Geology and Geomorphology of the Southwestern Moenkopi Plateau and Southern Ward Terrace, Arizona

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By G.H. BILLINGSLEY

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Geology and Geomorphology of the Southwestern Moenkopi Plateau and Southern Ward Terrace, Arizona

By G.H. Billingsley

Abstract

In the study area, sedimentary rocks of Permian through Jurassic age dip 1° to 2° from the Little Colorado River northeastward to the Moenkopi Plateau. Tributary drainages, however, flow southwestward from the plateau, opposite the direction of the strong southwesterly winds. Several levels of resistant strata have formed a series of scarps and cuestas slightly inclined toward the Moenkopi Plateau. Subsequent drainages are entrenched within resistant strata near the base of retreating scarps, leaving a visual record of scarp retreat and development toward the Moenkopi Plateau during the past 2.4 million years. Sand eroded from local sedimentary strata was wind transported from the Little Colorado and its tributaries onto the Moenkopi Plateau about 2.4 million years ago, when the river valley was 680 ft higher, than at present and the plateau was about 5 mi closer to the river. Today the plateau averages about 1,000 ft higher, and the current supply of sand no longer reaches its surface.

INTRODUCTION

Fluvial erosion, influenced and modified by eolian activity, has been the primary agent in shaping the modern landscape of the study area, located in northeastern Arizona between the Little Colorado River and the Moenkopi Plateau. Since late Tertiary time--and possibly before--geomorphic relations between fluvial and eolian processes have been reflected both by drainage patterns on northeasterly dipping sedimentary rocks and by the northeastward retreat of cuestas along the southwest margin of the Moenkopi Plateau.

The study area extends from the Little Colorado River northeastward to the summit of the Moenkopi Plateau, encompassing 300 mi^2 (fig. 1). Its bedrock and surficial geology have been mapped at a scale of 1:31,680 (Billingsley, 1987). The area lies within the Navajo and Hopi Indian Reservations, about 45 mi northeast of Flagstaff. Elevations range from 4,200 ft at the Little Colorado River to 5,660 ft on the Moenkopi Plateau, over a horizontal distance of about 16 mi. The southwest edge of the plateau is defined by the Adeii Eechii Cliffs, an erosional scarp. Other major erosional scarps, to the southwest, are the Red Rock Cliffs and the southwest edge of Ward Terrace. These scarps, as well as many canyons of red sandstone, add beauty to the desolate area, but severely restrict travel through it.

Tohachi Wash and lesser drainages flow from the Adeii Eechii Cliffs southwestward to the Little Colorado in a direction nearly opposite that of strong seasonal southwesterly winds. These drainages, and the Little Colorado itself, are commonly dry for several months in spring and early summer.

Sedimentary rocks are interbedded limestone, silica-cemented sandstone, and multicolored shale that dip 1° to 2° to the northeast, forming northwest-trending ledges and cliffs. Bedrock is easily eroded by streams and winds. An abundant supply of loose sediment is thus available for redeposition, and much of the bedrock is mantled by alluvium and windblown sand.

The present climate of the study area is semiarid. The area's southern latitude, high rate of evaporation, and wind all contribute to the general aridity, while its elevation controls variations in precipitation and temperature. Slightly more precipitation falls on the Moenkopi Plateau than on Ward Terrace, whose elevation is lower, but the mean annual precipitation of the area is less than 10 in. The wetter seasons are winter and summer; fall and spring are relatively dry. Mean annual temperature is just above 51 °F (Sellers and Hill, 1974, p. 306-307). March through June are characterized by strong winds that produce blowing sand or duststorms.

Since 1980, weather data from an automated remote-monitoring geometeorological (GEOMET) station near Gold Spring on the Moenkopi Plateau have been collected by the U.S. Geological Survey (McCauley and others, 1984). Yearly data from this

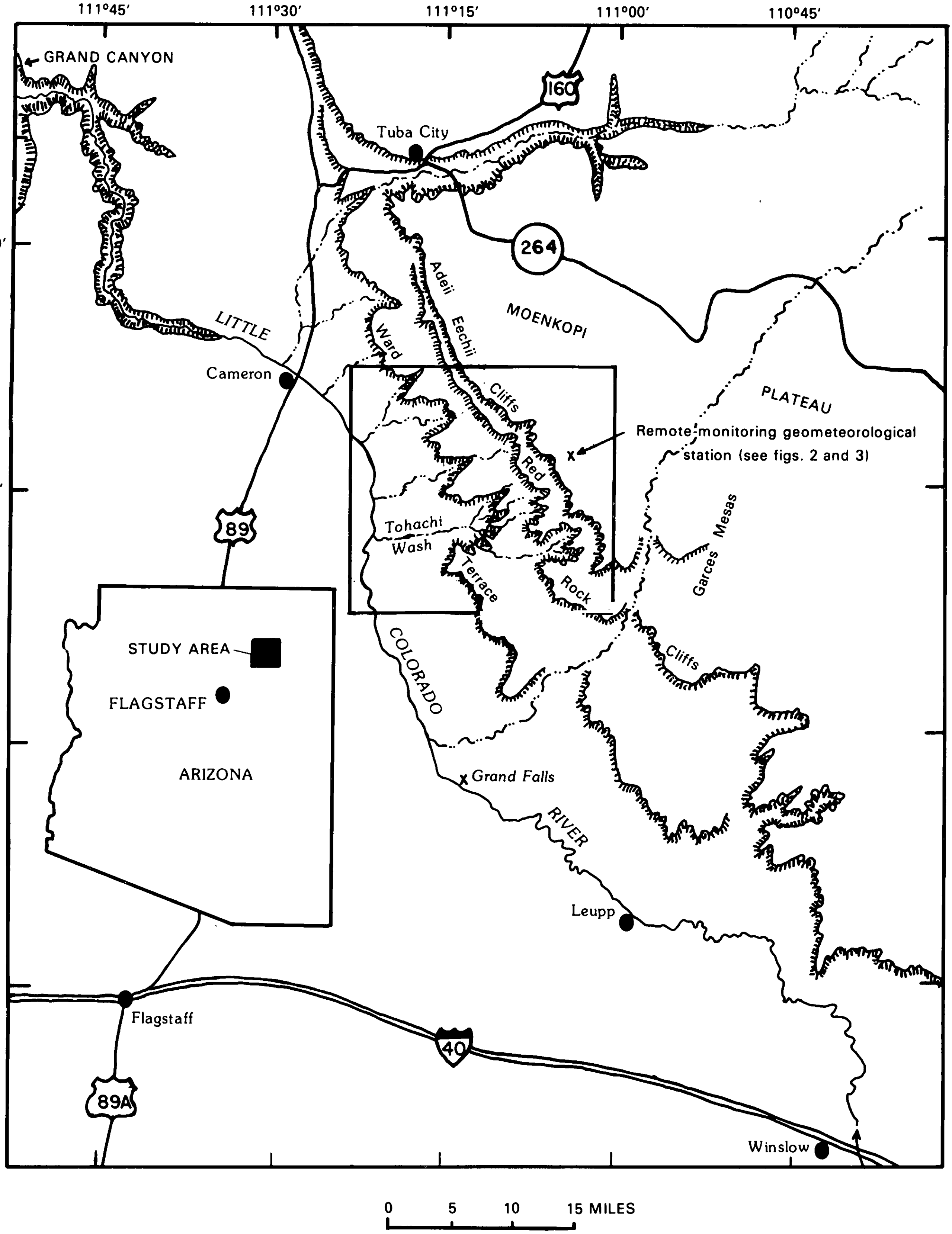

Figure 1. Index map showing location of study area.

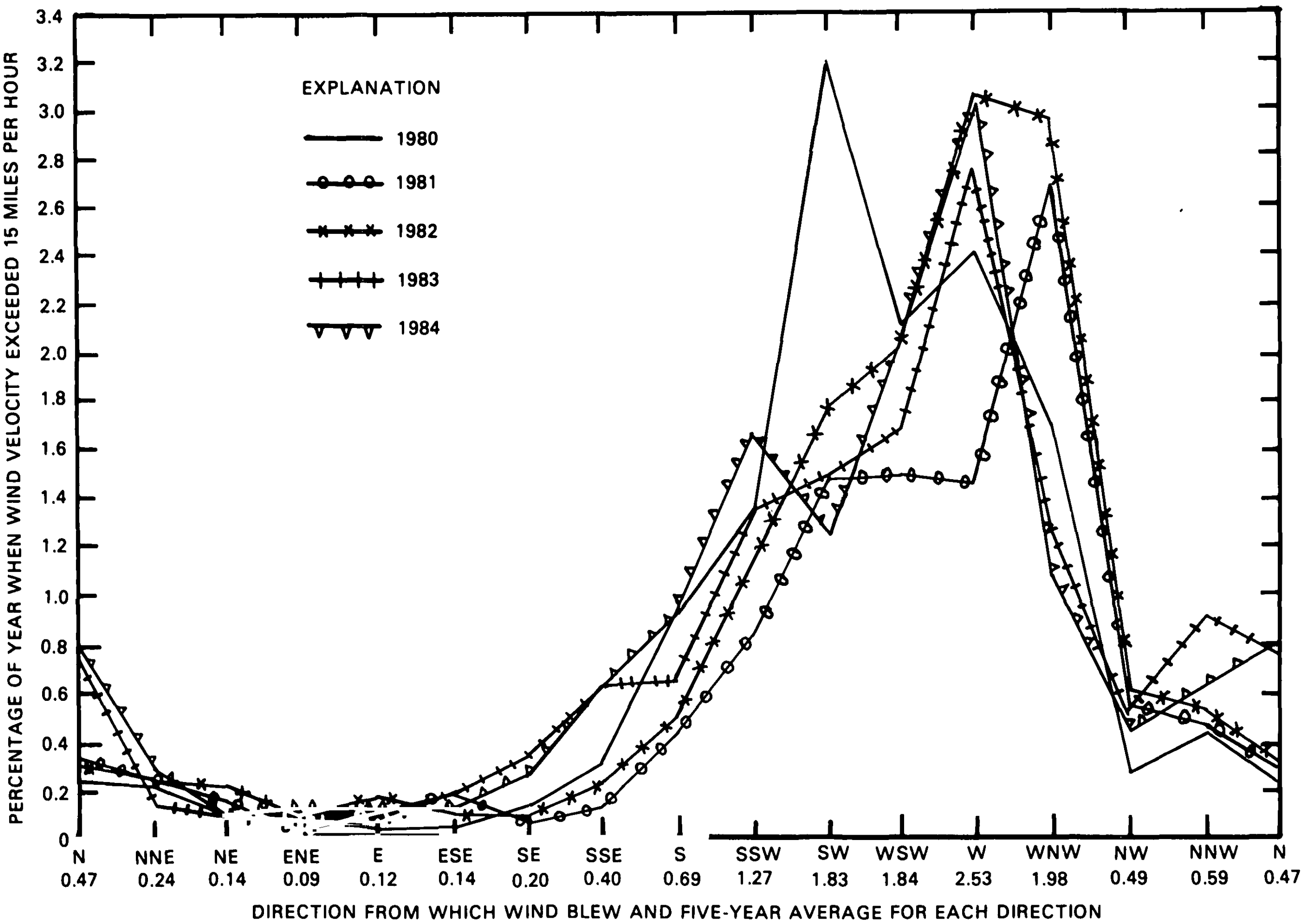

Figure 2. Percentage of year when wind velocity exceeded 15 mi/hr on Moenkopi Plateau from each of 16 compass directions, 1980 through 1984. Data from Desert Winds Project, U.S. Geological Survey, Flagstaff, Ariz.

station on wind and potential sand movement are given in figures 2 and 3 and summarized below.

Year	Percentage of year when wind velocity from all directions exceeded 15 mi/hr	Percentage of potential sand movement from all directions
1980	13.37	97
1981	10.75	95
1982	14.20	95
1983	12.51	97
1984	13.49	101
5-year average	13.02	96.8

Measurements from the beginning of 1980 through 1984 (fig. 2) show that the strongest winds having the greatest potential for sand movement have come from the southwest to west-northwest. The southwest and west-southwest directions are reflected in the alignment of all dune types of the area, but the west and west-northwest directions are not. A possible explanation is that the winds from approaching cold fronts during dry conditions are the southwesterlies; as the fronts pass and the winds veer to the north, sufficient precipitation may occur to retard sand movement.

Vegetation is restricted mainly to the Moenkopi Plateau and the flood plain of the Little Colorado River. Several species of grasses and shrubs thrive on the sandy plateau, whose eolian veneer retains sufficient moisture to sustain growth. Here the dominant shrub, Ephedra (Mormon tea), traps moving sand in small mounds, forming coppice dunes. On the Little Colorado flood plain, sagebrush and tamarisk (saltcedar) trees compete for space and locally form almost impenetrable thickets. Lying between the floodplain and the plateau are Ward Terrace and the Red Rock Cliffs, which together have the greatest topographic relief in the study area; they support virtually no vegetation except along the banks of small ephemeral tributaries.

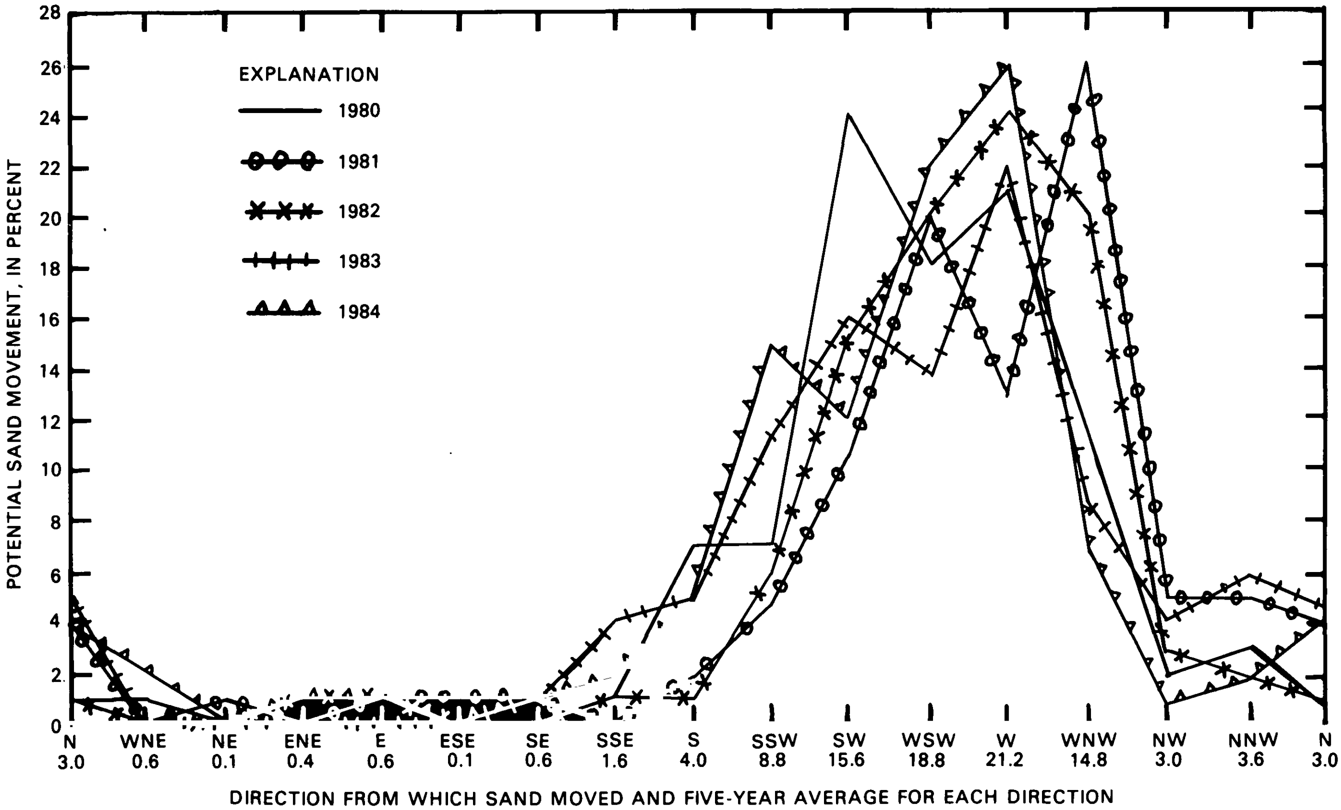

Figure 3. Cumulative percentage of potential sand movement (see text) on Moenkopi Plateau from each of 16 compass directions, 1980 through 1984. Percentages are based on calculations using Lettau-Lettau sand-flux equation (Fryberger, 1978) that do not take into account precipitation, soil moisture, or vegetation. Data from Desert Winds Project, U.S. Geological Survey, Flagstaff, Ariz.

STRATIGRAPHY

Sedimentary rocks of Permian through Jurassic age are exposed in the study area and are described in table 1. The Kaibab Formation (Lower Permian) crops out on the flanks of the Black Point monocline west of the Little Colorado River. The contrast in color at the unconformity between the gray Kaibab and the overlying red Moenkopi Formation (Middle(?) and Lower Triassic) makes the Paleozoic-Mesozoic boundary conspicuous.

Unconformably overlying the Moenkopi is the Chinle Formation (Upper Triassic), which is divided into three members whose contacts are gradational; from bottom to top they are the Shinarump, the Petrified Forest, and the Owl Rock. In the southern part of the study area, the Chinle grades upward into the Rock Point Member of the Upper Triassic Wingate Sandstone (Repenning and others, 1969); an arbitrary boundary is placed at the color change from the red and mottled shale of the Chinle to the yellowish-red shale and siltstone of the Rock Point. The Rock Point is about 100 ft thick at Tohachi Wash in the southwestern part of the study area but lenses out northward. At its top is a conspicuous disconformity with the Lukachukai Member of the Wingate. Where it is in contact with the Rock Point, the Lukachukai is primarily a flat-bedded sandstone with some small-scale crossbedding, but several miles to the east it is typically cross stratified. Like the Rock Point, the Lukachukai lenses out northward, leaving the Chinle and Moenave Formations in unconformable contact.

Because of extensive sand cover, the contact of the Wingate with the overlying Moenave Formation (Upper Triassic?) is rarely exposed in the study area. Where it is seen, the two rock types intergrade; the contact is arbitrarily placed at the change from light-reddish-brown, massive-bedded sandstone of the Wingate to the darker red siltstone and sandstone of the Moenave. Where the Wingate is absent north of Tohachi Wash, the base of the Moenave is easily recognized because of contrasts with the Chinle in color, rock type, and topographic expression.

The Moenave generally underlies gentle slopes smothered by dune sand; the Red Rock Cliffs formed in the Moenave owe their existence to a caprock of resistant silicified sandstone of the Kayenta Formation (Upper Triassic?). The dating of a dinosaur and other fossils by Colbert (1981, p. 56) suggests that the age of the Moenave, the Kayenta, and perhaps that of the lower part of the overlying Navajo Sandstone could be Late Triassic. The Moenave and Kayenta intertongue;

Table 1. Sedimentary rocks

[Color names and numbers from Munsell soil color charts (1954)]

NAVAJO SANDSTONE (JURASSIC AND UPPER TRIASSIC(?))--White (5Y 8/2), medium-grained, well-rounded, medium-crossbedded, eolian sandstone. Several outcrops of freshwater cherty limestone beds occur within sandstone on Moenkopi Plateau, weather out as flat-topped ridges. Forms hummocky knobs along Adeii Eechii Cliffs. As much as 120 ft exposed but top eroded.

NAVAJO SANDSTONE AND KAYENTA FORMATION, UNDIVIDED (JURASSIC AND UPPER TRIASSIC(?))--Pinkish-white (7.5YR 8/2), crossbedded, massive sandstone, interbedded with pale-red (10R 5/3) fluvial siltstone and fine-grained silty sandstone that contains authigenic quartz. Forms alternating steep slopes and cliffs. Approximately 200 to 280 ft thick.

KAYENTA FORMATION (UPPER TRIASSIC?)--Pale-red (5R 5/4), fluvial siltstone and fine-grained silty sandstone with interbedded purplish-red (2.5YR 6/4) shale. Forms slopes of approximately 480 ft maximum thickness.

MOENAVE FORMATION (UPPER TRIASSIC?)--Red (2.5YR 5/8), crossbedded, massive, fluvial siltstone and sandstone. Contains several thin beds of reddish-brown (2.5YR 5/4), fine-grained, crossbedded, fluvial and eolian siltstone and sandstone in lower part that may be interbeds of upper part of Wingate Sandstone. Unit forms cliffs and slopes of Red Rock Cliffs along eastern margin of Ward Terrace. Maximum thickness 300 ft.

WINGATE SANDSTONE (UPPER TRIASSIC)

Lukachukai Member--Light-reddish-brown (5YR 6/4), coarse- to fine-grained, fluvial and eolian sandstone; massive bedded; a few thin siltstone beds. Some crossbedding in upper part. Forms rounded knobs and cliffs as much as 120 ft thick. Conspicuous disconformity at base. Rests on Rock Point Member in southeastern part of study area and on Chinle Formation in central part. Pinches out northward.

WINGATE SANDSTONE-Continued

Rock Point Member--Yellowish-red (5YR 5/8), fine-grained, thick-bedded, fluvial siltstone and shale. Forms moderate to gentle slopes as much as 100 ft thick in southwestern part of study area. Pinches out northward near center of area.

CHINLE FORMATION (UPPER TRIASSIC)

Owl Rock Member--Mottled reddish-gray (10R 6/1) and pale-red (10R 6/1) to red (5R 5/3) interbedded limestone and calcareous siltstone. Widespread on Ward Terrace. Forms steep slopes as much as 240 ft thick with intervening thin ledges of resistant cherty limestone.

Petrified Forest Member--Multicolored claystone and siltstone and light-gray (2.5Y N7/0), medium- to coarse-grained, fluvial sandstone. Forms hummocky rounded knolls or gentle slopes. Maximum thickness about 380 ft.

Shinarump Member--Pale-red (10R 6/4), coarse-grained and granular, cross-bedded, fluvial sandstone and conglomerate; conglomerate contains small pebbles of quartz; thin lenses of siltstone. Forms low cliffs or ledges 5 to 45 ft thick in area of Little Colorado River. Unconformity at base.

MOENKOPI FORMATION (MIDDLE(?) AND LOWER TRIASSIC)--Light-red (10R 6/6) siltstone and fine-grained sandstone. Contains veinlets and stringers of gypsum and thin-bedded layers of green and red claystone. Basal conglomerate contains angular pebbles of white chert derived from underlying Kaibab Formation. Forms slope as much as about 400 ft thick with a few ledges. Crops out along Little Colorado River in southwestern part of study area. Unconformity at base.

KAIBAB FORMATION (LOWER PERMIAN)--Yellow to light-gray (10YR 8/6), calcareous sandstone and sandy, medium-bedded limestone interbedded with dolomitic limestone. Forms resistant surface of Black Point monocline. Thickness about 230 ft (Moore and others, 1974, p. 516).

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their contact is placed at the base of the lowermost purplish-gray, silicified sandstone or limestone of the Kayenta.

Above the slope-forming red siltstone and sandstone and purple shale of the typical Kayenta is a transition zone about 200 to 280 ft thick of Kayenta red shale interbedded with white, cliff-forming sandstone beds of Navajo. This zone was mapped by Billingsley (1987) as Navajo Sandstone and Kayenta Formation, undivided. Its boundaries are arbitary; the lower contact is placed at the base of the lowermost white sandstone bed, and the upper contact is at the top of the uppermost bed of red shale.

The Navajo Sandstone, of Jurassic and Late Triassic(?) age, underlies the Moenkopi Plateau. It erodes to rounded knobs and ledges and is largely mantled by surficial deposits. Local outcrops of thin-bedded siliceous sandstone and limestone at various elevations on the plateau surface probably represent interdunal lake beds formed during deposition of the Navajo (Gilland, 1979; Stokes, 1983). These resistant beds are eroded into elongated or circular flat-topped forms. Some outcrops of the Navajo have attained the classic elongated aerodynamic shape of bedrock yardangs in other arid regions (Breed and others, 1984).

The youngest bedrock unit in the study area is the Black Point basalt flow of Pliocene age. This flow forms Black Point west of the Little Colorado River (see figs. 5-9).

SURFICIAL DEPOSITS

Unconsolidated and weakly consolidated surficial deposits cover large parts of the study area. Fluvial deposits near the Little Colorado River have been described by Childs (1948), Rice (1974), and Hereford (1979). Eolian materials include sand sheets and dunes (barchan, parabolic, linear, and complex), some of which have been described by Hack (1941), Breed and Breed (1979), and Breed and others (1984). The age of the fluvial and eolian deposits below the Moenkopi Plateau is considered to be Holocene and Pleistocene, undivided (Billingsley, 1987). Many units are contemporaneous and they intertongue. Sand sheets and dune deposits that cover the Moenkopi Plateau may be older than Pleistocene. Other surficial material consists of localized landslide debris from the Black Point basalt flow.

Present-day stream deposits are primarily mud, silt, sand, and gravel. During seasonal dry spells in late spring and early summer, sand and silt are blown from stream channels, primarily Tohachi Wash, onto adjacent flood plains and higher terrain. Much of the sand occurs in sheets that advance northeasterly. Where the sand is sparse or relatively thin, it forms well-defined barchan or parabolic dunes; thicker sand sheets tend to form complex dunes. Some of the sand blown by wind from washes, however, is transported by streams back into the washes. This recycling operation, described by Breed and others (1984), takes place in all drainages east of the Little Colorado River, regardless of their orientation. Eventually most of the recycled sand and eroded material is removed by the Little Colorado River.

Persistent southwesterly winds in the fall and spring have effectively reshaped Tohachi Wash and other channels. When the Little Colorado and its tributaries are dry for several months, the winds blow sand and silt toward the centers and northeast margins of the channels. Here these deposits accumulate, especially where vegetation retards or slows sand movement, and form elongated ridges similar to natural levees. These ridges divert intermittent streamflows back and forth across the channels, eroding and widening them and enlarging the source areas from which new sand sheets and dunes can develop.

Fluvial deposits of silt, coarse sand, and gravel form terraces adjacent to the Little Colorado at heights of 10 to 240 ft above the river (Rice, 1974; Hereford, 1979). A few angular boulders 10 to 15 ft across of Kaibab Formation are embedded in the terrace deposits (Haines and Bowles, 1976). Deflation has winnowed most of the finer particles from the surfaces of these terraces and nearby alluvial fans, leaving behind lag gravels that are coated by desert varnish.

Many other sand dunes and sand-sheet deposits originate at or just above outcrops of the Lukachukai Member of the Wingate Sandstone. The weakly cemented sandstone of the Wingate and overlying Moenave Formation erodes relatively easily, providing materials for eolian transport. In contrast, the underlying Chinle Formation yields little sand to the winds and forms a nearly flat surface that neither collects sand nor retards its movement.

As windblown sand continues to migrate northeastward, it encounters the scarps and mesas east of the Little Colorado River. As the sand is blown over these partial barriers, it commonly forms climbing and falling dunes (Hack, 1941). Climbing dunes have reached the level of the Kayenta Formation, the caprock of the Red Rock Cliffs, at Paiute Trail Point (fig. 4). Elsewhere along these cliffs, however, climbing dunes generally reach the level of the Kayenta only where major drainages dissect the cliffs southeast of the study area. Above the Red Rock Cliffs, the Adeii Eechii Cliffs form a second barrier to the northeastward migration of sand from lower elevations.

Sand sheets and alluvium cover large areas on the Moenkopi Plateau (Billingsley, 1987). Analysis of well data (Breed and others, 1984) indicates that the average depth of the sand sheets and alluvial veneer on the Moenkopi Plateau today is almost 30 ft.

The linear (longitudinal) dunes on the Moenkopi Plateau are now topographically isolated from a formerly abundant sand supply and have been mostly stabilized by vegetation (Breed and others, 1984). These dunes form slightly sinuous ridges, commonly as long as 6,000 ft, of very fine to medium sand on which vegetation is moderate to sparse. Linear dunes on the Moenkopi Plateau are mostly inactive except near the Adeii Eechii Cliffs, where sand eroded by wind from the Navajo Sandstone has formed an active deposit along crests of the older dunes. This surface sand differs in color, grain size, composition, and sorting from the sand that forms the main body of the linear dunes (Breed and Breed, 1979; table 3, samples 1 and 2).

Along the Adeii Eechii Cliffs, sand derived from the Navajo Sandstone forms parabolic dunes that coalesce at their upwind edges and extend downwind to merge with preexisting linear dunes. Other parabolic dunes on the plateau have formed downwind of deflation hollows and stock tanks; many of these dunes are now stabilized by vegetation. The parabolic dunes below the plateau near the Red Rock Cliffs have complex combinations of barchanoid and parabolic shapes and form downwind of sandstone outcrops and streambeds that yield loose sand.

SEDIMENTOLOGY OF BEDROCK AND SURFICIAL UNITS

A reconnaissance sampling (fig. 5) of selected geologic units in the area was made to identify sources of the surficial deposits. Descriptive data based on binocular examination of bedrock and surficial samples

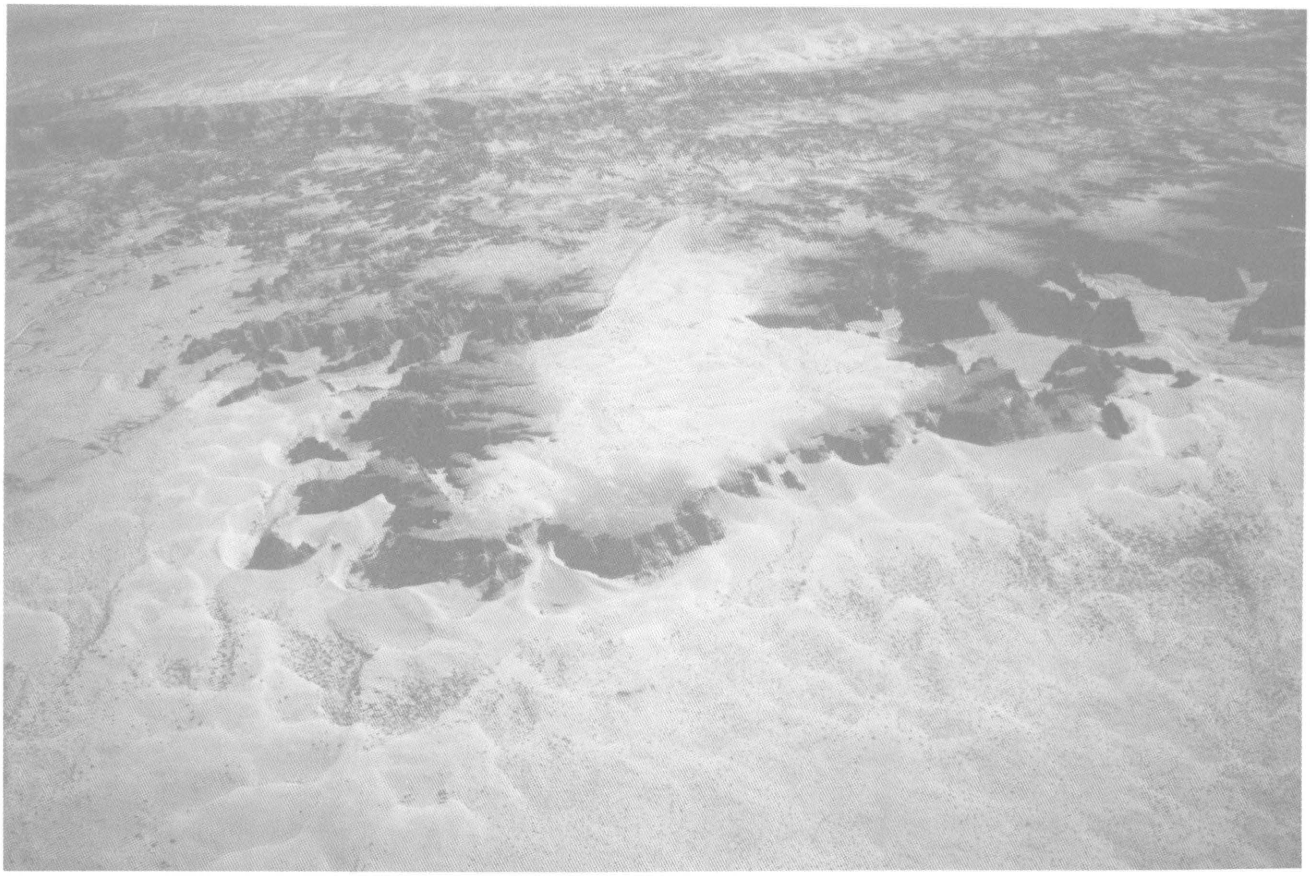


Figure 4. Aerial photograph of Paiute Trail Point (see fig. 5 for location) of Red Rock Cliffs, looking in direction of wind transport (northeast). Fluvial erosion is reducing this salient to a mesa. Prevailing southwesterly winds have piled sand against the 200-ft-high cliffs and upward onto the Kayenta Formation that caps them. Adeii Eechii Cliffs and Moenkopi Plateau appear in distant background. Width of foreground about 3 mi. Photograph by Carol S. Breed, U.S. Geological Survey.

are presented in tables 2 and 3, respectively. Because of lithologic variations within each geologic unit, none of the samples should be considered typical of an entire unit, but the reconnaissance data suggest the following general conclusions.

The Navajo Sandstone (samples 3 and 8, table 2) contains mostly medium to fine, very well rounded, well-sorted, frosted sand grains of clear quartz. These grains are easily discriminated from those of other potential source rocks in the area. The Navajo-derived grains make up about 18 percent of sample 22 from a sand sheet on the Moenkopi Plateau 1.5 mi east of the Adeii Eechii Cliffs at the GEOMET station (fig. 5), whereas they make up 37 percent of sample 2 from the active crest of a linear dune closer to the cliffs. Thus, wind erosion of the Navajo along the cliffs can be seen to supply sand grains to the linear dunes and to be the primary source of the present-day growth of dunes near the cliff edge.

Grains derived from the Navajo are present in all sampled surficial deposits in the area (table 3). Sample 9, from an active barchan dune on Ward Terrace, contains 32 percent Navajo grains derived from an upwind source 6 mi away and 820 ft higher. The Navajo grains were transported downslope by runoff to Tohachi Wash and then carried by wind northeastward to the dune field.

Two isolated climbing dunes occur on high ridges of the Kayenta Formation about 1 mi upwind and 400 ft below the nearest outcrops of Navajo Sandstone. Sample 26 from the first dune contains 12 percent Navajo grains, and sample 28 from the second contains 3 percent. Today these dunes are isolated from any local sand source; they are relicts from a time when dunes climbed the Red Rock Cliffs. Navajo grains transported downslope by runoff to lower elevations are also contained in the following samples from other surficial deposits: 10, 11, 12, 13, 14, 16, 16B, 17, 18, 19, 22A, 24, 29, 31, and 32.

Other bedrock units in the area that have contributed large quantities of material to the surficial deposits are the Lukachukai Member of the Wingate Sandstone and the Moenave Formation. These units are composed largely of pale- to dark-red and

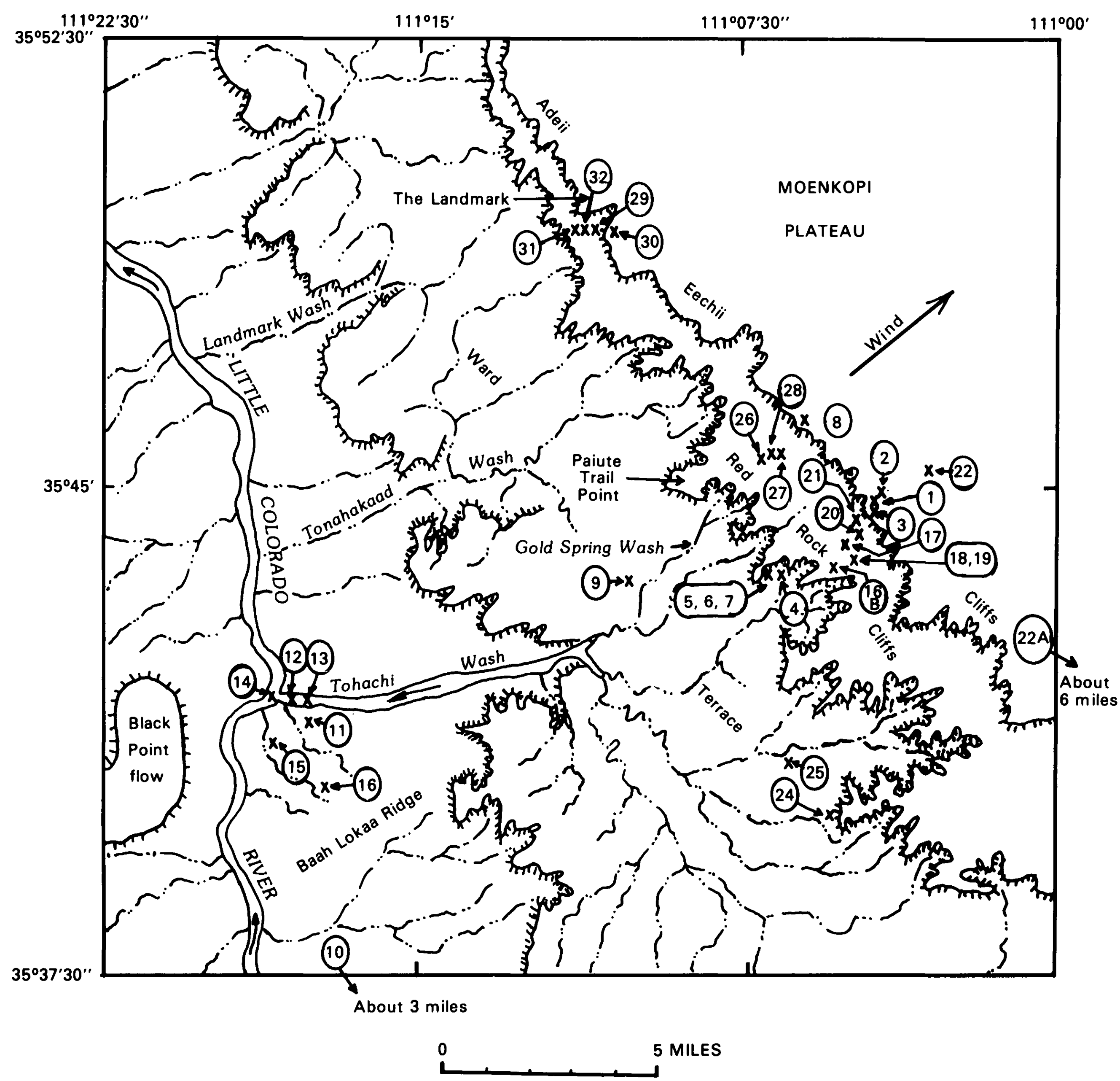


Figure 5. Sample localities (see tables 2 and 3). Arrow on Moenkopi Plateau indicates average of wind directions measured at remote-monitoring geometeorological station (location 22), 1980 through 1984.

yellow quartz grains, which account for about 80 percent of the Lukachukai (sample 25, table 2) and about 70 percent of the Moenave (samples 5, 6, and 7, table 2). The compositions of these units are so similar that they cannot be distinguished under the binocular microscope. Climbing dunes lower than the Lukachukai and Moenave outcrops contain 41 percent (sample 4) and 51 percent (sample 24) red and red-stained quartz sand derived from these units. This material was first deposited by streams and then transported by wind back toward the parent outcrops. Samples 18 and 19 from a climbing dune on the Kayenta surface just above the Moenave contain about 25 percent Lukachukai-Moenave sand grains, indicating that this sand was blown by wind from these two lower lying units onto and over the Red Rock Cliffs. Further evidence of wind transport of Lukachukai-Moenave sand grains onto the Red Rock Cliffs can be seen in the composition of all other surficial samples taken from the cliffs (16B, 26, 27, 28, 29, 31, and 32). Even on the Moenkopi Plateau, at the GEOMET station more than 1 mi east of the Adeii Eechii Cliffs, the sand of

Table 2. Composition of bedrock samples (in volume percent)

	Coarse grain (>1.0ø)	Fine grain (<1.0ø)
Sample 3. Navajo Sandstone, edge of Moenkopi Plateau		
Quartz sandstone grains	3	0
Clear frosted quartz, well- to very well rounded	94	97
Light-red quartz	3	3
Sample 5. Moenave Formation, upper part, Gold Spring Wash		
Quartz sandstone grains	5	0
Dark-red quartz	5	4
Light-red quartz	60	45
Clear quartz	10	48
Dark- and light-green mineral?	1	trace
Red chert?	4	trace
Biotite	11	1
Muscovite	3	trace
Magnetite?	1	2
Sample 6. Moenave Formation, middle part, Gold Spring Wash		
Red quartz sandstone grains	50	45
White quartz sandstone grains	1	2
Red quartz	48	52
Black quartz with iron	1	1
Biotite	0	trace
Gypsum	0	trace
Sample 7. Moenave Formation, lower part, Gold Spring Wash		
Light-red and yellow quartz	44	58
Dark-red quartz	3	1
Clear quartz, angular	10	11
Quartz sandstone grains	15	0
Schist fragments	12	4
Milky quartz	10	9
White chert? and calcite	3	4
Plagioclase	1	0
Red chert	1	trace
Gypsum	1	0
Biotite	0	7
Muscovite	0	5
Green mineral?	0	1
Sample 8. Navajo Sandstone and Kayenta Formation, undivided, upper part, shale, 1 mi south of The Landmark		
Clear quartz, angular (crystals)	50	19
Milky quartz (feldspar?)	8	40
Red siltstone grains	40	37
Green mineral?	1	trace
Biotite	trace	1
Red quartz	1	3
Sample 15. Chinle Formation, Petrified Forest Member, near mouth of Tohachi Wash		
Clear quartz	23	2
Red quartz	3	3
Reddish-brown chert?	13	1
Gray siltstone grains	61	79
Muscovite	trace	2
Biotite	trace	2
Green mineral?	trace	1
Purple quartzite or chert?	trace	10
Sample 20. Kayenta Formation, lower part, near Gold Spring Wash		
Clear quartz	8	50
Milky quartz	14	3
Light-red quartz	8	18
Dark-red quartz	trace	6
Purple sandstone grains	52	11
Muscovite	4	1
Biotite	12	8
Green mineral?	1	3
Hematite?	1	trace
Sample 21. Kayenta Formation, upper part, Gold Spring Wash		
Clear quartz, angular	0	8
Milky quartz	1	34
Light-red quartz	2	13
Purple quartz or silica clay?	49	40
Magnetite	0	2
Biotite	0	3
Purple sandstone grains	48	0
Muscovite	0	trace
Green mineral?	0	trace
Sample 25. Wingate Formation, Lukachukai Member, 1/2 mi south of Tohachi settlement		
Yellow quartz	14	80
Dark-red quartz	2	1
Light-red quartz	2	3
Pale-red sandstone grains	77	12
Clear quartz	2	0
Gray chert?	3	trace
Hematite?	trace	1
White sandstone grains	trace	3
Sample 30. Navajo Sandstone and Kayenta Formation, undivided, lower part, white sandstone, 1 mi southeast of The Landmark		
Clear quartz, angular		87
Clear quartz, rounded		2
Red-stained quartz		trace
Green mineral, stain?		trace
Biotite		trace
Gypsum		10
Smoky quartz?		1

sample 22 is about 39 percent Lukachukai-Moenave grains. Also on the plateau, Lukachukai-Moenave sand, silt, and clay particles average about 50 percent in surficial samples (1, 2, and 22A).

The schist fragments found in small quantities (less than 1 percent) in a linear dune on the Moenkopi Plateau (samples 1 and 2) have a unique source in the lower part of the Moenave Formation (sample 7, table 2). These fragments and the Lukachukai-Moenave grains could have reached the higher elevations on the Moenkopi Plateau only by wind transport earlier in geologic time, because their sources are lower lying and upwind of the plateau.

Basaltic ash fragments are found in most surficial deposits of the area. Their source was intermittent volcanic eruptions (Moore and others, 1976) in the San Francisco volcanic field southwest of the study area during late Tertiary and Quaternary time.

West of the Red Rock Cliffs, two sources of wind-transported sand can be distinguished. The first source was sediments along the Little Colorado River. Most of this sand was deposited within a few miles of the river; samples collected at progressively greater distances downwind (east) of the river contain progressively fewer river-sand grains and more grains

Table 3. Composition of surficial samples (in volume percent)

[Asterisks indicate sand grains characteristic of: *, Navajo Sandstone; **, Lukachukai Member of Wingate Sandstone and Moenave Formation]

	Coarse grain ($>1.0\phi$)	Fine grain ($<1.0\phi$)
Sample 1. Interior of linear dune, edge of Moenkopi Plateau		
Quartz sandstone grains	12	0
Light- and dark-red quartz**	40	69
Clear quartz, rounded*	43	20
Yellow quartz	5	6
Gray chert?	trace	2
Basaltic ash fragments	trace	2
Schist fragments	trace	1
Sample 2. Surface of dune sampled above		
Quartz sandstone grains	6	0
Clear quartz, rounded*	48	27
Milky quartz	12	3
Light- and dark-red quartz**	25	65
Schist fragments	trace	0
Gray chert?	3	3
Basaltic ash fragments	6	2
Sample 4. Surface of climbing dune, base of Moenave Cliffs, Gold Spring Wash		
Red quartz**	33	49
Clear quartz, rounded*	24	20
Milky quartz	18	12
Quartz sandstone grains	16	0
White chert	2	2
Red chert?	4	5
Basaltic ash fragments	2	12
Schist fragments	1	0
Magnetite	trace	0
Gypsum	trace	0
Sample 9. Slipface of barchan dune, active dune field on Owl Rock Member of Chinle Formation		
Dark-red quartz**	3	5
Light-red quartz**	16	9
Clear quartz, rounded*	32	32
Milky quartz	29	30
Green and black quartz	4	4
Bluish-gray chert	4	2
Red chert?	1	2
White chert?	5	1
Biotite	0	2
Muscovite	0	1
Basaltic ash fragments	6	12
Schist fragments	trace	0
Sample 10. Interior of terrace-gravel deposit, Black Falls roadcut about 7 mi southeast of Black Point		
Milky quartz	70	60
Quartz sandstone grains	12	0
Rose quartz	2	trace
Purple chert?	2	0
Black mineral quartzite	3	9
Clear quartz, angular	2	13
Clear quartz, rounded*	4	6
White chert? or calcite?	3	2
Red quartz**	2	2
Biotite	0	trace
Green mineral?	trace	1
Light-red quartz**	trace	7

	Coarse grain ($>1.0\phi$)	Fine grain ($<1.0\phi$)
Sample 11. Surface of sand sheet on Petrified Forest Member of Chinle Formation south of Tohachi Wash		
Basaltic ash fragments	30	40
Milky quartz	31	31
Clear quartz, rounded*	10	3
Clear quartz, angular	8	10
Light-red chert?	7	trace
Red and black quartzite?	7	3
Light-red quartz**	4	6
White ash? or calcite?	2	trace
Smoky quartz	trace	2
Green mineral?	1	3
Muscovite	0	1
Biotite	0	1
Sample 12. Surface of Tohachi Wash 1/4 mi from Little Colorado River		
Clear quartz, well rounded*	25	13
Clear quartz, angular	8	31
Feldspar, rounded	4	?
Light-red quartz**	12	24
Gray, brown, green chert?	19	18
Quartz with iron inclusions	2	trace
Basaltic ash fragments	6	4
Quartz sandstone grains	5	0
Siltstone flakes	8	0
White chert? or ash?	9	4
Travertine crystals	2	0
Green mineral?	trace	2
Biotite	0	4
Sample 13. Surface of Tohachi Wash 1/2 mi from Little Colorado River		
Clear quartz, rounded*	8	11
Clear quartz, angular	42	78
Dark-red quartz**	1	1
Light-red quartz**	3	3
Basaltic ash fragments	16	4
Quartz sandstone grains	10	0
Siltstone mud curls	7	trace
Milky quartz	4	trace
White mineral, calcite?	3	trace
Gray chert	3	trace
Green mineral, apatite?	trace	2
Biotite	trace	1
Green chert?	1	0
Purple quartzite? or chert?	2	trace
Gypsum	trace	trace
Muscovite	trace	trace
Schist fragments	trace	trace
Sample 14. Surface of small modern dune in center of Little Colorado River		
Basaltic ash fragments	20	3
Milky quartz	17	2
Clear quartz, angular	22	74
Clear quartz, rounded*	12	10
White quartz sandstone grains	6	0
Red quartz sandstone grains**	2	0
Light-red quartz**	3	2
Dark-red quartz**	1	3
Red chalcedony	2	2
Green mineral?	1	3
Biotite	trace	trace
Yellow quartz**	3	1
Light-reddish-brown quartz**	4	0
Gray chert	3	0
Red quartzite?	4	trace
Hornblende? magnetite?	trace	0
Siltstone mud curls	trace	0

Table 3. Composition of surficial samples--Continued

	Coarse grain (>1.0ø)	Fine grain (<1.0ø)
Sample 16. Interior of high terrace on Baah Lokaa Ridge		
White quartz sandstone grains........	4	0
Clear quartz, rounded*..............	3	10
Clear quartz, angular...............	42	39
Gray, red, white chert..............	30	13
Basaltic ash fragments?.............	6	7
Red quartz**........................	7	18
Yellow quartz**.....................	1	4
Clear quartz with iron inclusions....	2	trace
Black chert?........................	2	5
Travertine crystals.................	1	trace
Feldspar............................	2	trace
Biotite.............................	0	3
Green mineral?......................	0	1
Sample 16B. Surface of sand sheet on Kayenta Formation, above Red Rock Cliffs		
Basaltic ash fragments..............	4	6
Smoky quartz........................	4	6
Milky quartz? or feldspar?..........	16	10
Clear quartz, angular...............	20	18
Clear quartz, rounded*..............	8	6
Quartz sandstone grains.............	6	0
Light-red quartz**..................	35	37
Dark-red quartz**...................	3	12
Green mineral?......................	4	1
Biotite.............................	trace	4
Sample 17. Surface of undifferentiated dune on Kayenta Formation above Red Rock Cliffs		
Siltstone flakes....................	5	0
Basaltic ash fragments..............	5	5
Clear quartz, angular...............	8	25
Clear quartz, rounded*..............	7	3
Quartz sandstone grains.............	8	0
Light-red quartz**..................	53	35
Dark-red quartz**...................	trace	20
Milky quartz and feldspar...........	5	5
Smoky quartz........................	7	4
Biotite.............................	1	3
Muscovite...........................	1	trace
Sample 18. Surface of upper part of climbing dune on Kayenta Formation above Red Rock Cliffs		
Yellow quartz**.....................	60	65
Dark-red quartz**...................	1	3
Light-red quartz**..................	4	22
Quartz sandstone grains.............	9	trace
White quartz and feldspar...........	2	2
Green mineral?......................	trace	1
Fecal pellets.......................	16	0
Clear quartz, rounded*..............	4	trace
Clear quartz, angular...............	2	3
Dark smoky quartz with iron inclusions........................	1	4
Biotite.............................	1	0
Muscovite...........................	trace	0
Sample 19. Surface of lower part of same dune as sample 18		
Quartz sandstone grains.............	7	0
Clear quartz, rounded*..............	3	trace
Clear quartz, angular...............	8	23
Yellow quartz**.....................	72	58
Dark-red quartz**...................	1	2
Light-red quartz**..................	3	7
Iron (magnetite?)...................	1	4
Smoky quartz........................	4	4
Milky quartz and feldspar...........	1	1
Green mineral?......................	trace	1
Muscovite...........................	trace	0

	Coarse grain (>1.0ø)	Fine grain (<1.0ø)
Sample 22. Surface of sand sheet at GEOMET station, Moenkopi Plateau		
Light-red quartz**..................	50	33
Basaltic ash fragments..............	20	18
Dark-red quartz**...................	2	2
Clear quartz, angular...............	12	20
Clear quartz, rounded*..............	10	25
Gray chert?.........................	1	1
White milky quartz or ash?..........	4	0
Muscovite...........................	trace	0
Biotite.............................	0	1
Red chert?..........................	1	0
Sample 22A. Surface of active barchan dune on Garces Mesas about 6 mi southeast of study area (fig. 1)		
Clear quartz, angular...............	10	0
Clear quartz, rounded*..............	12	85
Clear quartz, stained light red**....	63	0
Dark-red quartz**...................	1	1
Red siltstone**.....................	2	0
Light-red quartz**..................	4	7
Milky quartz........................	1	trace
Volcanic glass or ash?..............	2	trace
Quartz with iron inclusions.........	trace	0
Basaltic ash fragments..............	2	4
Smoky quartz with iron inclusions....	1	1
Gray, red chert?....................	2	2
Muscovite...........................	trace	0
Biotite.............................	trace	0
Green mineral?......................	0	trace
Sample 24. Surface of climbing dune, base of Red Rock Cliffs		
Basaltic ash fragments..............	4	no data
Clear quartz, rounded*..............	7	no data
Clear quartz, angular...............	15	no data
Dark-red quartz**...................	2	no data
Light-red quartz**..................	9	no data
Milky quartz or chert?..............	6	no data
Smoky quartz........................	2	no data
Red chert or quartzite..............	3	no data
Red sandstone grains**..............	1	no data
Red-stained quartz**................	51	no data
Sample 26. Interior of dune 2 mi east of Paiute Trail Point		
Light-red quartz**..................	8	8
Dark-red quartz**...................	1	3
Clear quartz, angular...............	70	72
Clear quartz, rounded*..............	17	8
Grayish-white chert.................	4	7
Black mineral (iron?)...............	trace	2
Sample 27. Surface of climbing dune, 2 mi east of Paiute Trail Point		
Basaltic ash fragments..............	10	6
Sandstone grains	4	0
Clear quartz, angular...............	76	80
Clear quartz, rounded*..............	2	1
Light-red quartz**..................	3	trace
Milky quartz........................	trace	1
Biotite.............................	0	trace
Dark mineral?.......................	trace	1
Red and gray chert..................	5	1

Table 3. Composition of surficial samples--Continued

	Coarse grain (>1.0φ)	Fine grain (<1.0φ)
Sample 28. Surface of dune 2 mi east of Paiute Trail Point		
Basaltic ash fragments..............	4	trace
Clear quartz, angular...............	80	82
Clear quartz, rounded*..............	4	1
Milky quartz (chert?)...............	3	1
Light-red quartz**..................	6	11
Dark-red quartz**...................	2	2
Gray chert..........................	1	trace
Iron? trace.........................	2	
Biotite.............................	0	1
Green mineral?......................	0	trace
Sample 29. Interior of climbing dune, 1 mi south of The Landmark		
Red sandstone grains**..............	8	0
Light-red quartz**..................	83	22
Clear quartz, angular...............	1	73
Clear quartz, rounded*..............	3	1
Gray chert..........................	4	2
Milky quartz (chert?)...............	1	trace
Biotite.............................	0	trace
Muscovite...........................	0	trace
Smoky quartz?.......................	0	2
Sample 31. Interior of climbing dune 1 mi south of The Landmark		
White sandstone grains..............	1	trace
Clear quartz, angular...............	82	91
Clear quartz, rounded*..............	2	2
Light-red quartz**..................	5	3
Dark-red quartz**...................	2	trace
Gray and red chert..................	6	2
Milky quartz or chert?..............	2	1
Smoky quartz?.......................	trace	1
Sample 32. Surface of climbing dune 1 mi south of The Landmark		
Smoky quartz?.......................	3	3
Dark-red quartz**...................	1	1
Light-red quartz**..................	4	8
Clear quartz, angular...............	87	85
Clear quartz, rounded*..............	4	2
Milky quartz or chert?..............	1	1
Green mineral or stain?.............	trace	trace

of the local bedrock, mainly of the Chinle Formation (sample 15, table 2). The second source was tributary drainages containing grains derived from local bedrock (all samples listed in table 2). Nearly all of the wind-transported sand has undergone one or more of the following processes: (1) derivation by headward erosion of Triassic sedimentary rocks; (2) derivation by direct wind deflation of rock outcrops; (3) transport in sand sheets and dunes, by strong southwesterly and westerly winds, northeastward from tributary drainages; and (4) transport by streams to the Little Colorado River and out of the area.

GEOMORPHIC INTERPRETATIONS

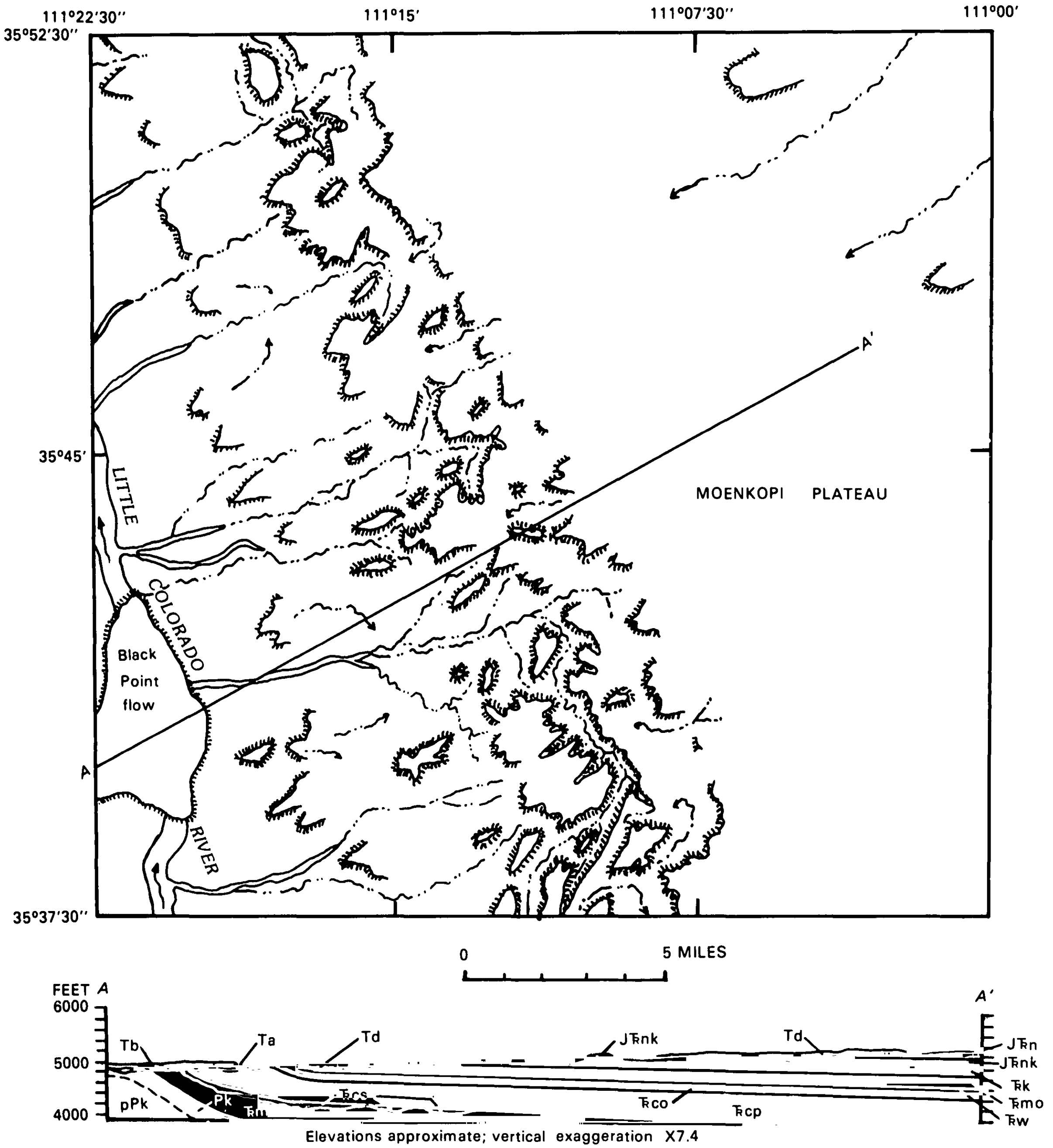
The gentle northeastward regional dip is the chief structural feature of the study area. As erosion removed bedrock, the resistant dipping strata formed hogbacks or cuestas that gradually retreated toward the northeast. Prior to extrusion of the Black Point basalt flow about 2.4 million years ago (Damon and others, 1974), the channel of the ancestral Little Colorado River was near its present site but 680 ft higher (fig. 6). The eastern tributaries of the river had already reduced the surrounding landscape to a near peneplain sloping toward the river from the northeast. Linear dunes that may have been derived from the Little Colorado flood plain possibly contributed to the alignment of the early drainage development as mapped by Stokes (1964) elsewhere in northeastern Arizona. The Moenkopi Plateau at that time was about 400 ft higher than the river; thus the average gradient was only 31 ft/mi, the same as the gradient of the peneplained surface of the Moenkopi Plateau today.

If the strongest winds 3 million years ago were from the southwest and were at least as effective as they are today, they could have easily transported sand from the Little Colorado channel and developing tributary washes up onto the surface of the ancestral Moenkopi Plateau, whose relief was much less than it is today (fig. 6). This transport was probably facilitated by ramps of sand formed by climbing dunes. Under the present wind regime, climbing dunes are ascending cliffs as high as 200 ft at elevations 600 ft above the Little Colorado flood plain (Breed and others, 1984; fig. 4).

About 2.4 million years ago, the channel of the Little Colorado River was diverted eastward more than a mile by the Black Point lava flow (compare figs. 6 and 7). This diversion may have initiated the headward erosion of Tohachi Wash and other nearby tributaries as the river was forced to cut into the sloping peneplain, creating an erosional scarp. Beginning at about the end of Tertiary time, small subsequent drainages began to flow northeastward (opposite the major direction of drainage) on resistant dipping surfaces of developing cuestas and to turn along strike valleys until they reached a major drainage flowing southwest to the river (figs. 7-9).

As downcutting continued, these strike-valley streams were incised into resistant rock and trapped in place. Cuestas continued to retreat northeastward, allowing several sets of strike-valley streams to became sequentially entrenched as they developed. The earlier set of subsequent streams has migrated very little, if at all, because of entrenchment; today they provide evidence of past sequential drainage patterns and cuesta positions. Erosional retreat of the cuestas has resulted in the present series of steplike, subparallel cliffs east of the Little Colorado River: the west edge of Ward Terrace, the Red Rock Cliffs, and the west edge of the Moenkopi Plateau (fig. 9).

After extrusion of the Black Point flow (about 2.4 million years ago), the combination of downcutting and headward erosion into higher terrain enlarged natural barriers to the northeastward movement of sand onto the Moenkopi Plateau. Fluvial erosion gradually removed the once-plentiful sand supply faster than wind could build sand ramps up the scarps. Today, virtually no sand reaches the plateau along the Adeii Eechii Cliffs because most of it is now returned to the Little Colorado River and transported from the area.



EXPLANATION

TERTIARY:

Ta Older alluvium

Tb Black Point basalt flow

Td Older dune sand

JURASSIC AND TRIASSIC(?):

JTRn Navajo Sandstone

JTRnk Navajo Sandstone and Kayenta Formation, undivided

TRIASSIC(?):

TRk Kayenta Formation

TRmo Moenave Formation

TRIASSIC:

TRw Wingate Sandstone (Lukachukai and Rock Point Members)

TRco Chinle Formation (Owl Rock Member)

TRcp Chinle Formation (Petrified Forest Member)

TRcs Chinle Formation (Shinarump Member)

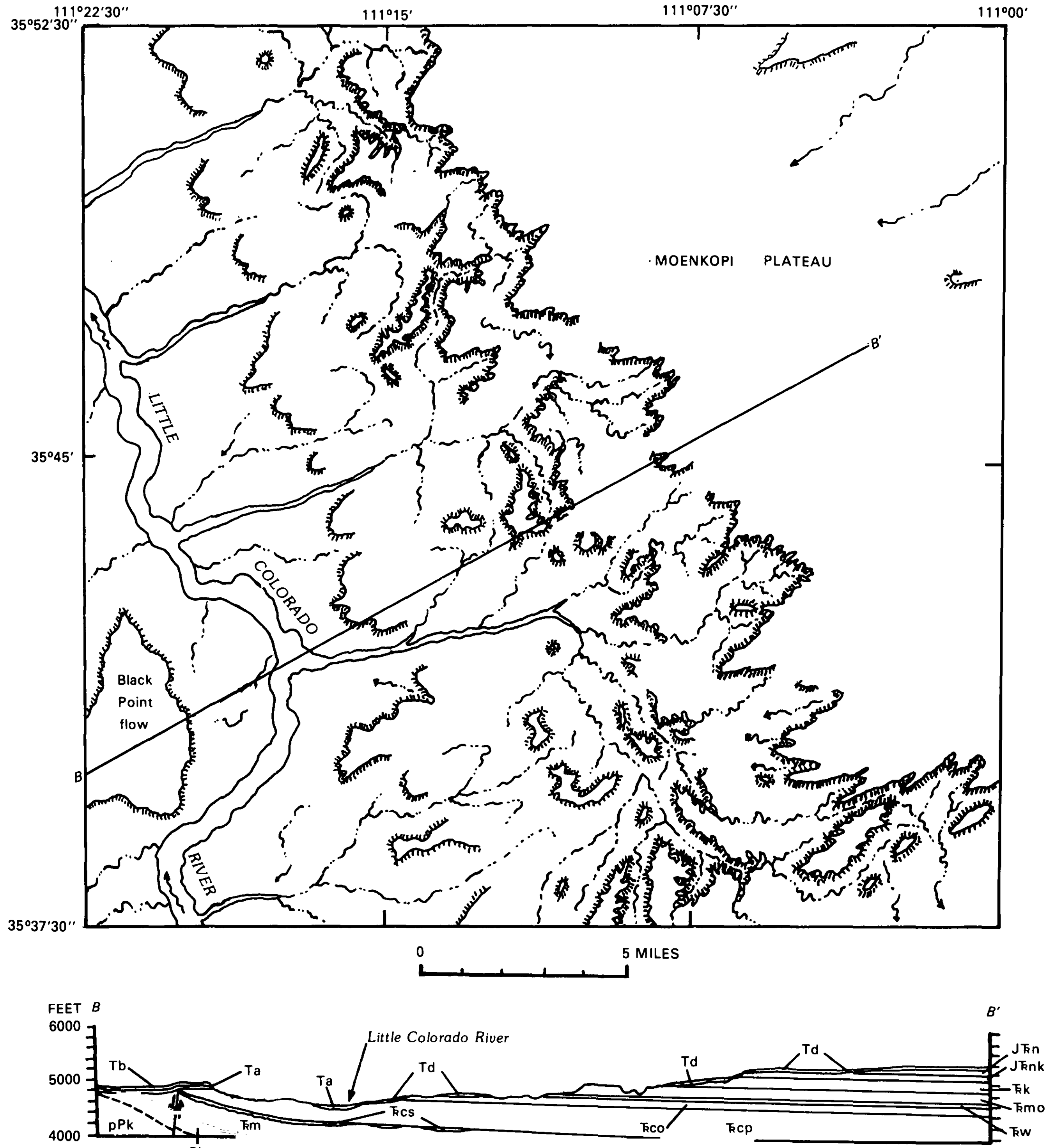
TRm Moenkopi Formation

PERMIAN AND OLDER:

Pk Kaibab Formation

pPk Pre-Kaibab formations

Figure 6. Probable positions of cliffs and drainages immediately after Black Point basalt flow entered Little Colorado River channel, about 2.4 m.y. ago (Damon and others, 1974).



Elevations approximate; vertical exaggeration X7.4. Arrows indicate direction of relative movement of fault

Figure 7. Probable positions of cliffs and drainages at end of Tertiary time (about 1.8 to 2.0 m.y. ago). Symbols for units explained in figure 6. (Normal fault at surface becomes a reverse fault at depth.)

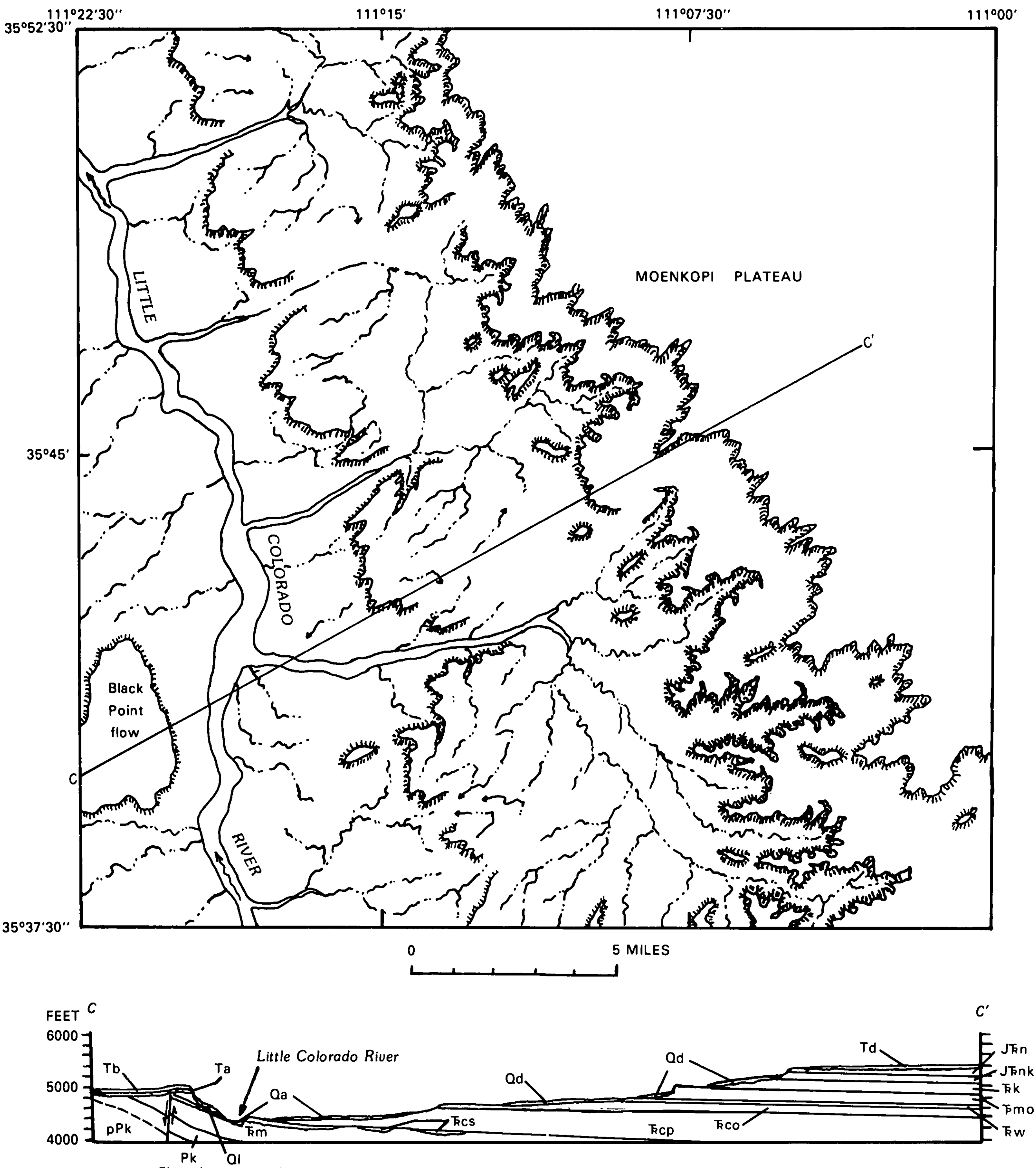


Figure 8. Probable positions of cliffs and drainages about 1 m.y. ago. Symbols for bedrock units explained in figure 6. Surficial deposits of Quaternary age: Qa, younger alluvium; Qd, younger dune sand; Ql, landslide deposits. Surficial deposits of Tertiary age: Td, older dune sand, Ta, older alluvium.

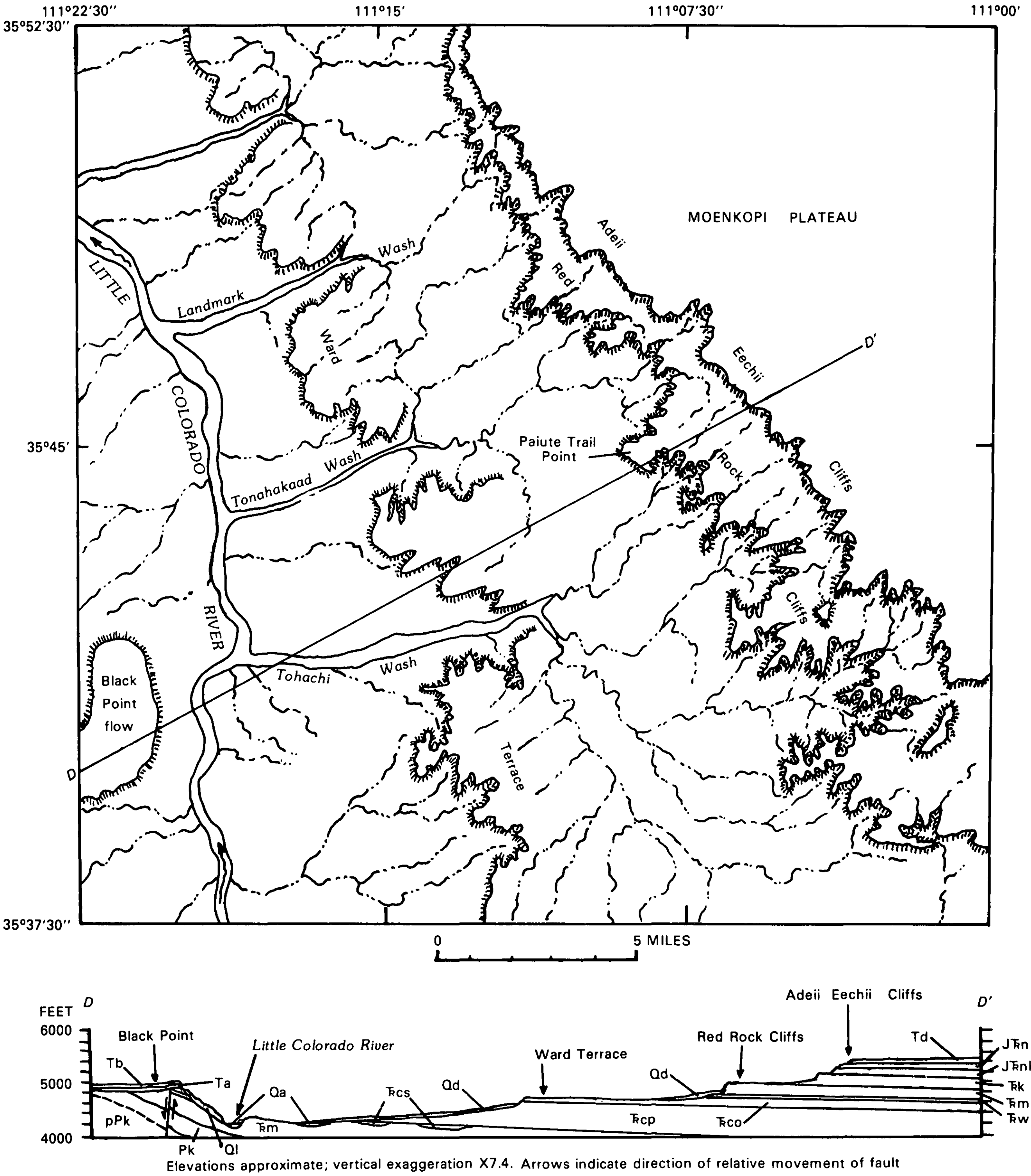


Figure 9. Present positions of cliffs and drainages. Symbols for bedrock units explained in figure 6. Surficial deposits of Quaternary age: Qa, younger alluvium; Qd, younger dune sand; Ql, landslide deposits. Surficial deposits of Tertiary age: Td, older dune sand; Ta, older alluvium.

Sand of climbing dunes piled against the lower cliff faces has modified fluvial and mass-wasting erosion patterns along the scarps. Climbing dunes are thickest and most common along salients of the Red Rock Cliffs, where the Moenave Formation that forms the cliffs is protected by a cap of resistant Kayenta Formation. It is no coincidence that these salients are all downwind (northeast) of large drainages where thick deposits of windblown sand are readily available. These deposits have slowed fluvial erosion enough to help produce the salients. Headward erosion of drainages is rapidly advancing around and behind these salients to create potential mesas (fig. 4), a process that is probably similar to the erosion of earlier periods (figs. 6-8).

Below the Moenkopi Plateau, seasonal fluvial erosion removes most of the eolian deposits from the washes (Breed and others, 1984). On the plateau, however, eolian deposits are largely isolated from fluvial transport except along the Adeii Eechii Cliffs. The plateau's veneer of surficial deposits and stabilizing vegetation has helped preserve this ancient surface by preventing runoff and slowing erosion rates.

The present stabilized linear dunes on the Moenkopi Plateau are considered to be of Pleistocene age (Breed and others, 1984) on the basis of the occurrence in a dune of volcanic ash that these workers have correlated with an eruption 730,000 years ago. Stokes (1964) attributed the development of parallel stream courses in other parts of northern Arizona to topographic control by linear dunes; he suggested that such dunes may be as old as one million years. Detailed geologic mapping (Billingsley, 1987), analyses of dune sands and source materials, geomorphic relations of cliff retreat, present drainage patterns, and the known age of the Black Point basalt flow all indicate that the eolian veneer on the Moenkopi Plateau is at least 2.4 million years old.

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