin Fill (sandstone and breccia) Basin Fill (fine grained) Strongly cemented sandstone (Basin Fill sandstone and breccia or Camels Head Formation)	C, L

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
ASE-40B	Rotosonic	1119	130	93 (1026)	125 (994)	0 – 8 8 – 93 93 – 115 115 – 125 125 – 130	Fill and uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (sandstone) Uppermost Camels Head Formation	C, L
ASE-41B	Rotosonic	1119	140	97 (1022)	126 (993)	0 – 7 7 – 97 97 – 112 112 – 126 126 – 140	Fill and uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate) Camels Head Formation	C, L
ASE-42C	Rotosonic	1116	95	62 (1054)	NE	0 – 16 16 – 62 62 - 95	Fill and uppermost alluvium Salt River Gravels Camels Head Formation: 45 – 50°	L, C
ASE-43B	Rotosonic	1121	143	100 (1021)	134 (987)	0 – 7 7 – 100 100 – 116 116 – 123 123 – 134 134 – 143	Fill and uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate) Weathered bedrock or Basin Fill (silt, sand, and breccia) Camels Head Formation	L
ASE-43C	Rotosonic	1121	220	102 (1019)	134 (987)	0 – 7 7 – 102 102 – 117 117 – 122 122 – 130 134 – 220	Fill and uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate) Weathered bedrock Camels Head Formation: 30 – 40°	C, L
ASE-44B	Rotosonic	1122	139	95 (1027)	130 (992)	0 – 5 5 – 95 95 – 115 115 – 121 121 – 130 130 –139	Fill Salt River Gravels Basin Fill (fine grained) Basin Fill (conglomerate) Weathered bedrock Camels Head Formation	C, L

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
ASE-45B	Rotosonic	1121	128	91 (1030)	126 (995)	0 – 8	Fill and uppermost alluvium	C, L
						8 – 91	Salt River Gravels	
						91 – 126	Basin Fill (fine grained): probable unconformity at 91'	
						126 – 128	Camels Head Formation	
ASE-46B	Rotosonic	1119	131	94 (1025)	120 (999)	0 – 15	Fill and uppermost alluvium	C, L
						15 – 94	Salt River Gravels	
						94 – 111	Basin Fill (fine grained and cemented sandstone)	
						111 – 120	Basin Fill (conglomerate)	
						120 – 130	Weathered bedrock	
						130 – 131	Camels Head Formation	
ASE-47B	Rotosonic	1112	204	130 (982)	175 (937)	0 – 10	Uppermost alluvium	C, L
						10 – 130	Salt River Gravels	
						130 – 136	Basin Fill (fine grained)	
						136 – 175	Cemented sandstone with concretions (Basin Fill sandstone or weathered Tempe Formation)	
						175 – 187	Weathered bedrock or Basin Fill (sandstone and breccia)	
						187 – 204	Camels Head Formation	
ASE-48B	Rotosonic	1121	141	93 (1028)	127 (994)	0 – 5	Uppermost alluvium	C, L
						5 – 93	Salt River Gravels	
						93 – 112	Basin Fill (fine grained): caliche at 110 – 112'	
						112 – 117	Basin Fill (sandstone): cemented	
						117 – 127	Basin Fill (conglomerate)	
						127 – 130	Weathered bedrock	
						130 – 141	Tempe Formation or Camels Head Formation: 55°	
ASE-49B	Rotosonic	1121	129	80 (1041)	118 (1003)	0 – 13	Uppermost alluvium	C, L
						13 – 80	Salt River Gravels	
						80 – 115	Basin Fill (fine grained)	
						115 – 118	Basin Fill (sand)	
						118 – 129	Cemented sandstone (Tempe Formation in logs)	

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary: Depth (in feet)	Lithologic Summary: Unit	Source of Data
ASE-50C	Rotosonic	1121	200	95 (1026)	122 (999)	0 – 12	Uppermost alluvium	C, L
						12 – 95	Salt River Gravels	
						95 – 115	Basin Fill (fine grained)	
						115 – 122	Basin Fill (sandstone)	
						122 – 194	Tempe Formation: 30 – 50°	
						194 – 200	Camels Head Formation: 45°; probably depositional contact with Tempe Formation	
BC-1	Air Rotary	1020	133	85 (1035)	133 (987)	0 – 13	Fill and uppermost alluvium	L
						13 – 85	Salt River Gravels	
						85 – 120	Basin Fill (fine grained)	
						120 – 133	Basin Fill (sandstone)	
						133	Tempe Formation	
BC-2	Air Rotary	1118	116	80 (1038)	114 (104)	0 – 20	Uppermost alluvium	L
						20 – 80	Salt River Gravels	
						80 – 90	Basin Fill (fine grained)	
						90 – 100	Basin Fill (fine grained with conglomerate)	
						100 – 114	Basin Fill (sandstone)	
						114 – 116	Camels Head Formation?	
BC-3	Air Rotary	1117	102	95 (1022)	100 (1017)	0 – 11	Uppermost alluvium	L
						11 – 95	Salt River Gravels	
						95 – 100	Basin Fill (sandstone)	
						100 – 102	Camels Head Formation	
BC-4	Air Rotary	1119	117	99 (1020)	115 (1004)	0 – 14	Uppermost alluvium	L
						14 – 99	Salt River Gravels	
						99 – 115	Basin Fill (fine grained)	
						115 – 117	Weathered bedrock	
						117	Camels Head Formation?	
BC-6	Air Rotary	1115	113	99 (1016)	113 (1002)	0 – 6	Fill and uppermost alluvium	L
						6 – 99	Salt River Gravels	
						99 – 113	Basin Fill (fine grained)	
						113	Camels Head Formation?	

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary: Depth (in feet)	Lithologic Summary: Unit	Source of Data
BC-7A	Air Rotary	1120	76	50 (1070)	74 (1046)	0 – 6	Uppermost alluvium	L
						6 – 50	Salt River Gravels	
						50 – 60	Basin Fill (sandstone)?	
						60 – 74	Basin Fill (fine grained)	
						74 – 76	Tempe Formation	
BC-8A	Air Rotary	1116	96	94 (1022)	NR	0 – 5	Fill	L
						5 – 94	Salt River Gravels	
						94 – 96	Basin Fill (fine grained)	
BC-8B	Air Rotary	1117	114	96 (1021)	112 (1005)	0 – 6	Fill	L
						6 – 96	Salt River Gravels	
						96 – 107	Basin Fill (fine grained)	
						107 – 112	Basin Fill (fine grained) with gravel and sand	
						112 – 114	Camels Head Formation	
BC-9	Air Rotary	1116	92	75? (1041?)	91 (1025)	0 – 10	Uppermost alluvium	L
						10 – 75	Salt River Gravels	
						75 – 91	Basin Fill (sandstone)?	
						91 – 92	Camels Head Formation	
BC-10B	Air Rotary	1113	165	141 (972)	165 (948)	0 – 17	Fill and uppermost alluvium	L, C
						17 – 141	Salt River Gravels	
						141 – 165	Basin Fill (fine grained)	
						165	Tempe Formation (Camels Head Formation in logs)	
BC-11A	Air Rotary	1111	245	130 (981)	243 (868)	0 – 15	Fill and uppermost alluvium	L
						15 – 130	Salt River Gravels	
						130 – 243	Basin Fill?: logs suggest possible Tempe Formation	
						243	Camels Head Formation	
BC-12	Air Rotary	1116	71	71 (1045)	NE	0 – 10	Uppermost alluvium	L
						10 - 71	Salt River Gravels	
BC-13	Air Rotary	1128	102	40 (1088)	100 (1028)	0 – 20	Fill and uppermost alluvium	L
						20 – 40	Salt River Gravels	
						40 – 100	Basin Fill (fine grained)	
						100 – 102	Camels Head Formation	

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
BC-14	Air Rotary	1130	100	45 (1085)	100 (1030)	0 – 15	Fill and uppermost alluvium	L, C
						15 – 45	Salt River Gravels	
						45 – 60	Basin Fill (fine grained)	
						60 – 75	Basin Fill	
						75 – 100	Basin Fill (clay, sandstone, and breccia)	
						100	Camels Head Formation?	
BC-15	Rotosonic	1122	133	82 (1040)	133 (989)	0 – 11	Uppermost alluvium	L
						11 – 82	Salt River Gravels	
						82 – 116	Basin Fill (fine grained)	
						116 – 125	Basin Fill (sandstone)	
						125 – 133	Basin Fill (sandstone and breccia)	
						133	Tempe Formation or Camels Head Formation?	
BC-16	Rotosonic	1116	102	80 (1036)	102 (1014)	0 – 11	Uppermost alluvium	L
						11 – 80	Salt River Gravels	
						80 – 102	Basin Fill (sandstone and breccia) or possible weathered bedrock	
						102	Camels Head Formation?	
BC-17	Rotosonic	1119	116	107 (1012)	116 (1003)	0 – 5	Uppermost alluvium	L, C
						5 – 107	Salt River Gravels	
						107 –110	Basin Fill (sandstone and breccia)	
						110 – 116	Weathered bedrock	
						116	Camels Head Formation	
BC-18	Rotosonic	1116	135	134 (982)	NE?	0 – 8	Fill and uppermost alluvium	L
						8 – 134	Salt River Gravels	
						134 – 135	Weathered bedrock	
BR-1	Reverse Air Hammer	1111	95	57 (1054)	NE	0 – 5	Fill and uppermost alluvium	L
						5 – 57	Salt River Gravels	
						57 – 95	Camels Head Formation	
BR-2	Reverse Air Hammer	1112	95	54 (1058)	NE	0 – 54	Salt River Gravels	L
						54 – 95	Camels Head Formation	
BR-3	Reverse Air Hammer	1113	95	57 (1056)	NE	0 – 6	Fill and uppermost alluvium	L, C
						6 – 57	Salt River Gravels	
						57 – 66	Weathered bedrock	
						66 – 95	Camels Head Formation: 45 – 50°	

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
BR-4	Rotosonic Core	1116	100	53 (1063)	NE	0 – 53 53 – 100	Salt River Gravels Camels Head Formation and weathered bedrock	L
BR-5	Rotosonic Core	1116	111	86 (1030)	NE	0 – 8 8 – 86 86 – 111	Fill and uppermost alluvium Salt River Gravels Camels Head Formation: 45 – 50°	L
DM-102	Cable Tool Continuous Core Wireline	1215	499	NE	61 (1154)	0 – 61 61 – 499	Basin Fill (sandstone and breccia) Precambrian granite: variably shattered with red matrix above 208'; intact (not shattered) below 208'	C, L
DM-104	Cable Tool Continuous Core Wireline	1165	306	NE	105 (1060)	0 – 105 105 – 169 169 – 181 181 – 291 291 – 306	Basin Fill (sandstone and breccia) Tempe Formation: 20 – 30° Uppermost Camels Head Formation: 24 – 35° Camels Head Formation: 23 – 58° Camels Head Formation landslide breccia: 40 – 50°	C, L
DM-106	Cable Tool Continuous Core Wireline	1182	370			0 – 126 126 – 171 171 – 232 232 - 370	Basin Fill Tertiary volcanics Camels Head Formation Precambrian granite	
DM-111	Hollow Stem Auger	1201	24	NE	22 (1179)	0 – 22 22 – 24	Basin Fill (sandstone and breccia) Precambrian granite	C
DM-115	Hollow Stem Auger	1190	56	NE	55 (1135)	0 – 55 55 – 56	Basin Fill (sandstone and breccia) Precambrian granite	C
DM-201-OB1	Conventional Mud Rotary	1196	120	NE	47 (1149)	0 – 47 47 – 120	Basin Fill (sandstone and breccia) Precambrian metarhyolite	L
DM-310	Conventional Mud Rotary	1180	155	NE	125 (1055)	0 – 125 125 – 150	Basin Fill (sandstone and breccia) Tertiary volcanic or volcanic-derived Basin Fill	L, C
DM-313	Conventional Mud Rotary	1176	105	NE?	73 (1103)	0 – 20 20 – 73 73 – 105	Exotic-clast gravels with strongly calcareous matrix (either Basin Fill conglomerate or Salt River Gravels) Basin Fill (sandstone and breccia) Camels Head Formation landslide breccia	C, L

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
DM-501	Conventional Mud Rotary	1137	420	58 (1079)	214 (923)	0 – 18	Uppermost alluvium	L, C
						18 – 58	Salt River Gravels	
						58 – 117	Basin Fill (fine grained)	
						117 – 214	Basin Fill (sandstone and breccia)	
						214 – 420	Tempe Formation: 15° at top, increasing to 25 – 30° at base	
DM-502	Conventional Mud Rotary	1157	350	NE	136 (1021)	0 – 136	Basin Fill (sandstone and breccia)	C, L
						136 – 237	Tertiary volcanics	
						237 – 267	Tempe Formation: upper contact depositional and parallel to 20°	
	Diamond Core					267 – 350	Precambrian granite: locally shattered; probable fault contact at 267'	
DM-503	Conventional Mud Rotary	1161	93	NE	63 (1098)	0 – 63	Basin Fill (sandstone and breccia)	C, L
						63 – 93	Precambrian granite	
DM-504	Conventional Mud Rotary	1138	245	48 (1090)	213 (925)	0 – 8	Uppermost alluvium	C, L
						8 – 48	Salt River Gravels	
						48 – 210	Basin Fill (sandstone and breccia)	
						210 – 213	Basin Fill (fine grained)	
						213 – 245	Tempe Formation: 5 – 15°	
DM-506	Conventional Mud Rotary	1127	396	78 (1049)	227 (900)	0 – 78	Salt River Gravels	C, L
						78 – 210	Basin Fill (sandstone and breccia)	
						210 – 220	Basin Fill (fine grained)	
						220 – 227	Basin Fill (sandstone and breccia)	
	Diamond Core					227 – 280	Tempe Formation: 10 – 20°; logs call top of Tempe Formation at 195'	
						280 – 320	Uppermost Camels Head Formation: 15°	
						320 – 396	Camels Head Formation: 15 – 30°	
DM-507	Conventional Mud Rotary	1117	330	99 (1018)	196 (921)	0 – 13	Uppermost alluvium	C, L
						13 – 99	Salt River Gravels	
	Diamond Core					99 – 196	Basin Fill (sandstone and breccia)	
						196 – 330	Camels Head Formation or Tempe Formation	

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
DM-508	Conventional Mud Rotary	1125	230	67 (1058)	215 (910)	0 – 12	Uppermost alluvium	C, L
						12 – 67	Salt River Gravels	
						67 – 110	Basin Fill (fine grained)	
						110 – 181	Basin Fill (sandstone and breccia)	
						181 – 197	Basin Fill (fine grained with granules)	
						197 – 215	Basin Fill (sandstone and breccia)	
						215 – 230	Tempe Formation	
DM-509	Conventional Mud Rotary	1115	215	98 (1017)	155 (960)	0 – 13	Uppermost alluvium	L, C
						13 – 98	Salt River Gravels	
						98 – 155	Basin Fill	
						155 – 215	Camels Head Formation	
DM-510	Air Rotary	1107	310	106 (1001)	148? (959)?	0 – 16	Uppermost alluvium	L, C
	Diamond Core					16 – 106	Salt River Gravels	
						106 – 148	Basin Fill (sandstone) or Tempe Formation	
						148 – 310	Camels Head Formation: dips 40° top, 50° bottom	
DM-511	Air Rotary	1112	310	102 (1010)	141 (971)	0 – 102	Salt River Gravels	L, C
	Diamond Core					102 – 141	Basin Fill	
						141 – 310	Camels Head Formation: 30 – 55°	
DM-512	Air Rotary	1121	375	140 (981)	187 (934)	0 – 24	Uppermost alluvium	L, C
						24 – 140	Salt River Gravels	
	Diamond Core					140 – 187	Basin Fill (fine grained)	
						187 – 212	Tempe Formation: 10 – 20°	
						212 – 375	Camels Head Formation, including thin uppermost part: 20 – 35°; breccia at base	
DM-513	Air Rotary	1123	337	117 (1006)	203? (920)?	0 – 17	Uppermost alluvium	L, C
	Diamond Core					17 – 117	Salt River Gravels	
						117 – 203?	Basin Fill	
						203 – 337	Camels Head Formation: 25 – 40°; fault at 312'	
DM-514	Air Rotary	1109	318	90 (1019)	92 (1017)	0 – 14	Uppermost alluvium	L, C
	Diamond Core					14 – 90	Salt River Gravels	
						90 – 92	Basin Fill (fine grained)	
						92 – 318	Camels Head Formation	

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
DM-515	Air Rotary Diamond Core	1109	406	162 (947)	230 (879)	0 – 162 162 – 230 230 – 406	Salt River Gravels Basin Fill (sandstone with local conglomerate, cemented) Camels Head Formation: 35 – 45°	C, L
DM-516	Air Rotary Diamond Core	1105	419	175 (930)	230 (875)	0 – 20 20 – 175 175 – 230 230 – 419	Uppermost alluvium Salt River Gravels Basin Fill Camels Head Formation: 45 – 55°	L
DM-517	Air Rotary Diamond Core	1111	387	140 (971)	205 (906)	0 – 11 11 – 140 140 – 205 205 – 251 251 – 387	Uppermost alluvium Salt River Gravels Basin Fill (sandstone, cemented) Tempe Formation: 25 – 40° Camels Head Formation: 40 – 60°	L
DM-518	Air Rotary Mud Rotary	1107	160	117 (990)	138? (969)?	0 – 13 13 – 117 117 – 138 138 – 160	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Camels Head Formation or Basin Fill (sandstone and breccia)	L
DM-703	Conventional Mud Rotary Core	1198	72	NE	30 (1168)	0 – 30 30 – 72	Basin Fill (sandstone and breccia) Precambrian metarhyolite	L, C
DSV-1	Rotosonic Core	1120	118	80 (1040)	NE	0 – 80 80 – 118	Salt River Gravels Camels Head Formation	L
DSV-3	Rotosonic Core	1120	114	95 (1025)	110 (1010)	0 – 13 13 – 95 95 – 106 106 110 110 – 114	Fill and uppermost alluvium Salt River Gravels Basin Fill (fine grained) Weathered bedrock Camels Head Formation?	L
EW-1	Air Percussion	1129	90	38 (1091)	NR	0 – 23 23 – 38 38 – 90	Uppermost alluvium Salt River Gravels Basin Fill (fine grained)	L
EW-3	Air Percussion	1115	110	90 (1025)	NR	0 – 10 10 – 90 90 – 110	Uppermost alluvium Salt River Gravels Basin Fill (fine grained)	L

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
EW-4	Air Percussion	1111	112	85 (1026)	NR	0 – 15 15 – 85 85 – 112	Uppermost alluvium Salt River Gravels Basin Fill (fine grained)	L
EW-6	Air Percussion	1098	112	NR	NE	0 – 112	Salt River Gravels	L
EW-7	Air Percussion	1105	129	NR	NE	0 – 8 8 – 129	Uppermost alluvium Salt River Gravels	L
EW-12	Air Percussion	1099	248	175 (924)	244 (855)	0 – 10 10 – 175 175 – 235 235 – 244 244 – 248	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Weathered bedrock? Camels Head Formation	L
PL-201A	Air Percussion	1117	117	112 (1005)	NR?	0 – 112 112 – 117 117	Salt River Gravels Basin Fill (fine grained) Sandstone (Basin Fill or bedrock)	L
PL-2103	Air Percussion	1120	137	100 (1020)	137 (983)	0 – 5 5 – 100 100 – 120 120 – 137 137	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (fine grained) and Basin Fill (sandstone) Camels Head Formation	L
PZ-1B	Rotosonic	1117	140	88 (1029)	138 (979)	0 – 8 8 – 88 88 – 118 118 – 126 126 – 138 138 – 140	Uppermost alluvium Salt River Gravels Basin Fill (fine grained) Basin Fill (clay, sandstone, and breccia) Weathered bedrock or Basin Fill (sandstone and breccia) Camels Head Formation	L
MW-1 (TEXACO)	Air Rotary	1112	91	74? (1038)?	NE	0 – 8 8 – 74 74 – 91	Uppermost alluvium Salt River Gravels Camels Head Formation	L
MW-2 (TEXACO)	Air Rotary	1112	91	58 (1054)	NE	0 – 7 7 – 58 58 – 91	Uppermost alluvium Salt River Gravels Camels Head Formation	L

Table 1. Summary of information for selected drill holes in the eastern Phoenix basin, Arizona

Drill Hole	Drilling Method	Elev. (feet amsl)	Total Depth (in feet)	Depth to (Elev. of) Base of SRG (in feet)	Depth to (Elev. of) Base of BF (in feet)	Lithologic Summary		Source of Data
						Depth (in feet)	Unit	
MW-3 (TEXACO)	Air Rotary	1113	86	46 (1067)	NE	0 – 8 8 – 46 46 – 86	Uppermost alluvium Salt River Gravels Camels Head Formation	L
MW-4 (TEXACO)	Air Rotary	1112	86	55 (1057)	NE	0 – 8 8 – 55 55 – 86	Uppermost alluvium Salt River Gravels Camels Head Formation	L
MW-5 (TEXACO)	Air Rotary	1113	91	69 (1044)	NE	0 – 8 8 – 69 69 – 86 86 – 91	Uppermost alluvium Salt River Gravels Caliche Camels Head Formation (called granite in logs)	L
B-6 (TEXACO)	Air Rotary	1112	65	56 (1056)	NE	0 – 6 6 – 56 56 – 65	Uppermost alluvium Salt River Gravels Camels Head Formation	L

amsl – above mean sea level
NE - Not Encountered
NR - Not Reached
Elev.- Elevation of ground surface (in feet above mean sea level)
UA – Upper Alluvium
SRG - Salt River Gravels
BF - Basin Fill
Source of Data:
L - Interpreted from boring logs
C - Interpreted from cuttings, core, or chips
If both, first indicated method was primary source

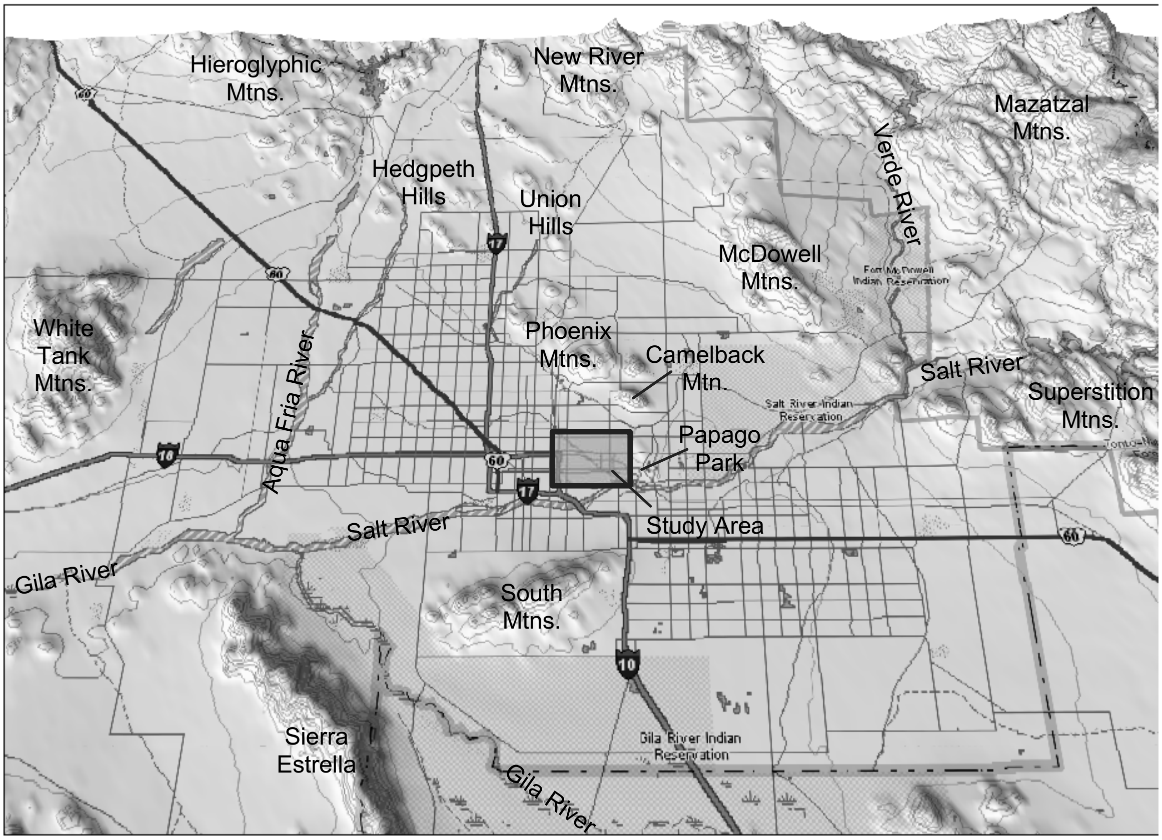


Figure 1. Shaded relief map of the Phoenix area showing the approximate location of the study area with respect to local physiographic features.

Figure 2. Locations of wells and physical features.

File Name: Fig-02.Dwg

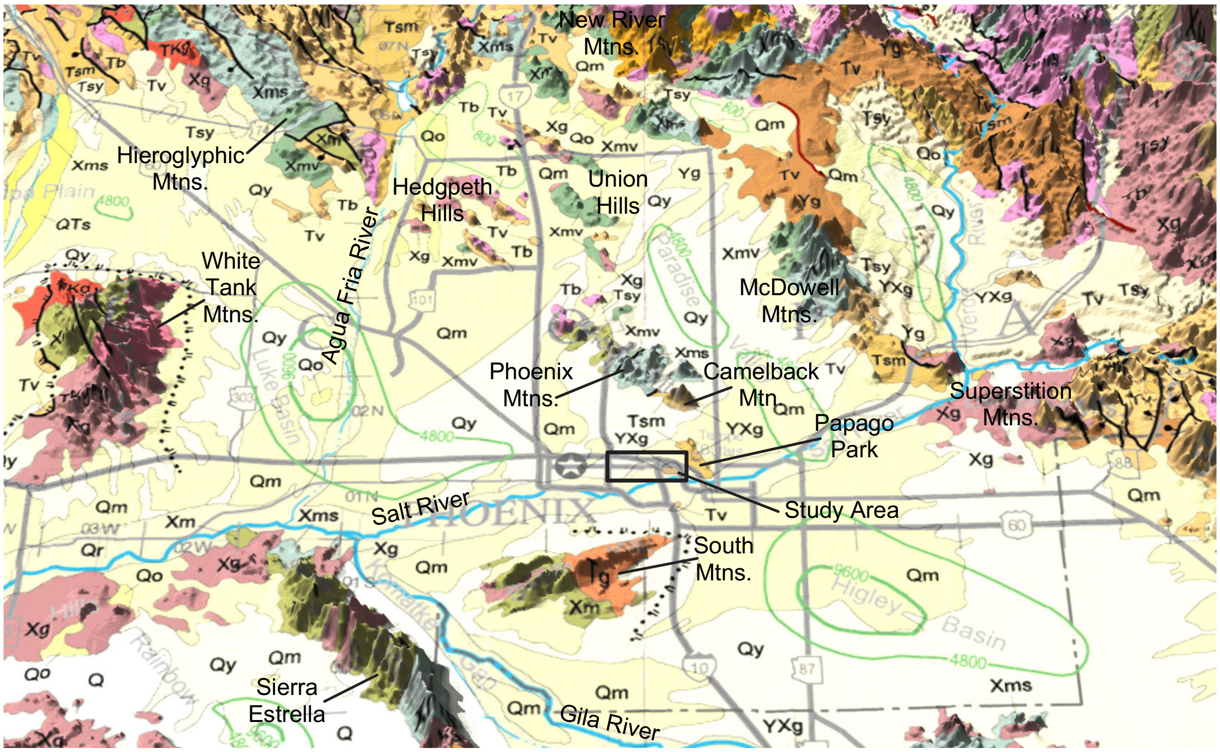


Figure 3. Geologic map of the Phoenix region draped over digital topography. Units are from the Geologic Map of Arizona (Richard and others, 2000).

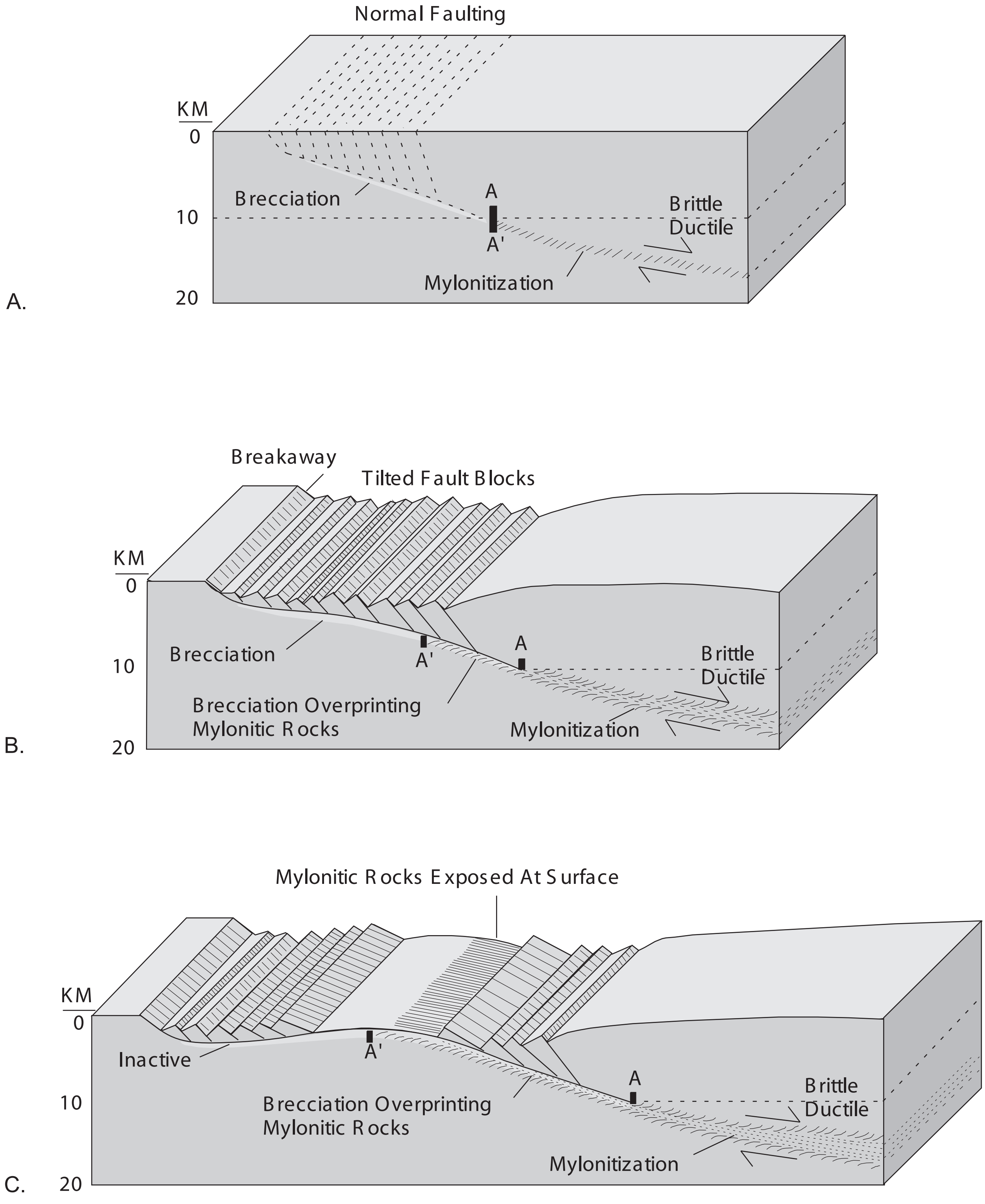
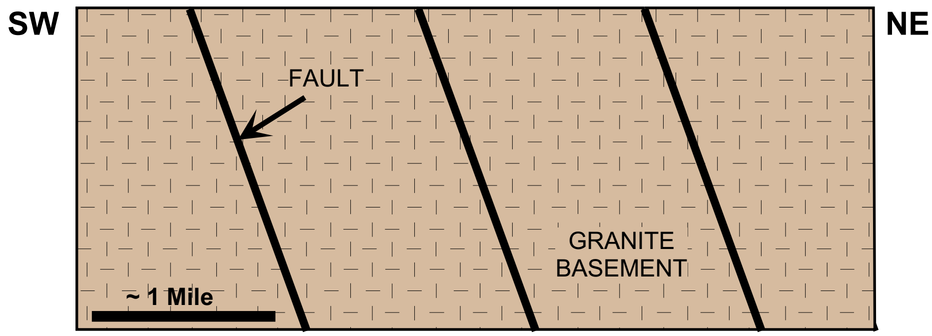
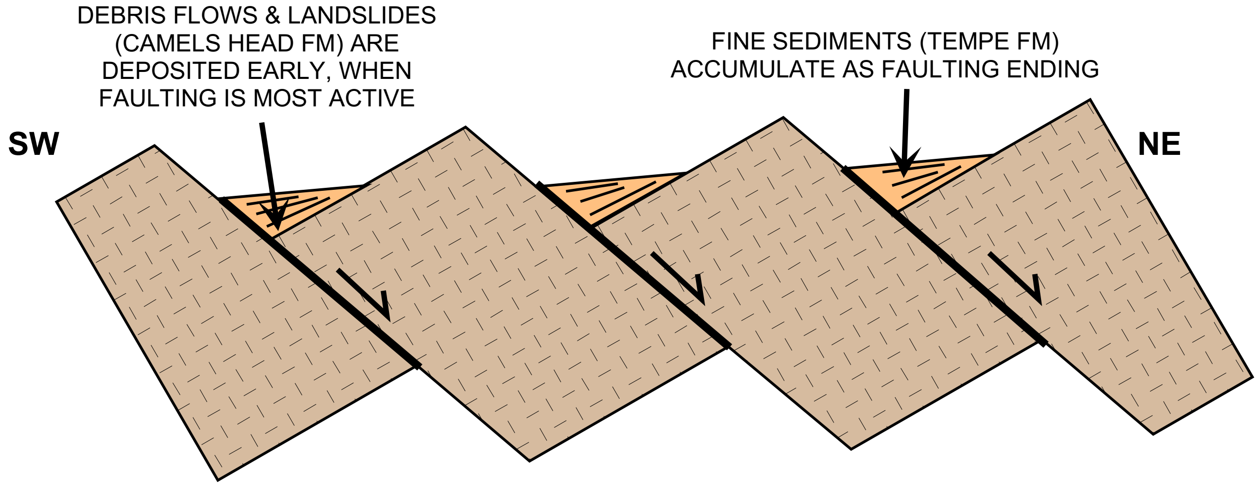


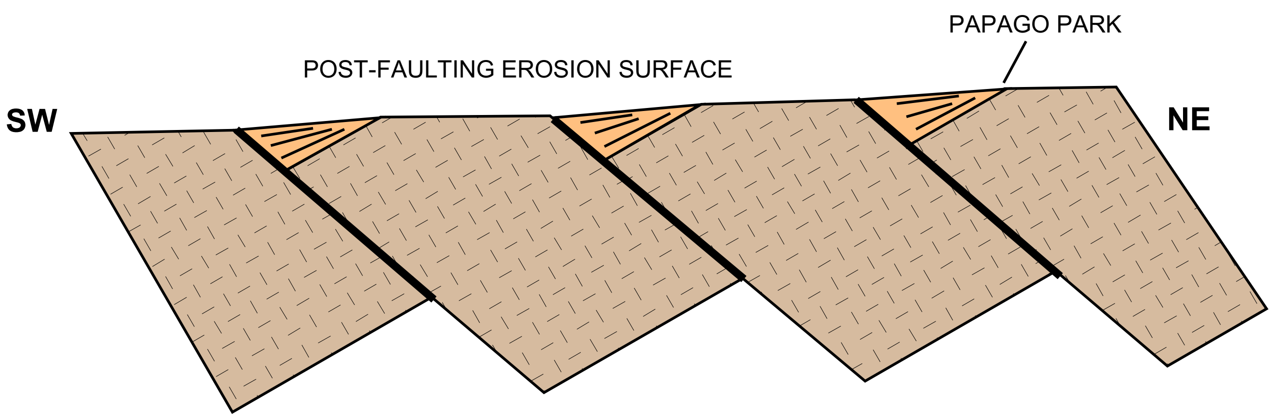
Figure 4. Evolutionary development of a metamorphic core complex. Mid-Tertiary crustal extension across southern Arizona formed mountain ranges, including the South Mountains, composed of ductilely sheared (mylonitic) igneous and metamorphic rocks. Shearing was associated with huge detachment faults that dip gently to the northeast beneath the entire Phoenix basin. The Papago Park - Bedrock Ridge area is situated in the array of tilted fault blocks above the deatchment fault.



A. Precambrian granite cut by faults that dip in the same direction and are spaced ~1 mile or less apart (~22 m.y.).

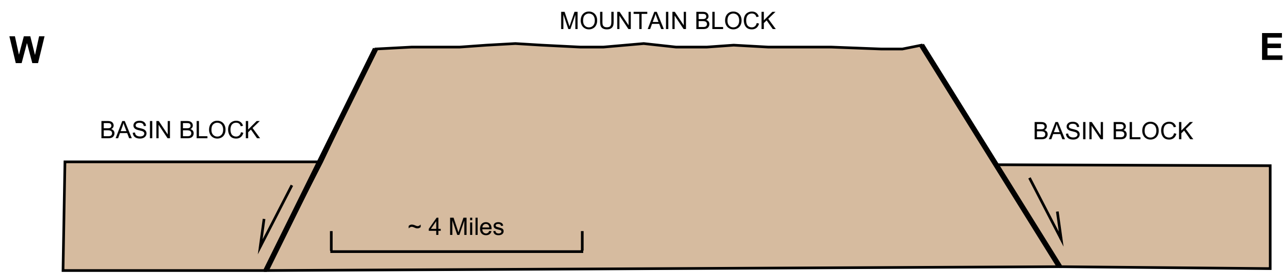


B. Mountains (upper corners) are eroded, producing debris flows, landslides, and finer sediment that is deposited in low corners (~19 m.y.). Sediment in each basin will reflect what kinds of rock are present in flanking mountain ranges.

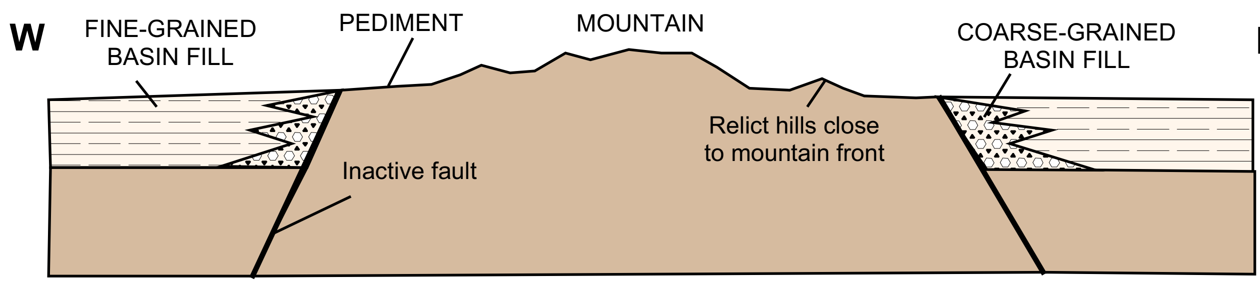


C. Erosion during and after faulting bevels across the fault blocks, forming a low-relief erosion surface (~15 to 5 m.y.). This section is intended only to illustrate the geologic style and origin of the Phoenix region, not as an actual geologic cross section. Number and position of faults are schematic.

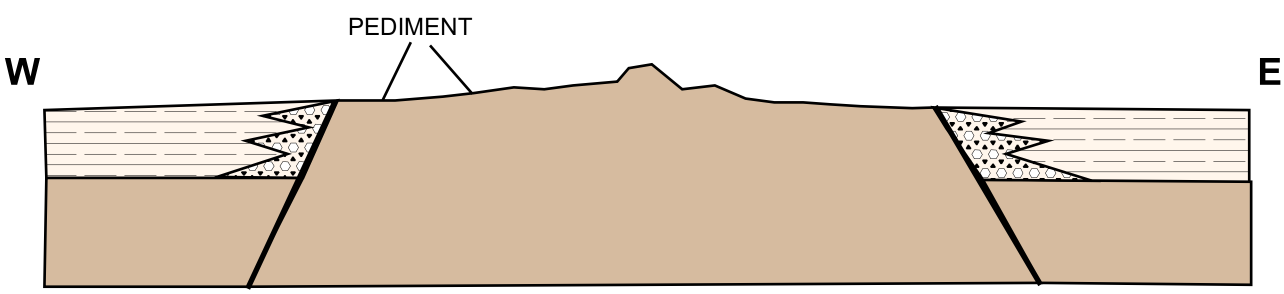
Figure 5. Formation and evolution of middle Tertiary tilted fault blocks in the Phoenix region. Figures are not to scale.



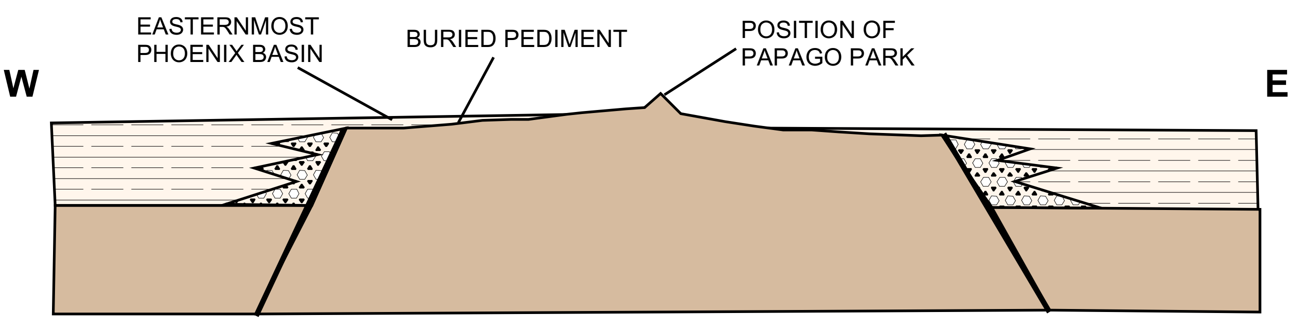
A. Faulting downdrops basin blocks relative to mountain range (~12 m.y.).



B. Erosion begins to cut pediment (gently sloping erosion surface) on bedrock next to basin. Sediment eroded from mountain is deposited in basin (~10 m.y.).



C. Pediment is eroded back into range, and relief on outer part of pediment is lowered (~7 m.y.). Hills and peaks are present only near the crest of the range.



D. Basin fill overtops basin, depositing a thin veneer on low-relief pediment (~5 m.y.). After this (not shown), basin fill is eroded to form some paleochannels, which are later infilled by deposition of Salt River Gravels (<2 m.y.).

Figure 6. Formation and evolution of basins and ranges and a pediment. Figures are not to scale.

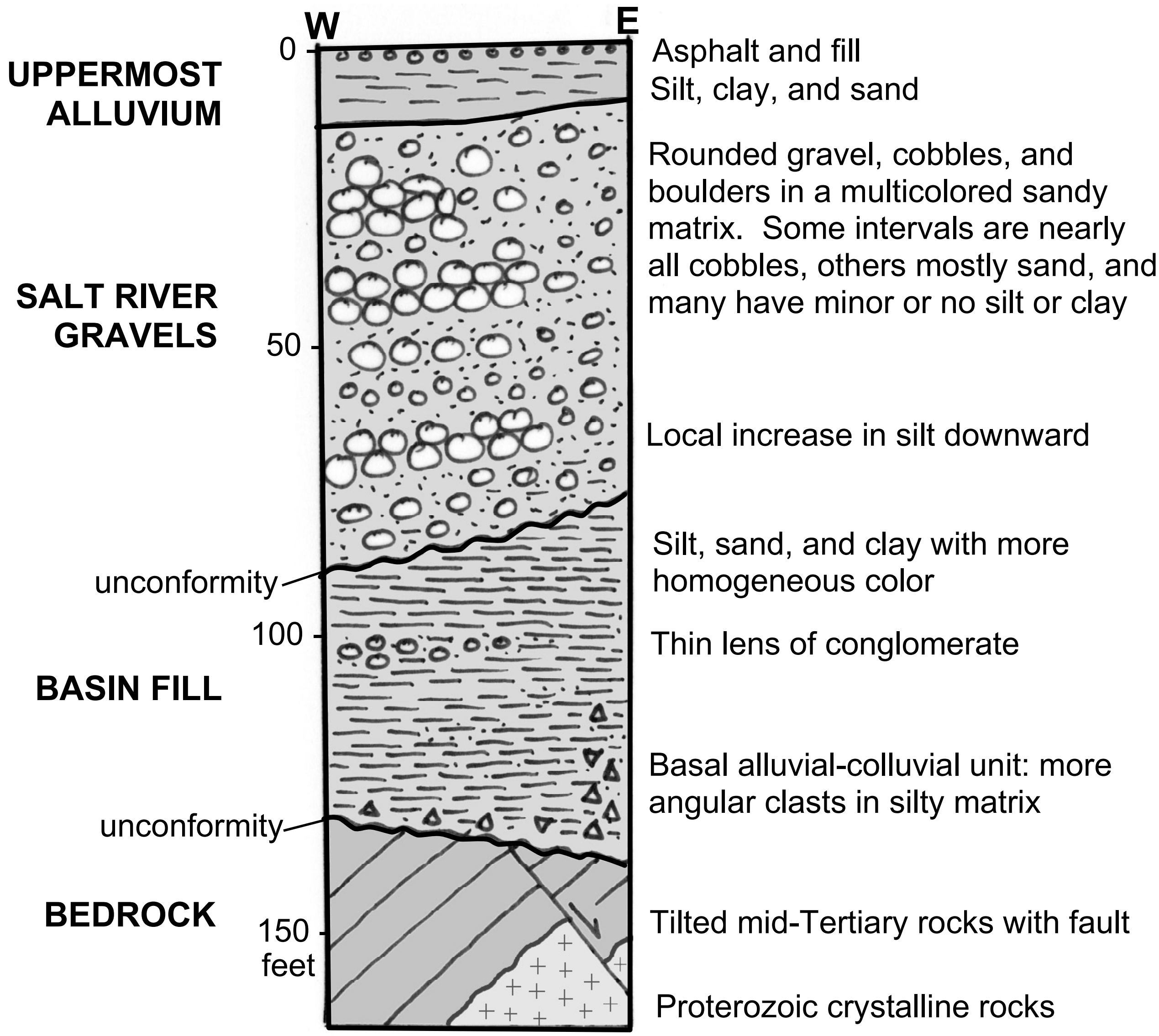
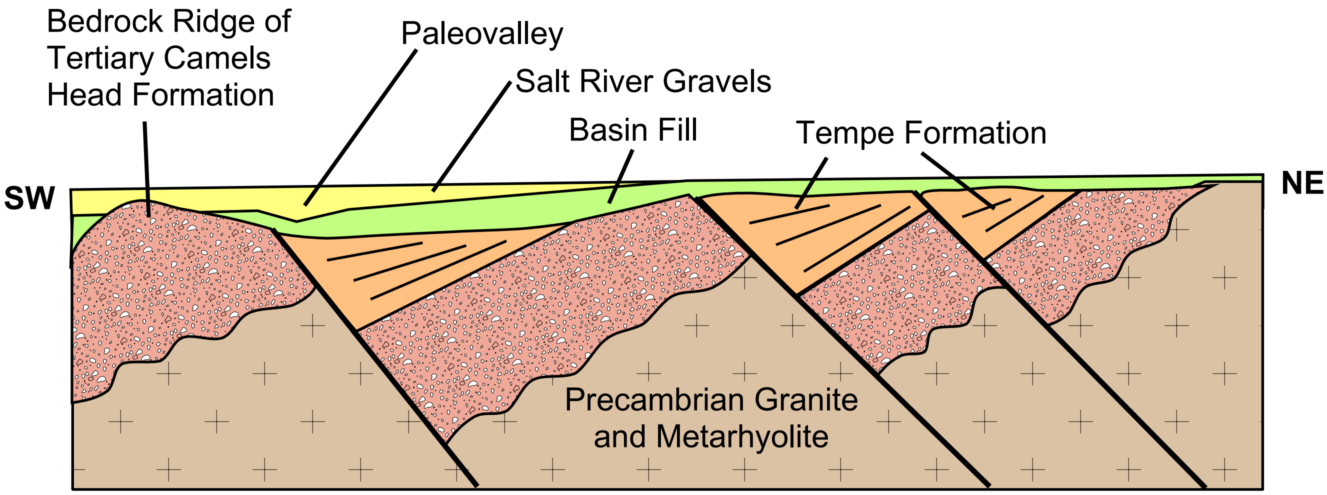
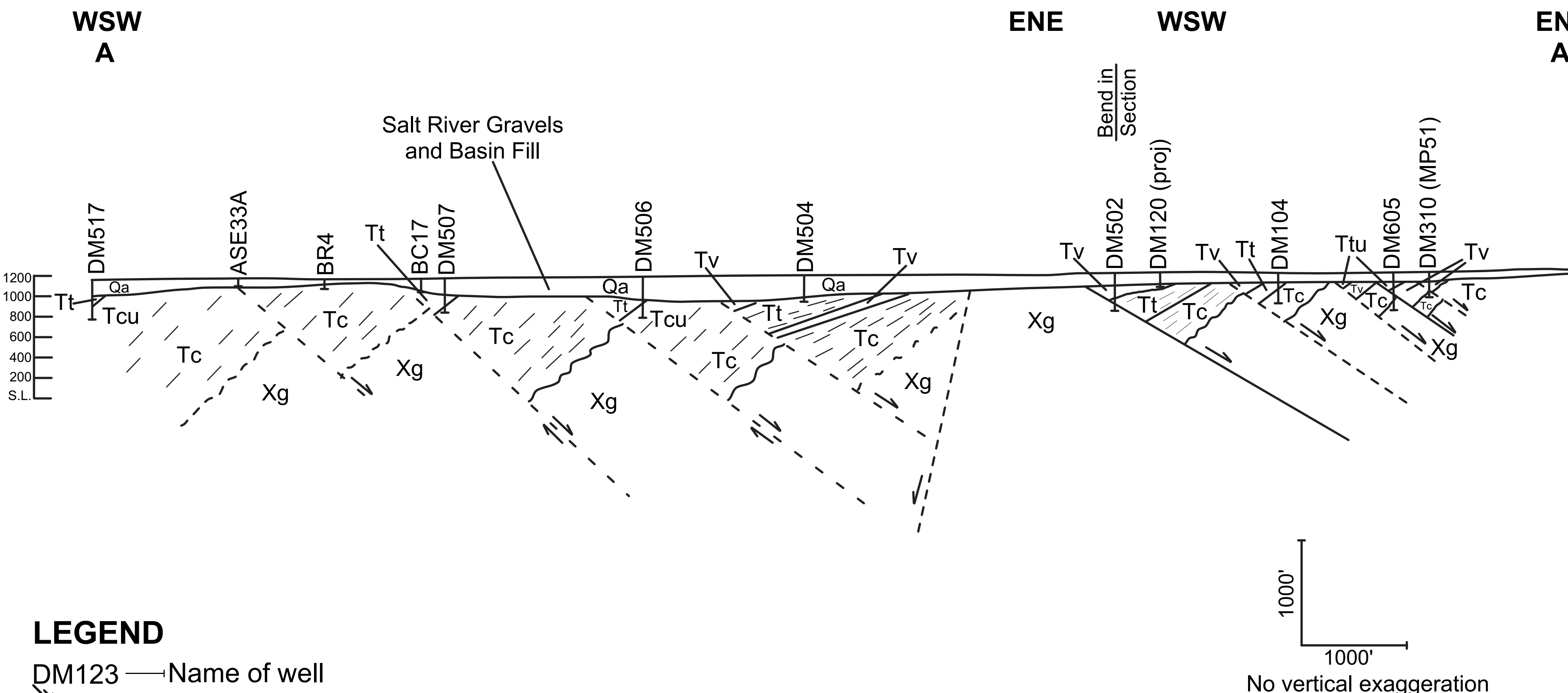


Figure 7. Composite stratigraphic section of the easternmost Phoenix basin.



Note: Normal faults dip steeply to the northeast. The number and location of faults are schematic, intended only to illustrate the structural style. Topography and thickness of units not precisely to scale, but somewhat vertically exaggerated. Note the broad trough infilled by basin fill and a younger, smaller paleovalley infilled by Quaternary Salt River Gravels.

Figure 8. Schematic geologic cross section showing the structural style of the easternmost Phoenix basin.



LEGEND

DM123 —— Name of well

- Fault with relative direction of movement; dashed where inferred

Qa - Salt River Gravels and Basin Fill (Quaternary to late Tertiary)

Ttu - Uppermost Tempe Formation (middle Tertiary)

Tv - Volcanic rocks (middle Tertiary; ~17 - 18 my)

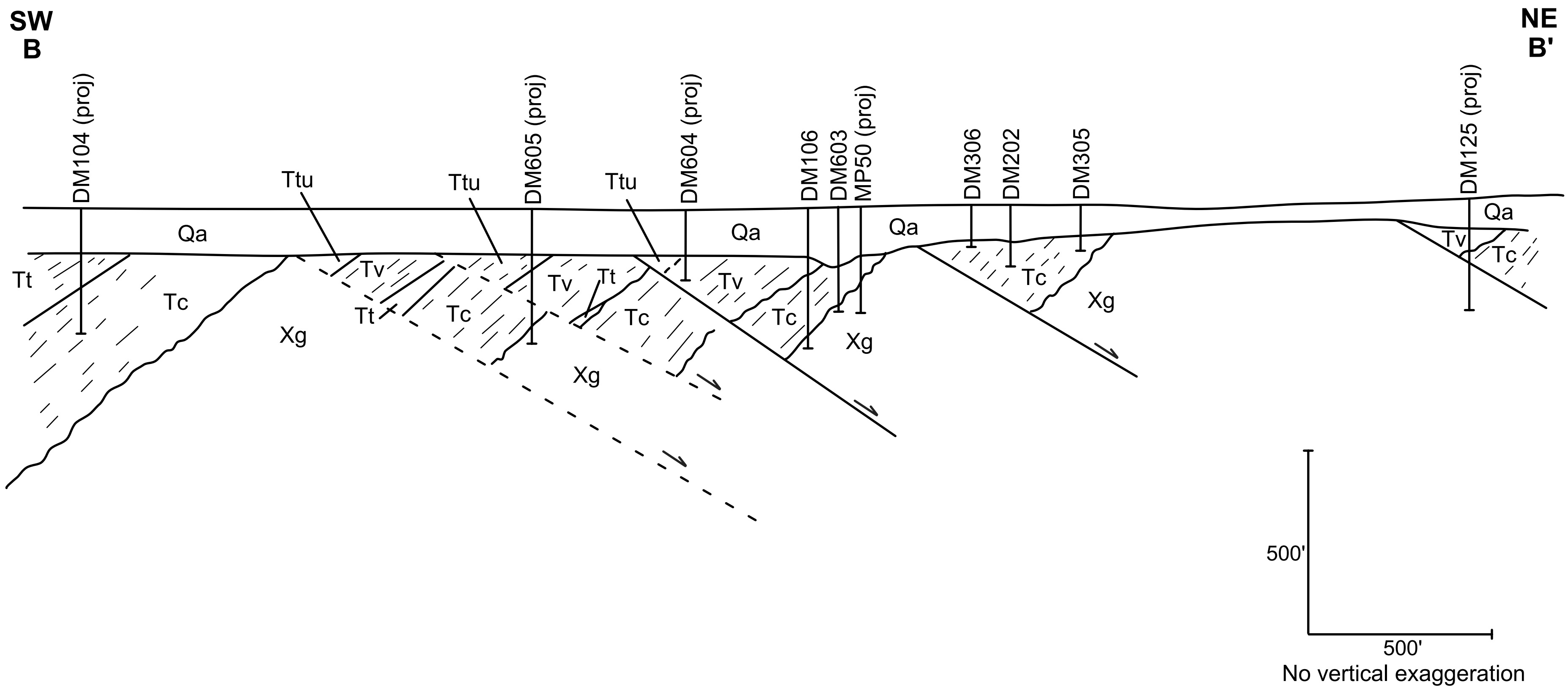
Tt - Tempe Formation (middle Tertiary)

Tcu - Uppermost Camels Head Formation (middle Tertiary)

Tc - Camels Head Formation (middle Tertiary)

Xg - Granite (Precambrian)

Figure 9. Cross section depicting the geometry and correlation of middle Tertiary rocks and structures. Section extends nearly the length of the study area. The number and location of faults are locally constrained but partly schematic and intended only to illustrate the structural style. Location of section shown on Figure 2.



LEGEND

DM123 —— Name of well (proj = projected into line of section)

- Fault with relative direction of movement; dashed where inferred

Qa - Alluvium and Basin Fill (Quaternary to late Tertiary)

Ttu - Uppermost Tempe Formation (middle Tertiary)

Tv - Volcanic rocks (middle Tertiary)

Tt - Tempe Formation (middle Tertiary)

Tc - Camels Head Formation (middle Tertiary)

Xg - Granite (Precambrian)

NOTES

Assume: Faults dip 30° NE

Beds dip 30° at top, 40° at base

Tc = 500 feet thick (max)

Tv = 300 feet thick

Tt pinches out below Tv/Tc unfonformity

Tc is cut out to NE below Tv unconformity at base of TV

Figure 10. Detailed cross section B-B' depicting the geometry and correlation of middle Tertiary rocks and structures in the easternmost part of the study area. Location of section shown on Figure 12.

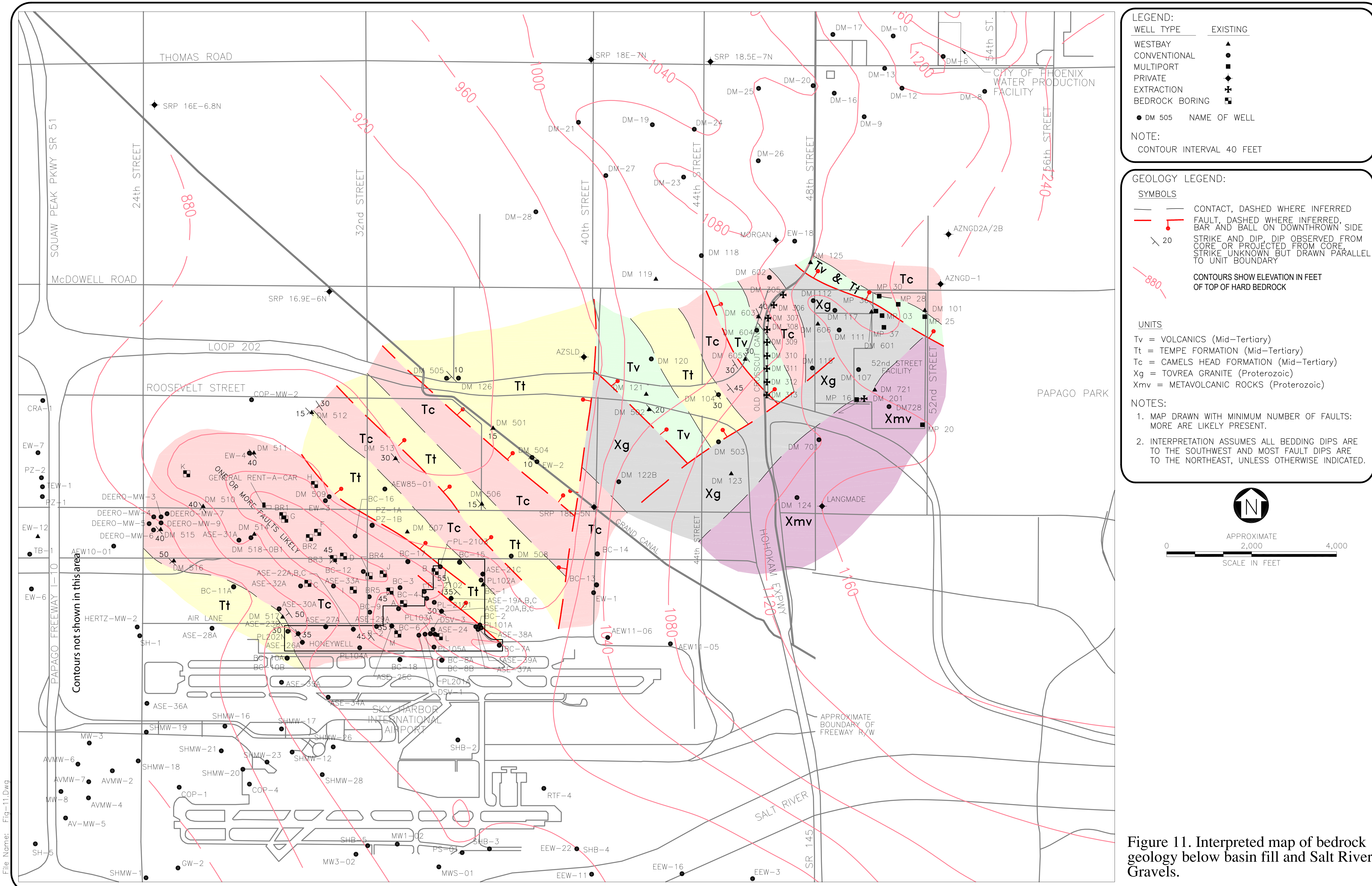


Figure 11. Interpreted map of bedrock geology below basin fill and Salt River Gravels.

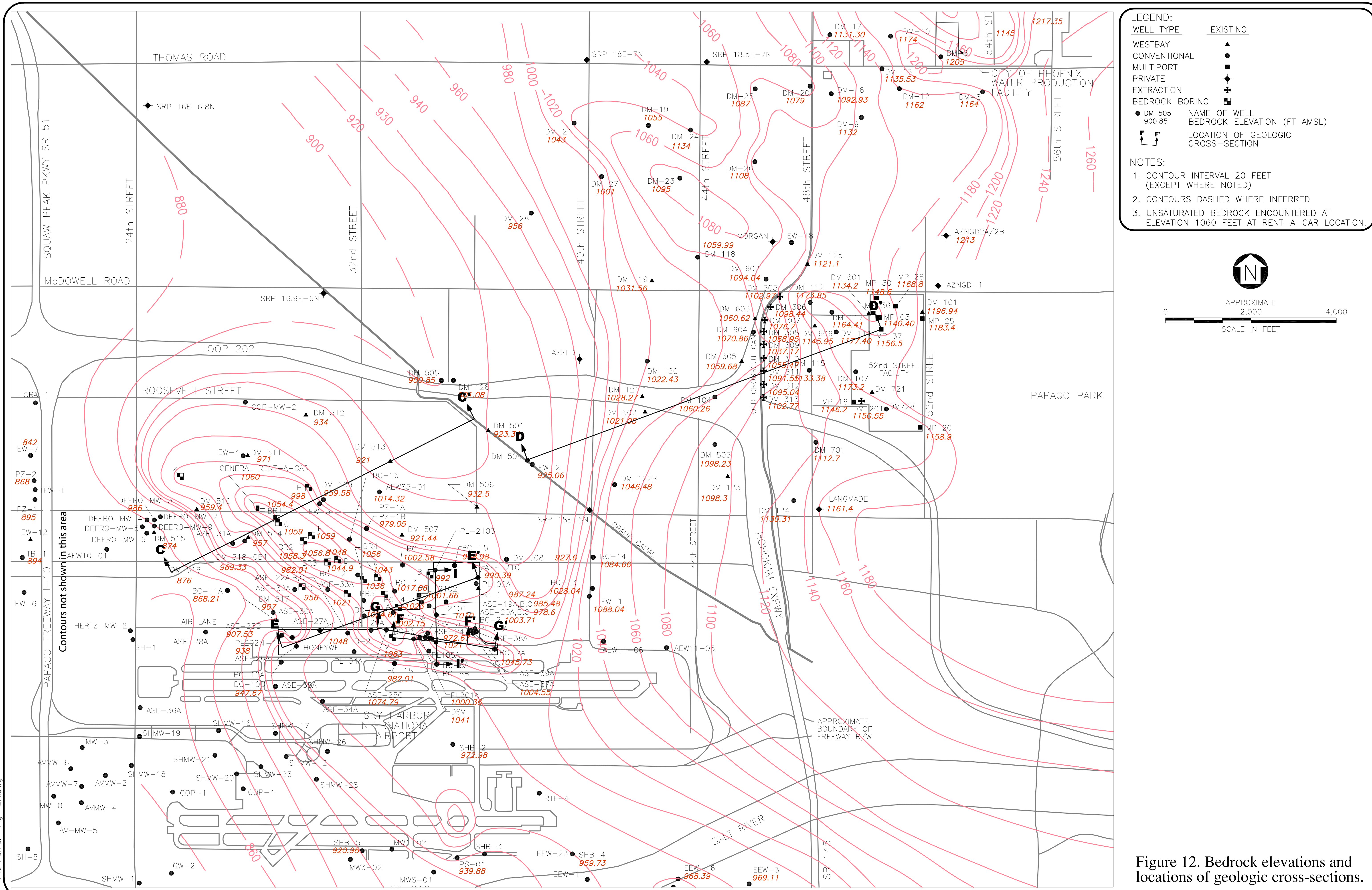


Figure 12. Bedrock elevations and locations of geologic cross-sections.

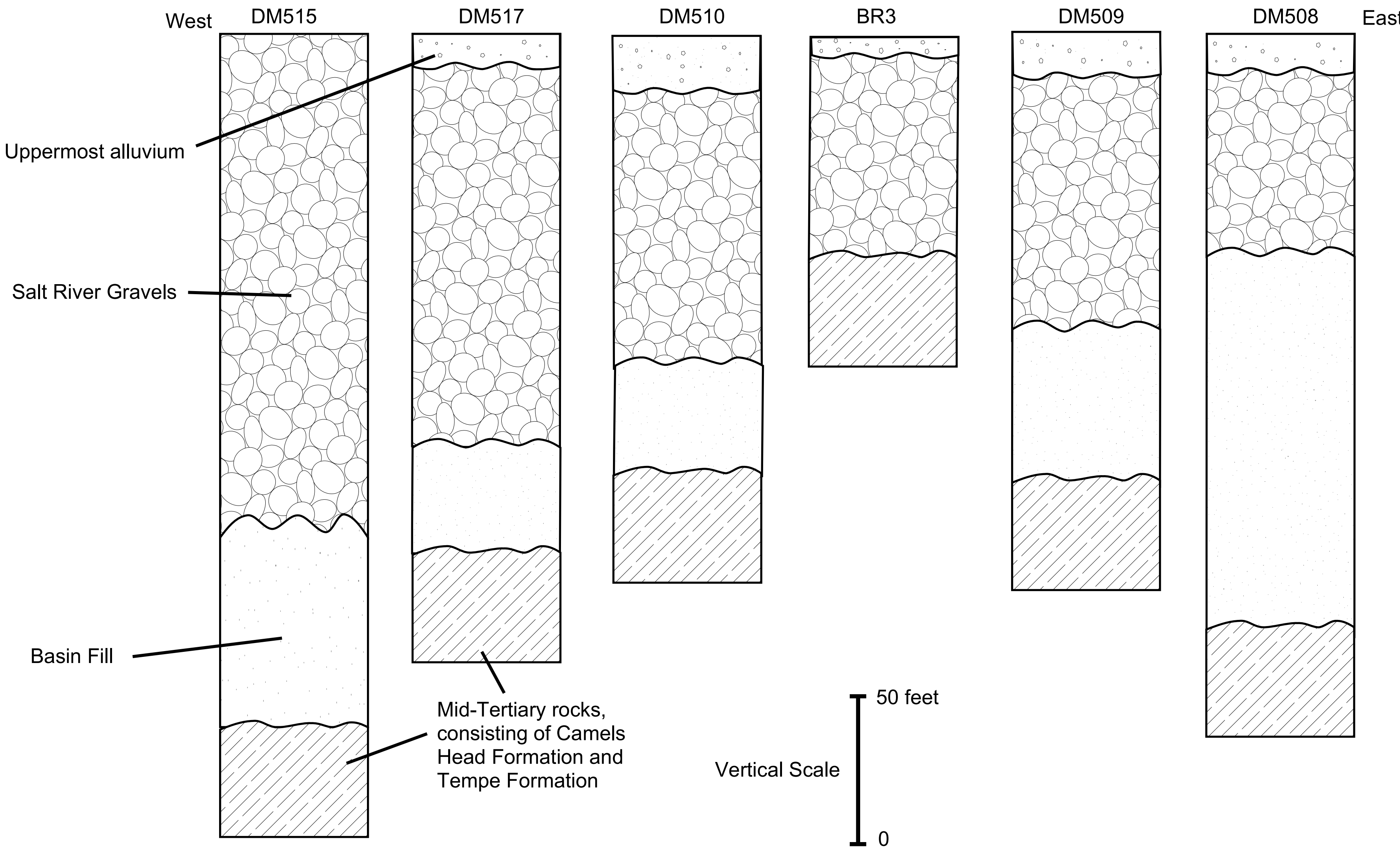
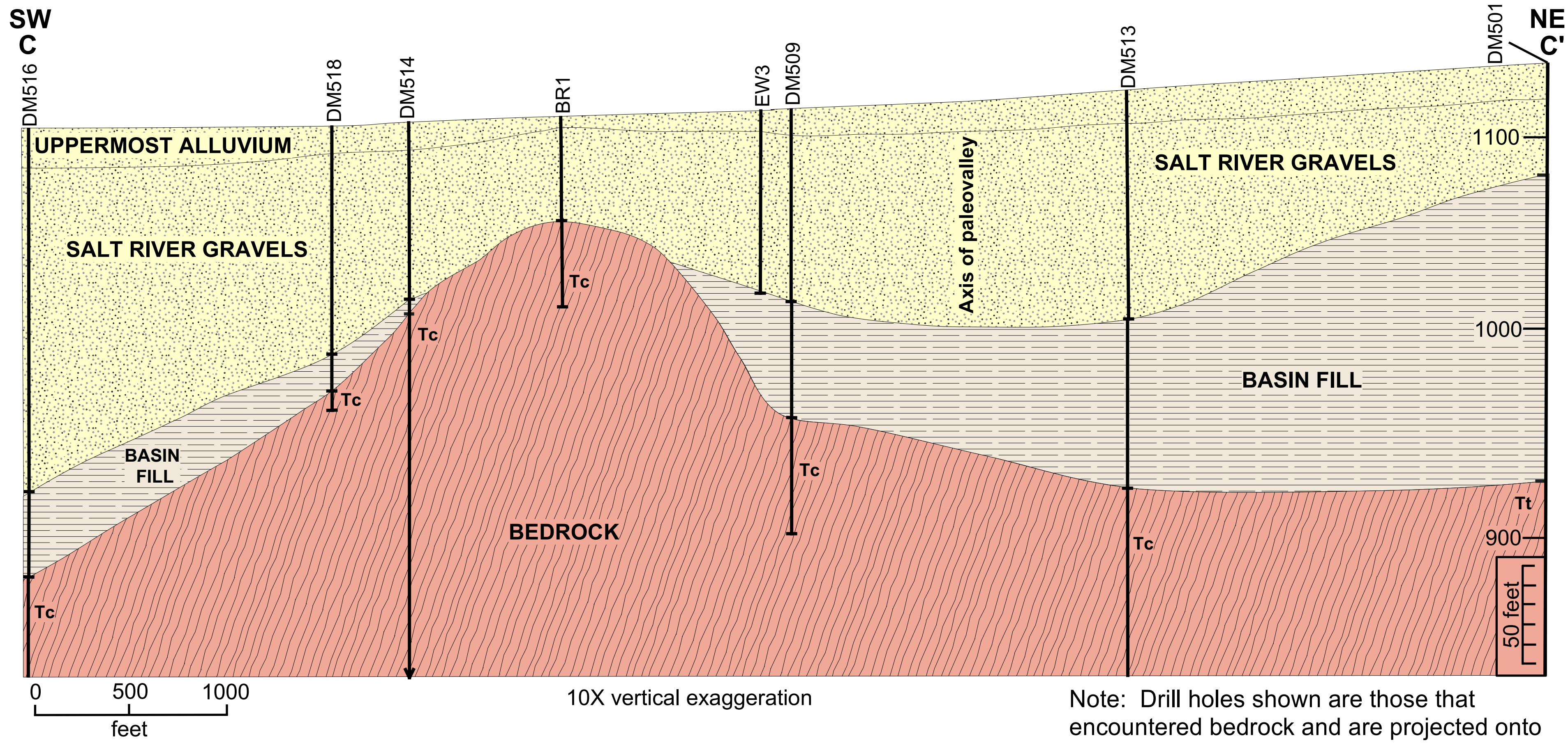


Figure 13. Stratigraphic sections of the bedrock ridge area. Sections are arranged according to their positions relative to the axis of the bedrock ridge. The axis of the ridge is at driil hole BR3, where Salt River gravels directly overlie tilted Camels Head Formation. On both sides of the ridge, Salt River Gravels overlie basin fill, probably along an unconformity. The gravels fill a paleovalley east of the ridge (DM 509).



Note: Drill holes shown are those that encountered bedrock and are projected onto the line of cross section from within 300 feet, except DM501 (projected ~600 feet parallel to basin-fill contours).

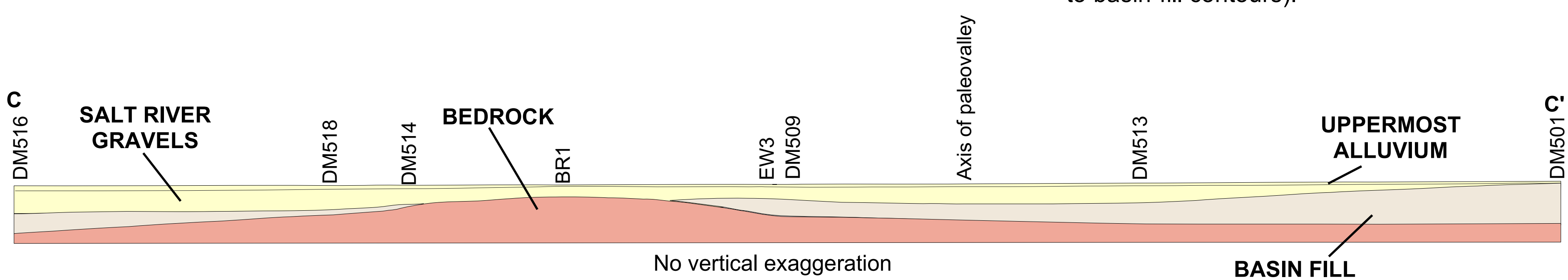


Figure 14. Cross section C-C' across the northern part of the bedrock ridge. Location of section shown on Figure 12.

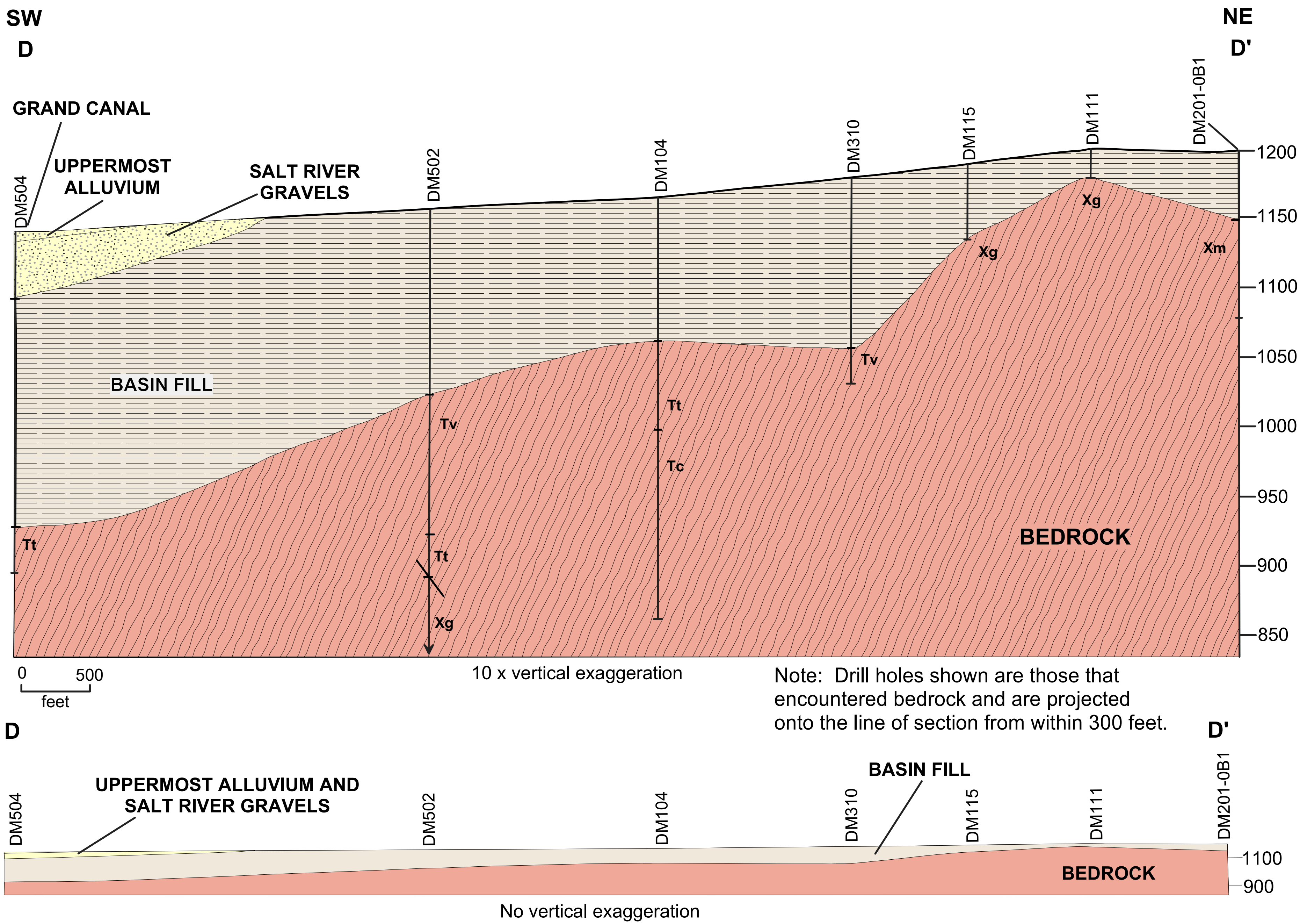
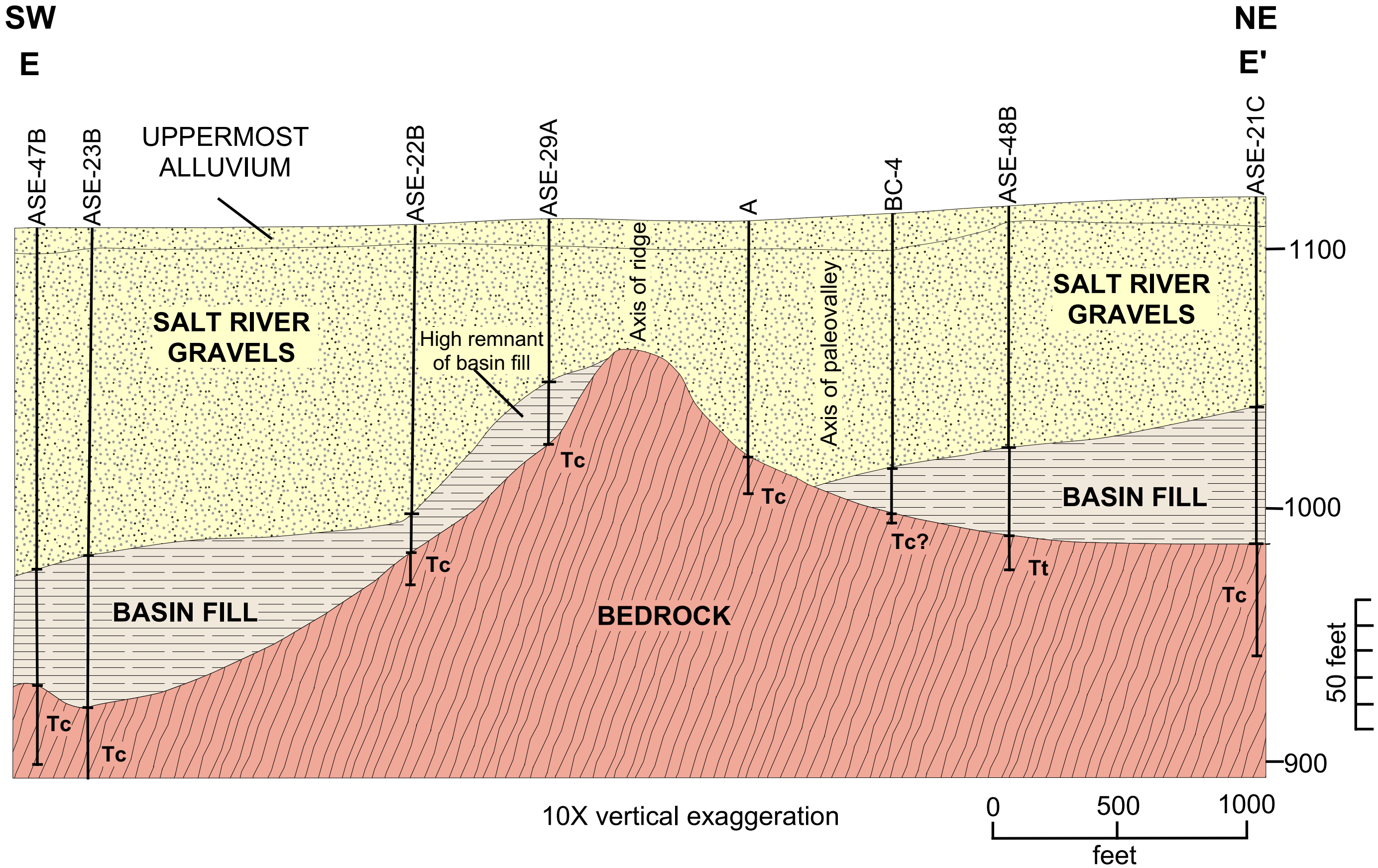


Figure 15. Cross section D-D' from the 52nd Street facility (on the right) to the Grand Canal. Location of section shown in Figure 12.



Note: Drill holes shown are those that encountered bedrock and are projected onto the line of cross section from within 300 feet.

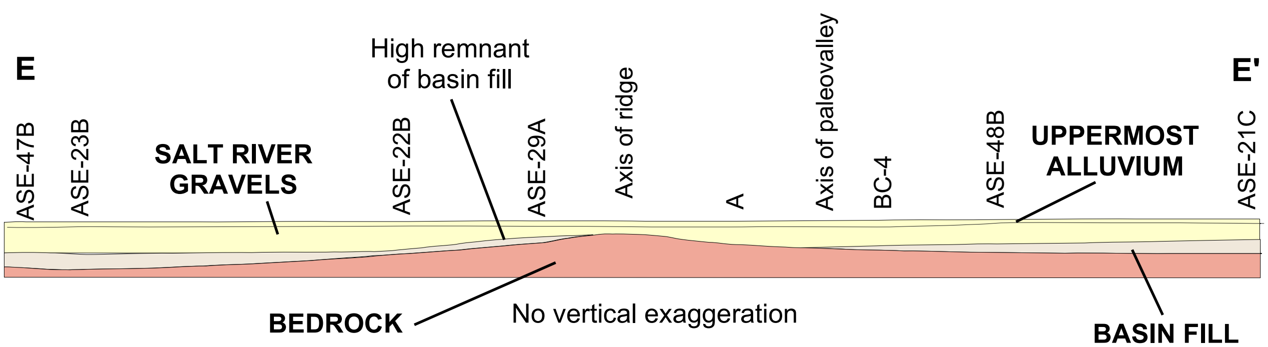
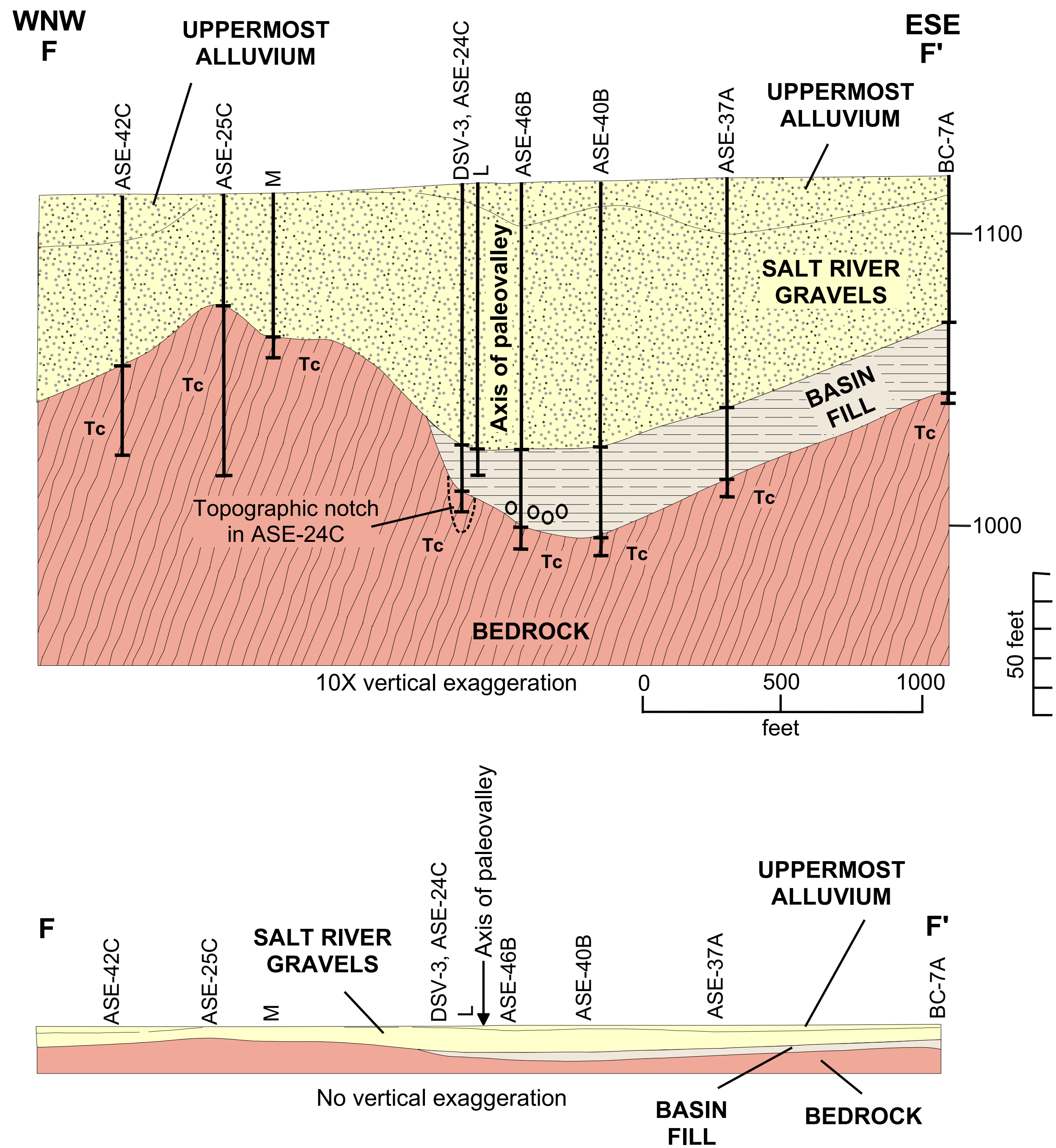
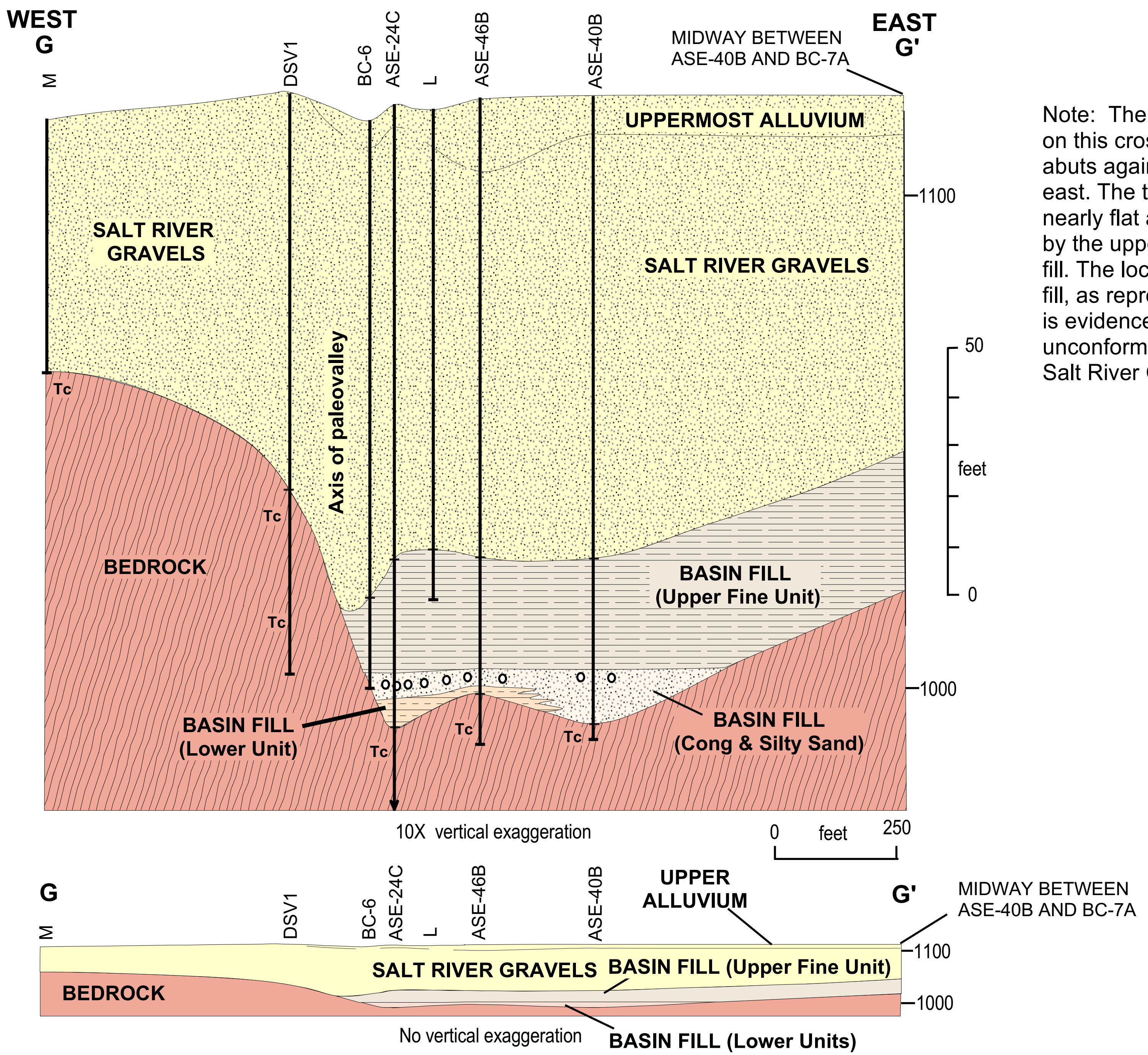


Figure 16. Cross section E-E' across the southern part of the bedrock ridge. Location of section shown in Figure 12.



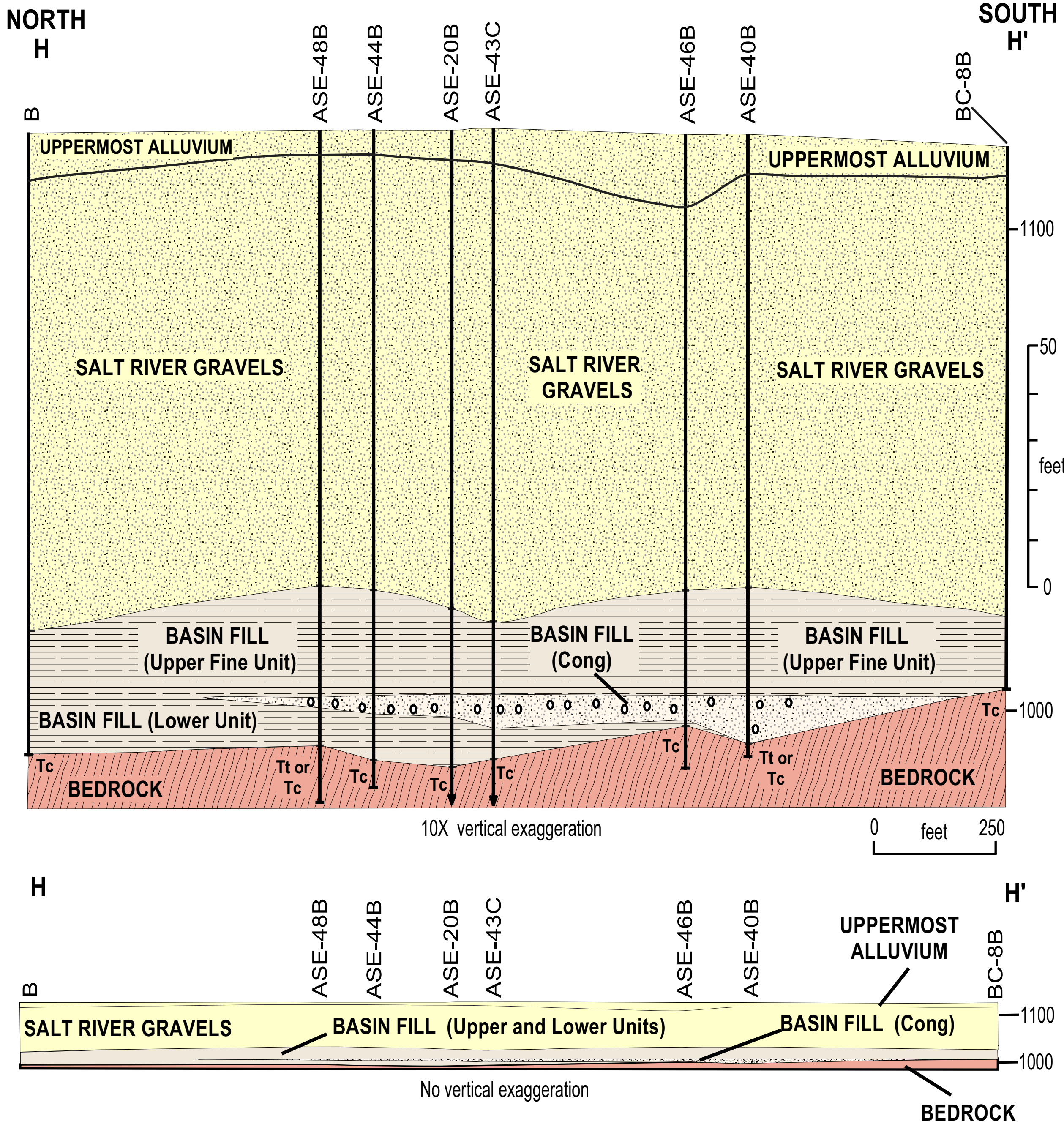
Note: Drill holes shown are those that encountered bedrock and are projected onto the line of cross section from within 400 feet. ASE-37A is projected parallel to basin-fill contours. Drilling intercepts are shown for DSV3, but slightly deeper notch into bedrock at same location is shown for ASE-24C by dashed line.

Figure 17. Cross section F-F' across the southern saddle. Location of section shown in Figure 12.



Note: The conglomerate depicted on this cross section forms a lens that abuts against bedrock to the west and east. The top of the conglomerate is nearly flat and is everywhere overlain by the upper fine-grained unit of basin fill. The local relief on the top of basin fill, as represetned in the paleovalley, is evidence of scouring along the unconformity between basin fill and Salt River Gravels.

Figure 18. East-west cross section G-G' of the southern saddle. Location of section shown in Figure 12.



Note: The conglomerate depicted on this cross section forms a lens that thins and grades into silty units to the north and that abuts against rising bedrock to the south. The top of the conglomerate is flat, implying that bedding in basin fill is also flat. The local relief on the top of basin fill is consistent with scouring along the unconformity between basin fill and Salt River Gravels.

Figure 19. North-south cross section H-H' across the southern saddle. Location of section shown in Figure 12.

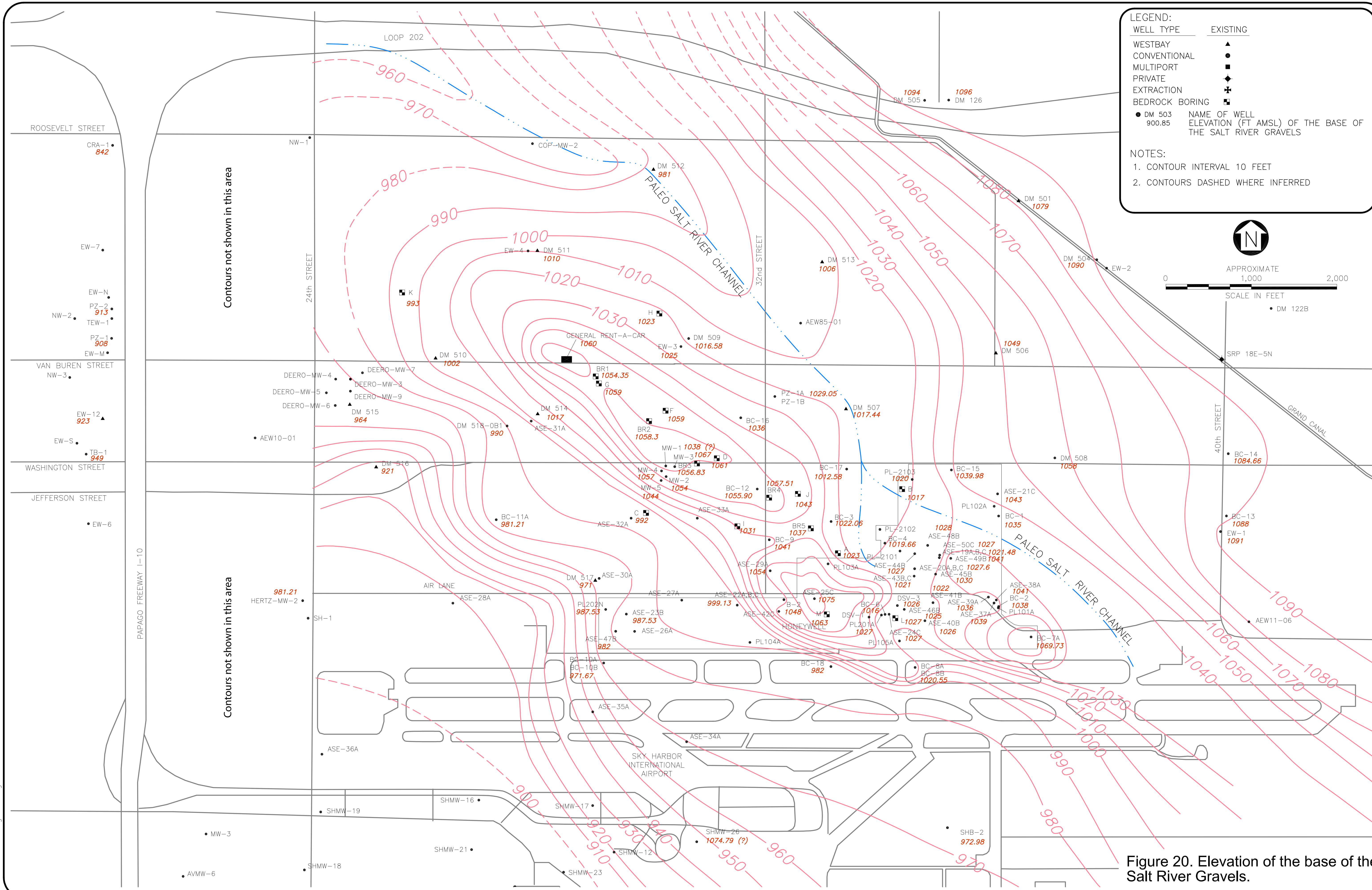
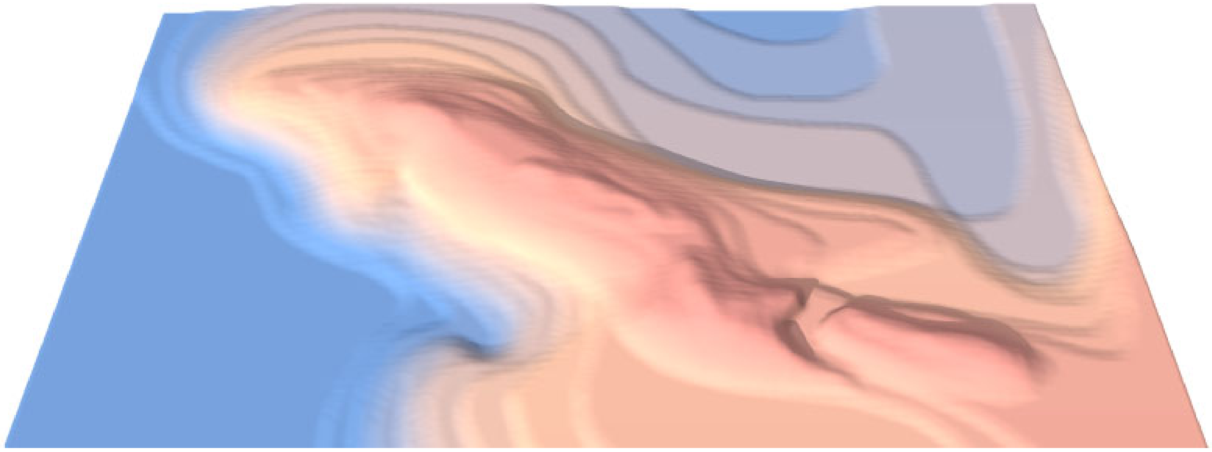
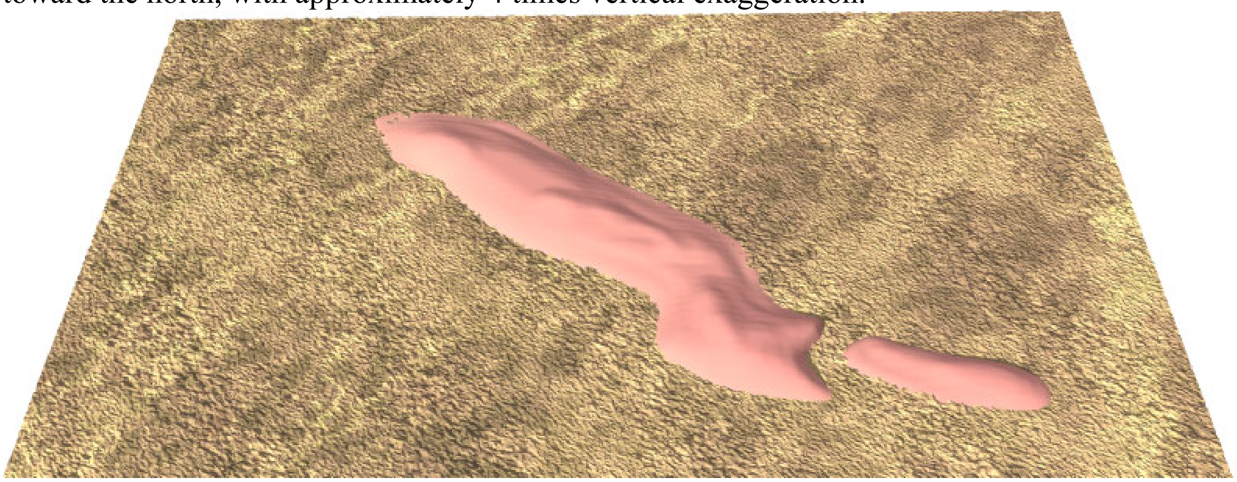


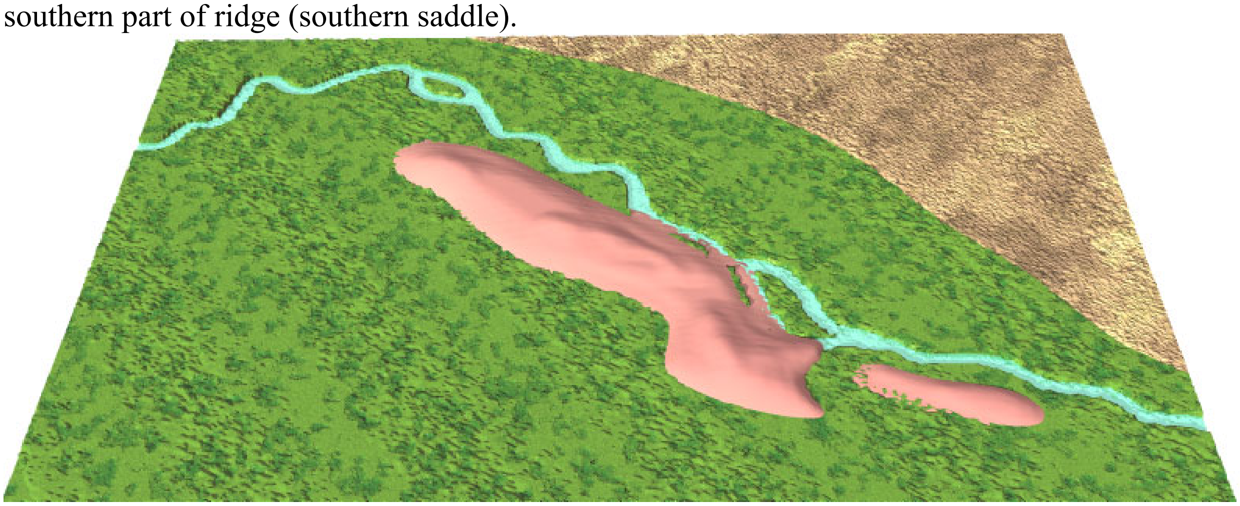
Figure 20. Elevation of the base of the Salt River Gravels.



A. Topography of hard bedrock as it existed before its burial by basin fill. Bedding, faults, and formations are not shown. Note the pre-basin-fill trough east of the bedrock ridge. Viewed toward the north, with approximately 4 times vertical exaggeration.



B. Partial burial of the bedrock ridge by basin fill, largely before the development of a through-going drainage system (e.g., Salt River). Note that basin fill has infilled the saddle in the southern part of ridge (southern saddle).



C. Deposition of the early part of Salt River Gravels, with a smaller paleovalley carved into basin fill east of the bedrock ridge and occupied by the main Salt River or a major channel of the river.

Figure 21. Three-dimensional perspectives illustrating the geologic evolution of the bedrock ridge area. Each perspective is looking north. Geometry of basin fill and Salt River Gravels are shown in a schematic and simplified manner.

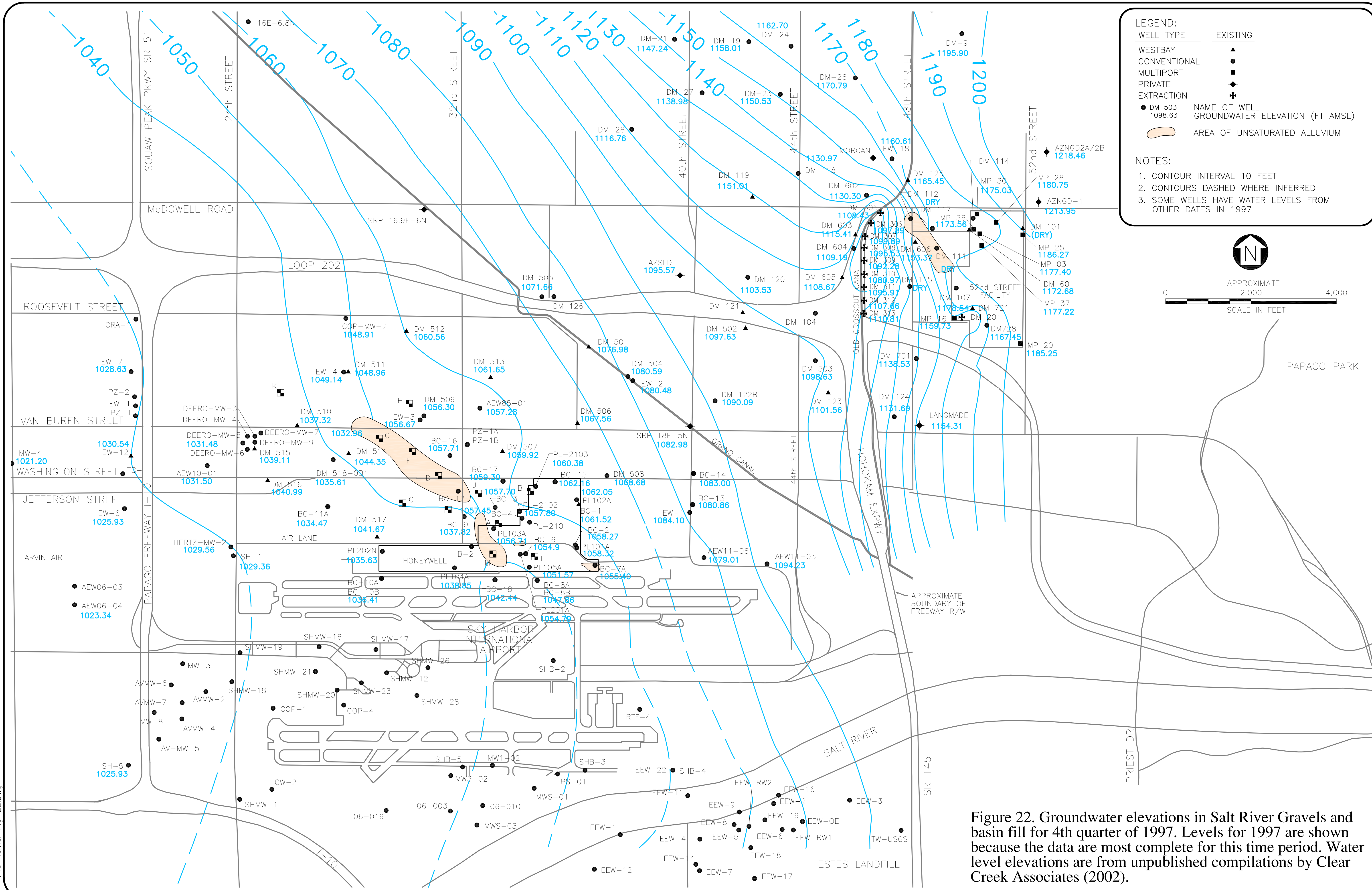


Figure 22. Groundwater elevations in Salt River Gravels and basin fill for 4th quarter of 1997. Levels for 1997 are shown because the data are most complete for this time period. Water level elevations are from unpublished compilations by Clear Creek Associates (2002).