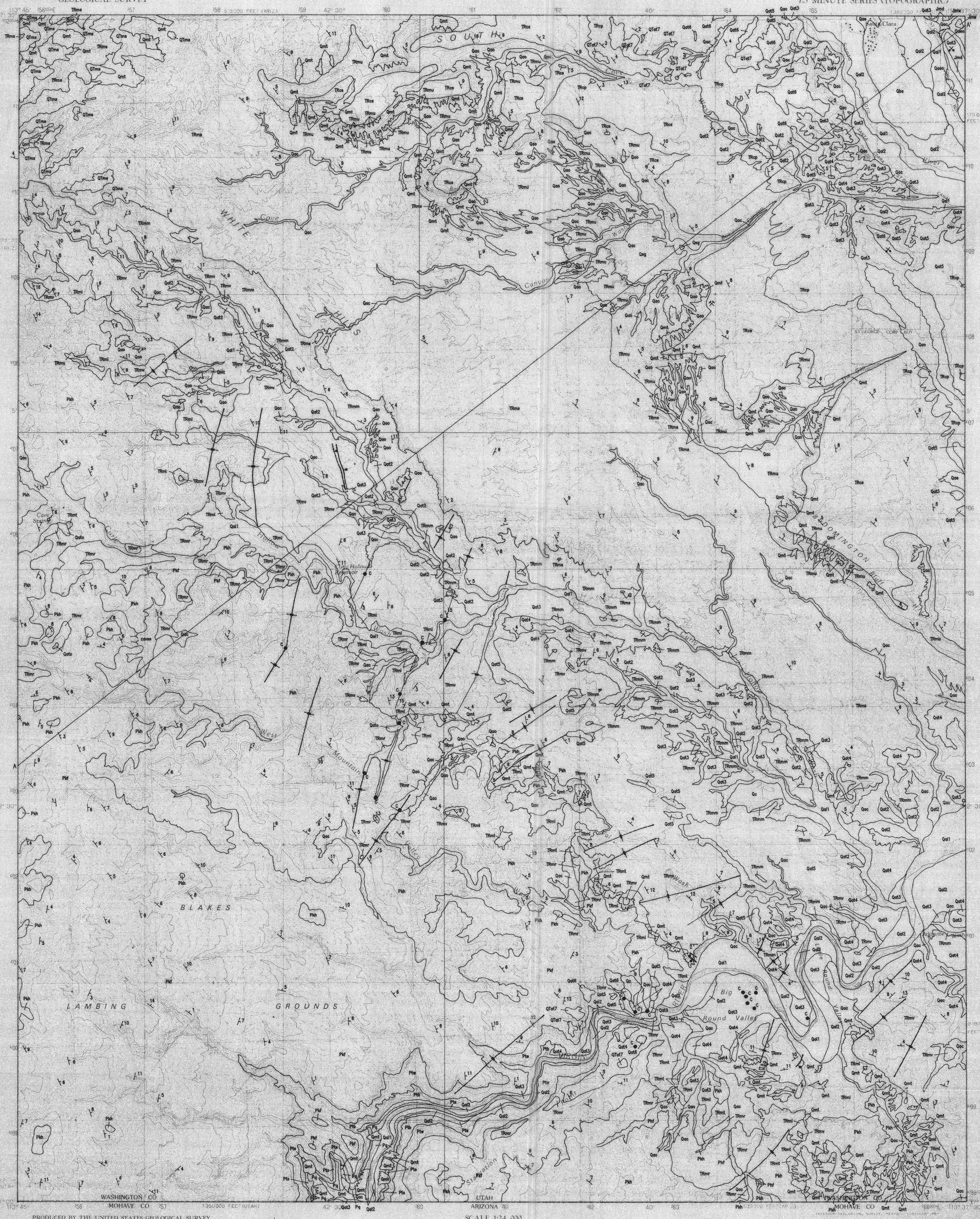
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

WHITE HILLS QUADRANGLE
UTAH-ARIZONA
7.5 MINUTE SERIES (TOPOGRAPHIC)



PRODUCED BY THE UNITED STATES GEOLOGICAL SURVEY
CONTROL BY . . . . USGS, NOS/NOAA
COMPILED FROM AERIAL PHOTOGRAPHS TAKEN 1978
FIELD CHECKED . . . . 1979 MAP EDITED 1986
PROJECTION . . . . LAMBERT CONFORMAL CONIC
GRID: 1000-METER UNIVERSAL TRANSVERSE MERCATOR . . . . ZONE 12
10,000-FOOT STATE GRID TICKS . . . . UTAH, SOUTH ZONE
ARIZONA, WEST ZONE
UTM GRID DECLINATION . . . . 1°37' WEST
1986 MAGNETIC NORTH DECLINATION . . . . 14° EAST
VERTICAL DATUM . . . . NATIONAL GEODETIC VERTICAL DATUM OF 1929
HORIZONTAL DATUM . . . . 1927 NORTH AMERICAN DATUM

To place on the predicted North American Datum of 1983, move the projection lines as shown by dashed corner ticks (6 meters north and 70 meters east)
There may be private inholdings within the boundaries of any Federal and State Reservations shown on this map
Where omitted, land lines have not been established
All marginal data and lettering generated and positioned by automated type placement procedures

PROVISIONAL MAP
Produced from original manuscript drawings. Information shown as of date of field check. 2

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
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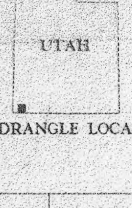

QUADRANGLE LOCATION

1	2	3	1 Shivwits 2 Santa Clara 3 Washington 4 Jarvis Peak 5 St George 6 Mountain Sheep Spring 7 Purgatory Canyon 8 Lizard Point
4		5	
6	7	8	

ADJOINING 7.5' QUADRANGLE NAMES

ROAD LEGEND

Improved Road . . . .
Unimproved Road . . . .
Trail . . . .

PLATE 1
Interim Geologic Map of the White Hills Quadrangle Washington County, Utah

Open-File Report 352 September 1997

UTAH GEOLOGICAL SURVEY
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Utah Department of Natural Resources
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PLATE 2
Interim Geologic Map of the White Hills Quadrangle
Washington County, Utah
Open-File Report 352 September 1997
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Description of Map Units

QUATERNARY-LATE TERTIARY

Alluvial Deposits

Qal_{1-2} **Alluvial-stream deposits** -- Moderately to well-sorted clay to small gravel deposits in large active drainages. Qal_1 includes benches up to 10 feet (3 m) above current channels; 0-10 feet (0-3 m) thick. Qal_2 includes deposits adjacent to and dissected by Qal_1; upper surface up to 30 feet (9 m) above active channels; 0-20 feet (0-6 m) thick.

Qat_{2-6}, $QTat_7$
Stream-terrace deposits -- Gravel to cobble size clasts in a muddy to coarse sand matrix; forms a poorly sorted, indurated pedogenic carbonate-cemented conglomerate at several levels above the present floodplain; clasts are well-rounded and many are exotic to the quadrangle, indicating a source several miles upstream; pedogenic carbonate (caliche) thicker in older deposits; subscripts denote relative heights above the current drainage and relative ages; level 2 deposits are 10-30 feet (3-9 m); level 3 deposits are 30-90 feet (9-27 m); level 4 deposits are 90-140 feet (27-42 m); level 5 deposits are 140-190 feet (42-57 m); level 6 deposits are 190-270 feet (57-82 m); and level 7 deposits are 270-350 feet (82-106 m) above present channels; typically 0-40 feet (12 m) thick.

Qao **Older alluvial deposits** -- Remnants of older, locally derived and moderately sorted clay- to gravel-sized alluvial deposits; are 10-30 feet (3-10 m) higher than, and dissected by, minor drainages. 0-10 feet (0-3 m) thick.

Qato **Older stream-terrace deposits** -- Gravel- to cobble-sized clasts in muddy to coarse sand matrix; forms isolated, indurated conglomerate; 20-50 feet (6-15 m) higher than, and not correlative to, current drainage; 0-20 feet (0-6 m) thick.

Colluvial Deposits

Qc **Colluvial deposits** -- Poorly sorted, angular- to-rounded blocks in muddy to sandy matrix, deposited by sheet wash and slope-creep on moderate slopes; only larger deposits mapped; locally includes eolian, talus, debris flow and alluvial deposits too small to map separately. 0-20 feet (0-6 m) thick.

Mass Movement Deposits

Qmt **Talus deposits** -- Very poorly sorted, angular boulders with minor fine-grained interstitial sediment; deposited on and at the base of steep slopes; 0-10 feet (0-3 m) thick.

QTms **Old landslide deposits** -- Very poorly sorted, boulder- to clay-size debris in chaotic mounds; caps ridges and knolls that are over 400 feet (120 m) above drainages in northwest part of quadrangle; some boulders are in excess of 30 feet (9 m) across; blocks were derived primarily from Shinarump Conglomerate; 20-80 feet (6-24 m) thick.

Mixed-Environment Deposits

Qac **Alluvial and colluvial deposits** -- Poorly to moderately sorted clay- to boulder-size sediment in minor drainages; gradational with colluvial deposits; includes terrace outcrops too small to map separately; 0-10 feet (0-3 m) thick.

Qae, Qaeo
Alluvial and eolian deposits -- Moderately to well-sorted, clay- to sand-size alluvial sediment that locally includes abundant eolian sand and minor gravel. Qaeo is dissected by current drainages; forms higher bench and has strong pedogenic carbonate (caliche), compared to Qae; mapped in broad, sloping areas north of the Santa Clara River; 0-30 feet (0-9 m) thick.

Qsg **Gypcrete and alluvial gravel** -- Pale-gray to pinkish-gray, punky gypcrete; basal part locally includes poorly to moderately stratified, moderately sorted, lenticular channel deposits of silt- to small boulder-size material; gypcrete forms a resistant ledge; present only on the highly gypsiferous Moenkopi Formation; 0-5 feet (0-1.5 m) thick.

Basalt Flows

Qbs **Santa Clara lava flow** -- Dark-brownish-black to black, subalkine basalt flow; rocks have abundant small olivine phenocrysts in an alphanitic groundmass; very jagged aa surface; 10-30 feet (3-9 m) thick; estimated 10,000-20,000 years old.

unconformity

JURASSIC

Jmw **Whitmore Point Member of the Moenave Formation** -- Pale-red-purple to greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone with several 2-6 inch (0.05-0.15 m) thick beds of light-greenish-gray dolomitic limestone that contain algal structures and fossil fish scales of *Semionotus kanabensis* (Hamilton, 1984); nonresistant and poorly exposed; about 55 feet (17 m) thick.

Jmd **Dinosaur Canyon Member of the Moenave Formation** -- Interbedded moderate-red-brown siltstone and very fine-grained, thin-bedded, pale-reddish-brown to grayish-red sandstone with laminated cross-beds; forms ledgy slope; 250 feet (76 m) thick.

unconformity

TRIASSIC

TRcp **Petrified Forest Member of the Chinle Formation** -- Light-brownish-gray to grayish-red-purple bentonitic shale and siltstone with several lenticular interbeds of pale-yellowish-brown, cross-bedded sandstone up to 10 feet (3 m) thick; petrified wood is common; shales weather to a "popcorn" surface with abundant mudcracks due to bentonitic clay swelling and shrinking with moisture; forms well-developed strike valleys adjacent to the more resistant dip slope of the Shinarump Conglomerate Member; 700 feet (215 m) thick.

unconformity

TRcs **Shinarump Conglomerate Member of the Chinle Formation** -- Varies from a grayish-orange to moderate-yellowish-brown, medium- to coarse-grained sandstone with locally well-developed limonite bands ("picture rock" or "landscape stone") to a moderate-brown, chert-pebble conglomerate; forms a dark-brown to moderate-yellowish-brown caprock above the Moenkopi Formation; along the northern edge of the quadrangle, conglomerate is overlain by a sandstone ledge; in some places, the two ledges are separated by up to a few feet of brownish-gray to grayish-purple bentonic shale; variable in composition and thickness because it represents stream channel deposition; ranges from 5-200 feet (1.5-61 m) thick.

unconformity

TRmu **Upper red member of the Moenkopi Formation** -- Moderate-reddish-brown, thin-bedded siltstone and very fine-grained sandstone with some thin gypsum beds and abundant discordant gypsum stringers; ripplemarks common in the siltstone; forms a slope with a few minor sandstone ledges; locally includes 20-foot-thick, (6-m-) fine-grained, resistant sandstone near base; 450 feet (136 m) thick.

TRms **Shnabkaib Member of the Moenkopi Formation** -- Light-gray to pale-red, "bacon-stripe", gypsiferous siltstone with several thin interbeds of dolomitic, unfossiliferous limestone near the base; upper portion is very gypsiferous and weathers into a powdery soil; forms a valley except where held up by more resistant overlying units; 900 feet (272 m) thick.

TRmm **Middle red member of the Moenkopi Formation** -- Interbedded moderate-red to moderate-reddish-brown siltstone, mudstone, and thin-bedded, very fine-grained sandstone with thin interbeds and veinlets of greenish-gray to white gypsum; forms a slope; commonly covered with stream terrace gravels; 375 feet (114 m) thick.

TRmv **Virgin Limestone Member of the Moenkopi Formation** -- Five distinct medium-gray to yellowish-brown marine limestone ledges interbedded with nonresistant, moderate-yellowish-brown, muddy siltstone, pale-reddish-brown sandstone, and light-gray to grayish-orange-pink gypsum; limestone beds are 3-15 feet (1-5 m) thick and contain five-sided echinoderm and shell fragments; total thickness is 200 feet (61 m).

TRml **Lower red member of the Moenkopi Formation** -- Moderate-reddish-brown siltstone, mudstone, and fine-grained, slope-forming sandstone; generally calcareous with interbeds and stringers of gypsum; ripple marks and small-scale cross-beds are common in the siltstone; thickness varies considerably from 0-200 feet (0-61 m) because of deposition over paleotopography.

TRmt **Timpoweap Member of the Moenkopi Formation** -- Dark-yellowish-orange and moderate reddish-brown, thin- to very thin-bedded, calcareous siltstone with thin, medium-gray limestone beds and medium- to coarse-grained sandstone near the base; gypsiferous near the top with lenses of gypsum and sandstone; gypsum forms punky surface; poorly lithified and forms slope; varies from 0-100 feet (0-30 m) thick due to deposition over paleotopography.

TRmr **Rock Canyon Conglomerate Member of the Moenkopi Formation** -- Yellowish-gray to light-olive-gray, clast-supported, but grading upward to a matrix-supported conglomerate with pebble- and cobble-sized clasts; basal layers contain angular to sub-angular limestone ripup clasts and brecciated blocks from the Harrisburg Member, locally cemented with sparry calcite; rounding increases upward to sub-rounded, mostly chert clasts near top; grades upward to calcareous, gritty, poorly sorted, pebble conglomerate with coarse sandstone lenses; thick, locally lenticular bedding; indurated; cliff forming; filled paleocanyons eroded into the Kaibab Formation; thickness 0-200 feet (0-61 m).

unconformity

PERMIAN

Pkh **Harrisburg Member of the Kaibab Formation** -- Light-gray, fossiliferous, sandy, fine- to medium-grained limestone interbedded with red and gray gypsiferous siltstone, sandstone, and gray gypsum beds several feet thick; beds of cherty limestone and sandy limestone about 20 foot-thick (6 m) form resistant ledges near upper middle; solution of interbedded gypsum causes local distortions; forms slope with limestone ledges; thickness varies greatly due to subaerial erosion; 0-300 feet (0-91 m) thick.

Pkf **Fossil Mountain Member of the Kaibab Formation** -- Yellowish-gray, abundantly fossiliferous, cherty limestone that forms a prominent cliff; silicified fossils include corals, brachiopods, crinoids, and bryozoans; reddish-brown and black chert forms irregularly bedded nodules and causes the outcrop to appear black-banded; 100-300 feet (30-91 m) thick.

unconformity

Pt **Toroweap Formation** -- shown in cross section only

Ptw **Woods Ranch Member of the Topoweap Formation** -- Grayish-pink to very-pale-orange massive gypsum with interbeds of light-brownish-gray siltstone and pale-red shale; forms slope, commonly covered with talus; beds distorted from dissolution of gypsum; 200 feet (61 m) thick.

Ptb **Brady Canyon Member of the Toroweap Formation** -- Medium-light-gray to dark-gray, medium- to coarse-grained, thick-bedded, fossiliferous limestone with reddish-brown chert nodules; forms prominent cliff; 250 feet (76 m) thick.

Pts **Seligman Member of the Toroweap Formation** -- Consists of three sections: upper section of medium-gray, thin-bedded, sandy limestone; middle section of interbedded yellowish-gray, calcareous, very fine-grained sandstone and grayish-yellow, gypsiferous, calcareous siltstone; and basal section of pale-yellowish-brown, fine-grained sandstone; forms recess in cliff of Virgin River Gorge; 100 feet (31 m) thick.

unconformity

Pq **Queantoweap Sandstone** -- Pale-yellow to grayish-pink, calcareous, thickly-bedded, fine-grained sandstone; forms steep slope in Virgin River Gorge; only the upper 150 feet (45 m) is exposed in the quadrangle.

Subsurface Units

Pp **Pakoon Dolomite** -- shown in cross section only

PENNSYLVANIAN

IPc **Callville Limestone** -- shown in cross section only

MISSISSIPPIAN

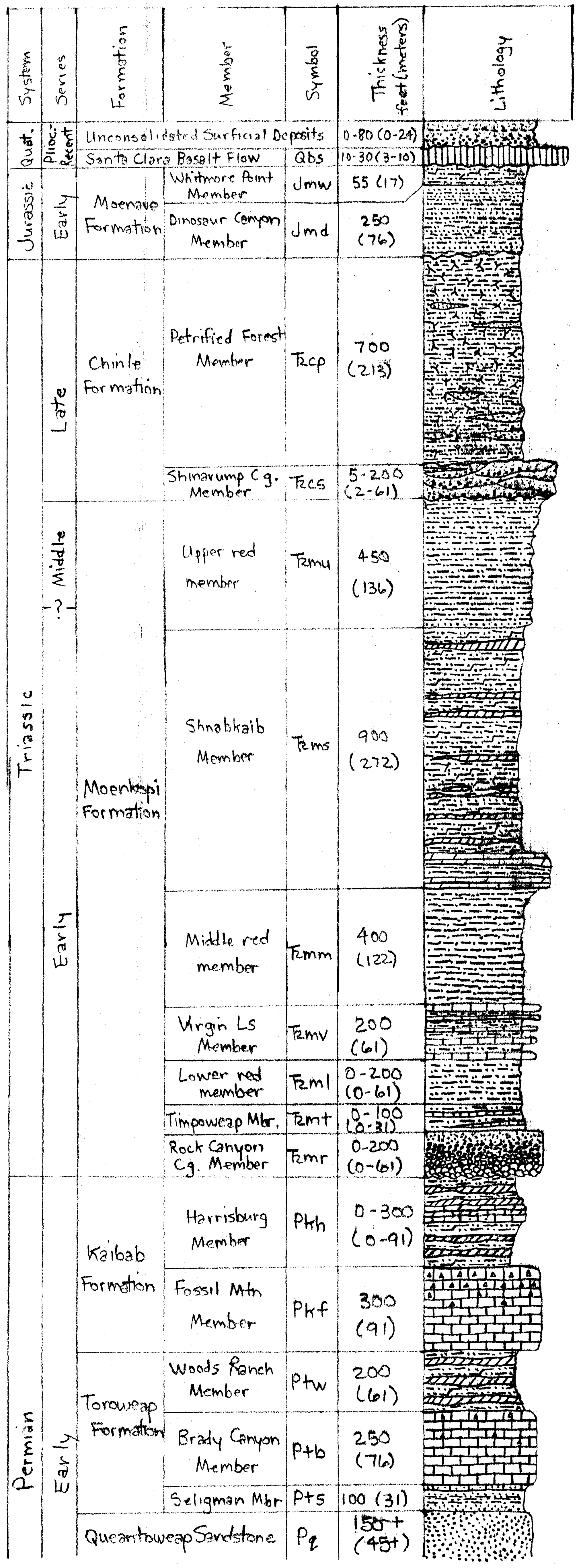
Mr **Redwall Limestone** -- shown in cross section only

DEVONIAN

Dm **Muddy Peak Dolomite** -- shown in cross section only

CAMBRIAN

Cn **Nopah Dolomite** -- shown in cross section only



System	Series	Formation	Member	Symbol	Thickness feet (meters)	Lithology
Quat.	Plioc.-Recent	Unconsolidated Surficial Deposits			0-80 (0-24)	
		Santa Clara Basalt Flow		Qbs	10-30 (3-10)	
Jurassic	Early	Moenave Formation	Whitmore Point Member	Jmw	55 (17)	
			Dinosaur Canyon Member	Jmd	250 (76)	
Triassic	Late	Chinle Formation	Petrified Forest Member	TRcp	700 (213)	
			Shinarump Cg. Member	TRcs	5-200 (2-61)	
	Middle	Moenkopi Formation	Upper red member	TRmu	450 (136)	
	-?- Early		Shnabkaib Member	TRms	900 (272)	
			Middle red member	TRmm	400 (122)	
			Virgin Ls Member	TRmv	200 (61)	
			Lower red member	TRml	0-200 (0-61)	
			Timpoweap Mbr.	TRmt	0-100 (0-31)	
			Rock Canyon Cg. Member	TRmr	0-200 (0-61)	
Permian	Early	Kaibab Formation	Harrisburg Member	Pkh	0-300 (0-91)	
			Fossil Mtn Member	Pkf	300 (91)	
		Toroweap Formation	Woods Ranch Member	Ptw	200 (61)	
			Brady Canyon Member	Ptb	250 (76)	
			Seligman Mbr	Pts	100 (31)	
		Queantoweap Sandstone		Pq	150+ (45+)	

Key to Map Symbols

- Contact
- High-angle fault -- dashed where approximately located, dotted where concealed, bar and ball on down-thrown side
- Axial trace of syncline -- dotted where concealed
- Strike and dip of inclined bedding
- Gravel or road-fill pit
- Quarry
- Spring
- Cave

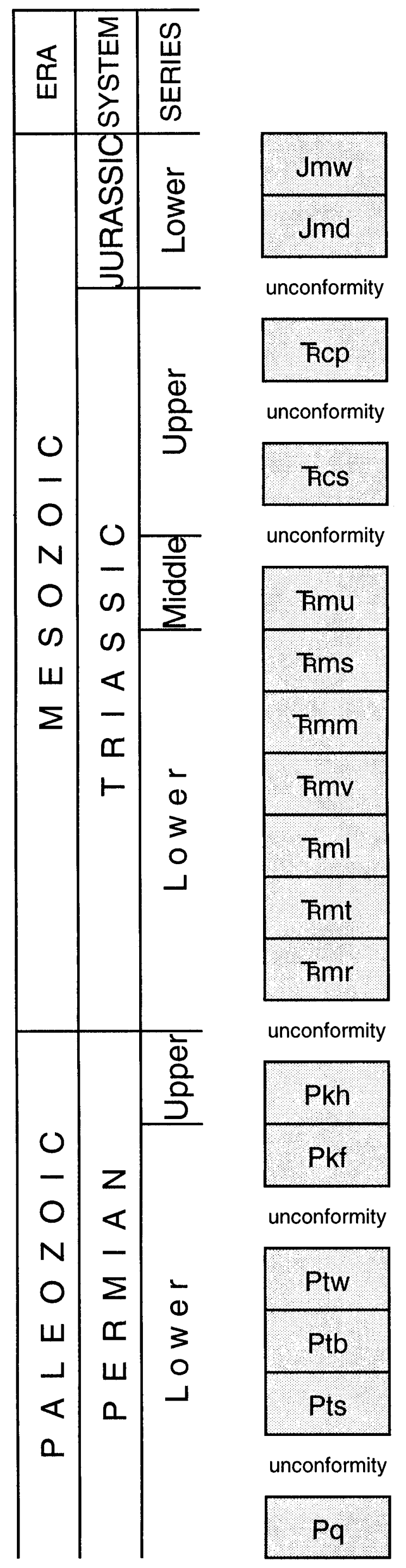
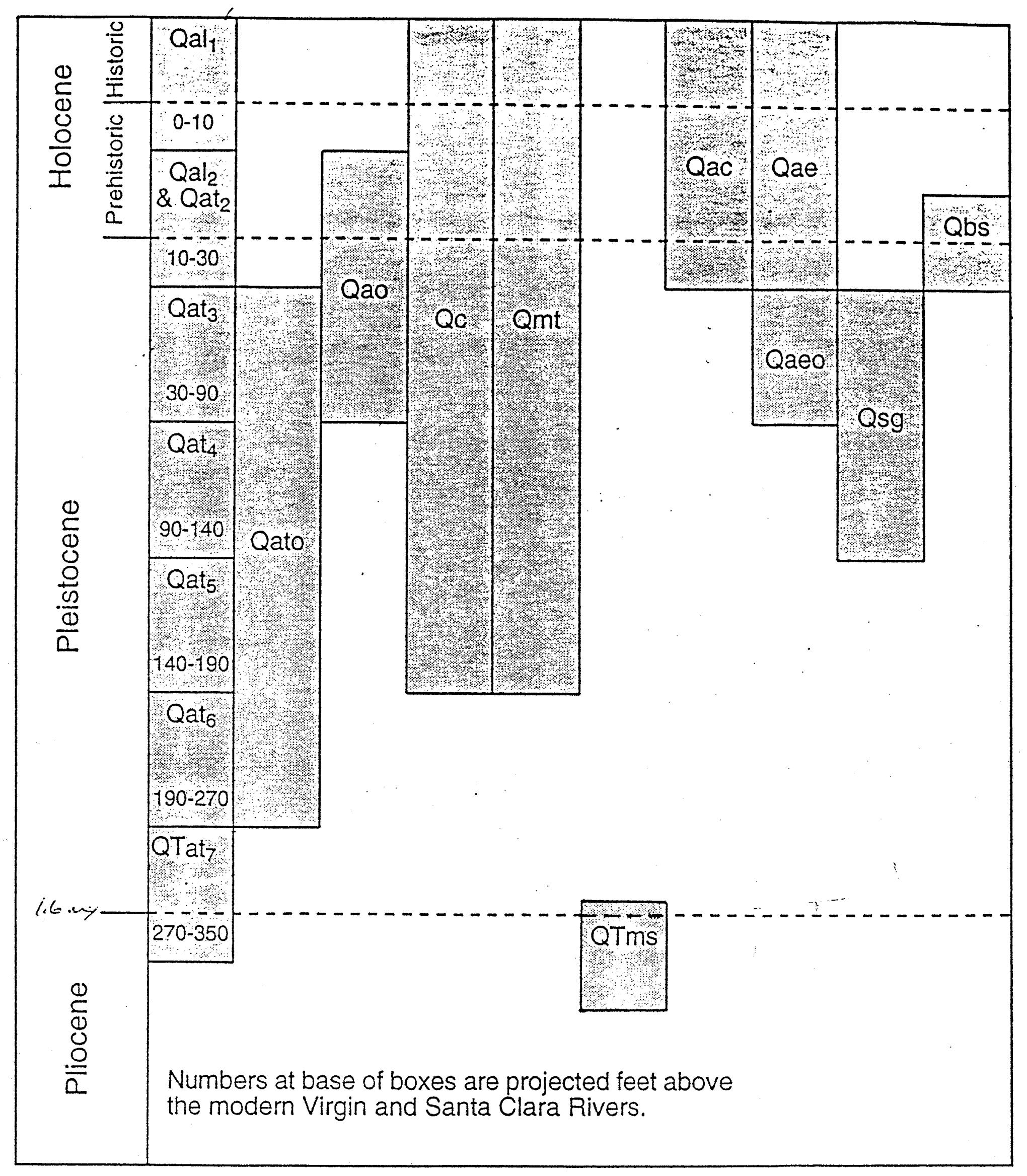


PLATE 2
WHITE HILLS QUADRANGLE
J. M. HIGGINS

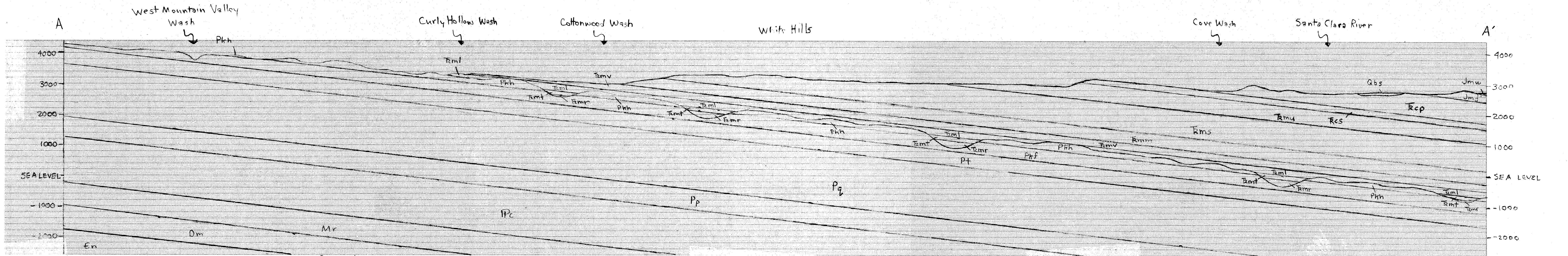
CORRELATION OF
BEDROCK UNITS



Numbers at base of boxes are projected feet above the modern Virgin and Santa Clara Rivers.

PLATE 2
WHITE HILLS QUADRANGLE
J. M. HIGGINS

CORRELATION OF SURFICIAL DEPOSITS



Note: TRmt & TRmr are not exposed at the surface along section line. Locations shown beneath the surface are hypothetical.

INTERIM GEOLOGIC MAP OF THE WHITE HILLS QUADRANGLE, WASHINGTON COUNTY, UTAH

by

Janice M. Higgins

OPEN-FILE REPORT 352
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

INTRODUCTION

The White Hills quadrangle is located in southern Washington County in the southwest corner of Utah (figure 1). Development of the rapidly growing cities of St. George and Santa Clara is spilling over into the quadrangle along it's eastern and northern edges and many geologic concerns are arising as the population increases. One of the seemingly most controversial issues facing these communities is the preservation of open space. The city of Santa Clara has recently entered into a cooperative agreement with the Bureau of Land Management (BLM) to create the Santa Clara Federal Preserve along the Santa Clara River, eight square miles of which includes the South Hills in the northern portion of the White Hills quadrangle. The city of St. George is currently proposing a similar agreement to form the St. George Federal Preserve that would encompass an additional 38 square miles within the quadrangle. Both perserve areas butt up against a Paiute Indian Reservation, Shivwits Band, in the northwest corner of the quadrangle.

In addition to open space concerns, water supplies are limited and must be protected from contamination and misuse. Construction materials, particularly gravel, are in short supply. Expansive, soluable, and collapsible soils that adversely affect buildings, roads, and other structures are present and need to be recognized by planners and builders. Other geologic hazards include flooding, mass movement possiblilties, active earthquake faults, and volcanoes.

[figure 1 near here]

Maximum topographic relief in the quadrangle is just over 2,200 feet (667 m) from the base of the Virgin River drainage at 2,360 feet (715 m) above sea level to the edge of the White Hills at 4,560 feet (1,382 m) in the northwest corner of the quadrangle. The hills of Blake's Lambing Grounds also reach above 4,400 feet (1333 m) as the foothills of the Beaver Dam Mountains to the west. The South Hills and Bloomington Hill form a prominent ridge across the northeast portion of the quad. Strata that comprise these hills form two risers or steps on the "Grand Staircase" (Gregory, 1950) that stretches across southern Utah and northern Arizona: the Kaibab Formation of Blake's Lambing Grounds also forms the rimrock of the Grand Canyon, and the Shinarump Member of the Chinle Formation forms the Chocolate Cliffs, locally called South Hills and Bloomington Hill.

The Virgin River lowland has the lowest elevation, warmest climate, and the longest growing season in Utah. It receives about 8 inches (20 cm) of precipitation annually (Cordova and others, 1972). Natural vegetation includes sparse grasses, sagebrush, creosote bush, and several varieties of cactus and yucca.

The U.S. Army Topographical Survey and U.S. Geological Survey investigated the regional geology of southwestern Utah during the latter half of the 19th century (Powell, 1875; Dutton, 1882). Dobbin (1939) produced a small-scale geologic map of the St. George area that focused on structural geology. Gregory (1950) mapped the Zion Canyon area to the east and established many of the geologic names in use today. Cook (1960) completed a map of Washington County at a scale of 1:125,000 that is still the most detailed map available for a large part of the county. Christenson and Deen (1983) mapped the surficial geology of the St. George area, including a portion of the

White Hills quadrangle, focusing on engineering aspects of the geology. Eppinger and others (1990) compiled a 1:250,000-scale map of the Cedar City 1°x2° quadrangle that includes the White Hills quadrangle. Billingsley (1993) mapped four quadrangles in Arizona south and southeast of the White Hills quadrangle at a scale of 1:31,680. All 7 1/2 minute quadrangles bordering White Hills are mapped at a scale of 1:24,000 (figure 1): Hammond (1991) mapped the Jarvis Peak quadrangle to the west; Hintze and Hammond (1994) mapped the Shivwits quad to the northwest; Willis and Higgins (1995) mapped the Santa Clara quadrangle (1996) to the north and the Washington quadrangle to the northeast; Higgins and Willis (1995) mapped the St. George quadrangle to the east. Many topical studies have been done on structure, stratigraphy, volcanism, hazards, and economic and water resources of the area.

DESCRIPTION OF MAP UNITS

The oldest rocks exposed in the White Hills quadrangle, the Early Permian Queantoweap Sandstone and Toroweap Formation, form the Virgin River Gorge along the south-central edge of the study area. The Early-Late Permian Kaibab Formation forms the rim of the gorge and is extensively exposed, covering the southwest one-third of the quagrangle. The Triassic section, including the Early Triassic Moenkopi and the Late Triassic Chinle Formations, crops out over the rest of the quadrangle except the northeast corner where the Early Jurassic Moenave Formation is poorly exposed.

The Santa Clara basalt flow, derived from a cinder cone north of the quadrangle, extends about one mile (1.6 km) onto the quad in the northwest corner. It is considered the youngest flow (Best and others, 1980; Hamblin and others, 1981; Willis and Higgins, 1996) in the immediate area, a region that is famous for classic examples of inverted topography, where erosion removes less resistant strata leaving the resistant flow standing as a high linear ridge (Hamblin, 1963, 1987). This flow is just beginning the inversion process but past uplift and erosion of the area is confirmed by seven main levels of gravel terraces. Thin alluvial, colluvial, eolian, and mass movement deposits cover much of the quadrangle.

Permian and Mesozoic strata in the quadrangle were deposited in shallow marine to low-level terrestrial conditions and lithologies strongly reflect sea-level fluctuations (figure 2a). Vail and others (1977), Mitchum (1977), and Van Wagoner and others (1990) recognized major cycles in the depositional record that are divisible into first-order megasequences through fifth-order parasequences, according to duration and extent of the cycle. Permian rocks exposed in the quadrangle were deposited near the end of the Paleozoic megasequence and the Triassic rocks mark the beginning of the Mesozoic/Cenozoic megasequence (figure 2a). A Permian lowstand near the end of the Paleozoic megasequence exposed the Kaibab Formation to erosion. After the lowstand, sea level rose to near the record high where it fluctuated but remained high until the Early Jurassic, when it dropped to about 500 feet (150 m) below present sea level (Vail and others, 1977). These fluctuations in sea level define eight supercycles (second-order sequences) (Van Wagoner and others, 1990). However, only five of the eight are documented in rocks in the quadrangle (figure 2a).

[figure 2 near here]

Permian

The Permian rock exposed in the quadrangle includes the upper portion of the Queantoweap Sandstone, the Toroweap Formation, and the Kaibab Formation. Outcrops of the two older units are confined to the nearly vertical walls of the Virgin River Gorge, while the younger Kaibab Formation is extensively exposed over the southwest one-third of the quadrangle.

These rocks make up two second-order cycles at the end of the Paleozoic first-order megasequence. The Queantoweap Sandstone represents the highstand systems tract of a third-order cycle within the older of these two second-order cycles. The Toroweap and Kaibab Formations constitute the other second-order cycle with each formation being a third-order cycle (figure 2a). In addition, the Toroweap Formation can be divided into two fourth-order cycles with the Seligman Member and the Brady Canyon Member constituting the transgressive systems tract and the highstand systems tract of the older cycle, respectively, and the Woods Ranch Member constituting only the highstand systems tract of younger cycle (figure 2a).

The Kaibab Formation represents only the highstand systems tract of the younger third-order cycle of the final second-order cycle that began in the early Permian (figure 2a). A subsequent late Permian lowstand resulted in subaerial exposure and extensive erosion of the Kaibab Formation, which completely removed the Harrisburg Member and cut deeply into the Fossil Mountain Member in some places (Jenson, 1984). The Kaibab Formation is late Early Permian to early Late Permian in age (Hintze, 1993).

Queantoweap Sandstone (Pq)

The package of clastic rocks usually considered as the Queantoweap Sandstone in Utah (Hintze, 1986a, b) continue farther south into the Virgin River Gorge of northwest Arizona and southeastern Nevada where the lower portion has been called either the Queantoweap Sandstone or the Esplanade Sandstone and the upper portion the Hermit Formation, Hermit Shale (McNair, 1951; McKee, 1975, 1982; and Rowland, 1987), or the Coconino(?) Sandstone (McKee, 1934). Steed (1980) introduced the name sandstone of the Virgin Gorge for the lower crossbedded sandstone and Langenheim and Schulmeister (1987) followed his lead. On the geologic map of Wolf Hole Mountain and vicinity that adjoins this study area to the south, however, Billingsley (1993) called the upper 1099 feet (333 m) of red and white, ledge- and slope-forming sandstone and siltstone the Sandstone facies of the Hermit Shale and only the lower portion the Queantoweap Sandstone. In his stratigraphic study of the area, Billingsley (1997) submits that since the clastic sequence apparently becomes a white, low-angle, crossbedded sandstone in southwestern Utah, the entire sequence in the White Hills Quadrangle should be mapped as Queantoweap Sandstone (figure 3). Only the upper 150 feet (45 m) is exposed within the quadrangle as a pale-yellow to grayish-pink, calcareous, thickly bedded, fine-grained sandstone that forms a steep slope in the Virgin River Gorge. The unconformable upper contact is placed at the break in slope that signifies the base of the Seligman Member of the Toroweap Formation.

[Figure 3 near here]

Toroweap Formation

The Toroweap Formation, which consists of sediment deposited during shallow sea regression, transgression, and subsequent regression (Rawson and Turner-Peterson, 1979), is exposed only in the canyon walls of the Virgin River Gorge. It is mapped using nomenclature defined by Nielson (1981, 1986) that divides the formation into three members: Seligman Member, Brady Canyon Member, and Woods Ranch Member.

Seligman Member (Pts): The Seligman Member forms a recess in the cliff of the Virgin River Gorge. It consists of a basal section of pale-yellowish-brown, fine-grained sandstone; a middle section of interbedded yellowish-gray, calcareous, very fine-grained sandstone and grayish-yellow, gypsiferous, calcareous siltstone; and an upper section of medium-gray, thin-bedded, sandy limestone. The Seligman Member is 100 feet (31 m) in the quadrangle. Neilson (1981) measured an average thickness of 80 feet (24 m) to the northwest and Billingsley (1993) reported a thickness of 125 feet (38 m) just to the south. The upper contact placed at the base of the massive cliff of the Brady Canyon Member is conformable.

Brady Canyon Member (Ptb): The Brady Canyon Member consists of medium-light-gray to dark-gray, medium- to course-grained, thick-bedded, fossiliferous limestone with reddish-brown, rounded chert nodules. The limestone is silghtly dolomitic near its base and top, and contains abundant poorly preserved crinoid stems and disarticulated brachiopods, as well as coral and sponge fragments. It forms a massive cliff within the Virgin River Gorge that is 250 feet (76 m) thick in SE1/4 of section 30, T. 43 W., R. 16 W. The unconformable upper contact is placed at the top of the massive cliff where the gypsiferous slope of the Woods Ranch Member begins (figure 4).

[Figure 4 near here]

Woods Ranch Member (Ptw): The slope-forming Woods Ranch Member is commonly covered with talus. It is grayish-pink to very pale-orange massive gypsum with interbeds of light-brownish-gray siltstone and pale-red shale. The bedding is distorted from dissolution of gypsum. This member is 200 feet (61 m) thick near the gaging station (SE1/4 of section 30, T. 43 W., R. 16 W) in the Virgin River Gorge. The upper contact with the Fossil Mountain Member of the Kaibab Formation is unconformable and channel erosion into the Woods Ranch Member produced local relief of as much as 12 feet (3 m). The contact is drawn at the base of the masive cliff of the overlying Fossil Mountain Member of the Kaibab Formation.

Kaibab Formation

The Kaibab Formation consists of sediment deposited by a transgressive, then regressive shallow sea (Nielson, 1981). It is divided into two members after Nielson (1981) and Sorauf and Billingsly (1991): the Fossil Mountain Member and the Harrisburg Member.

Fossil Mountain Member (Pkf): The Fossil Mountain Member forms the rimrock of the Virgin River Gorge (figure 4) and is extensively exposed over the southwest one-third of the quadrangle. It consists of yellowish-gray, abundantly fossiliferous, cherty limestone that forms a prominent cliff. The fossils, including corals, brachiopods, crinoids, and bryozoan, are silicified. The outcrop often appears black banded because of reddish-brown and black chert that forms irregularly bedded nodules. The total thickness of the Fossil Mountain Member is calculated as 300 feet (91 m), at least 200 feet (61 m) of which has been removed by channel erosion in places and subsequently filled in with the Rock Canyon Conglomerate Member of the Moenkopi Formation (figure 5). The upper contact with the Harrisburg Member is conformable and is drawn at the base of the first thick gypsum bed, just above the top of the massive limestone cliff.

[Figure 5 near here]

Harrisburg Member (Pkh): The Harrisburg Member is well-exposed in the White Hills quadrangle. It is light-gray, fossiliferous, sandy, fine- to medium-grained limestone interbedded with red and gray gypsiferous siltstone and sandstone, and gray gypsum beds several feet thick. Beds of cherty limestone and sandy limestone about 20 feet (6 m) thick form resistant ledges. Dissolution of interbedded gypsum locally distorts the bedding. Additionally, many large collapse structures exist, several of which have northeast-southwest linear orientations (figure 6). The member forms a slope with limestone ledges, referred to as the "medial limestone" by Nielson (1981), two-thirds of the way up (figure 7). The excellent exposure in the quadrangle is unusual since the member is generally poorly exposed (Billingsley, 1993).

[figure 6 near here]

[figure 7 near here]

Several hundred feet of post-depositional, subaerial erosion during Late Permian and Early Triassic time completely removed the Harrisburg Member in several places, creating channels as deep as 500 feet (152 m). Jenson (1984) describes karst topography with more than 594 feet (180 m) of relief formed during this 15-million-year period of erosion. The Rock Canyon Conglomerate Member of the Moenkopi Formation was locally deposited on the Fossil Mountain Member of the Kaibab Formation where the Harrisburg Member was previously removed by erosion (figure 5). Elsewhere, the Harrisburg Member is overlain by the Timpoweap Member, the lower red member, or the

Virgin Limestone Member of the Moenkopi Formation (figure 8). The upper contact, which is poorly exposed, highly variable, and unconformable, is placed above the last pinkish-gray, massive gypsum. The thickness of the Harrisburg Member varies from 0 to about 300 feet (0-91 m).

[figure 8 near here]

Triassic

The Lower Triassic Moenkopi and Upper Triassic Chinle Formations are separated by an unconformity of about fifteen million years (figure 2a). These formations denote two major second-order supercycles of Vail and others (1977) separated by a smaller rise and subsequent fall of sea level during middle Triassic time (Paull and Paull, 1994).

Moenkopi Formation

The Moenkopi Formation is divided into seven members (figure 9) after Reeside and Bassler (1922) and Stewart and others (1972a) with a total thickness of 2,450 feet (742 m). The lower three members (Rock Canyon Conglomerate, Timpoweap, and lower red) were measured south of the Virgin River in section 33, T. 43 S., R 16 W. while the Virgin Limestone Member was measured in the SW 1/4 of section 17, T. 43 S., R. 16 W. The upper three members (middle red, Shnabkaib, and upper red) were measured in a southwest-to-northeast line starting in the SE 1/4 of section 27 and ending in the SW 1/4 of section 24, T. 42 S., R.17 W., in the northwest corner of the quadrangle. This formation is early to middle Triassic in age (late Scythian to early Anisian)(Dubiel, 1994).

[figure 9 near here]

The Moenkopi Formation was deposited on a very gentle slope where sea level changes of several feet translated into shoreline changes of many tens of miles. It represents a second-order supercycle that can be subdivided into three distinct third-order sequences depicting smaller transgressive-regressive cycles in an overall sea level rise (figures 2a, 2b). Paull & Paull (1994) state that the Early Triassic global rise in sea level from the Permian lowstand was greater than 660 feet (200 m). Only the lowest of the three third-order sequences includes a lowstand systems tract that is documented within the quadrangle (represented by the Rock Canyon Conglomerate). Above the Rock Canyon Conglomerate is the transgressive systems tract of the Timpoweap Member, which Dubiel (1994) correlated to the Smithian-age transgression that flooded this area from the northwest. It is overlain by the highstand systems tract of the lower red member, correlated to Smithian-Spathian age regression of Dubiel (1994), which completes the lowest third-order sequence. The Virgin Limestone Member and the middle red member, respectively make up the transgressive and highstand systems tracts of the middle third-order sequence, whereas the Shnabkaib Member and the upper red member form similar systems tracts for the top third-order sequence in the Moenkopi Formation. These two third-order sequences are correlated to the early to late Spathian transgressions and regressions of Dubiel (1994). Paleogeographic maps and time-rock stratigraphy charts in Blakey and others (1993) and Paull & Paull (1994) depict these changes.

Rock Canyon Conglomerate (Trmr): Although Nielson (1991) proposed that this member be elevated to formation status, Hintze (1993) and other subsequent authors still treat it as a member of the Moenkopi Formation. The Rock Canyon Conglomerate fills paleocanyons eroded into the Kaibab Formation (figure 8). The outcrops in the quadrangle overlie either the resistant limestone ledges of the Harrisburg Member of the Kaibab Formation where only the upper gypsum layers were eroded during the Permian-Triassic unconformity (figure 7), or the Fossil Mountain Member of the Kaibab Formation where the Harrisburg Member was completely removed by erosion (figure 5). This member is composed of yellowish-gray to light-olive-gray, poorly to moderately sorted conglomerate with angular to subrounded clasts. Thick beds, some of which are lenticular and indurated, form a cliff with a rough, angular surface. The basal layers include limestone rip-up clasts and blocks eroded from the Harrisburg Member as large as 14 inches (35 cm) in diameter that have been healed with sparry calcite during several episodes. The basal layers weather into angular, brecciated clasts. Rounding in the conglomerate varies from mostly angular in the lower part to sub-angular to sub-rounded toward the top. Clasts are pebble- to cobble-size and composed primarily of chert weathered from the Kaibab Formation. The conglomerate is mostly clast supported but where matrix supported, the matrix is limestone and coarse-grained sandstone. The unit grades upward into calcareous, gritty, pebble conglomerate that is poorly sorted and includes some sandstone and some yellowish-gray, sandy limestone lenses. The upper contact is conformable where exposed and is gradational with dark-yellowish-orange to light-pinkish-gray, gritty siltstone beds of the Timpoweap Member. The Rock Canyon Conglomerate Member varies in thickness from 0 to 200 feet (0-61 m).

Timpoweap Member (TRmt): The Timpoweap Member generally overlies the Rock Canyon Conglomerate Member of the Moenkopi Formation but locally overlies either the Harrisburg Member or, locally, the Fossil Mountain Member of the Kaibab Formation (figure 8). In most exposures it consists of thin-bedded siltstone and limestone with very fine-grained lenticular sandstone near the base. Typically, five distinct 0.25- to 2-inch-thick (0.5-5 cm) beds of medium-gray limestone and bedded gypsum are separated by alternating bands of dark-yellowish-orange and moderate-reddish-brown gypsiferous siltstone. The sandstone generally fines upward. The bedded gypsum is punky and weathers to form a slope covered with cryptogamic soil.

The thickness of the Timpoweap Member decreases dramatically as the siltstone beds between the limestone intervals thin and as the entire member pinches out against paleotopography of the Permian beds. The Timpoweap Member varies in thickness from 0 to 100 feet (0-30 m). The conformable upper contact is placed at the top of a dark-yellowish-orange, friable sandstone, and below the predominantly light-reddish-brown mudstone of the lower red member. Locally, very thin beds of dark-yellowish-orange siltstone, widely separated by light- to moderate-reddish-brown mudstone and siltstone, are included in the lower red member.

Lower red member (TRml): The lower red member consists of interbedded siltstone, mudstone, sandstone, and gypsum that also pinches out next to paleotopography. The siltstone and mudstone are moderate-reddish-brown, generally calcareous, commonly ripple marked, and exhibit small-scale cross-bedding. Dark-yellowish-orange siltstone is thin-bedded. The sandstone is reddish brown, calcareous, very fine grained, and thinly bedded. Stringers and thin veinlets of gypsum cut across the member. The lower red member is exposed as a slope beneath the more resistent ledge of the basal Virgin Limestone Member. The upper contact with the Virgin Limestone Member is placed at the base of the lowest limestone ledge. The lower red member varies in thickness from 0 to 200 feet (0-91 m) due to stratigraphic thinning over paleohills of the Kaibab Formation (figure 10).

[figure 10 near here]

Virgin Limestone Member (TRmv): The Virgin Limestone Member is well exposed as a series of resistant ridges that trend northwest across the quadrangle. It consists of five well-developed, resistant, medium-gray to yellowish-brown, marine limestone ledges interbedded with nonresistant, moderate-yellowish-brown, gypsiferous, muddy siltstone, pale-reddish-brown sandstone, and light-gray to grayish-orange-pink gypsum. This member, together with the middle red member, is a third-order sequence that can be subdivided into five fourth-order sequences (figure 2b). Each of the five limestone ledges (figure 11) are transgressive systems tracts that are separated from an overlying muddy siltstone highstand systems tract by a maximum flooding surface.

[figure 11 near here]

The five limestone ledges, which vary from 3 to 15 feet (1-5 m) thick, can be further divided into distinct fifth-order parasequences (Van Wagoner and others, 1990). The lower part of each limestone is finer grained, muddy, and non-fossiliferous (transgressive systems tract), whereas the upper portion is a coarser wackestone with birdseye structures, five-sided crinoid columnals, and bivalve shell fragments (highstand systems tract). The two limestone portions are divided by an inch (2.5 cm) or less of dark-grayish-brown shale (maximum flooding surface).

This member is 200 feet (41 m) thick. It is the oldest Triassic unit in the White Hills quadrangle not directly affected depositionally by paleotopography, although the basal limestone does, on occassion, sit directly on the Harrisburg Member of the Kaibab Formation. The conformable upper contact with the middle red member is drawn at the top of the highest limestone ledge.

Middle red member (TRmm): The middle red member is a slope-forming unit that is easily eroded off of the dip-slope of the Virgin Limestone thus forming the center of the quadrangle's drainage system which feeds the Virgin River. The best exposures are along the northwest portion of the quadrangle where there is less alluvium covering the outcrops. It is composed of interbedded, moderate-red to moderate-reddish-brown siltstone, mudstone, and very fine-grained, thin-bedded sandstone. Very thin interbeds and veinlets of gypsum that vary in color from greenish-gray to white are locally common. The thickness of the middle red member is 400 feet (121 m) and is relatively consistent throughout the quadrangle. The upper contact is placed where the moderate-red siltstone of the middle red member gives way to predominantly light-gray, unfossiliferous, dolomitic limestone beds that mark the base of the Shnabkaib Member.

Shnabkaib Member (TRms): The Shnabkaib Member is well exposed and forms the White Hills of the White Hills quadrangle. It consists of light-gray to pale-red gypsiferous siltstone with several thin interbeds of unfossiliferous, dolomitic limestone near the base. The alternating resistant and nonresistant beds form ledge-slope topography and make the lower portion slightly more resistant to erosion than the upper portion. The gypsiferous upper portion weathers to a powdery soil and generally forms a valley except where it is held up by more resistant overlying units. Alternating light and dark colors give this member a "bacon-striped" appearance that shows up especially well on aerial photographs. The upper contact is gradational and conformable and is drawn where the greenish-gray, gypsiferous siltstone of the Shnabkaib Member grades into reddish-brown mudstone of the upper red member. This member is 900 feet (272 m) thick.

Upper red member (TRmu): The upper red member is well exposed in the northeast one-third of the quadrangle as a steep slope with at least one prominent sandstone ledge beneath the resistant ledge formed by the Shinarump Conglomerate. Where sandstone ledges near the base are thickened, the weathering and slope retreat of the overlying units is slowed, creating resistant points on the cuestas that form the South Hills and Bloomington Hill. The member consists of moderate-reddish-brown, thin-bedded siltstone and very fine-grained sandstone with some thin gypsum beds. Ripplemarks are common in the siltstone. A massive, pale-reddish-orange, very fine-grained sandstone forms a prominent ledge near the top. The upper contact is unconformable, representing approximately 10 million years of middle Triassic time (figure 2a), and is mapped at the base of the first coarse-grained, thick-bedded, pale-yellowish-brown sandstone caprock (figure 12). The upper red member is 450 feet (136 m) thick.

[figure 12 near here]

Chinle Formation

The Chinle Formation consists of the Shinarump Conglomerate and the Petrified Forest Members in the quadrangle (Stewart and others, 1972b). The Shinarump forms a prominent cuesta in the middle and eastern parts of the quadrangle whereas the Petrified Forest is nonresistant and forms low hills at the base of a broad dip slope. The Chinle Formation varies in thickness mostly because of thickness changes in the basal Shinarump Member, but it averages about 800 feet (245 m)thick. Dubiel (1994) assigned it an early Carnian to late Norian age with an unconformity of several million years separating the two members.

The Chinle Formation represents the last Triassic second-order supercycle (figure 2a) (Vail and others, 1977) and can be subdivided into two distinct third-order cycles. The lower third-order cycle consists of the Shinarump Member sourced from the ancestral Uncompahgre highlands to the northeast and from a magmatic arc near the continental margin to the southeast (Blakey and others, 1993). The basal Shinarump was deposited in the lowest parts of paleovalleys cut into the upper red member of the Moenkopi Formation (Dubiel, 1994), which signifies the beginning of base level rise. The Shinarump grades upward from massive conglomerate and tabular-planar stratified sandstone to medium-grained, trough cross-stratified sandstone (a highstand systems tract) formed by hinterland braided stream deposits. The Petrified Forest Member is the highstand systems tract of a separate third-order cycle. Its fluvial systems mimicked paleoflow in the lower Shinarump system except that these stream deposits were of much higher sinuosity as evidenced by ample floodplain mudstone (Dubiel, 1994). Abundant bentonitic mudstone intervalsin the Petrified Forest Member indicate that volcanic ash formed a significant component of the sediment supply, most of which was derived from the magmatic arc at the continental margin to the southwest (Blakey and others, 1993).

Shinarump Conglomerate (TRcs): The Shinarump Conglomerate is very resistant and forms the dark-brown to moderate-yellowish-brown sandstone cuesta of South Hills and Bloomington Hill, which stretches northwest across the northeast one-third of the quadrangle. It is grayish-orange to moderate-yellowish-brown, medium- to coarse-grained sandstone with intermittent gravel conglomerates across most of the quadrangle, but near the northern edge of the quadrangle, the map unit consists of both a moderate-brown, chert pebble and gravel conglomerate layer and a sandstone layer. In some places, the sandstone rests directly on the conglomerate but in others, the two layers are separated by several feet of bentonitic mudstone. The sandstone contains fragments of petrified wood in some areas. Locally, it has well-developed liesegang bands that give rise to the nicknames of "picture rock" or "landscape stone" (Bugden, 1993).

The Shinarump Conglomerate is 5 to 200 feet (1.5-61 m) thick in the White Hills quadrangle. It is highly variable in composition and thickness because it backfills paleotopography and was deposited in braided stream channels (figure 12). Only minor channels a few feet deep are found in the White Hills quadrangle. Measured thickness variations may also be due to difficulty in picking the upper contact and unrecognized slumping. Slickensides with multi-directional lineations at the base of or within the sandstone indicate that it commonly slides on either the upper red member of the Moenkopi Formation or the bentonic clays that may be present within the Shinarump itself. Hintze and Hammond (1994) describe several masses of Shinarump that slumped or slid in the Shivwits quadrangle northwest of the study area. Similar slump blocks may be present in the White Hills quadrangle. The upper contact is placed at the base of the first variegated, bentonitic shale of the Petrified Forest Member.

Petrified Forest Member (TRcp): The Petrified Forest Member of the Chinle Formation forms a well-developed strike valley where the Santa Clara River flows adjacent to the more resistant cliffs of the Shinarump Conglomerate in the northeast corner of the quadrangle. It is well exposed only where it is protected from erosion by stream terraces (figure 13). It consists of light-brownish-gray to grayish-red-purple bentonitic shale and siltstone with several lenticular interbeds of pale-yellowish-brown, cross-bedded, thick-bedded, resistant sandstone up to 10 feet (3 m) thick. Shaly beds weather to a "popcorn" surface due to swelling and shrinking of bentonitic clay. Petrified wood is common. The upper contact is placed at the top of the highest purplish-gray shale and below reddish-brown siltstone of the Dinosaur Canyon Member of the Moenave Formation. This contact is unconformable and represents perhaps ten million years of Late Triassic and Early Jurassic time (figure 2a). The member is 700 feet (215 m) thick as estimated from map relationships in the adjacent St. George quadrangle (Higgins and Willis, 1995).

[figure 13 near here]

Jurassic

Only one Early Jurassic formation, of Sinemurian and Pliensbachian age, is present in the quadrangle. It forms the base of the youngest second-order supercycle in the White Hills quadrangle, and was deposited after sea level dropped dramatically from somewhat higher, to 500 feet (150 m) lower, than current sea level (figure 2a) (Vail and others, 1977). There is no evidence of a relatively small second-order base level rise commonly placed by sequence stratigraphers in the Late Triassic to earliest Jurassic in the Whita Hills quadrangle because Hettangian age rocks are not present (figure 2a).

These Early Jurassic rocks also represent a third-order sequence comprised of the three members of the Moenave Formation. The Dinosaur Canyon Member is the transgressive systems tract, the Whitmore Point Member represents the maximum flooding stage, and the Springdale Sandstone Member, just off of the northeastern corner of the quadrangle, comprises the highstand systems tract.

Moenave Formation

Miller and others (1989) assigned this formation to the Lower Jurassic rather than the Upper Triassic largely because of the presence of fish scales from the holostean fish, *Semionotus kanabensis* (Hamilton, 1984), and because of Jurassic palynomorphs found in the Moenave Formation of northern Arizona (Olsen and Galton, 1977). Dinosaur footprints in Warner Valley, just east of the study area, indicate a relatively advanced stage of dinosaur development, which also suggests an Early Jurassic age (Miller and others, 1989) although no dinosaur footprints have been found within the White Hills quadrangle. This formation is divided into three members. The lower Dinosaur Canyon and Whitmore Point Members are Sinemurian in age whereas the upper Springdale Sandstone Member, which is exposed off the northeast corner of the quadrangle, is lower Pliensbachian. The exposed thickness of the two lower members is about 300 feet (91 m) thick in the extreme northeastern corner of the quadrangle.

Dinosaur Canyon Member (Jmd): The Dinosaur Canyon Member is exposed in the northeast corner of the quadrangle only where it is protected from erosion by stream terraces and in the drainages associated with the Santa Clara River. It is comprised of interbedded ledge- and slope-forming, moderate-red-brown siltstone and very fine-grained, thin-bedded, pale-reddish-brown to grayish-red sandstone with laminated cross-beds. The upper contact is conformable and is placed between the highest, reddish-brown sandstone of the Dinosaur Canyon Member and the pale-red-purple to greenish-gray claystone of the Whitmore Point Member. The measured thickness of the member in the St. George quadrangle to the east is 250 feet (76 m) (Higgins and Willis, 1995).

Whitmore Point Member (Jmw): This member is poorly exposed in the northeastern corner of the quadrangle and only in two vacant lots that are slated for construction. It is composed of pale-red-purple to greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone. Several 2- to 6-inch-thick (0.05-0.15-m-) beds of light-greenish-gray, dolomitic limestone contain algal structures and fossil fish scales of *Semionotus kanabensis* (Hamilton, 1984). In the St. George quadrangle, just east of the study area, this member is 55 feet (17 m) thick (Higgins and Willis, 1995).

Quaternary and Tertiary

Basalt Flow

Although several different basaltic lava flows cap prominent mesas in the vicinity, only the youngest of these flows is present in the White Hills quadrangle. The flows erupted from volcanic vents north of the quadrangle and flowed southward along tributary streams of the Virgin River (Hamblin, 1963; Willis and Higgins, 1995). Due to regional uplift of the area, downcutting of the streams along the sides of the resistant basalt flows creates "inverted" valleys (Hamblin, 1970a, 1987; Hamblin and others, 1981). The oldest inverted valleys are now at the highest elevations above present drainages. Since downcutting has been the dominant geomorphic process during the late Cenozoic, the relative height above drainages provides a way of estimating relative age of the flows, and, coupled with radiometric dating, allows determination of a downcutting rate for the area. Hamblin and others (1981) calculated a downcutting rate of 300 feet (91 m) per million years for this structural block. Not all data is consistent for the area, however, since Hintze and Hammond dated the Gunlock lava flow, which is also about 300 feet (91 m) above current drainages, at 1.6±0.1 Ma (1994). Hamblin (1970a, 1987, and unpublished mapping) mapped flows in the region as stages I to IV, based on the amount of inversion and erosion of the basalts (stage IV are very young flows with little or no inversion, whereas stage I are high remnants that bear no apparent relation to the present topography). Hamblin (1963, 1970a), Best and others (1966), Lowder (1973), Best and Brimhall (1970, 1974), Best and others (1980), Hamblin and others (1981), and Hamblin (1987) described the flows. Best and Brimhall (1974) and Best and others (1980) discussed the petrogenesis and tectonic setting of the flows.

Santa Clara lava flow (Qbs): The Santa Clara flow, which is the youngest flow in the St. George basin, erupted from two cinder cones at the upper reaches of Snow Canyon along Highway 18 north of the quadrangle (Willis and Higgins, 1996). The lava flowed westward through a pass in a sandstone ridge and then spread out and cascaded into Snow Canyon through several gaps and open joints in the sandstone, creating the popular scenery of Snow Canyon State Park with the striking contrast of black lava draped over reddish-orange and white sandstone. The various lobes rejoined to form one main flow in the lower part of the canyon, and then spread out in a large flat area and continued to flow south. The distal end of the flow extends almost one mile (1.6 km) onto the northeast corner of the White Hills quagrangle.

The Santa Clara flow is composed of subalkaline basalt and has a distinctly higher iron content than other flows in the area (Willis and Higgins, 1996). It consists of dark-brownish-black to black aa lava with a very jagged upper surface. A few poorly developed lava tubes, some collapsed, are locally present, although none are known within the White Hills quadrangle. Within the quadrangle, the flow is typically 10 to 30 feet (3-9 m) thick, but it thickens to as much as 60 feet (18 m) where it fills washes and gullies farther north.

The Santa Clara flow has not been radiometrically dated. Hamblin (1963, 1987) estimated it as slightly more than 1,000 years old However, Willis and Higgins (1996) estimate an age between 10,000 and 20,000 years old based on the lack of an irridescent sheen typical of younger flows, the development of pedogenic carbonate that coats joints in some roadcuts (Machette, 1985; Birkeland and others, 1991), and a height of several feet of the flow base above the Santa Clara River. Stream deposited sediment is exposed beneath the flow, but it is not a mappable unit.

Alluvial Deposits

Older alluvial deposits (Qao): Remnants of older alluvial deposits mapped as Qao are locally derived and found associated with minor drainages. These moderately sorted clay- to gravel-sized deposits are currently 10 to 30 feet (3-10 m) higher than, and are dissected by, incised minor drainages. They are 0 to 10 feet (0-3 m) thick.

Older stream-terrace deposits (Qato): Older stream-terrace deposits are composed of gravel- to cobble-size clasts in a muddy to coarse sand matrix. They form small, isolated outcrops of poorly sorted, indurated conglomerate that cannot be directly correlated to the current major drainage pattern and thus not to Qat_2-Qat_6. They are 20 to 50 feet (6-15 m) higher than current drainages and 0 to 20 feet (0-6 m) thick.

Stream-terrace deposits (Qat_2-Qat_6, $QTat_7$): Gravel- to cobble-size clasts in a muddy to coarse sand matrix form a poorly sorted, indurated conglomerate at several levels above the present floodplains of the Santa Clara River, Virgin River, and Cove Wash. The clasts are well-rounded and many are exotic to the quadrangle, indicating a source several miles upstream. Most terraces have a thick pedogenic carbonate (caliche) with up to a Stage VI carbonate development (Birkeland and others, 1991). The deposits correlate with paleo-channels of modern rivers and streams, unlike Qao and Qato. The terrace gravels are combined into six groups for mapping that denote relative ages and relative heights above the current drainage. Level 2 deposits are 10 to 30 feet (3-9 m) above the present drainage; level 3 deposits are 30 to 90 feet (9-27 m); level 4 deposits are 90 to 140 feet (27-42 m); level 5 deposits are 140 to 190 feet (42-57 m); level 6 deposits are 190 to 270 feet (57-82 m); and level 7 deposits are 270 to 350 feet (82-106 m) above present channels, making them Tertiary-Quaternary in age. The ages of the terraces (correlation diagram plate 2) are estimated using a downcutting rate of approximately 300 feet (91 m) per 1.6 million years, as determined from the Gunlock lava flow which is four miles (2.5 km) north of the quadrangle (Hintze and Hammond, 1994). These stream terrace deposits are from 0 to about 40 feet (0-12 m).

Terraces are most extensive near the Santa Clara River. The river is in a strike valley developed on a resistant Shinarump Conglomerate dip slope and cut into the non-resistant Petrified Forest Member (figure 13). As the river cut down, it consistently shifted northeast, cutting the softer unit and leaving terrace deposits on the southwest side of the river. In contrast, the Virgin River has meandered back and forth near its present channel, cutting away many older terraces, but leaving several high on the walls of the Virgin River Gorge. Cottonwood and Curly Hollow Washes have both eroded down the resistent dip slope of the Virgin Limestone Member of the Moenkopi Formation and meandered back and forth near their present channels in the middle red member, sometimes resulting in the removal of an intermediate terrace level. Thus, in several places on the map, Qat_3 and Qat_4 are up against Qat_1 or Qac and Qat_4 is sometimes adjacent to Qat_2 or Qac.

Alluvial-stream deposits (Qal_1-Qal_2): Moderately to well-sorted clay to small gravel deposits are mapped in large active drainages, including the Virgin and Santa Clara Rivers, and Curly Hollow and Cove Washes. Qal_1 includes deposits in, and bench deposits up to 10 feet (3 m) above, current channels and is 0 to 10 feet (0-3 m) thick. Qal_2 deposits are adjacent to and dissected by drainages containing Qal_1 deposits and are up to 30 feet (9 m) above active channels. They are 0 to 20 feet (0-6 m) thick.

Even though both Qal_2 and Qat_2 are the same elevation above current drainages, Qat_2 is coarser grained, associated with usually dry washes, more locally derived, and not as well sorted as Qal_2 deposits, which are left as terraces along perennial drainages.

Colluvial Deposits (Qc)

Colluvium covers many moderate slopes within the quadrangle but has only been mapped where it covers large areas of bedrock. It consists of poorly sorted, angular to rounded blocks up to a few feet in diameter in a muddy to sandy matrix. The colluvium is deposited by sheet wash and slope creep processes. It is gradational with, and locally includes talus, debris flow and alluvial deposits. Deposits are 0 to 20 feet (0-6 m) thick.

Mass-Movement Deposits

Old landslide deposits (QTms): Extremely poorly sorted, boulder- to clay-size, chaotic debris with angular blocks up to 30 feet (9 m) in diameter caps several knolls of the Shnabkaib Member of the Moenkopi Formation in the northwest corner of the quadrangle. These deposits are more than 400 feet (120 m) above nearby washes (figure 14). The blocks were derived from the Shinarump Conglomerate Member of the Chinle Formation. The nearest Shinarump Conglomerate outcrop is located about 0.5 miles (0.8 km) to the southeast, and at a lower elevation. Apparently these blocks slid from, and are the final remnants of, Shinarump Conglomerate outcrops once exposed to the west.

[figure 14 near here]

Hammond (1991) and Hintze and Hammond (1994) mapped the continuation of these outcrops 20 to 80 feet (6-24 m) thick in quadrangles to the west and northwest as old, high-level, alluvial gravel, however, Hintze (personal communication, April 16, 1997) agreed that they are more fittingly described as chaotic landslide deposits rather than bedded alluvial deposits.

Talus deposits (Qmt): Talus deposits are very poorly sorted, angular boulders with minor fine-grained interstitial sediments that have accumulated on and at the base of steep slopes. Most talus deposits consist of blocks of the Shinarump Conglomerate Member of the Chinle Formation that accumulate on the upper red member of the Moenkopi Formation, and blocks from the Virgin Limestone Member that rest on the lower red member. Only large deposits were mapped, but talus boulders are common on and at the base of all steep slopes in the quadrangle. Thickness varies from 0 to 10 feet (0-3 m).

Mixed-Environment Deposits

Mixed alluvial and eolian deposits (Qae, Qaeo): These deposits are moderately to well-sorted, clay- to sand-size sediment of alluvial origin that locally include abundant eolian sand and minor gravel. They are similar in composition, but Qaeo deposits are older and have a better developed pedogenic carbonate (caliche) horizon. They are mapped in the northeast corner of the quadrangle as they continue for a short distance from the St. George and Santa Clara quadrangles where they form broad, sloping benches dissected by current drainages north of the Santa Clara River. The deposits are typically 0 to 30 feet (0-9 m) thick, but locally may be thicker.

Mixed alluvial and colluvial deposits (Qac): Poorly to moderately sorted clay- to boulder-size sediment is mapped in minor drainages throughout the quadrangle. The alluvial deposits are transported along washes during heavy rainstorms while colluvial material is derived from side slopes along the washes. These deposits are gradational with colluvial deposits and include level 1 and 2 alluvial deposits (Qal_1, Qal_2) too small to map separately. They vary in thickness from 0 to 10 feet (0-3 m).

Gypcrete and alluvial gravel (Qsg): Gypsiferous silt and clay and local gypsum, collectively referred to as gypcrete, caps a sloping irregular surface cut across the Shnabkaib and upper red members of the Moenkopi Formation at the mouth of Box Canyon in the northeast quarter of the quadrangle. The gypcrete is pale-gray to pinkish-gray, punky, and forms a resistant bed up to five feet (1.5 m) thick. The basal part locally includes poorly- to moderately-stratified, moderately-sorted, lenticular channel deposits of silt- to small boulder-size sediment. It is similar in appearance to a thick pedogenic carbonate (caliche) soil layer. The qypcrete was probably eroded from the Shnabkaib Member of the Moenkopi Formation, which contains abundant gypsum. Additional deposits of gypcrete have developed on the Shnabkaib itself, but are difficult to map as a separate unit.

STRUCTURE

Regional setting

The White Hills quadrangle, a part of the St. George Basin, lies in the transition zone between the Colorado Plateau and the Basin and Range Provinces and contains structural elements of both (Hamblin, 1970b; Hintze, 1986a). The transition zone is also part of the active southern segment of the Intermountain Seismic Belt, which coincides with the boundary between relatively thin crust and lithosphere of the Basin and Range Province and thicker more stable crust of the Colorado Plateau Province (Arabasz and Julander, 1986). The zone consists of a series of north trending, down-to-the-west normal faults that step down from the Colorado Plateau into the Basin and Range Province. The intermediate-level fault block that includes the quadrangle is offset on its eastern edge 6,000 to 8,000 feet (1,830-2,440 m) by the Hurricane fault (Hamblin, 1970b), and is bounded on the west by the Grand Wash and Gunlock faults (figure 1). The Gunlock fault attains a maximum stratigraphic displacement of about 3,000 feet (917 m) near Gunlock and the Grand Wash fault has a displacement of about 1,500 feet (457 m) near the Utah-Arizona border (Hintze, 1986a).

The transition zone coincides with the leading edge of the Late Cretaceous Sevier orogenic thrust belt, which includes folds and minor detachments in front of the main thrust belt. A basal detachment is postulated in underlying Cambrian strata Spencer J. Reber, personal communication, 1994). The regional dip is to the northeast at 5 to 10 degrees, although the rocks have been compressed into the broad north-northeast trending St. George syncline and the much tighter Virgin anticline, which includes the Bloomington, Washington, and Harrisburg domes

Folds

St. George Syncline

Strata in the White Hills quadrangle dip an average of seven degrees to the northeast on the west flank of a north-northeast plunging, very broad, poorly defined syncline that Cordova (1978) called the St. George syncline. (It is called the Pine Valley Mountain syncline in some publications--for example Hintze, 1986a.) The fold axis is poorly constrained but lies just east of the study area in the St. George quadrangle and trends roughly north-northeastward (Higgins and Willis, 1995). Erosion results in a series of impressive cuestas and strike valleys.

Collapse Structures

In addition to the seven degree dip to the northeast, rocks in the quadrangle are locally contorted by the dissolution of gypsum and folded in to small circluar basins and linear synclines by breccia pipes. Many surface irregularities are due mostly to the dissolution of gypsum and gypsiferous siltstone, however, some may be collapse-formed breccia pipes originating from dissolution of the deeply buried Mississippian Redwall Limestone (Wenrich and Huntoon, 1989). Charles D. Snow and Daniel H. Clark propose that breccia pipe development began during Mississippian time and has been a more or less continuous process (personal communication, April 16, 1997 and June 19, 1997). That proposal is apparently supported in the White Hills quadrangle by the probable thickening of beds in the lower members of the Moenkopi Formation over these features (figure 6). Simple collapse structures are much younger features.

Currently, drilling seems to be the best way to determine whether breccia pipes exist at depth. They cannot with confidence be differientiated by their surface expression from shallow collapse structures caused by the dissolution of gypsum. Additionally, some deep-seated breccia pipes are known to be overlain by collapse features related to solution of gypsum (Wenrich and others, 1986). Deep-seated collpase structures are potential hosts for economic deposits of copper and uranium oxide minerals, whereas shallow structures are unlikely to be mineralized (Wenrich, 1985). None of these collapse features in the quadrangle have been drilled.

On the map, circular collapse features are marked with a dot and "C". They are commonly connected by linear synclinal features, shown on the map with syncline symbols. Although the small synclines are mapped only in the upper portion of the Harrisburg Member of the Kaibab Formation, through the Virgin Limestone Member of the Moenkopi Formation, and occassionally into the middle red member, they are probably more extensive but are difficult to trace in the gypsum beds of the lower Harrisburg and the Shnabkaib Member of the Moenkopi Formation. Additional collapse symbols are shown in alluvial terrace sediments next to the Virgin River (figure 15). It is not known if these, too, are associated with breccia pipe collapse features or simply related to river processes such as sediment sapping and piping.

[figure 15 near here]

Faults

High-Angle Faults

Even though the major north-south trending Grand Wash Fault is only about a mile (1.6 km) west of the White Hills quadrangle, only a few high-angle normal faults were mapped within the quadrangle. These small faults have just a few feet of displacement. They are associated with folding and collapse caused by the solution of gypsum and thus are considered surface structures rather than deep-seated faults.

Joints

All competent bedrock units in the quadrangle are fractured, but the most prominent joints are in the massive limestone beds of the Fossil Mountain Member of the Kaibab Formation where jointing, along with dissolution of limestone along the joints, has formed Bloomington Caves. The joints generally trend northwest in broad swatches and are usually parallel, high-angle, and open. In a few areas these joints form a conjugate set with northeast-trending joints. Although joint spacing is uniform over large areas, the pattern in the rock is not very prominent, even on aerial photographs, except in outcrops of the Shinarump Conglomerate Member of the Chinle Formation. Since joints are generally not healed or recemented and are differentially weathered in many areas, they form straight, narrow gaps in the rock a few inches to several feet wide and locally more than 50 feet (15 m) deep.

ECONOMIC GEOLOGY

A variety of geologic resources have been utilitized from the White Hills quadrangle. Gravel, sand, road fill, and riprap are currently in high demand because of rapid growth in the area. Stone has been quarried for ornamental uses, and numerous gypsum claims have been made. No metallic resources are known in the quadrangle, but some of the collapse structures may be deep-seated and would, therefore, be potential hosts for economic deposits of copper and uranium oxide minerals (Wenrich, 1985). Apex Mine, which is about two miles (3.2 km) west of the quadrangle, is in a somewhat similar setting (Bernstein, 1986).

Gravel, Roadfill, Riprap, and Sand

Gravel, essential for construction, is the most important resource in the quadrangle. The primary deposits in the quadrangle are near the Santa Clara River, Cove Wash, and Atkinville Wash. Small deposits are present along the Virgin River and along Curly Hollow Wash. Many gravel deposits are cemented with thick pedogenic carbonate (caliche). Most active pits are in the lower terrace deposits (Qat_3), which contain less carbonate.

Several large terrace remnants (Qat_3-Qat_5) are present on the Chinle Formation dip-slope south of the Santa Clara River and along Cove Wash in the northeast corner of the quadrangle, and a few large pits have been excavated in the deposits. The gravel has less silt and clay than most other deposits in the quadrangle but it is also older, as evidenced by its higher level and, therefore, is strongly cemented with pedogenic carbonate. Several deposits north of the river have been covered by recent construction and are no longer accessible.

Several terrace-gravel deposits were mapped along the Virgin River, but they are smaller than the Santa Clara terraces because the meandering Virgin River removed most older deposits. The remaining older deposits are now high above the current river channel and are well cemented by pedogenic carbonate (caliche). Some of the younger deposits have been utilitized locally, such as at the site of the Water Reclamation Facility next to the river along the east edge of the quadrangle.

Some gravel is present along Atkinville Wash in the southeastern part of the quadrangle. There are some gravel pits further south along the wash, however, in that area the deposits are typically less than 10 feet (3 m) thick. The gravel contains a large percentage of silt and clay compared to the river terrace gravels, but has less pedogenic carbonate cement. It requires extensive screening and washing for most uses.

Gravel deposits along Curly Hollow Wash also have a high percentage of fine-grained sediment similar to those of Atkinville Wash. They are used only locally to maintain and repair gravel roads.

Roadfill has been acquired from the previously described gravel locations. A few other small excavations for limited uses are scattered through other parts of the quadrangle. Large boulders from basalt and Shinarump Conglomerate talus are used as riprap along the rivers and washes. A few small pits have been opened adjacent to the basalt-capped ridge. However, like the gravel, many of these sources are being blocked by construction. Sand for local uses has been obtained from Virgin River deposits (Qal_2) near the eastern edge of the quadrangle.

Building Stone

Sandstones within the Petrified Forest Member of the Chile Formation are quarried locally from sites associated with home and golf course construction. This flagstone and crushed stone is also used locally for landscaping and retaining walls. Large rock-fall blocks of Shinarump Conglomerate Member of the Chinle Formation and those excavated during construction of homes on hillsides are reused to build retaining walls.

Ornamental Stone

Petrified wood from the Petrified Forest Member of the Chinle Formation is used to construct monuments, decorate rock gardens and fireplace mantles, and to sell as curiosities in gift shops. "Picture rock" or "landscape stone" (Bugden, 1993) from the sandstone beds within the Shinarump Conglomerate Member of the Chinle Formation is polished into spheres, coasters, and clock bases, and is cut into slabs that are mounted in picture frames. Currently, there are no active quarries for this stone within the quadrangle, but several outcrops of picture rock exist. Picture rock is well-cemented sandstone with extensive liesegang banding that imparts alternating light-brown, dark-brown, and orangish-brown swirls, bands, and other patterns in the rock. In cut pieces, these complexly intertwined bands resemble landscape silhouettes.

Gypsum

Numerous exploratory sites for gypsum occur in the Harrisburg Member of the Kaibab Formation, however, none of the sites have been quarried. The gypsum is pale gray to white with bands of clay and limestone. Thicknesses vary due to secondary flowage, but outcrops are typically 10 to 30 feet (3-9 m) thick. The Shnabkaib Member of the Moenkopi Formation also has bedded gypsum, but beds are thin and contain abundant claystone and sandstone interbeds.

Metals

No metal mines or mineralization are known in the White Hills quadrangle, although the currently inactive Apex Mine, which historically produced copper, lead and silver, but more recently germianium and gallium, is about two miles (3.2 km) from the west-central edge of the quadrangle (Bernstein, 1986). However, there are several collapse structures which could be deep-seated and, therefore, potential hosts for economic deposits of copper and uranium minerals (Wenrich, 1985). Those that originate in the deeply buried Mississippian Redwall Limestone provide the proper lithotectonic setting for such minerialization to have occurred (Wenrich and Sutphin, 1989). Currently, the best way to determine mineralization is by drilling, since deep-seated structures cannot be distinguished from shallow collapse structures by their surface appearance (Wenrich and Huntoon, 1989). Additionally, some deep-seated breccia pipes are known to be overlain by gypsum collapse features (Wenrich and others, 1986). None of the collapse structures in the White Hills quadrangle have been drilled.

Oil and Natural Gas

There has been no exploration for, or production of, oil or gas in the White Hills quadrangle. The nearest exploration was just to the east along the Virgin Anticline in the St. George quadrangle (Higgins and Willis, 1995), and the nearest production was from the Virgin oil field, 25 miles (40 km) northeast of the quadrangle, adjacent to Zion National Park. Production at the Virgin oil field through 1963 was 195,000 barrels (31,000 m^3) of oil from 30 wells (Eppinger and others, 1990). The oil was derived from a sandstone and vuggy limestone interval 1 to 8 feet (0.3-2.4 m) thick in the uppermost part of the Timpoweap Member of the Triassic Moenkopi Formation, with minor production from the Pennsylvanian Callville Limestone (Heylmun, 1993). The field lies in a small synclinal pocket near the axis of a broad, low-relief anticline that plunges gently northward. After erosion caused the reservoir pressure to dissipate, the oil drained into small synclinal pockets on the nose. The accumulations were also controlled by local porosity and fracturing (Heylmun, 1993). Although the Timpoweap Member crops out within the quadrangle, the thickness of the producing interval is minimal and no shows of oil or asphaltic material have been found (Eppinger and others, 1990).

A different oil or gas possibility in or near the quadrangle involves the Kaibab Formation. During the Late Permian sea-level lowstand, canyons were eroded into the Kaibab Formation and a shelf-margin wedge was deposited basinward. These coarse sediments would likely be sealed by shales of the lowstand systems tract, creating a possible stratigraphic trap.

Geothermal Resources

The quadrangle is in an area with geothermal potential (Mabey and Budding, 1985; Budding and Sommer, 1986). Quaternary basalt vents in the area, some as young as about 10,000 years old, also indicate that the area has geothermal potential. However, basalts are believed to ascend through relatively small pipes from depths of several miles and may not indicate a near surface heat source. No hot springs are known in the quadrangle, but hot springs are present within 35 miles (56 km) (Budding and Sommer, 1986).

WATER RESOURCES

Water is of great importance in the St. George area since the population is rapidly increasing and much of the valley receives less than 8 inches (20 cm) of precipitation per year (Cordova and others, 1972; Cordova, 1978; Clyde, 1987; Horrocks-Carollo Engineers, 1993; Utah Division of Water Resources, 1993). A study begun in July 1995 by the Utah Geological Survey, the Utah Division of Water Resources, and the U.S. Geological Survey Water Resources Division will study major aquifers in greater detail. Only a brief overview is given here.

Surface Water

Cordova and others (1972) and Sandberg and Sultz (1985) summarized flow data on the two main perennial streams in the quadrangle and reported on surface-water quality in the upper Virgin River basin. The Virgin River, with an average local annual flow of 145,600 acre-feet (179 hectares^3), flows diagonally across southern portion of the quadrangle. The Santa Clara River cuts across the northeast corner of the quadrangle and has an average annual flow of 14,600 acre-feet (18 hectares^3) as measured just north of the quadrangle. Both of these rivers are used extensively for agriculture and culinary water. In addition, a few washes have small spring-fed seeps that flow at the surface for short distances, some of which are collected in small reservoirs or tanks to water livestock.

Ground Water

The Virgin River controls base level in the quadrangle and the unconfined potentiometric surface slopes toward the river from both the north and the south (Cordova and others, 1972; Cordova, 1978; Clyde, 1987). Important aquifers in the quadrangle are in the Moenkopi and Chinle Formations, and in thin unconsolidated deposits (Cordova and others, 1972; Clyde, 1987). The water quality in many springs and wells in the quadrangle is reported in Cordova and others (1972), Cordova (1978), and Clyde (1987). All of the wells and springs in the quadrangle are utilized for irrigation and stock watering with the exception of one 580 foot (176 m) deep well in the northeast corner that provides 5 cubic feet per second of municipal water for the City of St. George. Several small springs with flows ranging from 0.001 to 0.014 cubic feet per second issue from the upper red, Shnabkaib, and lower red members of the Moenkopi Formation.

GEOLOGIC HAZARDS

The White Hills quadrangle is in a tectonically active area with several faults that could generate large earthquakes. The quadrangle also has many steep slopes with landslide and rock fall hazards, and it has formations that contain expansive, soluble, or compactible materials and radon-producing uranium. Flash floods and debris flows are also concerns. The St. George Community Development Department created a general plan that addresses many of these hazards, and geologic hazard maps covering particular areas of the city are available to the public through the city engineer's office, although these maps only provide coverage for the northeast corner of the White Hills quadrangle.

Earthquakes

The White Hills quadrangle is within the Intermountain Seismic Belt and the area has experienced several historic earthquakes of magnitude 4 or greater (Christenson and Deen, 1983; Anderson and Christenson, 1989; Christenson and Nava, 1992; Hecker, 1993). Historical earthquakes have not exceeded magnitude 6.5 in southwestern Utah, however geological studies indicate that faults in the region could produce earthquakes of magnitude 7 to 7.5 (Arabasz and others, 1992). The largest historical earthquake was an estimated magnitude 6.3 event in 1902 with an epicenter about 20 miles (32 km) to the north-northeast near the Pine Valley Mountains (Arabasz and others, 1979; Christenson and Deen, 1983). The most recent large earthquake was a 5.8 magnitude event on September 2, 1992 with an epicenter about 5 miles (8 km) east of St. George (Black and Christenson, 1993). Ground shaking associated with this 1992 event was strongly felt in the St. George area and caused damage as far as 95 miles (153 km) from the epicenter. Preliminary seismologic data indicate that the earthquake originated at a depth of 9 miles (15 km) and was caused by dominantly normal faulting on a north trending fault, possibly a subsurface part of the Hurricane fault (Arabasz and others, 1992). Ground acceleration could not be measured, so an empirical relationship was used to estimate peak horizontal ground acceleration (PHA) of 0.21 g for St. George (Black and others, 1992). Ground shaking probably triggered landslides that destroyed homes and utilities in Springdale and caused liquefaction in poorly graded sand along the Virgin River (Black and Christenson, 1993). It also caused a change in flow of Pah Tempe Hot Springs near Hurricane (figure 1) and triggered many rock falls, at least two of which caused property damage. No surface rupture was reported (Black and Christenson, 1993). The quadrangle is in the Uniform Building Code seismic zone 2B, an area of moderate earthquake risk with expected PHA of 0.1 to 0.2 g (International Conference of Building Officials, 1997; Christenson and Nava, 1992).

Three large fault zones in the area have documented Quaternary movement and a few smaller faults have possible Quaternary movement (Christenson and Deen, 1983;

Anderson and Christenson, 1989; Hecker, 1993). The Washington fault trends north-south about 5 miles (8 km) east of the quadrangle (figure 1). The Hurricane fault is about 20 miles (32 km) east of the quadrangle and the Grand Wash, Reef Reservoir, and Gunlock faults form a zone about 1 mile (1.6 km) west of the quadrangle (figure 1) (Hammond, 1991; Hintze and Hammond, 1994; Hintze and others, 1994).

Earthquakes generate ground shaking and related hazards such as surface rupture, slope failure, liquefaction, flooding, and tectonic subsidence (Christenson and Nava, 1992). Poorly consolidated sediment, such as the younger Quaternary surficial deposits in large parts of the quadrangle, amplifies waves that cause ground shaking, increasing damage. Flooding may result from failure of nearby dams; diversion or destruction of canals, aqueducts, water lines, or streams; increased ground-water discharge; or tectonic subsidence in areas of lakes, reservoirs, or shallow ground-water. Movement on a fault sufficient to cause surface rupture would likely damage many structures, especially older, unreinforced masonry buildings, and may rupture underground utilities. Rock falls caused by ground shaking are of increasing concern as development encroaches on steep slopes flanking resistant bedrock units.

Slope Failures

Many ridges and benches bounded by steep slopes in the quadrangle have the potential for slumps, landslides, and rock-fall hazards. The stability of natural slopes is dependent on lithology, ground-water conditions, and attitude of bedding or jointing (Christenson and Deen, 1983). The most common causes of slope destabilization include loss of support at the base of the slope because of stream erosion or excavations for construction, increasing pore pressure by adding water or increasing the load, ground shaking resulting from earthquakes. In 1992, the City of St. George enacted a hillside ordinance that affects the eastern part of the quadrangle in an effort to reduce hazards near steep slopes and to protect the hillsides.

Slumps and Landslides

Basal detachments of slumps and landslides in the area develop primarily in the clay-rich Petrified Forest Member of the Chinle Formation, which absorbs moisture, forming a weak, pasty substance (Harty, 1992). Landslides are common adjacent to the quadrangle where the Petrified Forest Member forms bluffs held up by gravel-terrace deposits along the Santa Clara River (Christenson, 1992). The same situation exists within the quadrangle. No slide masses have been mapped but the potential for their development increases with encroaching development. Although these slopes are apparently stable, they may slump if material is removed from the base, or if additional water or fill is added by construction on top of the slide mass. Both of the recent landslides reported by Christenson (1992), which occurred in the Petrified Forest Member adjacent to the quadrangle, were the result of human activity.

Rock Falls

Significant rock falls are common in the quadrangle, as evidenced by abundant rock debris both on and at the base of steep slopes. Rocks fall naturally when less resistant rock layers are eroded from beneath more resistant, fractured caprock. They may also result from ground shaking caused by earthquakes. Human activities that artificially increase the natural slope of a hillside, introduce significant moisture to hilltops or add substantial weight to the edge of hilltops also increase the potential for rock falls.

Major rock-fall hazards involve hills capped with the Shinarump Conglomerate Member of the Chinle Formation that stretch from northwest to southeast across the northeast portion of the quadrangle. The rock is jointed in two directions making it easier for blocks to detach and roll. The Moenkopi Formation is also a candidate for rock falls, but presently there is no development at the base of these slopes.

Although a rock-fall hazard exists near the base of all slopes, site-specific investigations indicate that the local degree of hazard varies significantly and is dependent upon several variables. These include the distance of the site from the base of the slope, the nature and stability of slope debris, the local protection provided by previous rock fall blocks, and the presence of erosional gullying in the slope which may deflect falling rocks (Christenson, 1992).

Problem Soil and Rock

Several highly publicized incidents of structural damage due to problem soil and rock prompted litigation that has increased local public awareness of potential problems (Daily Spectrum newspaper, various issues from 1990 to 1997). Several local governments now require site evaluations and laboratory reports for new subdivisions. Hazards are of three types: expansive soil and rock, soluble soil and rock, and collapsible or compressible soil.

Expansive Soil and Rock

Bentonitic clay from volcanic ash in the mudstone and shale intervals of the Petrified Forest Member of the Chinle Formation is present in the northeast corner of the quadrangle. These clays, commonly known as "blue clay," swell when moistened and shrink when dried. It is responsible for most of the expansive soil and rock problems in the St. George area. In swell tests using a 60-pound-per-square-foot (psf) (293 kg/m^3) surcharge load, expansion greater than 12 percent is classified as critical. Clay from the Petrified Forest Member is highly variable but typically swells 20 percent and some samples have tested as high as 38 percent (Joel Myers, Kleinfelder, personal communication, 1995). It is classified as cH soil, or "fat clay" using an Atterburg limit with a plastic index of 7 to 30 and liquid limit of 15 to 40 (Roy J. Rushing, Delta Geotech, personal communication, 1995). Thick overburden or other measures are necessary to protect a structure from this amount of swelling.

The Shnabkaib Member, and, to a lesser degree, mudstone intervals in the Virgin Limestone Member and the three red members of the Moenkopi Formation, and the Whitmore Point Member of the Moenave Formation (Christenson and Deen, 1983) also have expansive clays. In addition, easily eroded, fine-grained soil with moderate swell potential (4 to 8 percent) is common on flat to very gentle slopes on flood plains, alluvial lowlands, and benches (Christenson and Deen, 1983).

Common signs of expansive soils are cracked foundations, heaving and cracking of floor slabs and walls, and failure of wastewater disposal systems (Mulvey, 1992). Even if engineering precautions are taken to protect the building, expansive soils can damage neglected sidewalks, roads, porches, garages, driveway and patio slabs, and underground utilities. Damage can occur quickly. Thompson (1992) found an average time lapse of two years and seven months from construction to repairs in similar settings in the Denver, Colorado area.

Soluble Soil and Rock

Soluble soil and rock, deposits that contain minerals that dissolve in water, are common in the quadrangle. These include gypsiferous deposits, limestone, and pedogenic carbonate (caliche). The Harrisburg Member of the Kaibab Formation and the Shnabkaib Member, and to a lesser degree, the red members of the Moenkopi Formation, are subject to settlement, collapse, piping, and local heaving problems due to dissolution of gypsum (Christenson and Deen, 1983).

Pedogenic carbonates developed in terrace gravel and older geomorphic surfaces impede water percolation if undisturbed. However, construction damage may fracture the seal and increase weathering leading to dissolution of gypsum or swelling of clay in underlying units (Christenson, 1992).

Collapsible and Compressible Soil

The problem of hydrocompaction occurs in geologically young material (Qac, Qae, Qc) as loose, dry, low-density deposits decrease in volume or collapse when they are saturated or loaded (Mulvey, 1992). To measure collapsibility, a sample is weighted with 1,000 pounds per square foot and then saturated with water. The percent of volume change is then calculated. Debris flows deposited at the mouth of drainages during flash floods commonly contain collapsible soils. Other low-density deposits, such as eolian silt and sand, are commonly poorly consolidated and require compaction prior to construction.

Flooding and Debris Flows

Floods from spring runoff or intense summer storms are among the most frequent and consistently destructive natural hazards in the area. Historical records show frequent serious flooding along both the Santa Clara and Virgin Rivers (Utah Division of Comprehensive Emergency Management ,1981; Christenson and Deen, 1983). Although the conditions that cause flooding are not controllable, the relative hazard they pose is generally manageable with wise planning (Lund, 1992). The City of St. George General Plan (1994) calls for development that encourages preservation of natural flood plains and discourages man-made channelization and development within the 100-year flood plain.

On March 13, 1995, an extensive flood occurred as a result of an extensive rainstorm coupled with high meltwater runoff that involved most drainages in the area. Damage was most extensive along the Virgin and Santa Clara Rivers. In one area, the Santa Clara River eroded 120 feet (36 m) into adjacent property. In another place it broke through a riprap wall protecting townhomes that were constructed only 10 feet (3 m) from the river's edge. The preliminary damage assessment by the Utah Division of Comprehensive Emergency Management (May 20, 1995) for the City of St. George was $1,184,000. The cost of damage to private property was not included.

Debris flows are masses of clay- to boulder-size materials that flow in a muddy slurry. They generally develop after a period of unusually high precipitation as colluvium and other loose deposits become saturated with water and begin to flow. They are a concern in gullies and washes and in some areas near moderate and steep slopes in many parts of the quadrangle.

Radon

Radon gas forms as a product of three different radioactive decay series, but is derived primarily from the decay of uranium-238 (Solomon, 1992a). Alpha particles emitted by atoms as they decay are the main danger. Outside the body, alpha particles pose no danger because they cannot penetrate the skin. If radon gas is inhaled, however, these particles can damage sensitive cells and may cause lung cancer (Wilbraham and others, 1990). The U.S. Environmental Protection Agency estimates that 8,000 to 40,000 Americans die each year from lung cancer caused by long-term radon inhalation (Schmidt and others, 1990).

Radon can enter homes built on soil and rock rich in uranium through porous building materials, cracks in basement floors, walls or slabs, or other openings below grade. If the home is well insulated, the gas may be trapped inside and inhaled by the occupants. Because radon gas is colorless, odorless and causes no pain when it is inhaled, most people are never aware of its presence in their homes.

Indoor-radon levels measured in the southern St. George basin during a 1988 statewide survey conducted by the Utah Division of Radiation Control (UDRC) indicated local high radon levels (Sprinkel and Solomon, 1990). A map of potential radon hazards in Utah, modified from Sprinkel (1987), shows part of the St. George area as having a general elevated indoor radon concentration of 4 to 10 pico curies per liter (pCi/L) of air (Solomon, 1992a), well above the maximum of 4 pCi/L advised by the U.S. Environmental Protection Agency and U.S. Department of Health and Human Services (1986). Above this level, hazard-reduction procedures are recommended. The average ambient outdoor level of radon is 0.2 pCi/L (Monroe and Wicander,1992).

The primary geologic prerequisite for elevated indoor-radon levels is uranium in the soil around building foundations. Solomon (1992b) measured uranium levels in the southern St. George basin using gamma-ray spectrometry and found that high uranium levels originate from three distinct sources. A local primary source where levels were highest (up to 6.7 parts per million [ppm]) is the tuffaceous, fine-grained rock and residual bentonitic soil of the Petrified Forest Member of the Chinle Formation (Solomon, 1992a). Levels were also high (up to 3.4 ppm) in granular floodplain soils of the Santa Clara and Virgin Rivers, which are derived in part from Miocene intrusive igneous rocks eroded from the Pine Valley Mountains to the north (Cook, 1957). Secondary uranium mobilization, suggested by high uranium/thorium ratios, has resulted in uranium enrichment in local areas of rock and soil.

Two important geologic factors inhibit the ability of radon to migrate into buildings: (1) shallow groundwater, since pore water effectively traps radon, and (2) impermeable soil, since there must be soil pathways through which the gas can migrate. Solomon (1992b) contoured a map of the southern St. George basin showing depth to ground water using well data from Cordova and others (1972), and a map of soil permeability using data from a soil survey made by Mortensen and others (1977). He then used a combination of all three factors: uranium concentration, ground-water level, and soil permeability, to derive a map showing the relative potential for elevated indoor-radon levels in the southern St. George basin. His map indicated the highest hazard potential occurs in the small hills underlain by the Petrified Forest Member of the Chinle Formation, in the alluvial deposits of the river flood plains, and in a few other scattered areas.

Because of the many non-geologic factors that influence indoor-radon levels, a quantitative relationship between geologic factors and indoor-radon levels does not exist. However, the relative hazard potential can be used to prioritize indoor testing, to indicate the urgency with which homeowners should reduce the potential hazard in existing buildings, and to evaluate the need for radon-resistant new construction (Solomon, 1992b).

Volcanism

Volcanic hazards in the St. George area are of two main types, ash and lava flows from local sources, and wind-blown ash and dust from distant sources (Mabey, 1985; Bugden, 1992). Only hazards from local sources are discussed here. Volcanic activity in southwest Utah during mid-Cenozoic time was violent, large volume felsic eruptions of pyroclastic material, but late Cenozoic eruptions resulted in smaller, less violent mafic cinder cones and flood basalts. The toe of the most recent basalt flow in the St. George area, the Santa Clara flow, is within the quadrangle. Luedke and Smith

(1978) indicated this flow is less than 1,000 years old. However, it is believed to be 10,000 to 20,000 years old based on amount of downcutting next to the flow and amount of weathering of the basalt (Willis and Higgins, 1996). It is likely that flows from future eruptions would follow drainages into populated areas. Hazards from future eruptions include damage and injuries by molten lava, explosively ejected cinders and volcanic gas, blockage of transportation corridors and rivers, disruption of utilities, and fires (Mabey, 1985).

SCENIC AND RECREATIONAL RESOURCES

The White Hills quadrangle is in the "red rock" country of southwestern Utah and is flanked by buttes and mesas of red sandstone. Many are capped by black basalt, creating a striking visual contrast. The quadrangle is also near the lowest elevation in the state and has the warmest climate. The combination of the striking scenery and warm climate make the area a popular recreation and retirement destination.

Although the only paved roads are in the northeast corner of the quadrangle, several gravel roads along the foothills of the Beaver Dams Mountains are popular for their vistas across the St. George basin to the towering cliffs of Zion National Park, part of the "Grand Staircase" (Gregory, 1950). These roads also are used heavily by mountain bikes, ATV's, and motorcycles, as well as other sport utility vehicles. They provide access to such recreational destinations as Bloomington Caves and the Virgin River Gorge.

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Captions

Figure 1. Geographic and geologic features and 7 1/2' quadrangles near the White Hills quadrangle. Basaltic flows are shaded.

Figure 2a. Deposition of strata in the quadrangle was strongly influenced by world wide sea-level fluctuations, and rocks correlate well with the global sequence stratigraphic framework. Of the four recognized first-order megadepositional sequences (Archeozoic, Proterozoic, Paleozoic, and Mesozoic - Cenozoic), strata in the White Hills quadrangle cover the end of the Paleozoic and the beginning of the Mesozoic - Cenozoic megasequences. Vail and others (1977) showed eight second-order supercycles during the interval represented by strata exposed in the quadrangle (onlyfive of the eight are found within the quadrangle and in figure 2a). The St. George area underwent erosion and/or sediment bypass during three of the second-order sequences, so sea-level fluctuations during the late Permian, Middle Triassic, and earliest Jurassic (shown by the sea level curve) are not documented by rock in the quadrangle. The five documented second-order cycles are divided into nine third-order cycles that reflect smaller relative changes in sea level. Systems tracts are listed for the third- and fourth-order cycles. Figure 2b shows fourth- and fifth-order sequences of part of the Moenkopi Formation. Modified from Vail and others (1977), Hintze (1993), and Dubiel (1994). Time scale from Palmer (1983). Vertical scale is based on time of deposition, not on thickness.

Figure 2b. (A) The second-order sequence of the Moenkopi Formation is divided into three third-order sequences indicating three smaller transgressive-regressive sequences. (B) Similarly, the third-order sequence of the Virgin Limestone and middle red member is divided into five fourth-order sequences with transgressive system tracts (TST) of the limestone ledges separated from the muddy siltstone interbeds of the highstand systems tract (HST) by a maximum flooding surface (MFS). (C) Each limestone ledge is itself a fifth-order parasequence. The lower portion of each ledge is finer, more muddy, and non-fossiliferous, signifying a transgressive systems tract (TST), while the upper portion is a coarser wackestone with birdseye structures and fossils, signifying a highstand systems tract (HST). The two portions are divided by one inch (2.5 cm) or less of dark-grayish-brown shale, indicative of a maximum flooding surface. Modified from Vail and others (1977), Hintze (1993), Dubiel (1994), and additional work in this project.

Figure 3. Schematic cross section modified from Billingsley (1997) showing correlation of the Permian clastic rocks from northwestern Arizona to southwestern Utah. Thicknesses are relative and approximate. Vertical dashed line marks approximate area of nomenclature change for Queantoweap and Esplanade Sandstones.

Figure 4. Photo taken toward SE 1/4 of section 30, T. 43 S., R. 16 W. looking downstream into the Virgin River Gorge from the rimrock of the Fossil Mountain Member of the Kaibab Formation, which sits unconformably on the slope-forming Woods Ranch

Member of the Toroweap Formation. Lowest cliff is the Brady Canyon Member of the Toroweap Formation.

Figure 5. Photo taken looking north across Curly Hollow Wash toward the southeast corner of section 3, T. 43 S., R. 17 W. at meander bend of a paleo-channel that removed the Harrisburg Member and significantly cut into the Fossil Mountain Member of the Kaibab Formation during the late Permian lowstand. The channel was subsequently back-filled by the Triassic Rock Canyon Conglomerate Member of the Moenkopi Formation.

Figure 6. Large collapse structure in the Harrisburg Member of the Kaibab Formation associated with a northeast-southwest linear trend that also effects the limestone ledges of the Virgin Limestone Member of the Moenkopi Formation (in the middle of the photo). Flat beds of the Rock Canyon Conglomerate Member of the Moenkopi Formation fill the trough of the collapse structure which extends to the base of the hill of Virgin Limestone ledges. Photo looking northeast across West Mountain Valley Wash toward SE 1/4 of section 13, T. 43 S., R. 17 W.

Figure 7. Excellent exposure of the Harrisburg Member of the Kaibab Formation that crops out on the east side of West Mountain Valley Wash in the southeast corner of section 13, T. 43 S., R. 17 W. Limestone ledge in the bottom of the wash is the Fossil Mountain Member, overlain by the cone-shaped hill of the lower portion of the Harrisburg Member. The cone-shaped hill is capped by the resistant limestone beds in the

Harrisburg Member. The upper portion of the Harrisburg has been eroded from the hilltop but can be seen as the rounded hills in the distance. Note the broad, yet shallow collapse structure in the middle of the left side of the photo, next to the road where the resistant ledges of the Harrisburg sag. The sag has been filled by the Rock Canyon Conglomerate Member of the Moenkopi Formation.

Figure 8 Generalized cross-section showing common rock relationships across the Permian - Triassic unconformity. Kaibab Formation: Pkf-Fossil Mountain Member, Pkh-Harrisburg Member; Moenkopi Formation: TRmr-Rock Canyon Conglomerate, TRmt-Timpoweap Member, TRml-lower red member, TRmv-Virgin Limestone.

Figure 9. Photo looking east across West Mountain Valley Wash toward the SE 1/4 of section 13, T. 43 S., R. 17 W. at the members of the Moenkopi Formation. The Rock Canyon Conglomerate Member fills a linear depression created by a channel in the Harrisburg Member of the Kaibab Formation. The Toroweap Member is not visible. A thin lower red member lies beneath the rounded, ledgy, Virgin Limestone hills in the middle ground. Just beyond the rounded hills, the middle red member lies beneath the light-colored Shnabkaib Member. Above the Shnabkaib Member is the linear ridge of the upper red member, capped by the Shinarump Member of the Chinle Formation.

Figure 10. Permian-Triassic unconformity is evident here with the hill of Permian Harrisburg Member of the Kaibab Formation left of the dirt road next to the Triassic lower red member of the Moenkopi Formation to the right. Here, the lower red member

completed filling in the paleotopography created in the Kaibab Formation by the late Permian lowstand. Note the cone-shaped remnent of lower red member sitting on top the the Harrisburg Member hill. Strata in the foreground is the Rock Canyon Conglomerate Member of the Moenkopi Formation. Photo taken looking north-northeast toward the southeast corner of section 18, T. 43 S., R. 16 W.

Figure 11. The 200 foot thick (61 m)Virgin Limestone Member of the Moenkopi Formation consists of five limestone ledges separated by interbedded siltstone, sandstone, and gypsum. Photo taken looking east across Val Wash toward the SW 1/4 of section 17, T. 43 S., R. 16 W.,

Figure 12. The contact between the upper red member of the Moenkopi Formation and the Shinarump Conglomerate Member is unconformable, as shown by the erosional surface between the two. Note the varible thickness of the Shinarump Comglomerate, which was deposited by braided streams that backfilled paleotopography. Photo taken looking south toward the NE 1/4 of section 32, T. 42 S., R. 16 W.

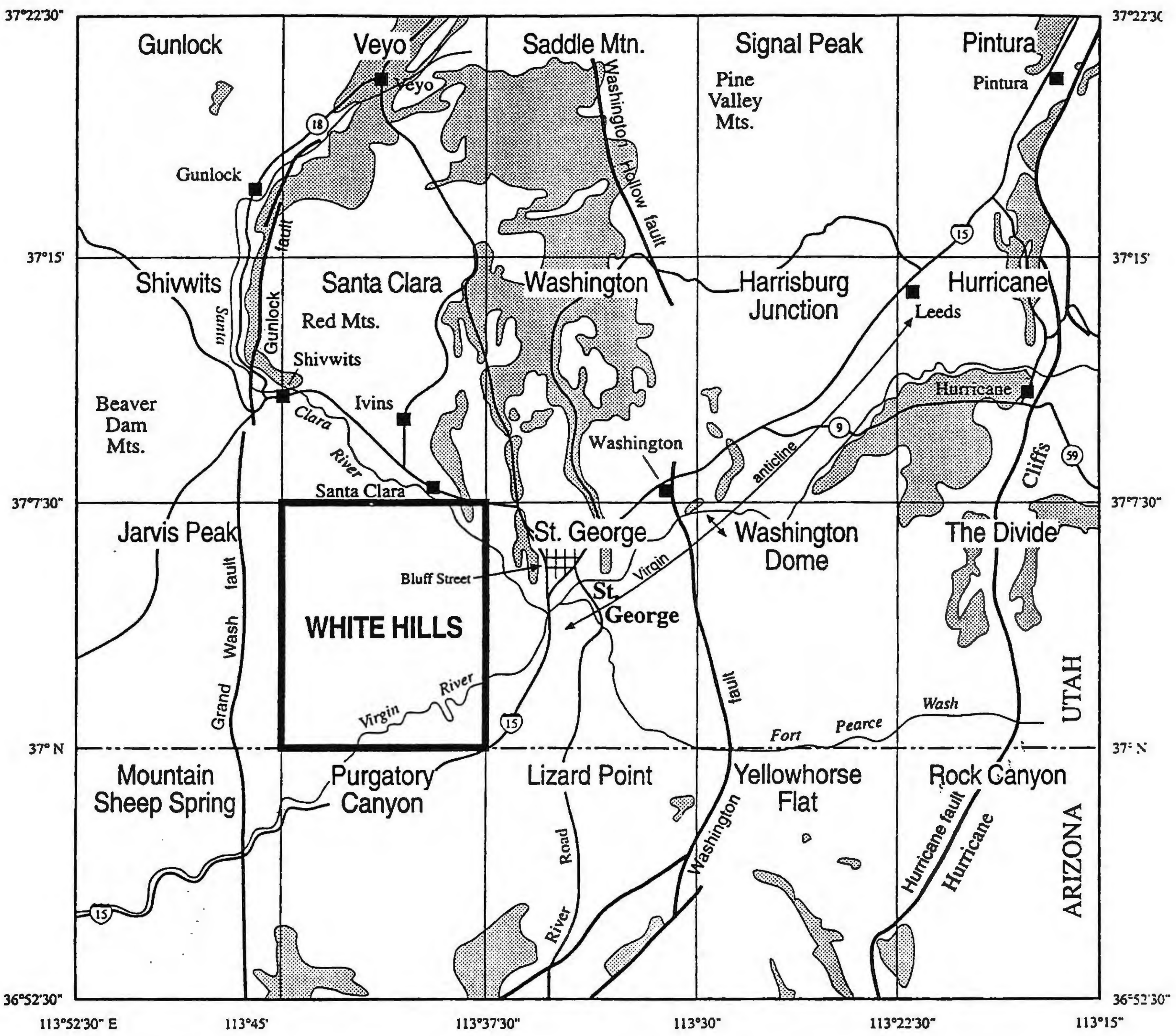
Figure 13. The Petrified Forest Member of the Chinle Formation is well exposed beneath resistant stream-terrace gravel deposited as the Santa Clara River formed a strike valley adjacent to the dip slope of the Shinarump Conglomerate Member. Note the gravel pit in the lower terrace at the right margin of the photo. Photo taken looking north across Cove Wash toward the SE1/4 of section 21, T. 42 S., R. 16 E. Note the

gently sloping lava flows that cap sandstone cliffs and the Pine Valley Mountain laccolith in the distance, north of the quadrangle.

Figure 14. On the skyline at the center of the photo, extremely poorly sorted, boulder- to clay-sized, chaotic debris with angular blocks up to 30 feet (9 m) in diameter rests on hills of the basal beds of the Shnabkaib Member of the Moenkopi Formation. They are about 400 feet (121 m) above local washes. Photo taken toward the NW 1/4 of section 22, T. 42 S., R. 17 W., in the northwest corner of the quadrangle

Figure 15 A. Collapse features in stream-terrace sediment (Qat_3) next to the Virgin River in Big Round Valley (NW1/4 of section 28, T. 43 S., R. 16 W.). The close-up shown (B) is of the feature in the left-center of the photo to the left of the dirt road.

B. This round collapse feature is approximately 80 feet (24 m) across and 60 feet (18 m) deep.


37°22'30"
37°22'30
37°15'
37°15'
37°7'30"
37°7'30"
37° N
37° N
36°52'30"
36°52'30"
113°52'30" E
113°45'
113°37'30"
113°30'
113°22'30"
113°15'
Gunlock
Veyo
Saddle Mtn.
Signal Peak
Pintura
Veyo
18
Washington Hollow fault
Pine Valley Mts.
Pintura
Gunlock
Gunlock fault
15
Shivwits
Santa Clara
Washington
Harrisburg Junction
Hurricane
Santa
Red Mts.
Leeds
Shivwits
Beaver Dam Mts.
Clara
Ivins
Hurricane
River
Washington
9
anticline
59
Cliffs
Santa Clara
Jarvis Peak
St. George
Washington Dome
The Divide
Bluff Street
Virgin
St. George
Grand Wash fault
WHITE HILLS
Virgin River
15
fault
Fort Pearce Wash
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Purgatory Canyon
Lizard Point
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Rock Canyon
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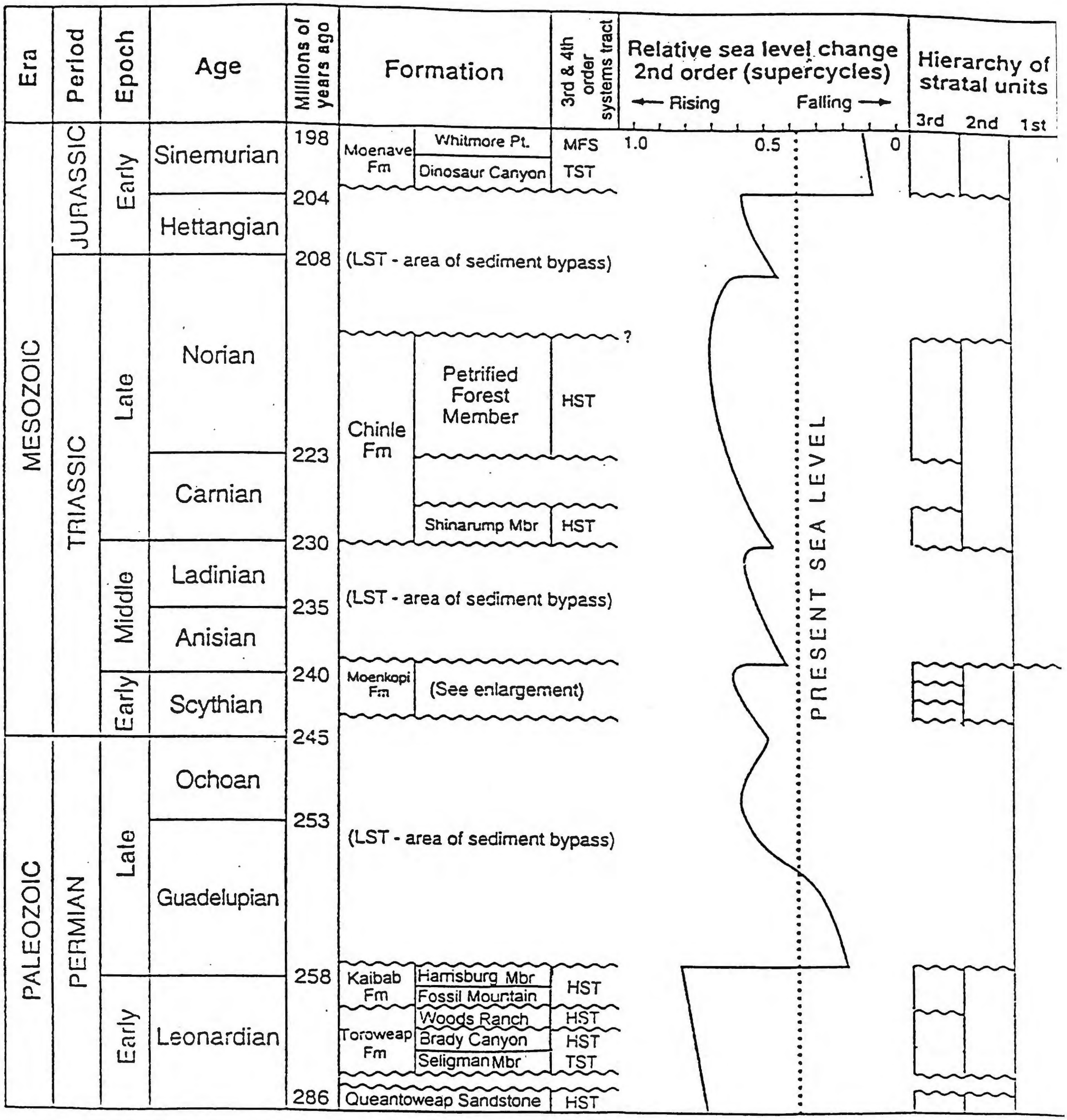
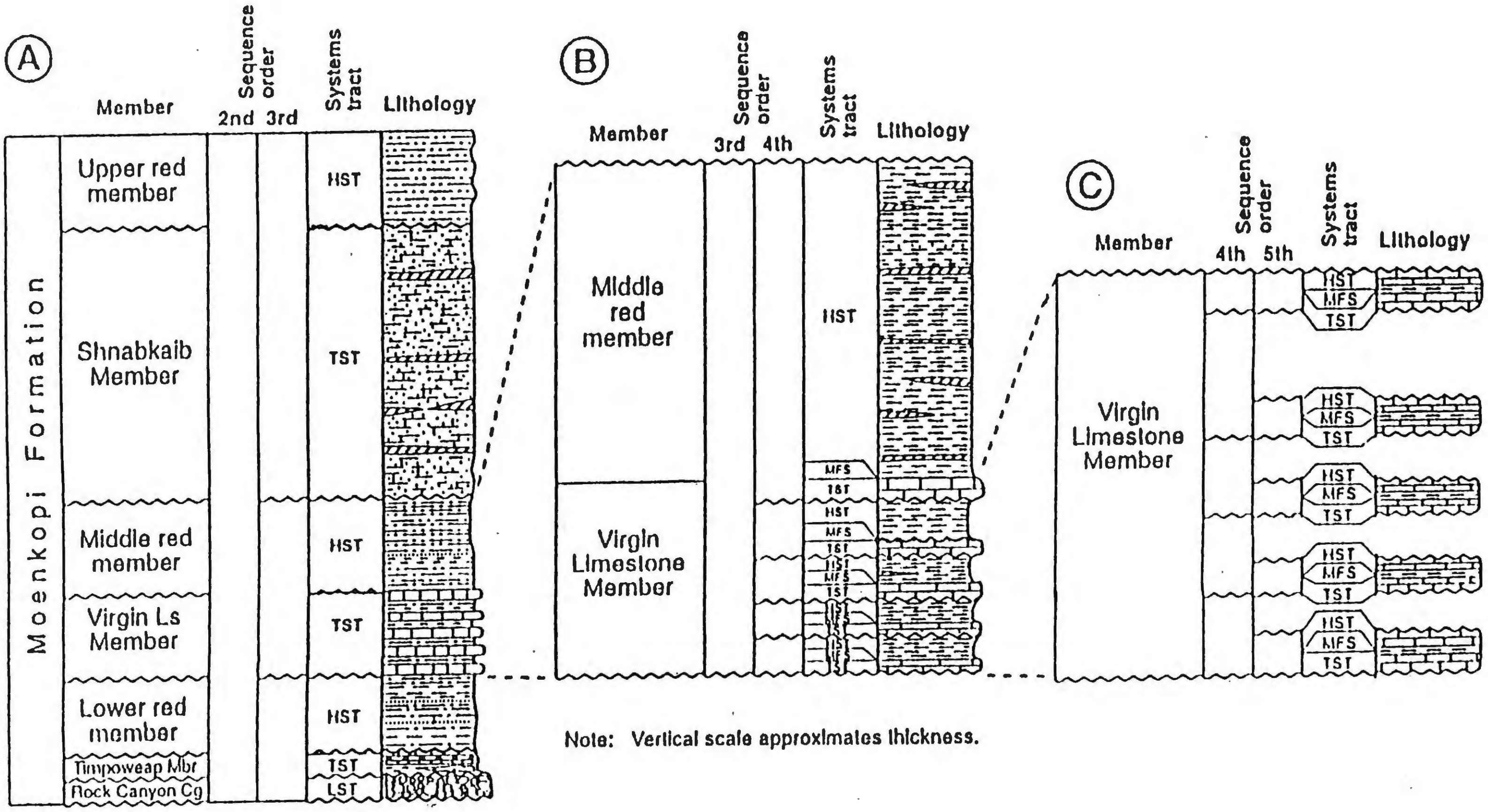
Road
Hurricane fault
Hurricane
ARIZONA
River
15



HST = highstand systems tract. MFS = maximum flooding stage. TST = transgressive systems tract. LST = lowstand systems tract.

Figure 2a



Note: Vertical scale approximates thickness.

Figure 2b

Higgins, 1997

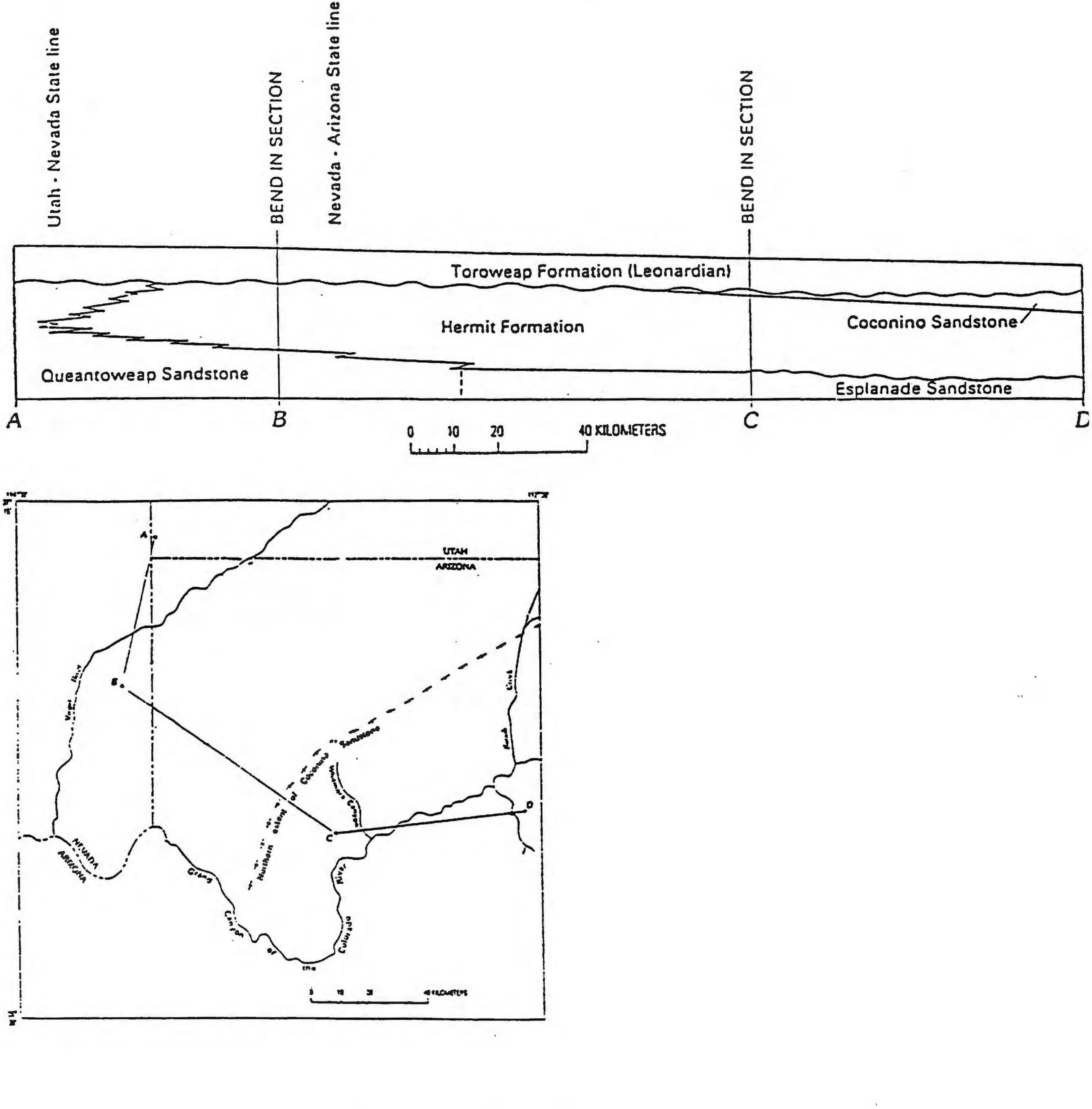

Utah - Nevada State line
BEND IN SECTION
Nevada - Arizona State line
BEND IN SECTION
Toroweap Formation (Leonardian)
Hermit Formation
Coconino Sandstone
Queantoweap Sandstone
Esplanade Sandstone
A
B
C
D
0 10 20 40 KILOMETERS
A
B
C
D
UTAH
ARIZONA
NEVADA
ARIZONA
Virgin River
Grand Canyon of the Colorado River
Northern extent of Coconino Sandstone
Kanab Creek
Wash
0 10 20 40 KILOMETERS

Figure 3

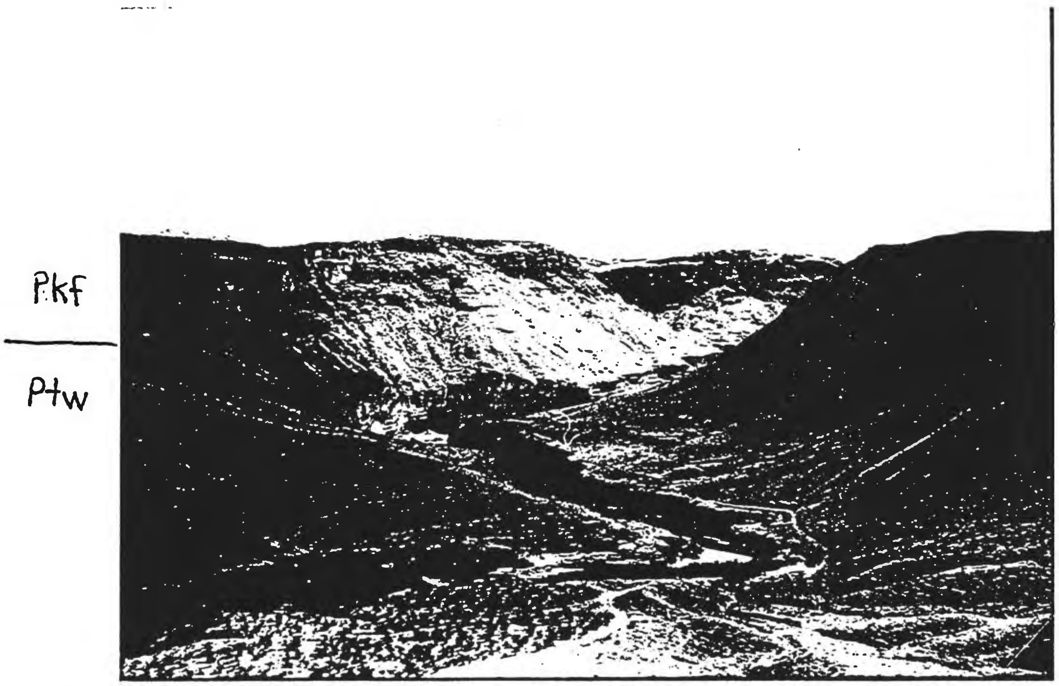


Figure 4

Figure 5

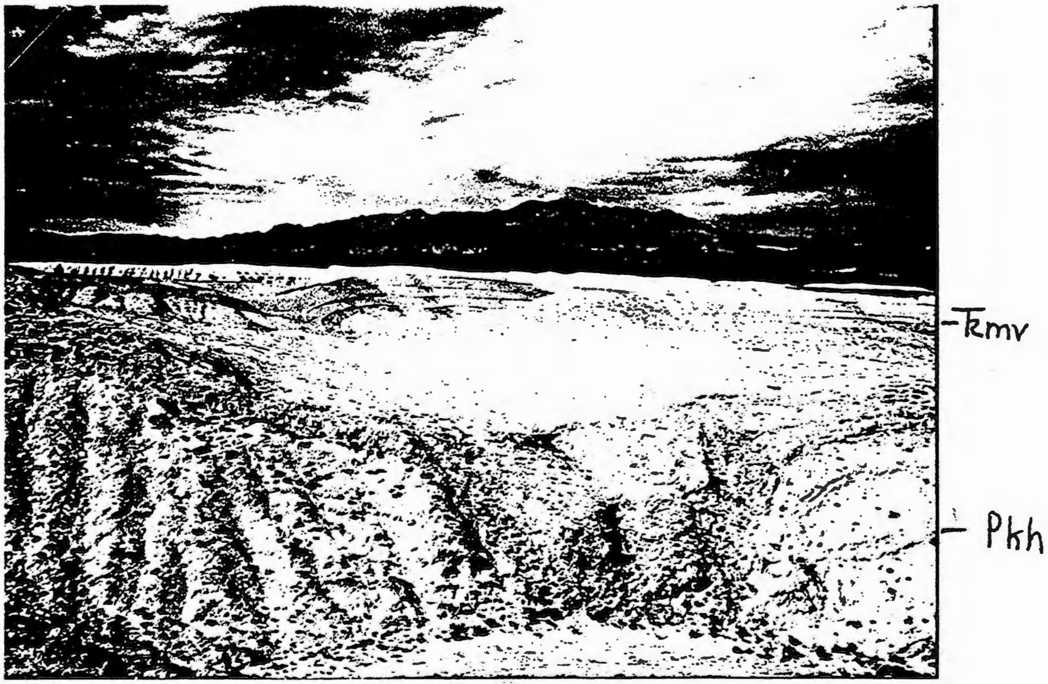


Figure 6

Figure 7

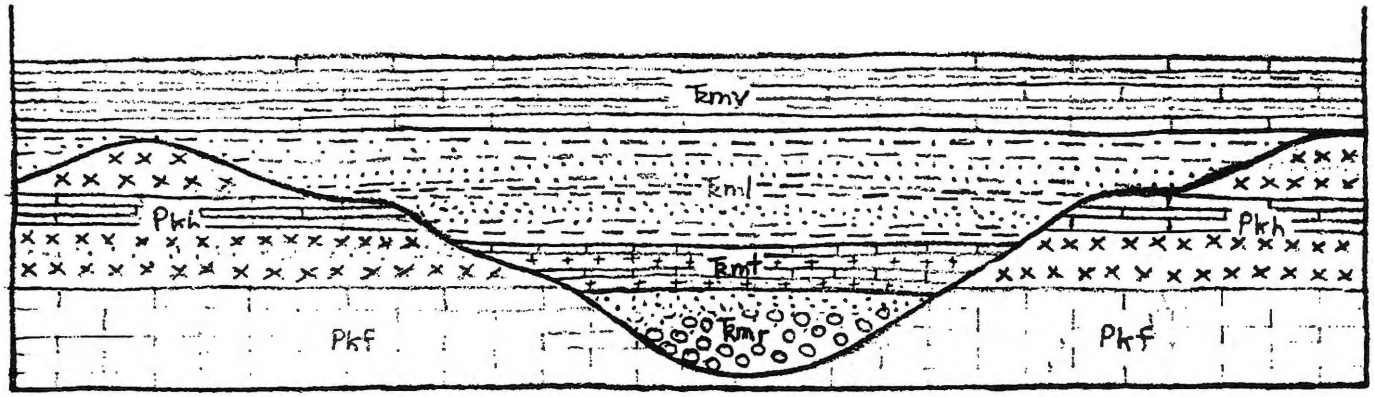


Figure 8

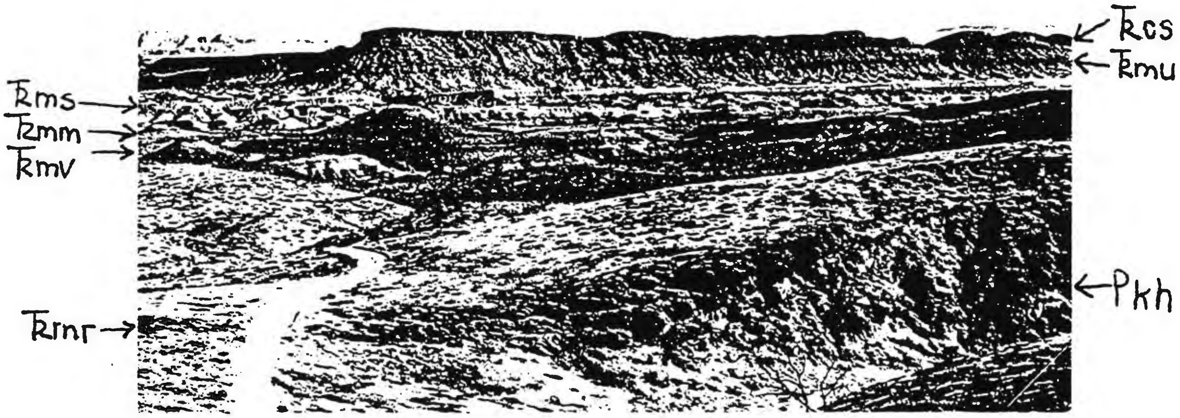


Figure 9

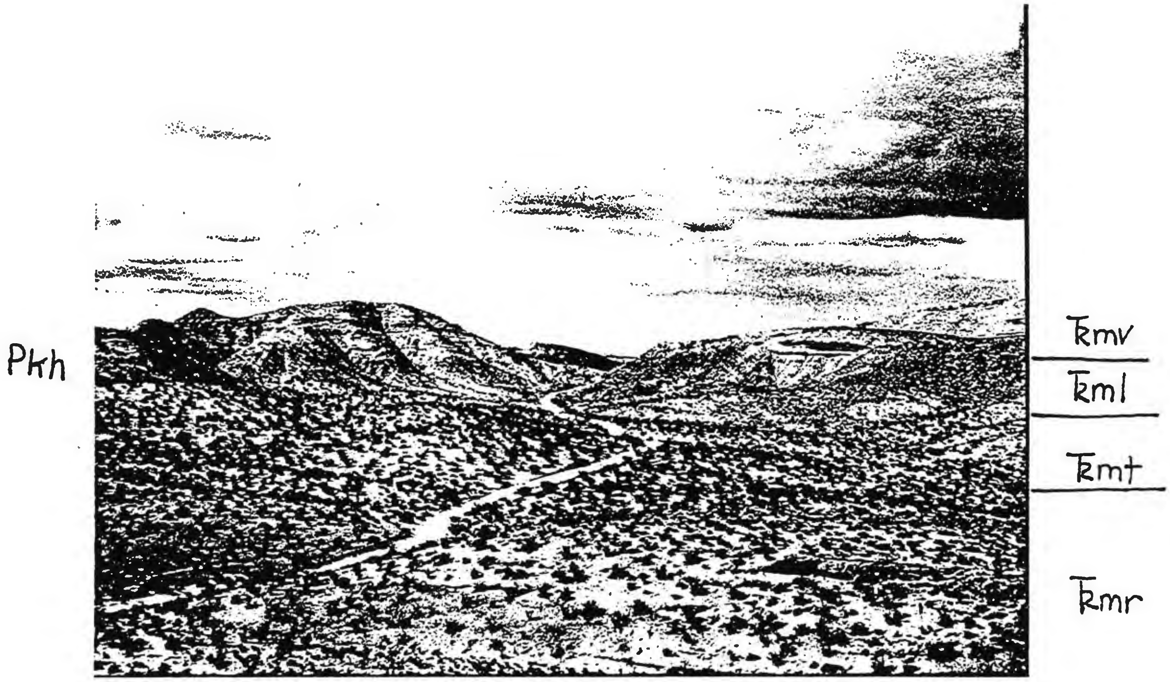


Figure 10

Figure 11

Figure 12

Figure 13

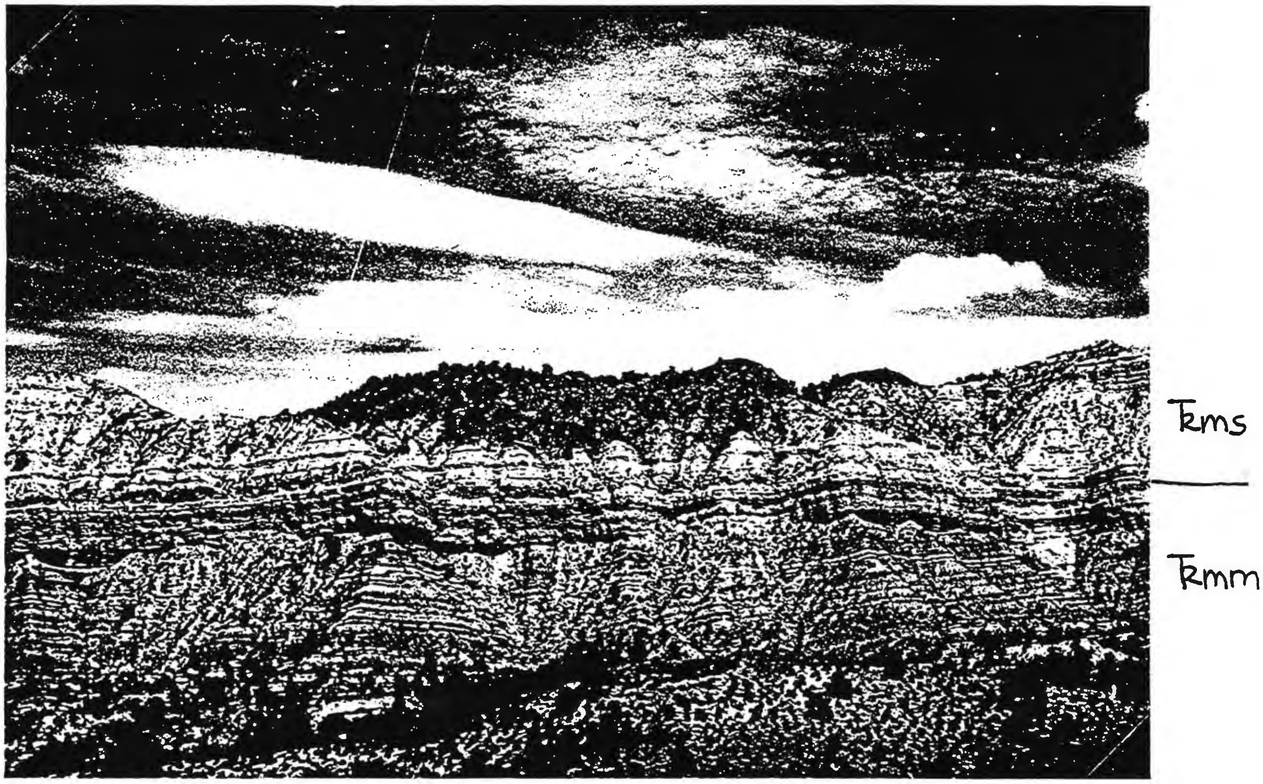


Figure 14

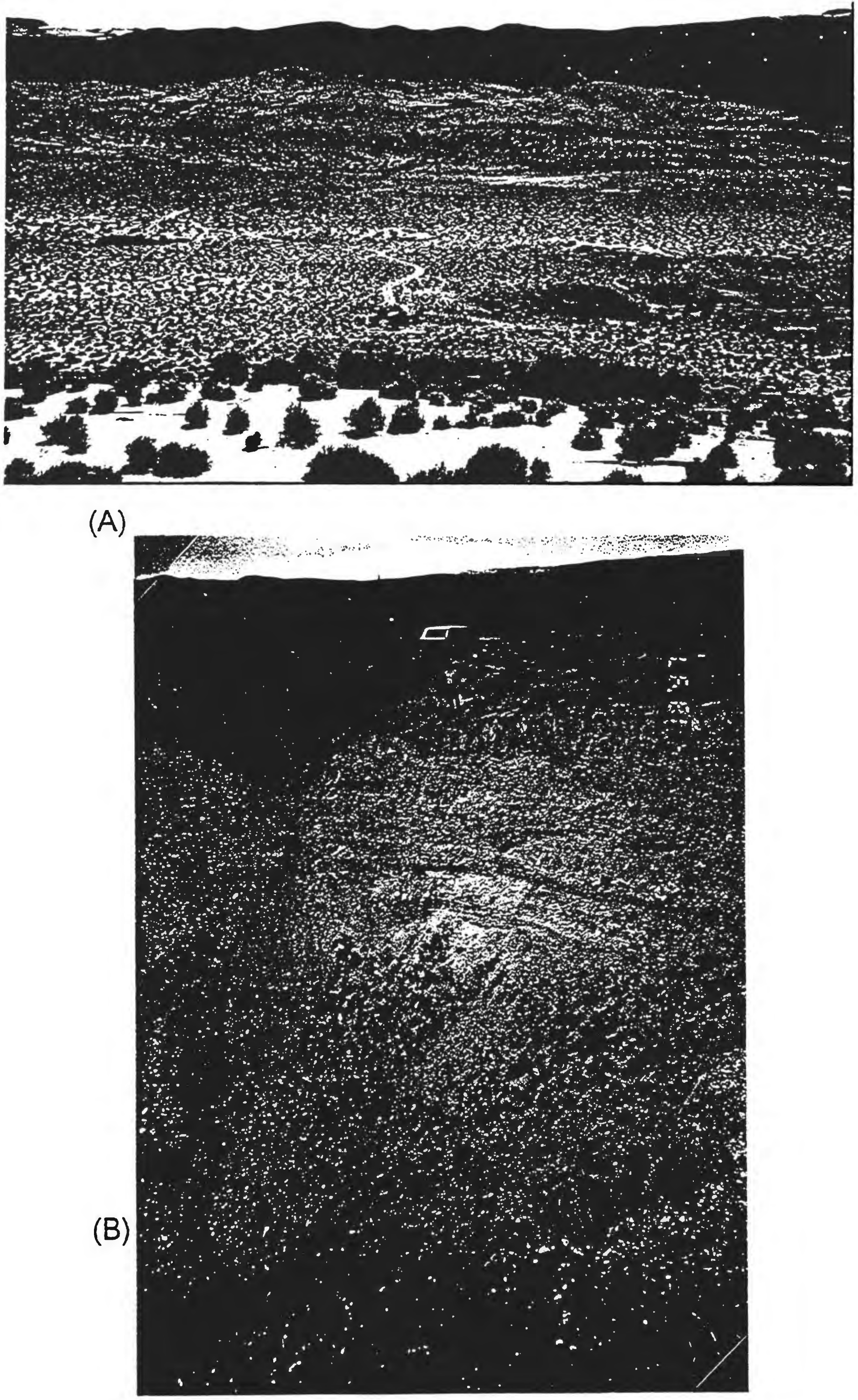


Figure 15