HYDROLOGY AND GROUND-WATER CONDITIONS OF THE TERTIARY MUDDY CREEK FORMATION IN THE LOWER VIRGIN RIVER BASIN OF SOUTHEASTERN NEVADA AND ADJACENT ARIZONA AND UTAH

Geological Society of America 2002 Rocky Mountain Section

Annual Meeting

Cedar City, Utah

May 10, 2002

FIELD TRIP LEADERS

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ABSTRACT

The lower Virgin River Basin is a complex structural basin formed by Neogene extension in Nevada, Arizona, and Utah. There is a large volume of ground water in transient storage moving through the basin. Ongoing investigations to characterize the basin have determined that it is one of the deepest in the Basin and Range Province. The estimated depth to basement underlying the carbonate rock may be as great as 5 miles. Subsequent filling of the basin with the Muddy Creek Formation has created a deposit as thick as 6,000 feet. Many normal faults have modified the Miocene Muddy Creek Formation, enhancing the hydrologic properties of the formation. Several communities within the basin obtain municipal water supplies from the Muddy Creek Formation. Mesquite, Nevada, is the largest of these and one of the fast growing communities in the United States. The potable water supply is obtained solely from the Muddy Creek Formation. Prior to 1994, ground water production was generally less than 400 gallons per minute and exceeded Safe Drinking Water Act standards. Generally the Muddy Creek has a low transmissivity of 1,300 ft^2/day and is considered an aquitard. Where faulting has occurred, ground-water production is greatly enhanced with production averaging 1,500 gallons per minute and a transmissivity of 20,000 ft^2/day. Water quality is substantially better and in compliance with the Safe Drinking

Water Act with the exception of the new arsenic standard of 10 parts per billion. The most recent production wells constructed by the Virgin Valley Water District have been installed to a maximum depth of 3,300 feet and completed with 20-inch diameter casing. Depth to water within the basin varies from 1,200 feet below land surface to 2 feet above land surface.

INTRODUCTION

The lower Virgin River Valley (figure 1) is located largely in southern Nevada, in Clark and Lincoln Counties but also extends into Mohave County, Arizona, and Washington County, Utah. The amount of surface water and ground water that flows into the lower Virgin River Valley is substantial. The revised water resource budget for the basin includes an average of about 150,000 acre-feet/year of river water and 85,000 acre-feet/year of ground water (Dixon and Katzer, 2002). The available water resources from the lower Virgin River Valley that can reasonably be obtained for public use are estimated at approximately 130,000 acre-feet/year from the Virgin River, and 40,000 acre-feet/year from the ground-water system. Ground water is the primary source of water utilized in the basin, with current usage estimated at 12.000 acre-feet.

There is a large volume of ground water in transient storage that is moving through the basin to discharge points within and out of the basin. Based on earlier geophysical surveys the basin is one of the deepest in the Basin and Range Province. It is estimated that the depth to basement of the underlying carbonate rock is as great as 5 miles, averaging 1-3 miles in depth. The significance of the depth is that, while the volume of water is great within the basin-fill sediments, so is the distance to the carbonate aquifer underlying the sediments. Although the carbonate rocks are likely to be the most productive aquifer in the basin, they are untapped in the lower Virgin River Valley. While it is possible to drill to these depths, this is a considerable distance to drill for water.

The basin is bounded on the north and northeast by the Clover and the Beaver Dam Mountains respectively and on the east and south by the Virgin Mountains. Black Ridge extends from the east side of the junction of the Virgin River with Lake Mead in a northeasterly direction and merges into the Virgin Mountains. On the west and northwest side of the river are Mormon Mesa, Mormon Mountains, and the East Mormon Mountains. Additionally the basin receives surface and ground water from the Tule Desert, Basin 221 (Rush, 1968). This 190 square mile basin is located directly adjacent to the lower Virgin River, Basin 222 (Rush, 1968). Thus Tule Desert is considered part of the lower Virgin River flow system.

Much of the ground-water recharge to the lower Virgin Valley ground-water basin moves through the carbonate rocks to the Muddy Creek Formation, where the majority of the municipal and industrial wells derive their water. Geologic surface mapping, in concert with geophysics, has provided a better understanding of the subsurface structural configuration, which controls the movement of ground water through faults and fracture zones.

GEOLOGIC SETTING

The Mesquite basin is in the lower Virgin River Valley. It is a large structural depression that has been extensively deformed since its inception in Miocene time about 24 million years ago (mya). The basin is approximately 19 miles wide and over 62 miles long. It lies between the East Mormon Mountains to the west, Tule Springs Hills to the northwest, Beaver Dam Mountains to the northeast and east, and the basin is sharply truncated to the south by the Virgin Mountains. Bohannon and others (1993) described the Mesquite and Mormon Mesa basins as older basins with respect to the larger Virgin River depression, which extends west from the Colorado Plateau and Basin and Range transition zone to the Muddy Mountains near the towns of Logandale and Overton, Nevada.

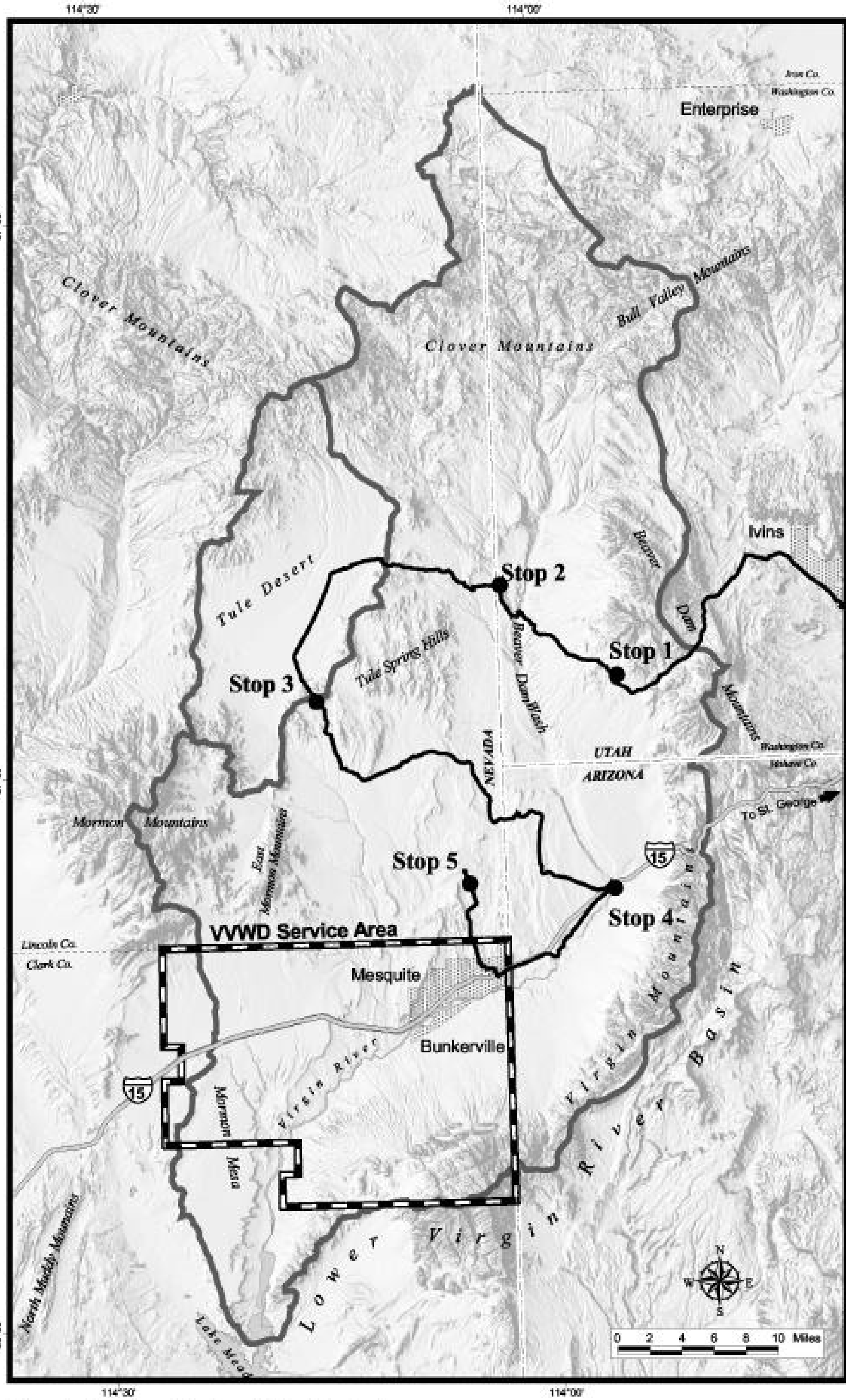


Figure 1.-- Location of the lower Virgin River Basin.

The period between 24 mya and 13 mya was marked by slow basin subsidence and accumulation of older sediments (including the Horse Springs Formation) in the Mesquite and Mormon basins. From 13 mya to 10 mya, a period of intense deformation separated the Mesquite basin from the Mormon Mesa basin to the southwest. Large displacement normal faults bounded both basins and the structural ridge that divided the two basins (Bohannon and others, 1993). Williams (1997) pointed out that, after the end of deposition of the Horse Springs Formation, the tectonic activity decreased. Bohannon and others (1993) showed that the upper part of these basin-fill deposits, the Muddy Creek Formation, is about 0.5 to 1 mile thick. Williams (1997, 1998) and Williams and others (1997) noted a similar thickness. Deposition of the Muddy Creek Formation into the Mesquite basin lasted about 6 million years, from 11.5 to 5.5 mya. The Muddy Creek Formation lies flat over most of its extent in this region, and is much less deformed than the underlying Horse Springs Formation. However, in the Mesquite basin, most of the Muddy Creek Formation and overlying calcrete deposits are moderately deformed, and dissected by modern-day washes.

At about 5.5 mya, the Colorado River, and most probably the Virgin River, were flowing into the Mesquite basin and formed Muddy Lake, an extensive body of water that extended from the base of the Clover Mountains southward into the Las Vegas basin. Subsequently, the Mesquite basin was breached and began draining into the Colorado River basin and eventually the Pacific Ocean. The subsequent lowering of base level after breaching caused a dramatic shift in deposition and erosion into and out of the Mesquite basin. Alluvial deposits record at least four cycles of incision and aggradation by the river and also record regrading of the surfaces between the river and the Virgin Mountains as their relative altitudes changed (Williams 1997). This rapid erosion of soft sediments in the basin provides modern day landforms.

Stratigraphically, rocks ranging from the Precambrian to Quaternary age sediments are observed in the Virgin River basin. A generalized synopsis is presented in Dixon and Katzer (2002).

HYDROLOGY

The lower Virgin River Valley is north trending and is about 80 miles long and about 35 miles at its widest point. It has a drainage area of about 1,723 mi^2, from the confluence of the Virgin River and Lake Mead on the Colorado River to the Virgin River gorge in the Beaver Dam Mountains (the U. S. Geological Survey (USGS) Narrows gage on the Virgin River near Littlefield, Arizona).

The climate of the lower Virgin River Valley varies from sub-alpine in the mountain blocks (precipitation exceeds 24 inches above an altitude of 8,000 feet), to a desert environment in the Mesquite area (precipitation is 6-7 inches at an altitude of about 1,500 feet). Daytime temperatures commonly exceed 100^o F during summer months, with lows near freezing during the winter. Precipitation rates vary throughout the Virgin River drainage area. Higher rates of precipitation occur at higher elevations, mostly in the form of snow. On the Kolob Plateau (above 10,500 feet elevation) precipitation rates generally exceed 30 inches of water per year. St. George and Bloomington (about 3,000 feet elevation) receive about 10 inches of precipitation per year, mostly in the form of rain. Precipitation decreases to about 6 inches per year at Mesquite (about 1,600 feet elevation).

The Virgin River is the main surface-water feature in the lower Virgin River Valley there is only one other perennial stream, Beaver Dam Wash. The headwaters of the Beaver Dam Wash are in the Clover Mountains in Nevada, and the Beaver Dam and Bull Valley Mountains in Utah, all in the northeast part of the basin. The wash flows perennially into the basin and also into the Virgin River about 40 miles downstream from the headwaters at Schroeder Lake. Throughout its course, however, it is intermittent with several sections becoming dry after spring runoff.

Ephemeral drainages are evidence of surface-water runoff from the surrounding mountain blocks into the basin. Depending on storm patterns, flow often originates directly on the alluvial fans. Flash floods produce large debris loads, particularly from the Virgin Mountains south of the river.

The land-surface gradients from the mountains to the river are generally less north of the river, but large debris flows are still much in evidence.

There are several aquifers in the basin, and the main aquifer for municipal and industrial use is the unconsolidated sediments that make up the Muddy Creek Formation. The Muddy Creek Formation is a sequence of fine-grained sediments, mostly interbedded sand, silt, and clay that were deposited in a lake environment starting about 11.5 mya (Bohannon and others, 1993). The most successful wells tapping this aquifer system are drilled along fault zones identified by field observations, geologic mapping, aeromagnetic, gravity, and seismic surveys. (Johnson, 1995, Dixon and Katzer, 2002). The ground-water flow direction is generally from the northeast to the southwest toward the confluence of the Virgin River and Lake Mead. The ground-water flow system for the lower Virgin River Valley consists of source areas, generally in the surrounding mountain blocks and respective alluvial fans, and several aquifers that may or may not be in hydraulic continuity depending on location and extent. The deepest aquifer is the saturated Paleozoic carbonate rocks, which underlie the entire basin. The Muddy Creek Formation overlies the carbonate rocks and is several thousand feet thick

ACKNOWLEDGMENTS

William Lund reviewed the manuscript and provided information about the Hurricane fault zone. We are grateful for comments about the geology of the Beaver Dam Mountains from Lehi Hintze, on a field trip he led for the Dixie Geological Society. Dave Brickey manipulated the graphics for the field trip guidebook.

ROAD LOG

Increment Mileage	*Cumulative Mileage*	*Description*
0	0	BEGIN TRIP AT PARKING LOT at northwest corner of 200 South and 1150 West, Cedar City (west of Eccles Coliseum, at the western edge of the Southern Utah University campus). Head north on 1150 West. On the left, west of I-15, the Cross Hollow Hills consist of basin-fill and alluvial-fan deposits uplifted along faults and locally containing intertongued basalt lava flows of about 1 mya (Averitt, 1967; Anderson and Mehnert, 1979). According to gravity data, the major normal faults of the Hurricane fault zone are west of the Cross Hollow Hills (Cook and Hardman, 1967), but significant north-striking faults also are east of the Cross Hollow Hills. Here the Hurricane fault separates the Colorado Plateau on the east from the Great Basin on the west.
0.1	0.1	AT STOP SIGN, TURN LEFT (WEST) ONTO CENTER STREET AND CROSS I-15.
0.3	0.4	Stop sign at 1650 West. TURN RIGHT (NORTH).
0.3	0.7	Stop light at 200 North (US 56). TURN RIGHT (EAST).
0.3	1.0	Entrance ramp (Exit 59, the middle Cedar City exit) to I-15. TURN RIGHT (SOUTH) ONTO I-15.

0.5	1.5	Cross Hollow Hills on the right. At 9:00, Cedar Canyon, where Coal Creek enters Cedar Valley. Although a large stream draining the mountains, Coal Creek supplies Cedar City with none of its drinking water because it has been naturally polluted by gypsum contained the Jurassic Carmel Formation and in other Mesozoic sedimentary units in the canyon. The red ridge on the northern side of Cedar Canyon, just east of Cedar City, is the eastern flank (Triassic Moenkopi, Chinle, Moenave, and Kayenta Formations, with Jurassic Navajo Sandstone and Carmel Formation east of the ridge), of a Sevier-age anticline whose western flank has been cut off and downthrown along the Hurricane fault scarp (Averitt and Threet, 1973). The anticline can be looked upon as the leading edge above an eastward-verging blind Sevier thrust. Capping the Markagunt Plateau at the skyline is Brian Head, the highest point (about 11,300 ft, 3,446 m) on the Plateau and home of a ski resort and underlain by 26-mya ash-flow tuffs derived from the Great Basin. Cedar Breaks National Monument is just southwest of Brian Head (Hatfield and others, 2000).
1.0	2.5	Exit 57, the southern Cedar City exit. We will now travel along the north-striking Hurricane fault scarp. At this location, most of the wooded hills are landslides off the scarp.
2.4	4.9	Roadcuts of 1-mya basalt left and right, and continuing to the south. The basalts are sitting on red basin-fill deposits that fill the graben beneath us. This graben, with its basin-fill sediments, is at least 3 kilometers deep (Cook and Hardman, 1967). These sediments, and their tectonic setting, are comparable to the Muddy Creek Formation that will be one of the main focuses of this field trip. Movement on the Hurricane fault has taken place during the basin-range episode of deformation, which also created the topography we see in the Great Basin. This deformation has largely taken place in the past 10 million years, with at least 300 meters of it in the Quaternary (W.R. Lund, written communication, 2001).
1.2	6.1	The southern part of the Iron Springs Mining District, 10 kilometers to the west, at about 2:00. The Iron Springs District was formerly the largest U.S. iron district west of the Great Lakes region and the reason for the settlement of Cedar City. The district is defined by a north-northeast-trending string (the Iron Axis) of quartz monzonite porphyry laccoliths of about 22-20 mya (Mackin, 1947, 1960, 1968; Mackin and others, 1976; Mackin and Rowley, 1976; Barker, 1995). The iron deposits consist of huge hematite replacement bodies in the Homestake Limestone Member of the Jurassic Carmel Formation, which are virtually adjacent to the concordant intrusive contacts. The light-gray scar at 2:00 is the Mountain Lion pit, the largest in the district, adjacent to the Iron Mountain pluton. The southern part of the Iron Axis, especially the huge Pine Valley laccolith (Hacker, 1998), will be visited during a field trip today (Hacker and others, 2002) to see gravity slides that were shed off the flanks of the rising laccoliths and to see volcanic products that erupted following deroofing (Blank and others, 1992; Rowley and others, 2001).

2.3	8.4	Exit 51, Kanarraville and Hamilton Fort. Hamilton Fort to the right, whereas Kanarraville is farther south and to the left. At about 2:00, the southern end of Quichapa Lake, in the center of the basin. It is dry most of the year. Just south of it is the well field for Cedar City's water supply, from ground water in basin-fill sediments. At 12:00 to 2:30 are the Harmony Mountains, made up of Tertiary ash-flow tuffs derived from calderas in the Great Basin (Anderson and Rowley, 1975). Most people consider the Harmony Mountains part of a Colorado Plateau transition zone, and that here the boundary between the Colorado Plateau and the Great Basin steps west. On the left, the North Hills, bounded by parts of the Hurricane fault zone east and west of it.
6.3	14.7	Exit ramp to Rest Area. To the left and right here and farther south, you will see several springs controlled by north-striking faults of the Hurricane fault zone. The road here starts to drop lower, as we head down the Colorado River drainage to St. George, which is 600 meters lower than our present elevation.
2.5	17.2	Exit 42, New Harmony. The high mountains to the right are the Pine Valley Mountains, underlain by apparently the world's largest laccolith, the 20-mya Pine Valley laccolith (Hacker, 1998). The Pine Valley Mountains are a Wilderness Area and a recharge area for the Navajo aquifer, the source of most of the water for Washington County, the fastest growing part of Utah (Heilweil and Freethey, 1992; Hurlow, 1998; Heilweil and others, 2000). This aquifer, in the Jurassic Navajo Sandstone, was the subject of a pre-meeting field trip (Heilweil and others, 2002) a few days ago. The Navajo forms massive red cliffs along the Hurricane scarp. To our left the Navajo Sandstone is carved into a series of beautiful ledges, known as the Five Fingers of the Kolob, although a much better view is afforded farther west of us. The valley to the right contains thin basin-fill deposits, a different ground-water basin from the one north of Hamilton Fort; this basin supplies much of the water for the New Harmony area (Heilweil and others, 2000).
2.0	19.2	Exit 40, Kolob section of Zion National Park. A road here climbs the Hurricane Cliffs to the left and goes several miles to the south, with hiking trails and great views of the Kolob Plateau and lower parts of Zion National Park.
2.9	22.1	On the right, Ash Creek Reservoir. At most times of the year, this is dry or nearly so because the dam on its south side is in Quaternary basalt flows and the dam leaks. Next pass through roadcuts in basalt flows and basaltic tephra.
0.6	22.7	Exit 36, Ranch Exit. Hills to the right belong to what local residents call Black Ridge, the highest part of a series of Quaternary basalt flows that were spread to the right and left of us, largely controlled by fractures from the Hurricane fault zone.
1.4	25.9	Exit 33, Ranch Exit.
1.6	27.5	Exit 31, Pintura. Pine Valley Mountains on our right.

1.1	28.6	Exit 30, Browse. On left, basalts dip east into the Hurricane fault zone.
3.2	31.8	Exit 27, Anderson Junction, with SR-17 to Toquerville and Hurricane. Basalts on left. west-dipping cuesta of Navajo Sandstone on right.
3.7	35.5	Exit 23, Leeds and Silver Reef. Silver Reef, to the right, was an important turn-of-the-century silver mining district (James and Newman, 1986; Proctor and Shirts, 1991). Navajo Sandstone on right.
3.9	39.4	As you go past Harrisburg on the left, note a water gap (Quail Creek) through a cuesta on the resistant Shinarump Conglomerate Member of the Triassic Chinle Formation, which here is part of the west flank of the Virgin anticline. To the west of the cuesta is the upper part of the Chinle Formation overlain by the Moenave, then the Kayenta Formations, whereas the overlying Navajo is west of I-15. Quail Creek Reservoir is east of the water gap.
4.0	43.4	Exit 16, Harrisburg Junction and SR-9 to Hurricane, which is east of the Virgin anticline.
4.6	48.0	Exit 10, Middleton Drive, Washington City. Red cuestas of Kayenta to the right and, farther on, Quaternary basalt flows sit on the Navajo and underlying Jurassic and Triassic units.
2.3	50.2	Exit 8, St. George Boulevard, St. George. Navajo Sandstone makes up the horizon on the right, on the northern side of St. George.
2.1	52.3	Exit 6, Bluff Street (SR-18), St. George. GO RIGHT, OFF I-15.
0.3	52.6	Stop sign on Bluff Street. TURN RIGHT (NORTH). The mesa west of Bluff Street is the home of St. George's airport, on Quaternary basalt flows. These flows rest on red, bentonitic shales of the upper member of the Kayenta and Chinle Formations. When buildings and roads are constructed in the east toe of this mesa, landslides are the result.
2.6	55.2	Stop light, intersection with Sunset Road. Get in the middle lane (that is, do not get in the far left lane) and TURN LEFT ONTO SUNSET.
2.2	57.4	Enter Santa Clara. The bluff above us on the right, with the houses on it, is the Petrified Forest Member of the Chinle Formation, infamous for its "blue clay" (bentonite) that is the bane of those homeowners who do not want their house sliding (Willis and Higgins, 1996).
1.2	58.6	Jacob Hamblin home on the right.
1.2	59.8	On the right, the road to Ivins. The high skyline on the right (Red Mouintain) supported by Navajo Sandstone. Low on the flank of

		this north-dipping cuesta is Kayenta, which intertongues upward with the Navajo.
2.5	62.3	On the right, the road to Kayenta development, a community of Santa Fe-style homes that are sitting, as you might expect, on the Kayenta Formation.
1.2	63.5	On the right, homes of the Shivwits Indian Reservation.
0.6	64.1	Cross the Santa Clara River, which drains the area to the north that contains the eastern Bull Valley Mountains and western Pine Valley Mountains. Shinarump Member of the Chinle Formation on the right.
0.7	64.8	Ghost town of Shivwits on left and right.
0.6	65.4	Road forks. BEAR LEFT. Shinarump Member above us to the right. The road to the right follows the Santa Clara River to Gunlock Reservoir, 8 kilometers to the north, then to Gunlock, just north of that. One of the main well fields utilized by St. George and Washington County Water Conservancy District is just south of the Gunlock Reservoir, sited in the Navajo Sandstone and just west of the Gunlock fault zone. The north-striking Gunlock fault zone, which is an oblique-slip fault (mostly normal and down on the west side, but locally left lateral) is considered by most people to mark the boundary between the Colorado Plateau transition zone to the east and the Great Basin to the west (Hintze and others, 1994). A major reason for the high water yield in the well field is fracture porosity due to the fault zone (Heilweil and others, 2000, 2002).
0.7	66.1	On the right, dirt road to Goldstrike, a former major disseminated gold deposit (Adair, 1986; Wilden and Adair, 1986), mined out and now reclaimed.
1.0	67.1	Start up into the northern Beaver Dam Mountains, an anticlinal uplift masterfully studied and analyzed by Hintze (1986), Hintze and others (1994), and Anderson and Barnhard (1993a, 1993b). On the left is the road to the mine and mill of the Apex rare-earths mine. Although the mill is just south of us, the mine is farther south and west, in replacement bodies in the Permian and Pennsylvanian Callville Limestone (Bernstein, 1986). Next start up through gray limestone of the Permian Toroweap and Kaibab Formations.
2.3	69.4	Light-yellow Permian Queantoweap Formation, as we continue down the stratigraphic section. The Queantoweap dips steeply east, part of a hogback capped to the east by the overlying Toroweap and Kaibab Formations (Hintze, 1986).
2.8	72.2	The road tops a low pass, Utah Hill, at the crest of the Beaver Dam Mountains. The road to the left goes to a relay tower. On the right and left, the rocks belong to the well-known carbonate aquifer of central and southern Nevada. This aquifer consists of the Mississippian Monte Cristo Limestone (Redwall equivalent) and other Paleozoic limestones. The streams to the west of this

drainage divide (the east side of the Beaver Dam Mountains) flow west into the lower Virgin River basin. But this current drainage follows an old (early Pleistocene or Pliocene) canyon that also drained west and cut through the Redwall and deposited a conglomerate in the old valley (L.F. Hintze, oral communication, 2001).

1.7	73.9	We are now in Precambrian basement gneiss and schist.
0.2	74.1	The sharp knob on the left with the tower on top of it is Castle Cliff, just east of a major high-angle, basin-range normal fault zone called the Piedmont fault zone. Most geologists consider this to be the boundary between the Colorado Plateau transition zone on the east and the Great Basin on the west. So the boundary has again jumped west. Castle Cliff consist of the Callville Limestone, which appears to be in the upper plate of a west-dipping, low-angle fault that has greatly attenuated the Redwall and underlying Devonian and Cambrian rocks in the footwall below (Hintze, 1986). The question is whether this fault is a Sevier thrust in which the hanging wall moved east, or a Tertiary detachment that moved west (L.F. Hintze, oral communication, 2001). On the right are the remains of a gas station that made a living supplying water and service to the cars formerly struggling eastward, and boiling over, up the long grade upward from Littlefield/Beaver Dam. Until construction of Interstate 15 through the Virgin River Gorge south of us, this road was the main highway from Las Vegas to St. George. Another gas station was at the summit of the road, Utah Hill (L.F. Hintze, oral communication, 2001).
2.3	76.4	Dirt road enters the blacktop we are on from the right. A sign at the intersection says “Big Cottonwood Game Ranch.” TURN RIGHT (WEST) ONTO THE DIRT ROAD. Enter the Mesquite basin, downthrown in the past 10 million years along the Piedmont fault zone and filled with 10 kilometers of basin-fill sedimentary rocks of Miocene through Quaternary age (Blank and Kucks, 1989; Bohannon and others, 1993; Jachens and others, 1998; Langenheim and others, 2000a, b, 2001; Dixon and Katzer, 2002). The oldest of these basin-fill deposits belong to the Horse Spring Formation, well below us. Above this in the graben is the Muddy Creek Formation, overlain by Pliocene(?) and Quaternary surficial deposits. As we make the turn, the mountain mass in the far distance at 9:00 is the Virgin Mountains.
1.5	77.9	**STOP 1, BASIN OVERVIEW. PULL OFF ON THE SIDE OF THE ROAD.** Discuss the geologic framework of the lower Virgin River Hydrographic Basin, Basin 222, as defined by the Nevada State Engineer and the surface and ground-water hydrology of the area (Johnson, 1995; Dixon and Katzer, 2002). The resistant hills, mostly on our right, that we have been driving through consist of brecciated Mississippian Redwall Limestone that is resting on basin-fill sediments. Wernicke and his colleagues (Wernicke and others, 1985; Axen and others, 1990; Wernicke,

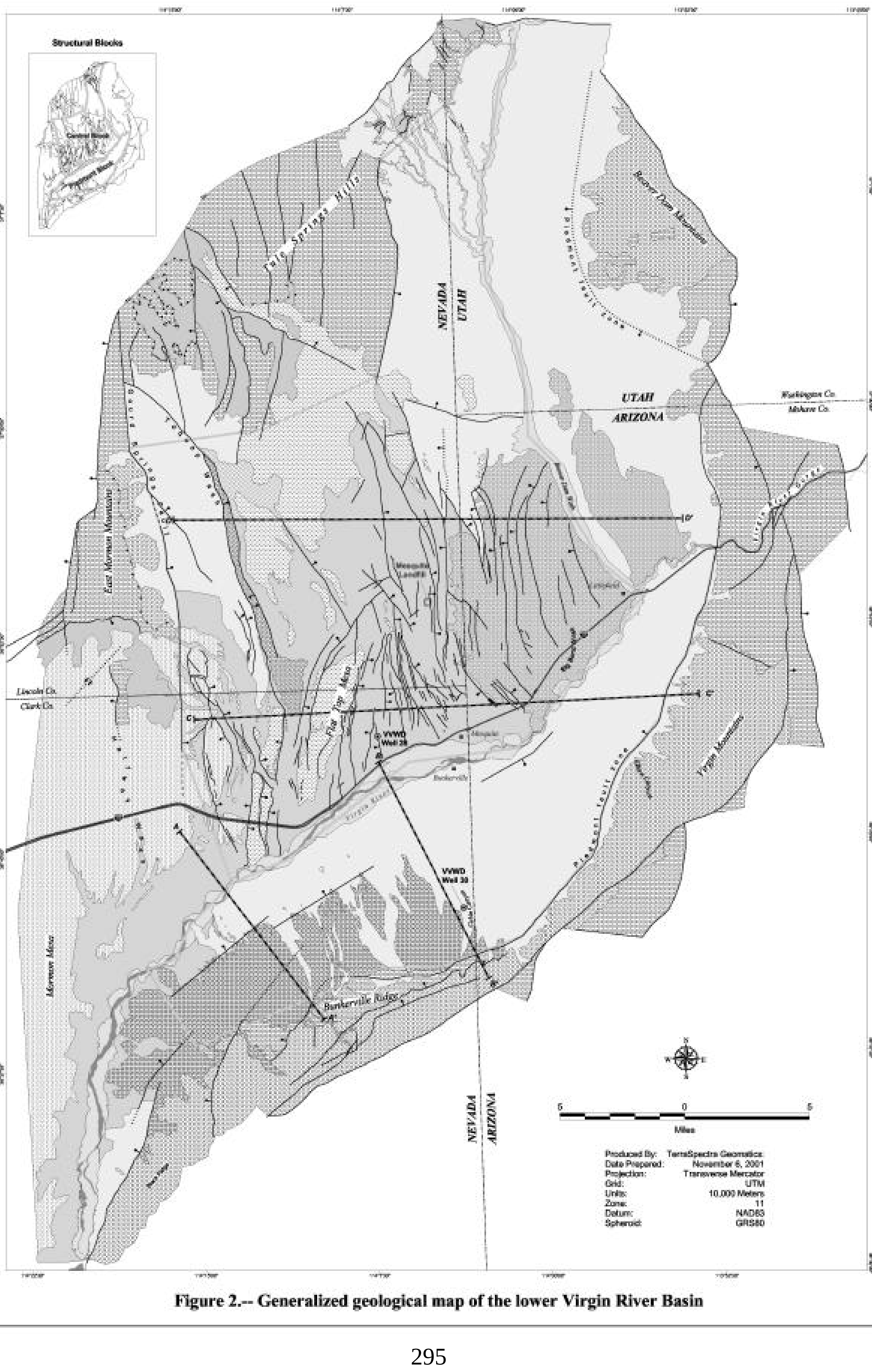
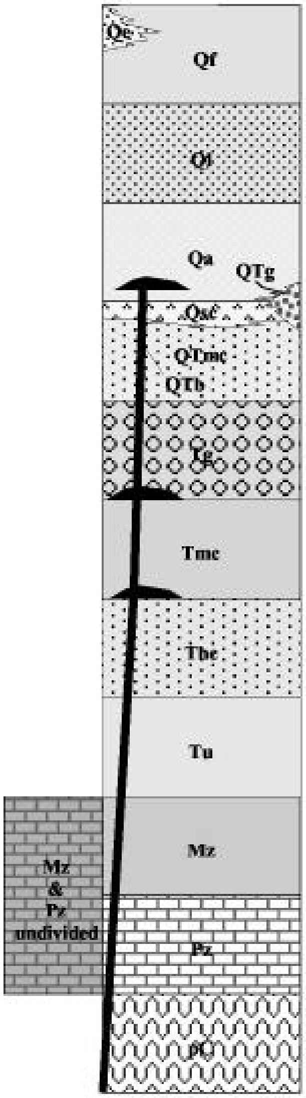


Figure 2.-- Generalized geological map of the lower Virgin River Basin



Qf Holocene Young Alluvium in washes and floodplains.

Qe Quaternary Evaporite discharge from fault zone in upper Toquop Wash.

Ql Quaternary Littlefield Formation. Sediments capped by spring-fed discharge deposits (1' - 2' thick).

Qa Quaternary Alluvium and colluvium.

QTg Quaternary to Tertiary gravel . In middle to upper Toquop Wash. Coarse-grained gravels, indurated, contains volcanic and sedimentary rocks.

Qsc Quaternary Spring fed carbonate overlying QTmc.

QTmc Mormon Mesa calcrete.

QTb Quaternary to Tertiary Basalt.

Tg Upper Tertiary Piedmont gravel. Mostly detritus of pC gneiss and schist detritus.

Tmc Middle Tertiary Muddy Creek Formation. Primarily fine to medium grained siltstone, sandstone, mudstone, and conglomerate.

Thc Middle Tertiary Red sandstone of Bohannon (1984) and Lovell Wash and Rainbow Garden members of the Horse Springs Formation of Bohannon (1984). Not exposed at surface.

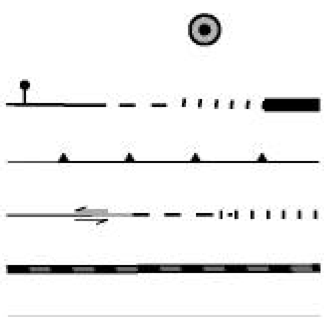
Tu Lower Tertiary sediments. Probably includes some volcanic tuffs and lacustrine deposits.

Mz Mesozoic Rocks. Includes Baseline Sandstone, Aztec Sandstone, Moenave, Kayenta, Chinle, Moenkopi, Kaibab, and Toroweap Formations, undivided.

Mz & Pz Mesozoic and Paleozoic rocks, undivided. Not exposed at surface.

Pz Cambrian to Permian rocks, undivided. Principally carbonate rocks with some quartzite and sandstone. Structually complex.

pC Complex crystalline rocks of Proterozoic age. Primarily granite, gneiss, and schist.



Virgin Valley Water District Well

Normal fault, bar and ball on downthrown side where known, dashed where inferred, dotted where concealed, thick solid line where intruded by basalt (QTb)

Thrust fault, teeth on upper plate, double arrows indicate sense of strike slip

Strike-slip fault, dashed where inferred, dotted where concealed

Geologic Cross-section Traverse

Structural Block Boundary

Figure 3.-- Legend for the generalized geological map of the lower Virgin River Basin.

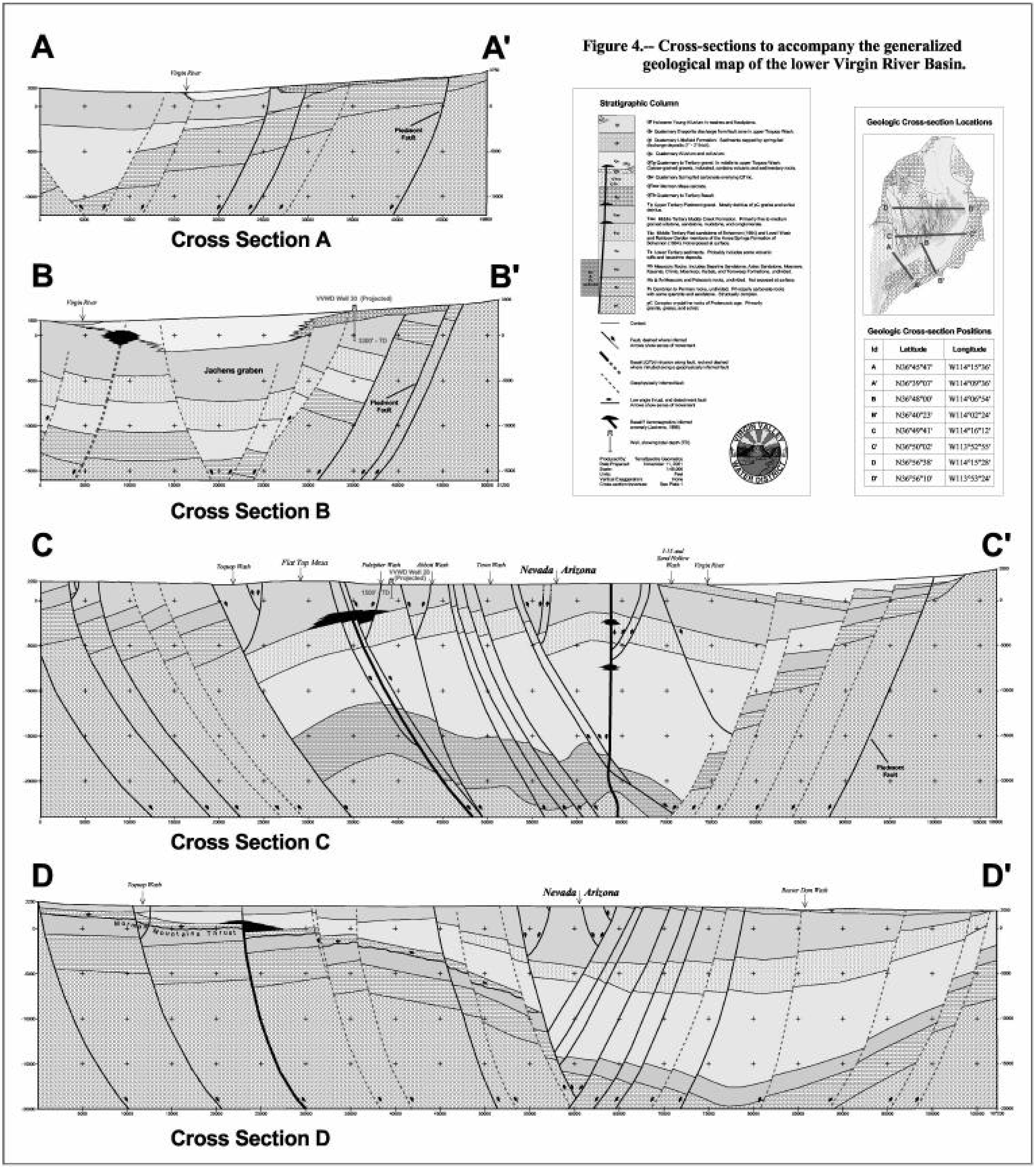


Figure 4.-- Cross-sections to accompany the generalized geological map of the lower Virgin River Basin.

Figure 5. - - Potentiometric surface of the Lower Virgin River Basin.

1992; Hintze and Axen, 1995, 2001) argue that these rocks have moved out from the Beaver Dam Mountains along detachment 1992; Hintze and Axen, 1995, 2001) argue that these rocks have moved out from the Beaver Dam Mountains along detachment faults, the breakaway zone of which is the fault beneath Castle Cliff, whereas others (Carpenter and Carpenter, 1994; L.F. Hintze, oral communication, 2001; Katzer and Dixon, 2002) ascribe these Mississippian masses to landsliding off the steep mountain flank that had been raised along high-angle normal faults of the Piedmont fault zone. The Mormon and East Mormon Mountains are on our west horizon. We have passed through lots of roadcuts of Muddy Creek Formation, and there are more to come.

1.9 79.8 Hill of Mississippian breccia on the left. Terry Benches at 11:00 to 1:00. We are in a forest of Joshua trees.

3.9 83.7 Pass beneath power lines. The Kern River gas pipeline is just to the west, where it is marked. As many as a dozen gas-fired power plants (predominately air-cooled) are proposed for southern Nevada and adjacent Arizona, to be supplied by this pipeline.

0.7 84.4 Fork in the road. BEAR RIGHT ON THE MAIN ROAD.

1.5 85.9 Enter the canyon of Beaver Dam Wash. Lytle Ranch on the right, a Brigham Young University Agricultural Research Station.

0.2 86.1 Cross Beaver Dam Wash. Flow in the wash at this location is perennial with a base flow of 2 to 5 cubic feet per second (cfs). The conglomerate (fanglomerate) that makes up the canyon walls here is considered Muddy Creek Formation by some workers, but Hintze and Axen (1995) considered it more likely that it is Pleistocene and Pliocene, somewhat younger than the Muddy Creek. If we were to take a barely passable dirt road that will take off shortly to the right and travel about a kilometer up the canyon, we would see vertical, north-northwest-striking dikes of travertine limestone, as much as 3 meters wide, that parallel the wash for more than 1 kilometer and cut the conglomerate (Hintze and Axen, 1995). These are orifices of springs that probably date to the middle to Pleistocene (Dixon and Katzer, 2002).

0.8 86.9 **STOP 2; BEAVER DAM WASH OVERLOOK. PULL OVER AT THE FENCE LINE.** The road forks just south of the fence line Discussion on the hydrology of Beaver Dam Wash, which drains the Bull Valley Mountains and brings low-TDS water into the Mesquite basin (Holmes and others, 1997; Fogg and others, 1998), and the geology and significance of the conglomerate. A pediment caps this bench. Beaver Dam Wash is a major conduit for significant amounts of ground water and surface water moving into the basin from the north. The upper drainage area is in the Beaver Dam and Bull Valley Mountains in Utah and the Clover Mountains in Nevada. Numerous faults in the Central Mesquite structural basin define the present trace of the Beaver Dam Wash. The faults are not expressed at the surface, but have been interpreted from gravity surveys (Baer, 1986; Blank and Kucks, 1989; Langenheim and others, 2000; and Jachens and others, written communication, 1998), seismic reflection data (Carpenter, 1989; Bohannon and others, 1993; and Carpenter and Carpenter, 1994), and resistivity soundings (Zohdy and others, 1994; Holmes and others, 1997). Gravity inferred faults are shown on cross sections as red dashed lines. Although we cannot find surface traces of these faults, in such an active wash, the fact that the wash is linear is reason to suspect that a fault zone controls the wash. In Bull Valley Wash, calcium carbonate veins 1 to 3 feet in diameter and up to several hundred feet long paralleling the wash. Hintze and Axen (1995) first recognized these veins while mapping the Scarecrow Peak quadrangle. The veins formed from ground-water discharge along existing faults that precipitated calcium carbonate as ground-water levels decreased.

RETURN TO THE VEHICLES AND TAKE THE RIGHT FORK.

1.8	88.7	Road takes a sharp turn to the left.
1.2	89.9	Road forks. GO LEFT.
1.0	90.9	Road forks. GO LEFT Enter the Tule Springs Hills, mapped by Hintze and Axen (1995, 2001).
2.6	93.5	Snow Spring. Road forks. BEAR RIGHT. The red hills here are mostly the Moenkopi Formation and the Shinarump Member of the Chinle Formation (Hintze and Axen, 2001). The road here will go west for several miles along a major fault zone, which we consider to be a transverse zone. Such features, most of which strike east, are common in the Great Basin and serve as either barriers or conduits to ground-water flow (Ekren and others, 1976; Rowley, 1998; Rowley and Dixon, 2001).
1.5	95.0	Red Moenkopi on right faulted against Queantoweap Sandstone on the left. The higher ridge to the left is the Permian and Pennsylvanian Bird Spring Formation (Hintze and Axen, 2001).
1.4	96.4	Leave Tule Springs Hills and enter the Tule Desert, Hydrographic Basin 221. The hills are separated by the north-northeast-striking East Tule Desert fault zone, a normal fault down to the west (Hintze and Axen, 2001). The Tule Desert (Tule basin) is part of the Virgin Valley ground-water flow system (Dixon and Katzer, 2002). The basins to the west of the Tule Desert, are part of the carbonate aquifer of the White River ground-water flow system (Harrill and others, 1988; Dettinger, 1989; Dettinger and others, 1995; Prudic and others, 1995; Schmidt and Dixon, 1995; Brothers and others, 1996; Thomas and others, 1996; Burbey, 1997; Harrill and Prudic, 1998). Ground water travels south-southwest in both flow systems (Dixon and Katzer, 2002). Recharge for both systems is mostly central Nevada. The Clover Mountains include the high mountain to the west as well as the mountains at 12:00 to 2:00. The Clover Mountains to the north are underlain by a major Tertiary caldera complex that is faulted (Rowley and others,

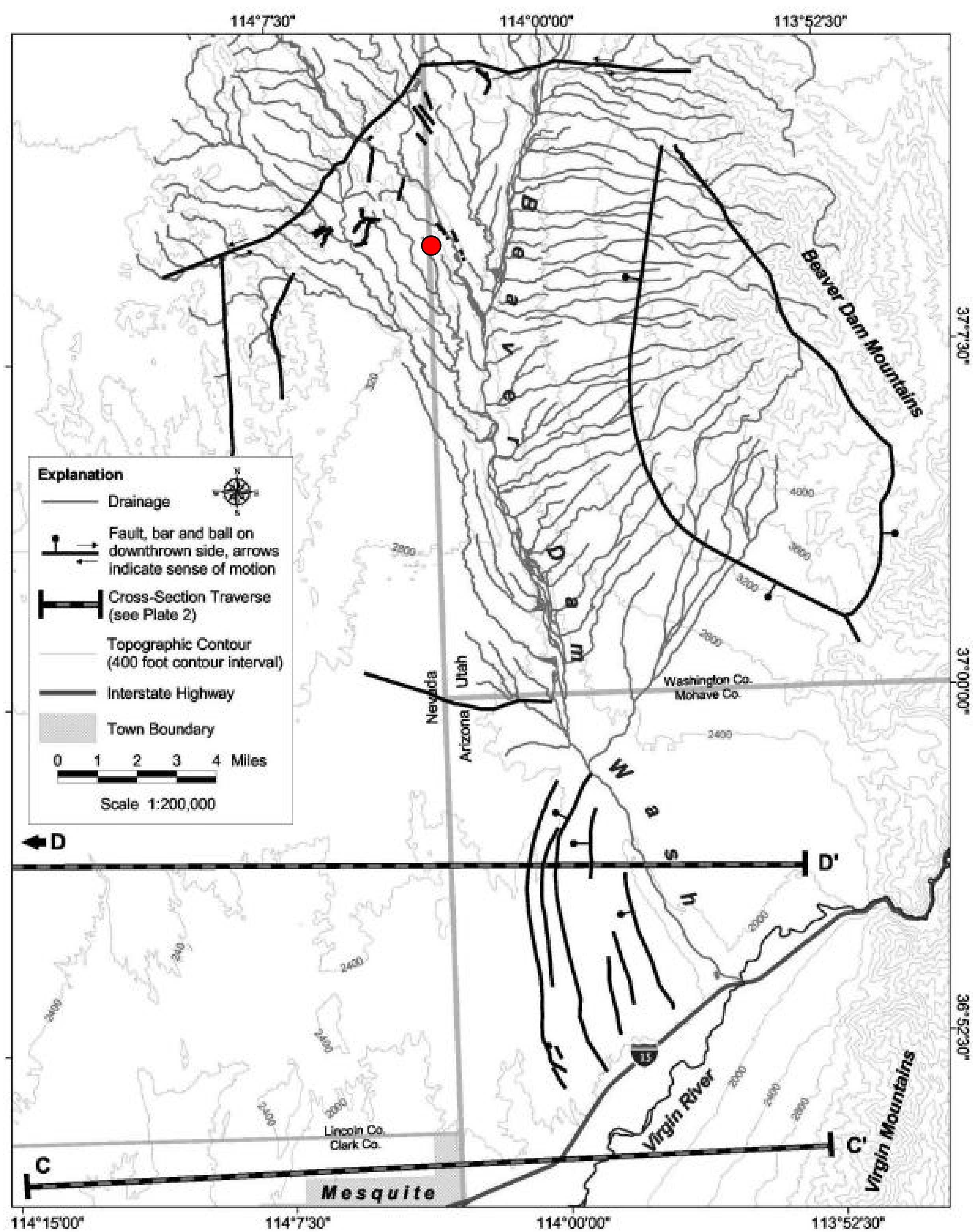


Figure 6. --Stop 2, Structural geologic controls for Beaver Dam Wash.

		1995). The Clover Mountains supply recharge to the local ground-water system.
2.1	98.5	Intersection with north-south road. Continue straight ahead.
0.4	98.9	Enter Sams Camp Wash.
0.7	99.6	Intersection with another north-south road. This one has a good deal of red flagging at the intersection, and the road to the left is as good as the one we are on. TURN LEFT (SOUTH). After we turn south, we are heading directly toward a jagged peak that is part of the East Mormon Mountains.
2.3	101.9	On the right is the well head for MW-2, a nested piezometer monitoring well installed by Vidler Water Company in 2001 to look for water in the Tule Basin. The Mormon Mountains are on the horizon at 12:00 to 2:30.
1.1	103.0	Cattle tank on the left, and another road comes in on the right. Continue straight ahead. Tule Springs Hills on the left.
2.0	105.0	Intersection with road to the left; this road goes southeast, out through the southern Tule Springs Hills. Continue straight.
0.5	105.5	On the right are the well heads for nested piezometer MW-1, monitoring wells MW-4 and MW-5, and VW-1, the first production well installed by Vidler Water Company last summer and last fall respectively (2001). The ground water is to be utilized primarily for the proposed Toquop Power plant and the Lincoln County Land Act. Toquop Power plant is a proposed 1,100 mega-watt, water-cooled power plant to be constructed along Toquop Wash about 15 kilometers south-southeast of here and powered by natural gas from the Kern River pipeline adjacent to the plant. Potentially over 7,000 acre-feet of ground water will be extracted and transferred into Basin 222. Some of the water production in the wells and MW-2 to the north are probably due to fracture porosity, perhaps caused by the East Tule Desert fault zone to the east. A west-northwest-trending seismic section runs very close to the wells (Carpenter and Carpenter, 1994; Hintze and Axen, 2001). Vidler Water has installed another monitoring well, MW-3, on the west side of the Tule Desert. Water levels from the three wells indicate that ground water flow in and near the Tule Desert (Basin 221) is to the south-southwest and drains through Toquop gap into the lower Virgin River Basin (Basin 222).
0.6	106.1	Intersect with an east-west road. GO LEFT.
0.9	107.0	Intersect with the southeast road of three stops ago, at a fence line. GO RIGHT. Enter the Tule Springs Hills.
0.8	107.8	Road enters on the left. STOP 3, SEVIER THRUST FAULT AT JUMBLED MOUNTAIN. On the high ridge (Jumbled Mountain) on the left, red rocks low on the slopes represent the Moenkopi Formation, over which is thrust gray Paleozoic carbonates that cap the ridge (Hintze and Axen, 2001).

2.9	110.7	Cabin and cattle tank on the left. Summit Spring, controlled by a fault. Just to the east, a north-striking normal fault that is down on the west side lifts up the high ridge of Mesozoic rocks to the east (Hintze and Axen, 2001). Discharge from the springs in Tule Hills and Tule Desert are small, ranging from 1 to 10 gallons per minute, and of poor water quality, (TDS greater than 1,000 mg/L).
0.3	111.0	Road enters on the right. STAY ON THE MAIN ROAD, BEARING LEFT.
3.6	114.6	Road comes in on the left. Continue straight ahead.
2.8	117.4	Cross a small wash, with caliche capping the pediment on the other side. Note small vertical calcium carbonate veins cutting this pediment cap, examples of probable orifices of spring discharge.
0.5	117.9	Road comes in on the left. Continue straight ahead.
1.6	119.5	Pass beneath a power line, where a road comes in sharply on the right. Continue straight ahead.
0.1	119.6	Cross the Kern River pipeline.
0.7	120.3	Road goes over the top of a caliche pediment and drops steeply down to the east.
0.1	120.4	Road enters on the left. Stay to the right.
1.3	121.7	Pop up on the top of a caliche mesa and bear right at the fence.
0.3	122.0	Road forks. Bear right and stay on the main road.
0.5	122.5	Road enters on the right. Bear left.
3.1	125.6	Come out of a soft (sandy) wash. On left is a corral.
0.9	126.5	Pass beneath electric transmission line. Cattle tank on right.
0.8	127.3	Well head of a USGS monitoring well on the left. Caliche outcrops in the Muddy Creek Formation.
8.0	135.3	Road enters on the left, then pass through a fence line.
1.0	136.3	Intersect with a blacktop road, Country Road 3454. GO RIGHT. Road runs parallel to I-15.
0.7	137.0	Stop sign at SR-91. GO RIGHT UNDER I-15.
0.3	137.3	Fence line crosses the road. TAKE A SHARP LEFT, HEADING TOWARD THE LITTLEFIELD, ARIZONA CEMETARY AND BACK TOWARD I-15.

0.2	137.5	**STOP 4, LITTLEFIELD RIVER GUAGE.** Go past the cemetery to an overlook above the Virgin River, below which is the green frame of the stream gauge. The gauge sits on a river terrace deposit that has indurated by caliche. One of the major orifices of Littlefield springs is on the opposite wall of the river (just right of the bridge abutment) (Trudeau, 1979; Trudeau and others, 1983). Littlefield Springs discharge 6,200 acre-feet of water per year, a significant part of the flow of the river in the winter. Littlefield gauge has been in continuous operation since 1933. Average annual flow of the Virgin River is 177,000 acre-feet per year (244 cfs) with an average TDS of 2,200 mg/L. Cliffs of Littlefield Formation on the left, an upper part of the basin-fill rocks. Spring flow is an important component of the water-resources budget because it provides a significant amount of water to the Virgin River Valley. Cole and Katzer (2000) defined a loss of river flow of about 30 cfs (22,000 afy) in the river reach from the junction of Black Rock Wash to the Narrows gage. Immediately below the Narrows gage the river flow begins to increase and continues to do so throughout the river reach downstream to the Littlefield gage and beyond. Additionally there is ground-water recharge and river flow loss to seepage that discharge to the river as spring flow. Thus, the average flow of the Virgin River at the Littlefield gage is about 177,000 acre-feet per year (Preissler and others, 1998, p. 56). According to Cole and Katzer (2000), about 142,000 acre-feet is direct surface-water runoff from the entire drainage area as measured at the Bloomington gage. There is also about 1.5 cfs (1,000 acre feet) of stream flow at the Beaver Dam gage (upstream about 1 mile from the mouth) according to Holmes and others (1997). Additionally, there are two bypasses around the Littlefield gage: (1) about 1 cfs in the Littlefield Irrigation Ditch diverted from Beaver Dam Wash (west side of the river), and (2) about 2-3 cfs from the Petrified Springs on the opposite bank (east side of the river). Both bypasses are used for irrigation downstream from the Littlefield gage. Early work by Moore (in Glancy and Van Denburgh, 1969, p.36) indicated that ground water or springs discharge into the river. In July 1968, Moore measured a 6 cfs increase in river flow between the Littlefield gage and the Mesquite diversion, about 8 miles down river. If 2 cfs for ET are added, the gain is about 8 cfs in 8 miles, or about 1 cfs/mile. If this same accretion occurs throughout the river length, then perhaps the spring flow to the river from ground water equals about 30 cubic feet per second (cfs) or ~ 22,000 acre-feet per year. Some of this may be accounted for by return flow from the Littlefield Canal which bypasses the gage on the west bank (about 1 cfs) and the flow from Petrified Springs which bypasses the gage on the east bank (about 2-3 cfs).

BOARD VANS AND RETURN TO THE BLACKTOP.

0.3	137.8	At SR-91, TURN LEFT (SOUTH, THEN WEST).
3.8	141.6	Cross a wash. Good outcrops of the Muddy Creek Formation on both sides of the road.
0.8	142.4	Roadcuts in Quaternary conglomerate.

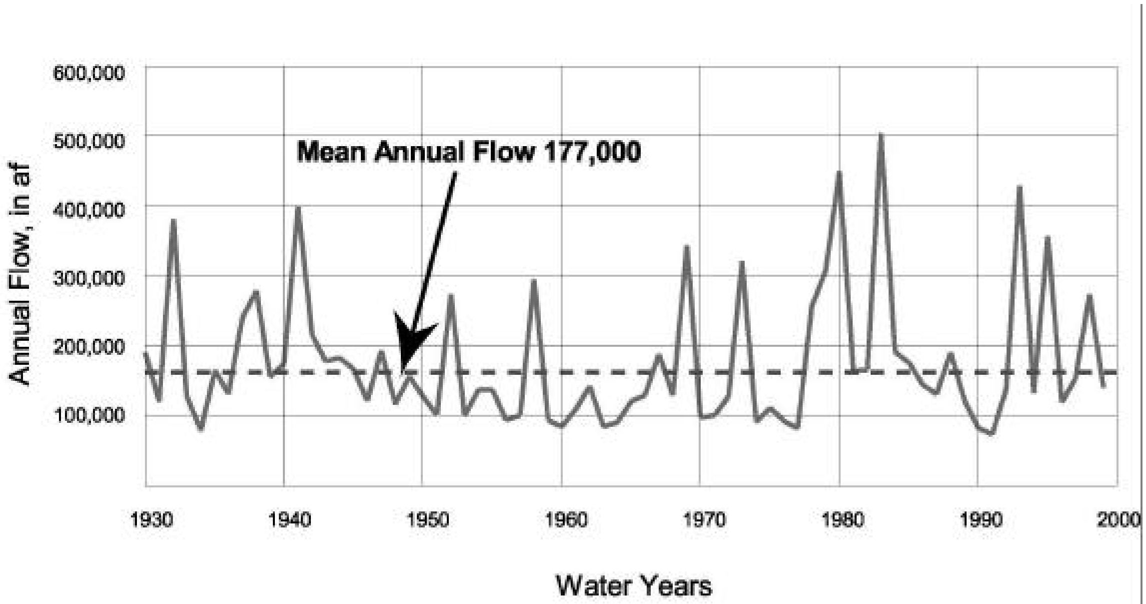


Figure 7. - - Hydrograph of annual flows for the Virgin River at Littlefield, Arizona

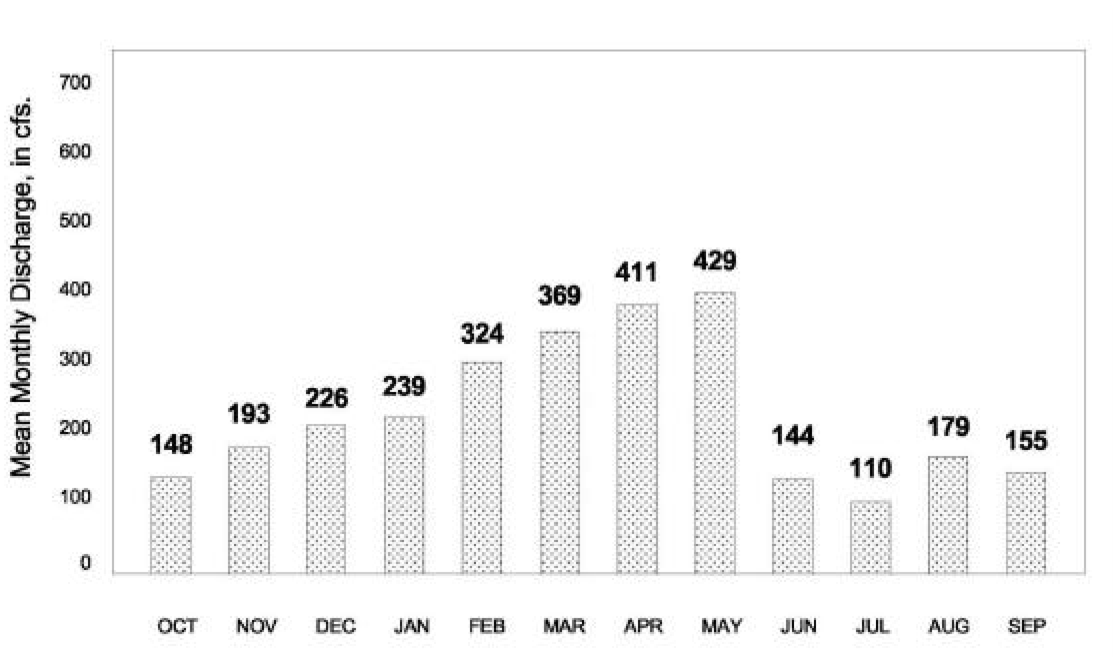


Figure 8. - - Mean monthly discharge for the Virgin River at Littlefield, Arizona

2.9	145.3	Johnson Flat, faults bound the flat on both the east and west sides. Palms Golf Course on the left or south side of highway. North of I-15 but south of the bluff to the north small basalt outcrop occurs.
1.0	146.3	State line; enter Mesquite, Nevada.
0.7	147.0	Stop light at intersection with Sandhill Road. GO RIGHT, THEN UNDER I-15.
0.7	147.7	Near the buildings about 600 feet to the right, the Virgin Valley Water District (VVWD) production well, VVWD Well No. 27 adjacent to Town Wash (by palm trees and water hazard at Oasis Golf Course). The well is on the downthrown side of a normal fault cutting the Muddy Creek Formation (Johnson, 1995; Williams, 1997, Williams and others, 1997; Johnson and others, 2000; Dixon and Katzer, 2002) and produces about 1,700 gpm. Excellent exposures of the Muddy Creek are observed on the north side of the interstate.
0.3	148.0	Intersection with Turtleback Road. GO RIGHT.
0.7	148.7	At power lines, a sign reading "Landfill" points right. GO RIGHT. After making the turn, note Flat Top Mesa on the left. The Mesa consists of Muddy Creek Formation that is held up by caliche, which forms the Mormon Mesa surface to the east. But Flat Top Mesa is uplifted by faults east and west of it and stands higher than Mormon Mesa.
1.2	149.9	Clark County – Lincoln County line. Signs advertise the Bureau of Land Management land sale in Lincoln County, as authorized by the Lincoln County Land Act of 2000. The first sale (October, 2001) was to be for more than 6,000 acres, but only a small part (112 acres) of the Land Act was purchased by private interests. Continue on blacktop road.
2.4	152.3	Gravel road intersects on left. TURN LEFT. A yellow metal gate spans the road. Continue through the gate.
0.9	153.2	Fenced compound securing municipal facility operated by Virgin Valley Water District. Continue through the gate.
0.2	153.4	**STOP 5, VIRGIN VALLEY WATER DISTRICT RESERVOIRS AND PRODUCTION WELL.** PULL OVER AT THE RESERVOIR. Discussion on how production wells are sited along faults. View east of a newly drilled production well in a graben in the valley. From this vantage point, also look south on the slope of Quaternary fans and pediments that leads up to the Virgin Mountains. Facilities installed to provide municipal water supply for the service area of the Virgin Valley Water District in Clark County Nevada. Here the Muddy Creek Formation is covered by these deposits, geophysics must be used to locate faults beneath the Quaternary cover (Johnson, 1995; Jachens and others, 1998; Johnson and others, 2000; Langenheim and others, 2000a, b, 2001; Dixon and Katzer, 2002).

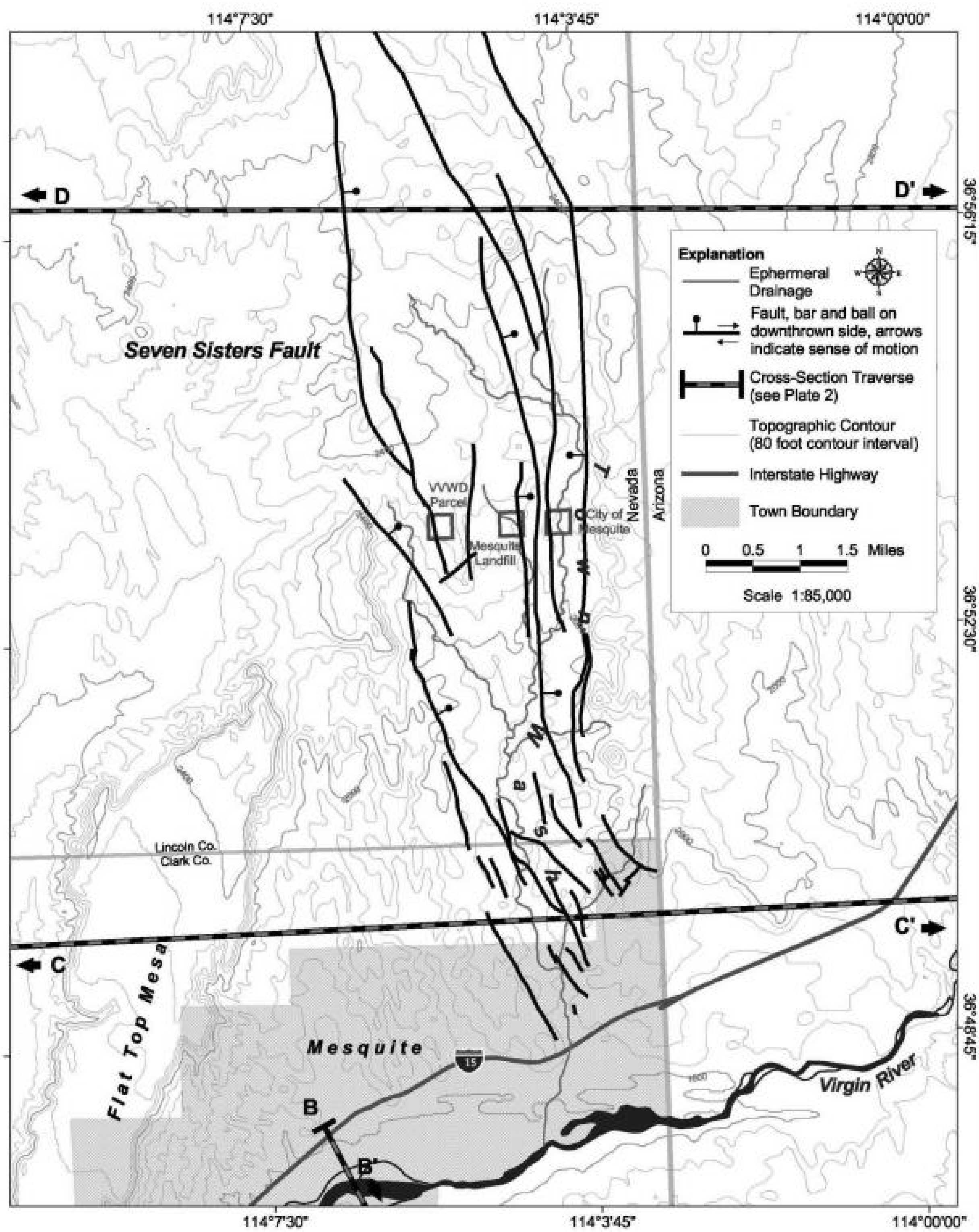


Figure 9. - - Structural geologic controls in the vicinity of Town Wash.

TURN AROUND AND RETURN TO I-15 EXIT NO. 122 IN MESQUITE, NV.

6.2	159.6	Entrance ramp to eastbound I-15. TURN LEFT AND ENTER I-15.
0.8	160.4	Nevada-Arizona state line. On left, excellent outcrops of subhorizontal Muddy Creek Formation. The mesa caps consist of caliche.
4.3	164.7	Muddy Creek outcrops continue to here on left. Virgin Mountains on the right, Beaver Dam Mountains ahead. Both are uplifted along the Piedmont fault zone along their northwest and west sides, respectively (Dixon and Katzer, 2002).
4.0	168.7	Exit 8, Littlefield and Beaver Dam. Beaver Dam Wash enters the Virgin River just north of the highway.
0.9	169.6	East side of the bridge crossing the Virgin River, with one of the major springs, with spring travertine, of the Littlefield spring complex just south of the east bridge abutment. Other springs of the complex continue east along the south side of the river. The conglomerates making up the bridge abutments have been informally called the Littlefield formation, but Billingsley and Workman (2000) map it as Muddy Creek Formation overlain by a Pleistocene calcrete.
0.4	170.0	Exit 9, Farm Road.
3.0	173.0	At entrance to The Narrows of the Virgin River, note well exposed fault on the right, one of the main faults of the Piedmont fault zone that here bounds the Beaver Dam Mountains. Movement on the Piedmont fault zone began in the Miocene and is as young as late Pleistocene, and possibly Holocene. The first rocks we see at the canyon entrance are gray and brown Mississippian Redwall Limestone, but several hundred meters south of the entrance, along the mountain front, the light-gray, well-bedded, Permian-Pennsylvanian Callville Limestone crops out (Billingsley and Workman, 2000). Bohannon and others (1991), however, correlated with rocks from the west and called these rocks the Mississippian Monte Cristo Limestone and the Permian-Pennsylvanian Bird Spring Formation, respectively. As we enter The Narrows, within a few hundred meters the rocks are dipping west more gently (15 to 25^{o}) and the Callville rests on the Redwall above the inner gorge. From here until the Black Rock exit, the canyon generally goes by the name Virgin River Gorge. Constructing the interstate through it was one of the most expensive projects of the interstate highway system.
0.9	173.9	At about here, the Redwall is underlain by about 60 meters of light-gray and yellow-gray Devonian limestone, then in turn by Cambrian rocks down to river level. If you can see the Virgin River below you, you will notice that here near the west end of the gorge, it has water in the channel, but upstream in a few miles, it commonly does not. This water has high TDS, as does that of the Littlefield springs, because it has been naturally polluted by gypsiferous Mesozoic and upper Paleozoic rocks

		(Trudeau, 1979; Trudeau and others, 1983; Dixon and Katzer, 2002).
2.8	176.7	As road bends to right, north-striking faults trend up the deep canyon to our left. They are downthrown on the east side (Bohannon and others, 1991).
0.4	177.1	The deep canyon entering on the right is Sullivan's Canyon, defined by a north-striking, oblique-slip fault (left-lateral and normal that is down on the east). This fault intersects another east-northeast striking, oblique-slip fault (left lateral and normal with the east side down) just south of the highway; this fault crosses the highway and continues parallel to us on our left (Bohannon and others, 1991). As the road bends left, Pleistocene river-terrace deposits are on our right.
0.6	177.7	On our left, Permian Toroweap Formation is dropped down along the north-northeast-striking fault, which is several hundred meters farther north of us; Redwall is north of this fault. More Pleistocene river terrace deposits on our right.
0.6	178.3	Exit 18, Cedar Pockets. More Pleistocene river terrace deposits on our right. The BLM plans to put an office at this exit. To our right is a lovely campground that is rarely used.
1.8	180.1	Start up out of the gorge at Cedar Pockets and cross the north-striking Grand Wash fault zone here. This is a major normal fault, with its west side downthrown, that to the south separates the Colorado Plateau to the east from the Basin and Range Province to the west (as, for example, where Grand Canyon ends and Lake Mead begins). To the north, this fault connects with the Gunlock fault. As we cross the fault the rocks are dipping gently east and consist of the Callville at road level and the Permian Queantoweap Sandstone just above us, and capping the hill just ahead and to our right. The Queantoweap is commonly red but generally yellow.
0.8	180.9	Pleistocene river terrace deposits to the left and right of us. At road level, the rocks still are Callville, but the Queantoweap is just above us. Just ahead of us, the road crosses an abandoned meander bend of the Virgin River; just to the right, the river is dry most of the time.
0.6	181.5	Small fault. Queantoweap on the east is downthrown against Callville on the west. Queantoweap dips gently to the east. The caprocks north and south of us, making the crest of the Beaver Dam Mountains, and likewise dipping east, are the Permian Toroweap and Kaibab Formations (Billingsley and Workman, 2000).
1.4	182.9	Here the Virgin River comes into the gorge from the north; from here, it generally parallels I-15 to the west.
4.3	187.2	Exit 22, Black Rock Road. To the north and south of us, the east-dipping Kaibab Formation goes below the surface and the Triassic Moenkopi Formation is exposed. The Virgin River is 3

kilometers north of us here, and by way of a rough jeep trail, a person may get down onto its flood plain. On and above the flood plain, sinkholes are abundant due to solution of gypsum and limestone in the Kaibab and Moenkopi Formations (Higgins, 1997; Katzer and others, 2000). Large parts of the river flow go into the sinkholes, to emerge at Littlefield springs (Katzer and others, 2000; Dixon and Katzer, in press).

1.9	189.1	Arizona-Utah State line.
0.9	190.0	Exit 1, Port of Entry.
3.6	193.6	Exit 4, Bloomington.
0.9	194.5	Cross the Virgin River.
1.0	195.5	Exit 6, Bluff Street, St. George. RETURN TO CEDAR CITY.
53.4	248.9	Eccles Coliseum.

END OF FIELD TRIP

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