Paper G 9

GEOLOGIC APPLICATIONS OF ERTS IMAGES ON THE COLORADO PLATEAU, ARIZONA

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ABSTRACT

Three areas in central and northern Arizona centered on the 1) Verde Valley, 2) Coconino Plateau, and 3) Shivwits Plateau were studied using ERTS photography. Image enhancement techniques were developed to extract the most useful subsets from the digital tape images in each area. The value of color combined ratio images for geologic mapping was tested. Extensive new field mapping was completed on the Shivwits and Coconino Plateaus.

Useful applications results include: 1) Upgrading of the existing state geologic map of the Verde Valley region; 2) Detection of long NW trending lineaments in the basalt cap SE of Flagstaff which may be favorable locations for drilling for new water supplies; 3) Tracing of the Bright Angel and Butte faults to twice their previously known length and correlating the extensions with modern seismic events, showing these faults to be present-day earthquake hazards; 4) Discovering and successfully drilling perched sandstone aquifers in the Kaibab Limestone on the Coconino Plateau; 5) Determining the relationship between the Shivwits lavas and the formation of the lower Grand Canyon and showing that the lavas should be an excellent aquifer, as yet untapped.

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INTRODUCTION

Three regions having a combined area of approximately 30,000 sq. km have been mapped using ERTS photography. Work was carried out on the Shivwits Plateau, Coconino Plateau and in the Verde Valley area, marked as A, B and D respectively in Fig. 1.

Standard NDPF products, 1:200,000 and 1:125,000 scale enlargements, as well as computer enhanced digital tapes, were used. Several types of computer processing were applied to the images and each was evaluated for the type of application encountered. The applications discussed below were derived, in some cases serendipitously, through the process of regional geologic mapping at ERTS scales. The synoptic view provided the key to the results discussed below.

VERDE VALLEY

The north-central Arizona test site was chosen originally because of the good geologic map coverage and, therefore, as an area in which automatic mapping methods based on spectral reflectivity could be tested. This test site includes areas that have been mapped in detail at 1:48,000 and 1:62,500 scale. However, a large part of the area has only been mapped in reconnaissance at 1:375,000 scale for the Geologic Map of the State of Arizona(1969); published at 1:500,000 scale. A part of the state geologic map that includes the north-central Arizona test site is shown, without explanation, in Fig. 2.

Geologic Map

The ERTS-1 images allow details of the distribution of several of the geologic units to be improved with respect to the state geologic map. The images, employed with the detailed geologic maps, led to the identification of the units that are shown in Figs. 3a and 3b. The legend is given in Fig. 3c. The product is a regional geologic map referenced to a near-orthographic photo-base. Geologic detail is degraded with respect to standard geologic quandrangle maps, but is improved with respect to areas that only have been mapped in reconnaissance. A geologic map referenced to an orthogonal photo-base allows relations of geologic units to physiographic, vegetational and structural characteristics if the terrain to be evaluated from a single display. Transfer of the planimetric geology to a topographic base allows complementary analysis using standard techniques.

Basalt of late Tertiary age was easily discriminated on the ERTS images, but, not unexpectedly, appeared similar to gabbro of Precambrian age. A tuff-bearing area in a basaltic flow sequence was identified and mapped in the southeastern part of the map area. Such features are not represented on the state map. Quaternary and Tertiary sediments overlie and underlie the Tertiary basalts, and were mapped with fair ease. Details of their distribution were improved with respect to the state map. However, details of the stratigraphy in the paleozoic rocks could not be resolved, although the red Supai Formation of Pennsylvanian and Permian age was apparent on

115° 114° U 113° T A 112° H 111°

37°

A   R   I   Z   O   N   A

NEVADA

AREA
EMPHASIZED

A

R I V E R

C
O
L
O
R
A
D
O

36°

C

Kingman

Williams   Flagstaff

35°

CALIF

A   R   I   Z   O   N   A

D

Prescott

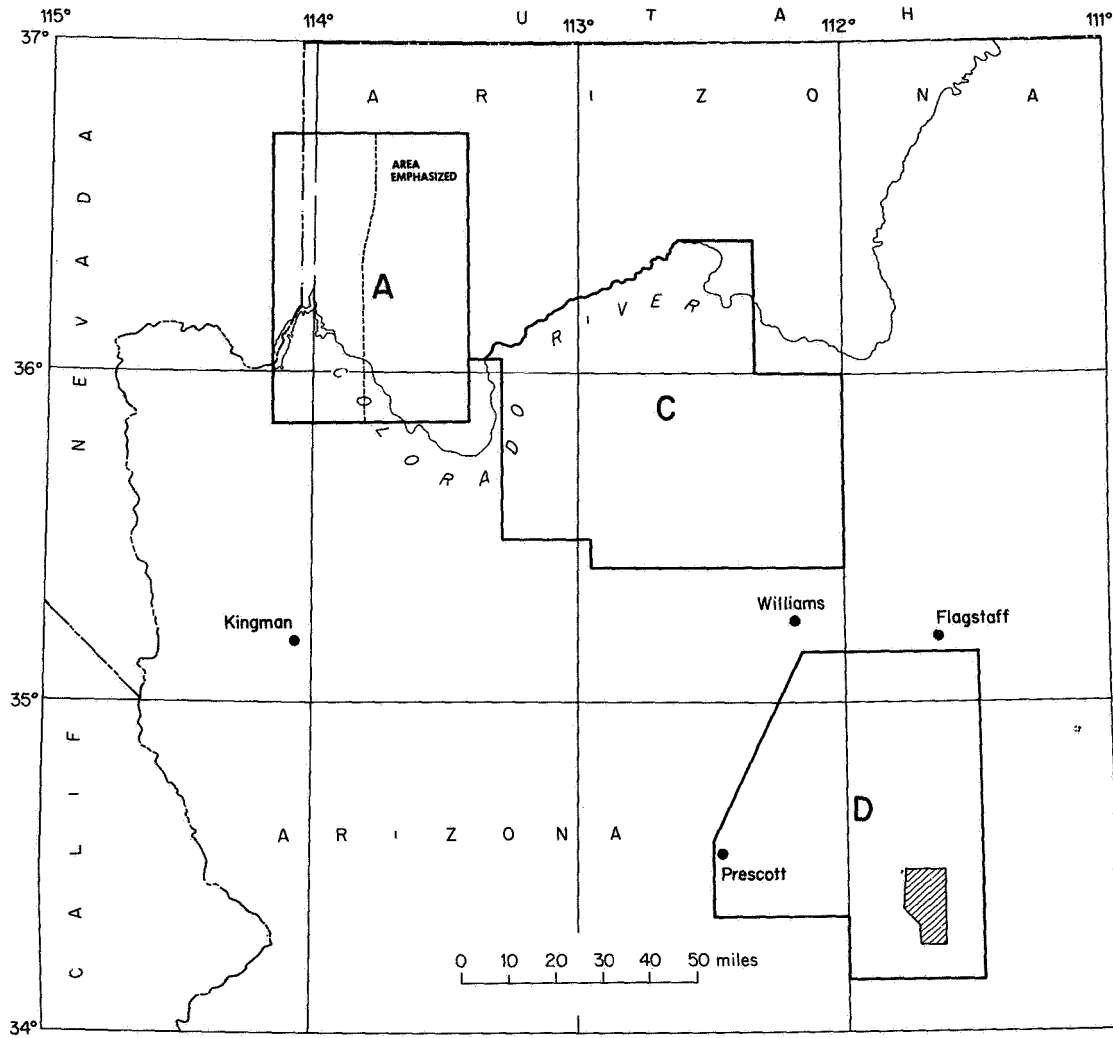0 10 20 30 40 50 miles

34°

Figure I. Location map showing areas in which ERTS
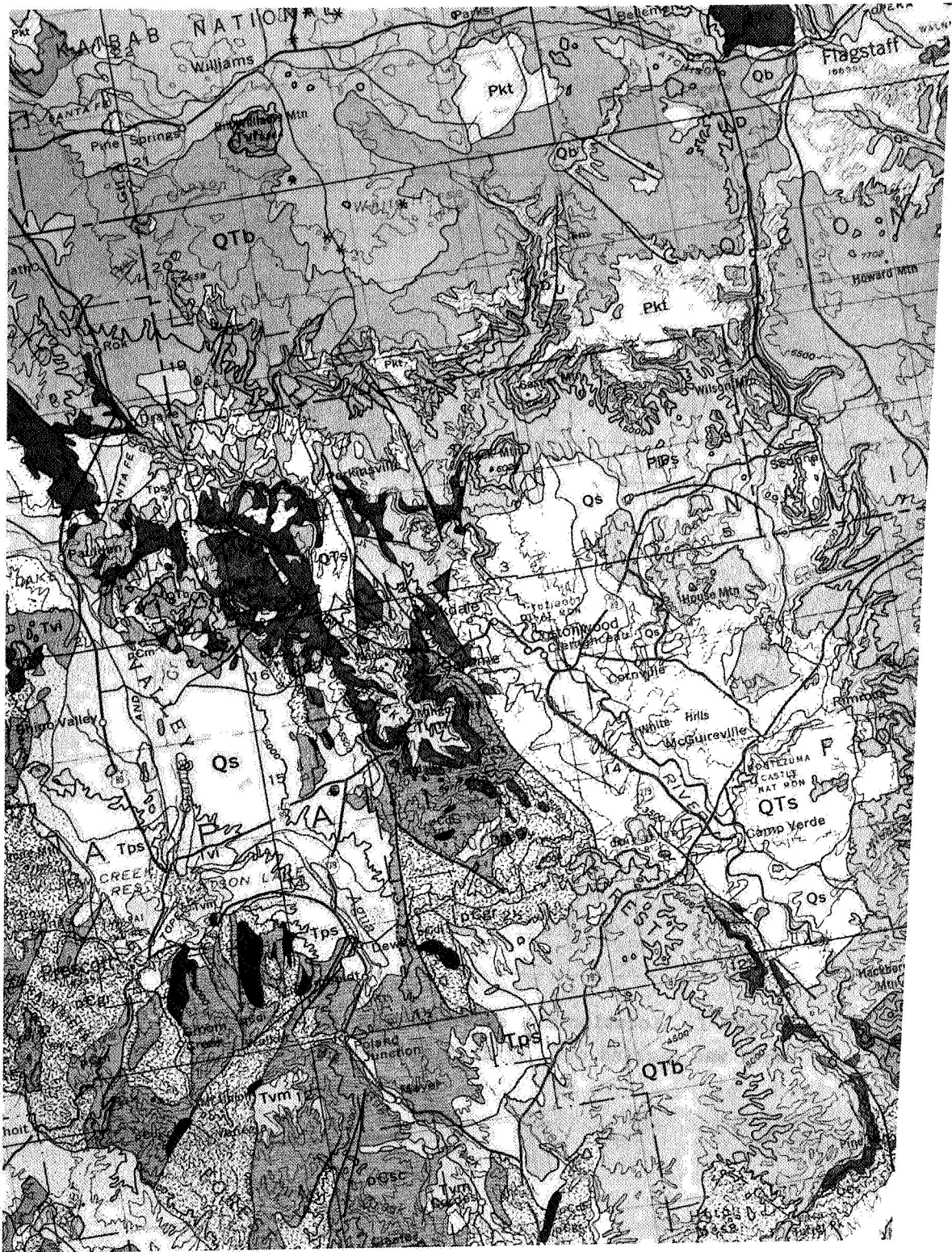work was carried out, as discussed in this paper.

Figure 2. Geologic map of north-central Arizona taken from the Geologic Map of the State of Arizona, 1969; I:500,000 scale.
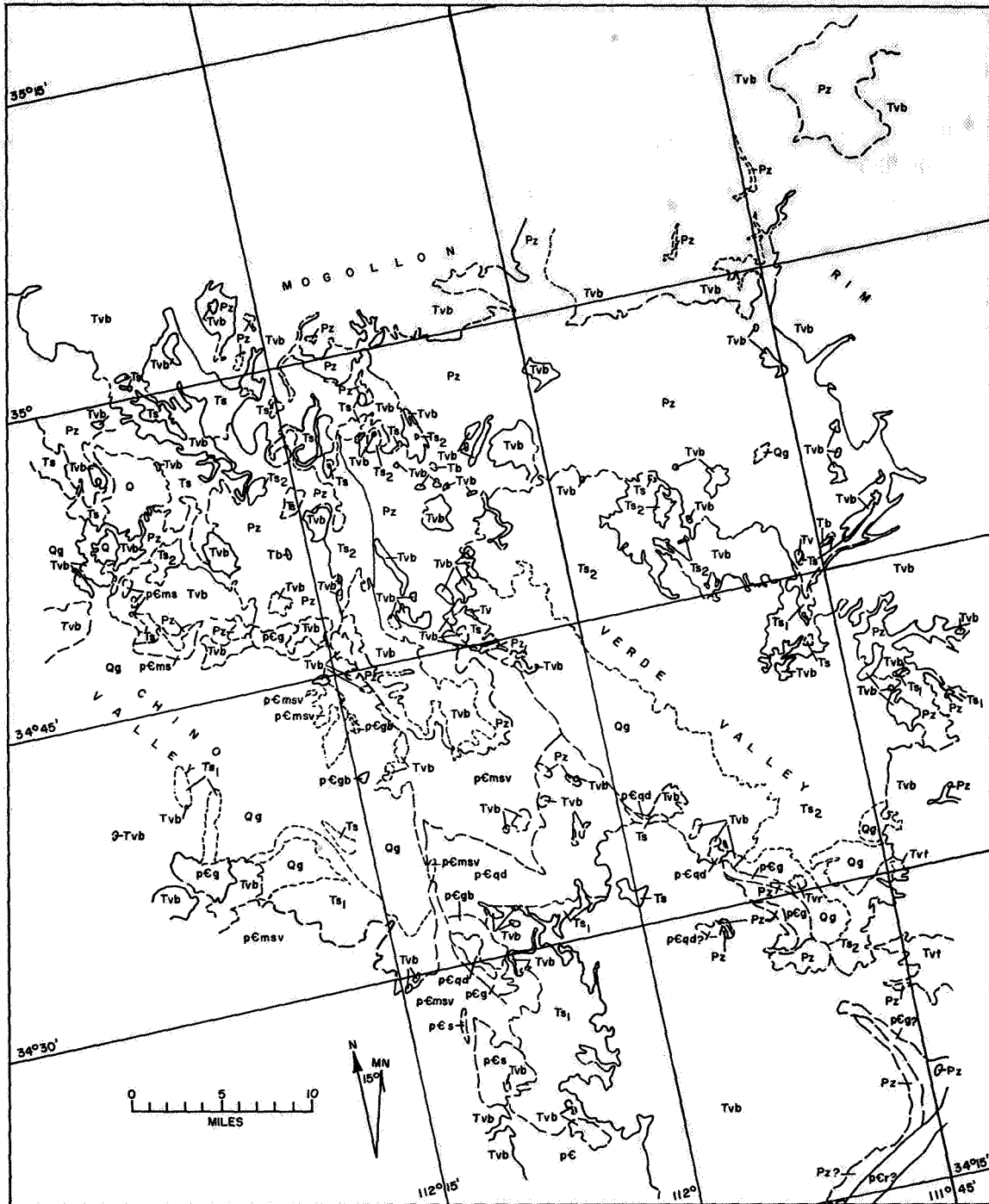
Figure 3a. Geologic map of north-central Arizona compiled from published
and unpublished information on ERTS-I photobase. Legend is given in Figure 3c.
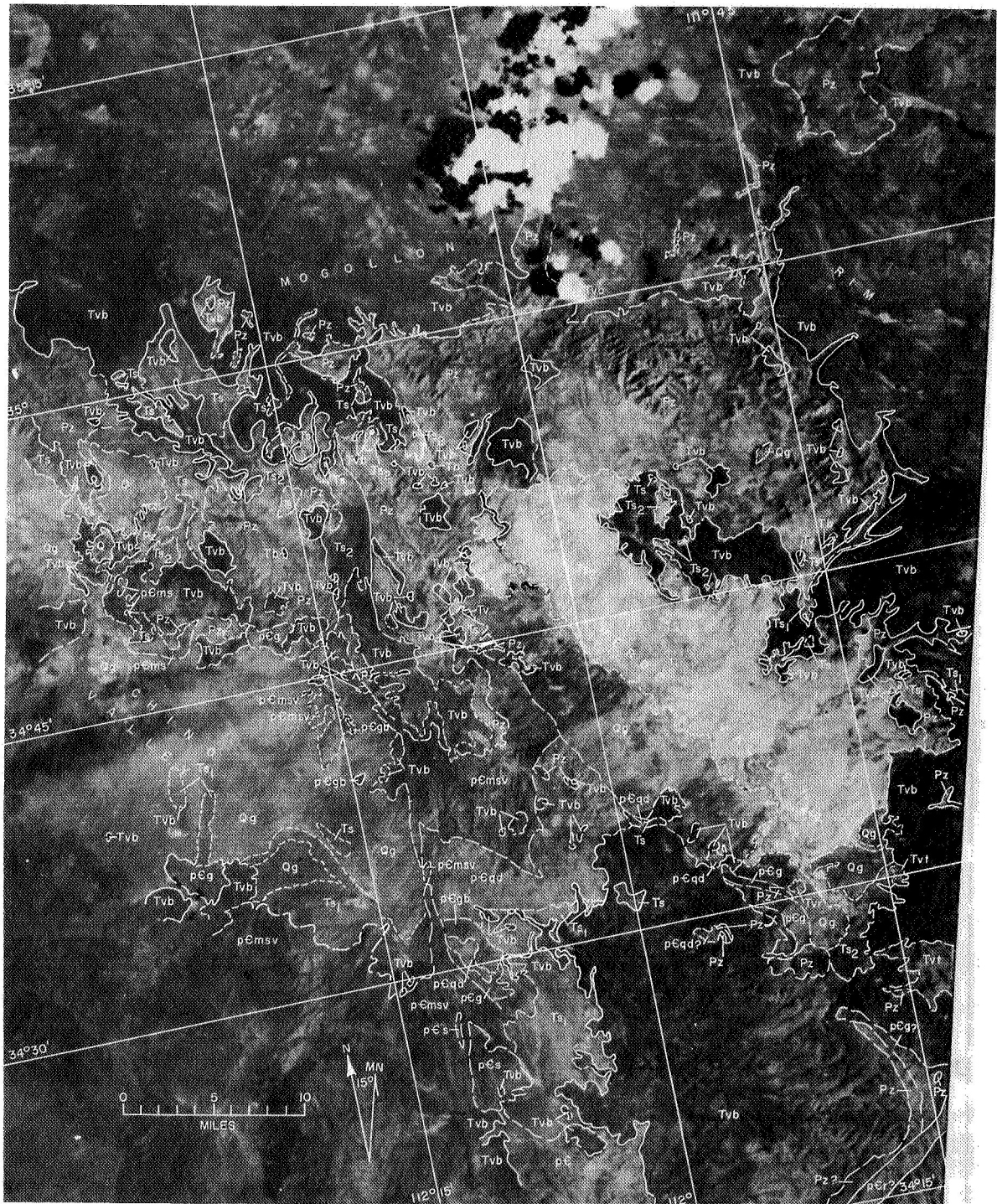
Figure 3b. Geologic map of north-central Arizona compiled on frame EIOI4-I7375 photobase from published and unpublished information. Legend in Figure 3c.

EXPLANATION

Sedimentary Rocks   Metamorphic Rocks   Igneous Rocks

Quaternary

| Qg |

Gravel and alluvium

Tertiary

| Ts_2 |

Sandstone and lake beds

| Ts_1 |

Sandstone

Paleozoic

| Pz |

Sandstone and limestone,
undivided

Precambrian

| pЄms |

Quartzite

Volcanic Rocks

| Tvb | Tvt |

Basalt
Tuff

| pЄqd | pЄg |

Quartz diorite
and granite

| pЄr |

Rhyolite

| pЄmsv |

Metasedimentary
and metavolcanic rocks

| pЄgb |

Gabbro

————— —— ——— ——————

Contact Dashed where approximately located; short dashed
where indefinite

Fault and Lineament map:

————+——— —— —— —————·········
     ↓

Fault; from published geologic maps. Bar and Ball
on downthrown side. Dashed where approximately located
dotted where concealed.

————————— —— ——·———— ···· —··

Lineament Long traces reflect strongly developed
trends, some of which are inferred to be faults. Inter-
mediate and short dashed lines reflect degree of trace-
ability of individual lineaments; dots reflect an align-
ment of one or more vague linear features.

Figure 3c. Legend for Figures 3 and 4.

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false color composites of the multispectral images. As a consequence, all Paleozoic rocks were mapped as one unit. In this respect, the state geologic map is far superior. In contrast, more Precambrian units could be identified in the ERTS images than are shown on the state geologic map, and for the older rocks the ERTS "photogeologic" map is an improvement. We conclude that ERTS images at ~ 1:200,000 scale, employed with conventional photogeologic and field geologic techniques, can lead to improved geologic reconnaissance maps.

Fault and Lineament Map

The most striking geologic aspect of the ERTS images is the synoptic view they provide of fracture and lineament patterns that occur in basement rocks and in surficial deposits that mask the bedrock and basement. Faults and lineaments in north-central Arizona are shown on Figures 4a and 4b. The faults are from published maps. In a number of cases, the trace of a fault was less clear than the trace of nearby lineaments. Faults are shown as heavy lines on Figure 4 merely to allow them to be distinguished from the lineaments in this black-and-white illustration.

The north-central Arizona test site lies within the structural boundary of the Colorado Plateau Province, and only comparatively simple high angle normal or gravity faults displace the Paleozoic and Tertiary rocks. Thus, where Precambrian rocks are exposed, the structure that is seen principally reflects structure of Precambrian age. The dominant Precambrian lineament systems trend north, northeast and east. The north- and northeast-trending systems are strongly developed. In contrast, northwest-trending faults and lineaments mainly appear to reflect comparatively recent structural adjustments in the Tertiary, and they are subdued with respect to the Precambrian systems. However, the Precambrian structural grain has been imparted to the younger Phanerozoic rocks, and the major lineament systems have been sites of renewed structural adjustments. The Oak Creek fault in the northeast part of the map area, which is seen to displace only Paleozoic and Tertiary rocks, almost certainly overlies a north-trending fracture system in the basement, analogous to the Shylock fault one in the south-central part of the map area. Similarly, northeast-trending lineament systems occur near Williams, Arizona, in the northern part of the map area (35° 45'N, $112^\circ12$'W). Eruptive centers of the late Tertiary San Francisco volcanic field in the Colorado Plateau are localized along these lineaments. Presumably, northeast-trending Precambrain fractures, analogous to the Chaparral and Spud faults in the southern part of the map area, underlie parts of the Plateau.

A myriad of fractures and lineaments occur in the Sedona area, west of the Oak Creek fault. ERTS images have revealed the existence of strongly developed east- and northeast-trending lineaments. Their existence apparently has led to the development of the erosional embayment in the margin of the Plateau here. Fracture systems in the Sedona area are currently being mapped in detail using NASA high altitude aircraft photographs in a first order photogrammetric plotter (Analytic Plotter Coordinograph). The photogrammetric analysis is being supplemented by geologic field mapping to produce ground truth data for comparative evaluations. Lineaments that have been plotted

Figure 4a. Fault and lineament map of north-central Arizona. Faults compiled from published information. Lineaments are from monoscopic and stereoscopic analysis of EI0I4-I7375.

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Figure 4b. Fault and lineament map from Figure 4a combined with EIOI4-I7375-7.

from ERTS images, and lineaments that are to be plotted from Skylab images, will be referenced to the detailed map information. This geologic work in the Sedona area also has the practical objective of defining areas structurally favorable for the localization of ground water resources in an area of burdgeoning population growth. This project is being carried out in close cooperation with the Water Resources Division of the USGS, Tucson as a part of their search for water in this area. Targets for future exploration of ground water are places where ancient and concealed karst (limestone cavern) ground in the Mississippian Redwall Limestone is intersected by through-going fracture systems at structurally favorable elevations, giving rise to potential underground 'rivers.'

On the plateau itself a set of northwest trending lineaments, seen on Fig. 4b near $35^{\circ}05'N$, $111^{\circ}40'W$, may also point to a favorable target for drilling for water in the Redwall Limestone approximately 700 m below the basalt cap. The lineaments have been provided to the City of Flagstaff and have been transferred to the city's working map. This map is being used for intermediate and long range planning for the development of Flagstaff's water resources.

Computer Enhancements

A number of types of enhancements were carried out using the digital data. The techniques are described in detail by Goetz and Billingsley (1973) elsewhere in these Proceedings. The most useful technique proved to be the simplest and least time consuming. Bands 4, 5 and 7 were contrast stretched by expanding the data to fill the dynamic range of the recording film. The color composites made from these stretched transparencies provided more information than any single band image. They also provided more than could be obtained from more sophisticated enhancements such as color ratio composites, and automatic classification routines. This result is due to the fact that most of the mapped units have strong absolute reflectivity differences in all bands, and a method such as ratioing which does not make use of the absolute brightness information fails.

COCONINO PLATEAU

Two specific problems and associated applications of the ERTS images evolved from the regional geologic mapping of the Coconino Plateau in the area shown in Figure 5. These applications are associated with faulting and the discovery of shallow, perched aquifers.

Faulting

Study of the low sun angle ERTS image of the Coconino Plateau (Fig. 6) revealed numerous faults in this previously, poorly mapped region (Fig. 7). In particular two parallel northeast-trending systems of normal faults, each of which can be traced at least 150 km, are seen. Many eruptive centers appear to be localized along these fault systems or along their extensions.

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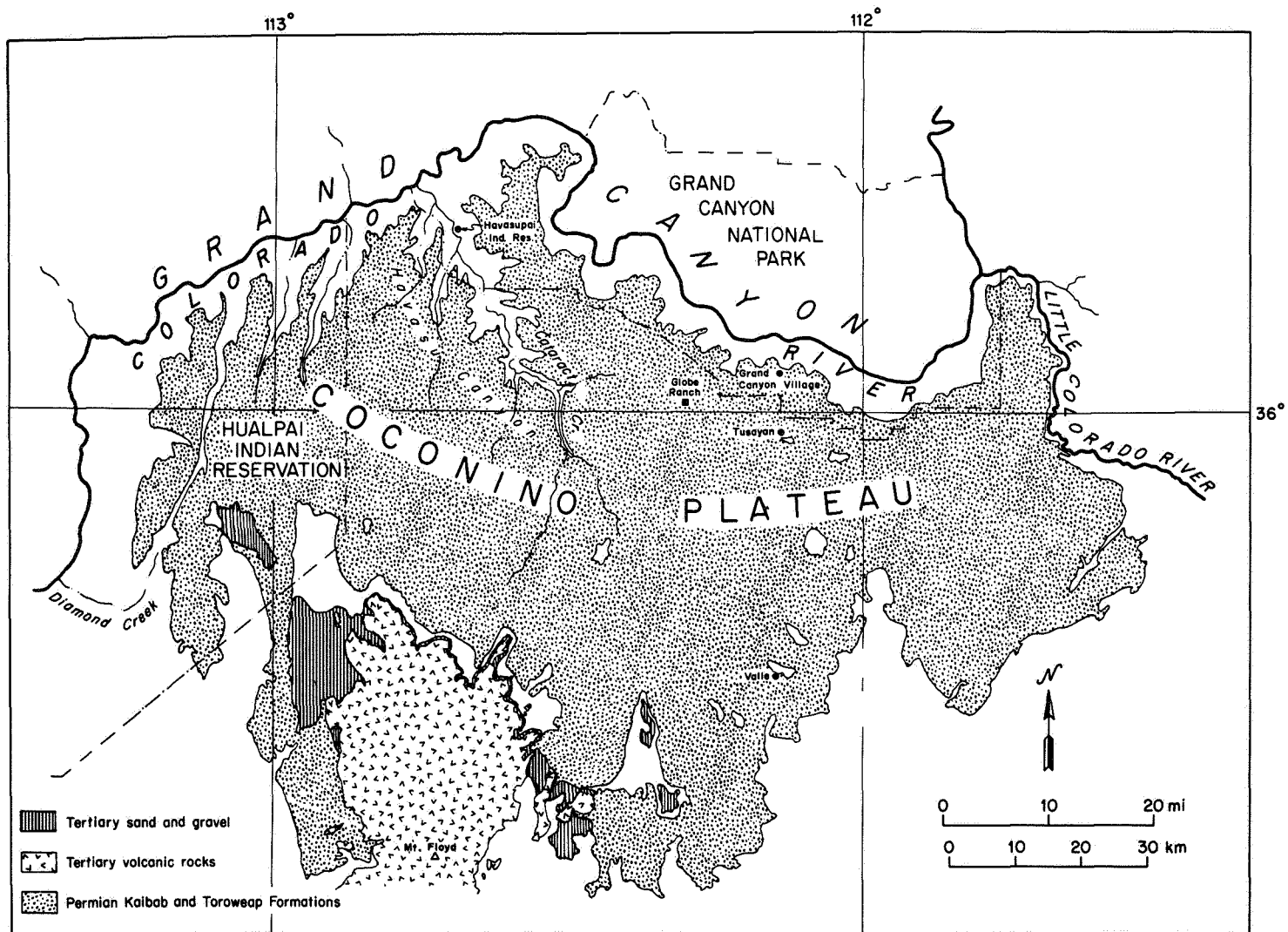Figure 5. Simplified geologic map of the Coconino Plateau, Arizona.

04NOV72 C N35-51/W112-19 N N35-48/W112-13 MSS D SUN EL33 AZ152 90-1450-G- N-D- L NASA ERTS E-1104-17382-7 0
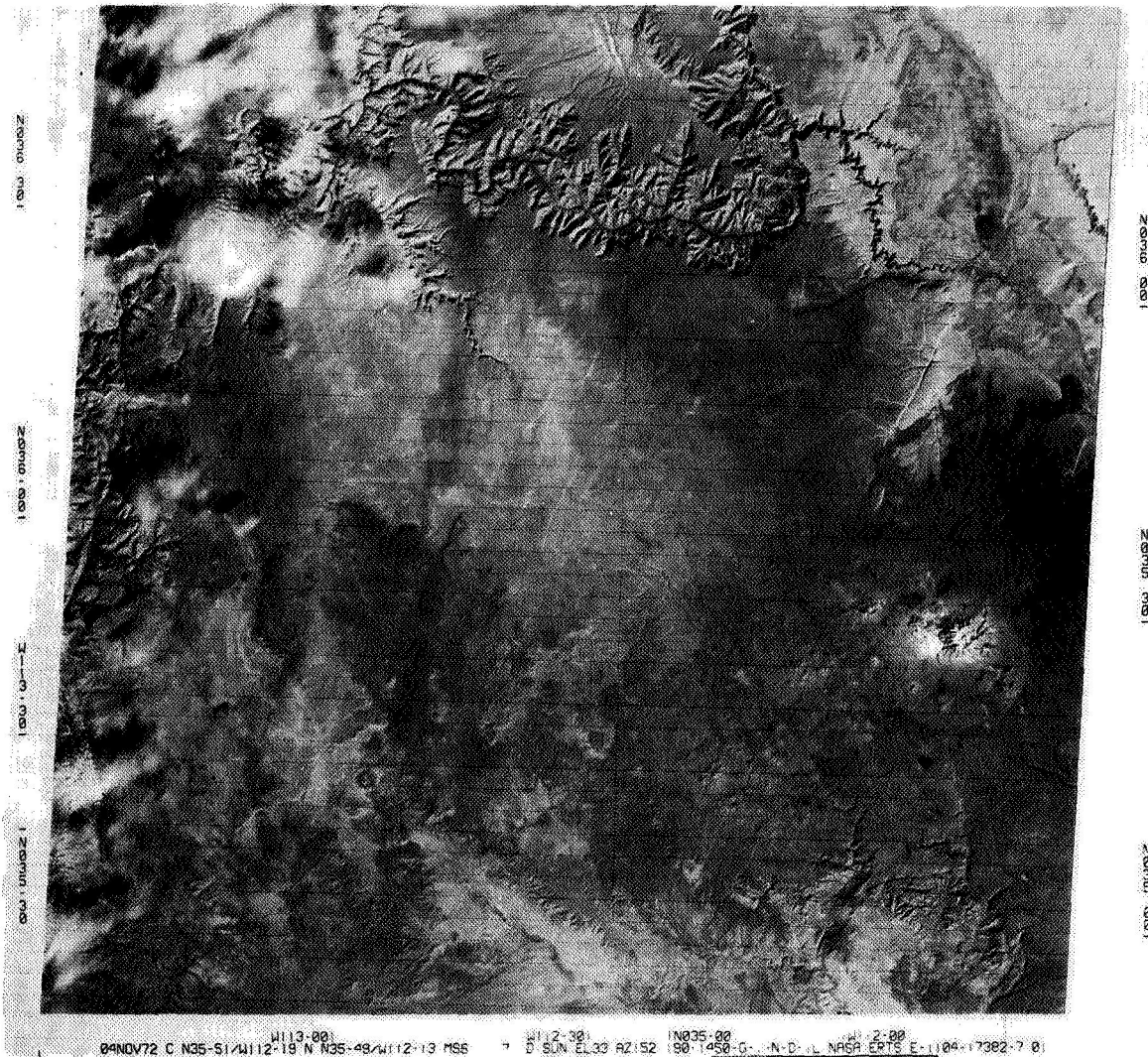
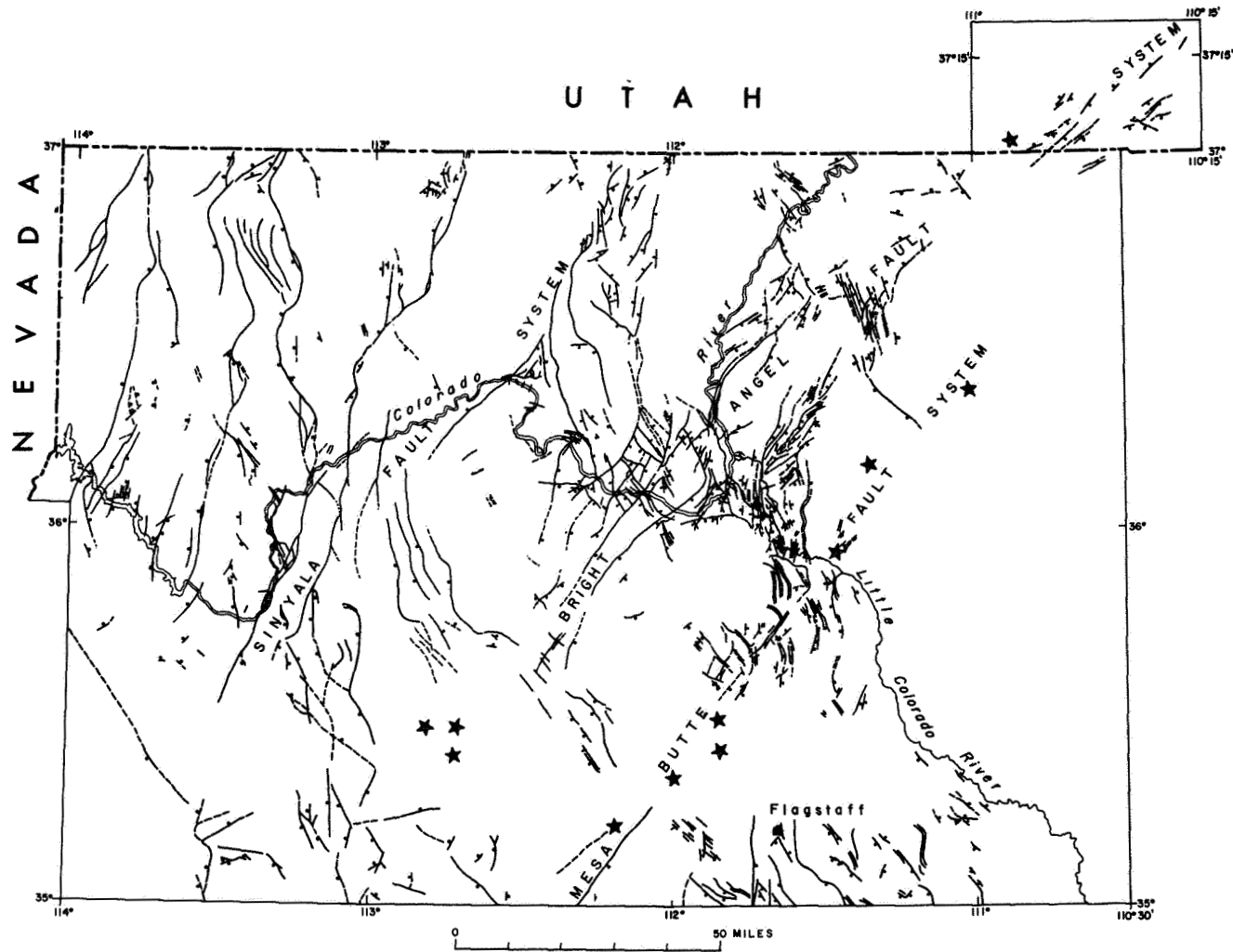Figure 6. Frame II04-I7382-7 showing Coconino Plateau and Grand Canyon.

Figure 7. Faults compiled from existing publications and new faults seen on ERTS mainly south of the Grand Canyon and west of the Mesa Butte Fault System. Stars are epicenters of magnitude 4 or greater earthquakes in the last 10 years.

The faults are chiefly observed in Phanerozoic rocks and have minor displacement, but are interpreted by us to reflect fault zones of major displacement in the crystalline Precambrian basement.

The Bright Angel fault system extends as a continuous zone of normal faults from Cataract Creek on the southwest to the Echo Cliffs on the northeast. Beyond the Echo Cliffs, the system continues northeastward, to the vicinity of Monument Valley, as a more diffuse, discontinuous zone of normal faults. The Navajo Mountain intrusive center lies along the discontinuous part of the system. Three major intrusive centers of the Mount Floyd volcanic field lie on the southwestern projection of the Bright Angel fault system. The Bright Angel fault and the Eminence fault are among the larger previously mapped individual members of the total system. If the eruptive centers are included as part of the recognizable structural system, the Bright Angel system has a total known length of 175 miles.

The Mesa Butte fault system, as now recognized, extends from the Tonto Rim on the southwest to Shadow Mountain on the northeast. Bill Williams Mountain, Sitgreaves Peak, and Kendrick Peak are principal calc-alkaline eruptive centers of the San Franciscan volcanic field that appear to be localized along the fault system. Red Mountain, Mesa Butte, and Shadow Mountain are prominent basaltic eruptive centers along the system, and the monchiquite diatremes at Tube and Wildcat Peak lie on the northeast projection of the fault system. The total distance from the Tonto Rim to Wildcat Peak is about 180 km.

Comparison of the Bright Angel and Mesa Butte fault systems with the residual aeromagnetic map of Arizona (Sauk and Sumner, 1970) reveals a close correspondence between the positions of the observed relatively minor normal faults and the margins of a series of large northeast-trending magnetic anomalies. Perhaps the most noteworthy feature of the aeromagnetic map is a 400 km-long northeast-trending belt of large positive aeromagnetic anomalies that extends from the vicinity of Congress Junction to the northern border of Arizona. The Mesa Butte fault lies along the southeast margin of this anomaly belt. Another large positive anomaly, bounded on the southeast by the Bright Angel fault, corresponds to a sequence of metamorphosed basic volcanic rocks (Brahma Schist of Maxson 1961), where the crystalline Precambrian is exposed in the Grand Canyon. Precambrian displacement on the Bright Angel fault was described by Maxson (1961), where the Precambrian rocks are exposed. We believe that most of the large positive aeromagnetic anomalies along the Bright Angel and Mesa Butte fault systems probably correspond to bodies of basic metavolcanic rocks in the crystalline basement complex which have been offset along two major and perhaps several minor faults of Precambrian age. The normal faults that displace the overlying Phanerozoic rocks have been formed by renewed movement along these ancient fault zones, in response to dilation of the crust from late Tertiary time to the present.

The ancient fault zones are inferred to be present along these ancient fault zones, in response to dilation of the crust from late Tertiary time to the present.

The ancient fault zones inferred to be present along the Bright Angel and Mesa Butte fault systems may be related in origin to the Shylock fault zone and Chaparral fault described by Anderson (1967) in central Arizona. Both the Shylock fault zone and the Chaparral fault have right-lateral transcurrent displacement. As shown by Anderson, the Shylock zone has a probable minimum horizontal displacement of five miles. A large contrast in the magnetic properties of the rocks on opposite sides of the fault zone, indicated by the aeromagnetic map, suggests the displacement may be several tens of miles or more. Comparably large right-lateral displacements may have occurred along the ancestral Bright Angel and Mesa Butte fault zones.

The location of epicenters of recent earthquakes, shown with stars in Fig. 7, and reports of earthquakes by residents in the region suggest that the Bright Angel and Mesa Butte fault systems are currently active. In 1912 an earthquake of intensity X (?) on the Rossi-Forel scale may have occurred on the Mesa Butte fault system.

Computer Enhancements

Figure 8 demonstrates a method for increasing the contrast greatly to enhance structural patterns. Figure 8a is an image of the relatively featureless Coconino plateau. Figure 8b is an image filtered to enhance the high spatial frequencies at the expense of radiometric accuracy. The origin of the fine NE and NW trending detail is not yet clear, although it may be a manifestation of the sub-resolution jointing pattern. Numerous faults, later mapped on the ground, can be seen in the otherwise featureless bright areas in the center of the image.

Figure 9a is a portion of Figure 6 near Cataract Creek and Havasu Canyon. Although the sun angle is only 33 degrees, the faulting in this region is barely visible. Figure 9b is a black and white rendition of a color combined ratio image, constructed specifically to locate perched sandstone aquifers discussed later. A side effect was to make visible the faulting in this area. The two white streaks in the lower left quadrant of the image are grabens filled with red colored alluvium. Without enhancement these faults are not visible or so faint that they could not be positively identified.

Water Studies

The Coconino Plateau is underlain chiefly by nearly flatlying to gently dipping sedimentary rocks of Paleozoic age. These rocks are locally offset along minor normal faults and along monoclines, structures which are typical of this part of the Colorado Plateau province. The Paleozoic rocks are locally overlain by the Moenkopi Formation of Triassic age and, in the southern part of the Plateau, by alluvial deposits and volcanic rocks of Tertiary and Quaternary age.

The Paleozoic rocks, about 1200 m thick, consist of an alternating sequence of sandstone, shale, and limestone (Fig. 10). These strata have been subdivided into ten mapped formations: The Tapeats Sandstone, Bright Angel Shale, and Muav Limestone, all of Cambrian age; the Temple Butte Limestone of

1014-17373-2 06AUG72 N36-01 W112-10 RED .6-.7 (1)
STRETCH
*** C A T A R A C T C R E E K *** FROM STRIPS 1 AND 2
INSECT
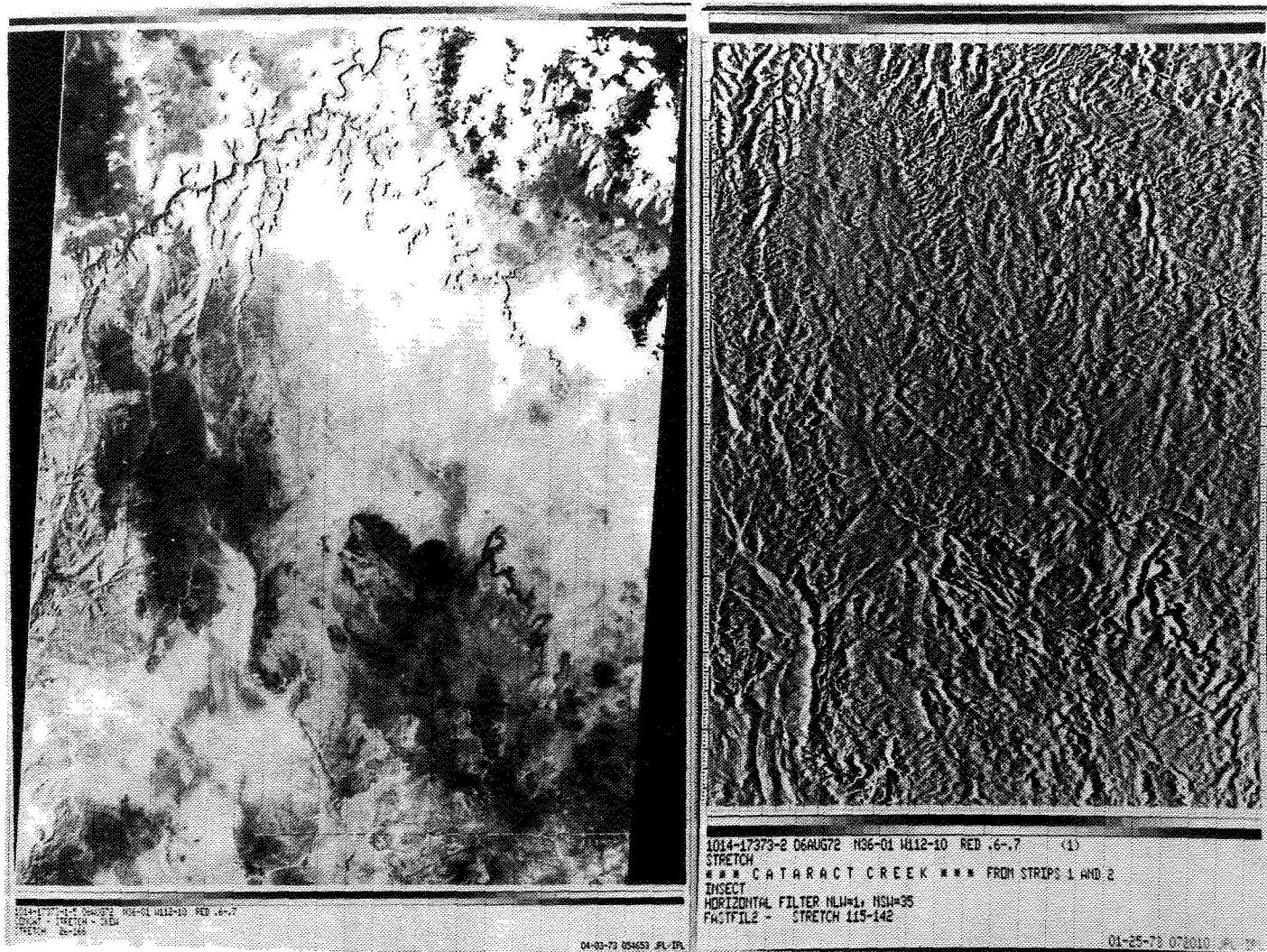HORIZONTAL FILTER NLW=1, NSW=35
FASTFIL2 - STRETCH 115-142

Figure 8a. Coconino Plateau EI014-17373-5 from digital tape.
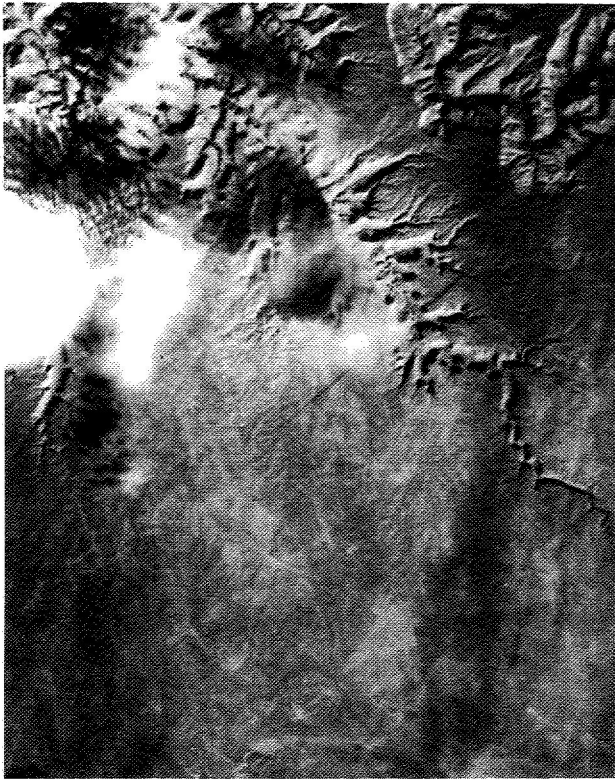Figure 8b. Spatially filtered version of Figure 8a to enhance linear elements.

Figure 9a. Portion of frame EIIO4-I7382-7.
Cataract Creek and Havasu Canyon bisects
the image.

Figure 9b. Black and white print taken from
a ratio color composite showing faults identified
as white in the lower left quadrant.

Devonian age; the Redwall Limestone of Mississippian age; the Supai formation of Pennsylvanian and Permian age; and the Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone, all of Permian age. About two-thirds of the Coconino Plateau is a stripped surface formed on the Kaibab Limestone, the highest Paleozoic unit; the total outcrop area of the Kaibab Limestone is about 8,000 square kilometers (Fig. 5). The older Paleozoic rocks are exposed chiefly in the Grand Canyon and in side canyons tributary to the Grand Canyon.

The Colorado River, at the bottom of Grand Canyon, flows at an elevation of about 1500 meters below the rim at the Coconino Plateau. Because the Canyon is so deep, and because most of the Paleozoic rocks underlying the Coconino Plateau are highly pervious, the water table beneath the Plateau lies at unusually great depth. In a general way, the water table slopes northward, toward the Grand Canyon. It descends from depths between 300 and 450 meters beneath the surface along the southern margin of the Coconino Plateau to depths as great as 900 to 1200 meters beneath the surface along the edge of the Canyon.

Only a small fraction of the annual precipitation on the Coconino Plateau is discharged directly by surface runoff. Most water not lost be evapotranspiration descends rapidly into the subsurface, along fractures and faults, and ultimately reaches the water table. This water is then discharged in two systems of very large springs, one deep in Havasu Canyon and the other deep in the Canyon of the Little Colorado River. The springs in Havasu Canyon are the source of a perennial stream that has sustained the simple agricultural economy of the Havasupai Indians for several centuries. The water issuing from both systems of springs is highly mineralized. A deep well that penetrates the water table south of Valle has shown that the water there is also highly mineralized.

Perched ground water occurs locally at depths much shallower than the water table (Fig. 10). This perched water is a major source of the water currently utilized on the ranches in the region and probably will continue to be a principal source of water produced locally for livestock, and for domestic consumption. The known supplies of perched ground water occur in five aquifers, the Coconino Sandstone, the Alpha Member of the Toroweap Formation, sandstone beds in the Alpha Member of the Kaibab Limestone, Tertiary deposits of alluvial sand and gravel beneath the Mount Floyd volcanic field, and Quaternary alluvium. The water is trapped, in a variety of structural settings above four different aquacludes. Water in the Coconino sandstone is trapped above the Hermit Shale. In the Alpha Member of the Kaibab Formation, water is trapped above claystone, siltstone and tightly cemented sandstone beds within the Kaibab. Important sources of water in Tertiary and Quaternary alluvial deposits are trapped above claystone and siltstone of the Moenkopi Formation.

In our investigation of the Cataract Creek Basin, the Alpha Member of the Kaibab Limestone has been divided into six stratigraphic units that have
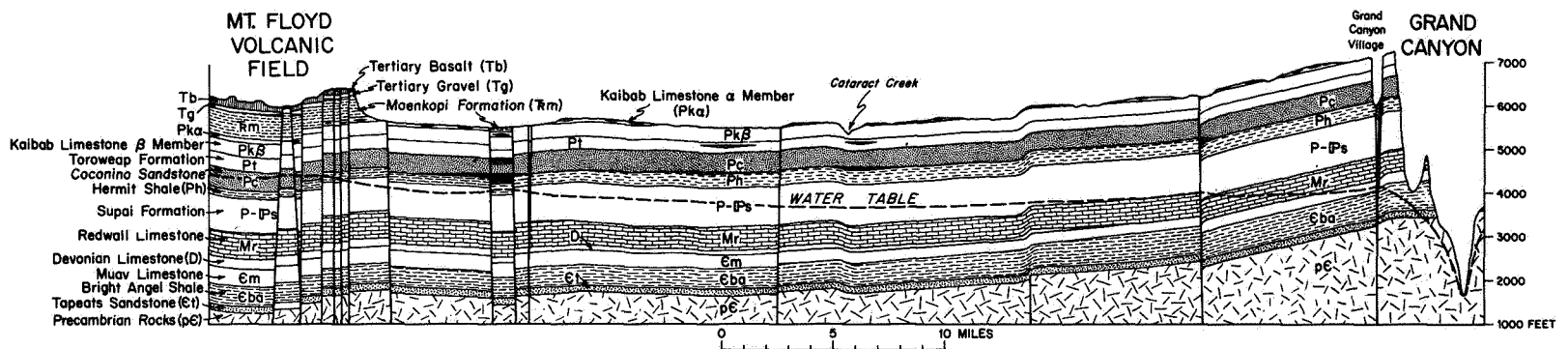
Figure IO. Cross-section derived from Coconino Plateau field mapping. Dark areas are inferred positions of perched groundwater.

been successfully traced across a major part of the basin. Three of these units consist of limestone. The limestone units are separated by two units of clastic rocks, one of which also contains local deposits of gypsum. A third unit of clastic rocks occurs at the base of the Alpha Member. The limestone units are gray to buff in color and form benches and ledges, whereas the intervening clastic units are typically reddish-brown in color and are slope-forming. In the work to date, we have shown that color ratio ERTS images can be used to discriminate and map individual units within the Alpha Member of the Kaibab. Ratio images, color combined so that the ratios 4/5, 4/6 and 6/7 are produced as blue, green and red respectively, make possible identification of the red sandstone units within the Alpha Member of the Kaibab which can be local perched aquifers.

At the Globe Ranch, near the rim of the Grand Canyon, a small amount of water is produced from a shallow well in a sandstone lens within the Alpha Member of the Kaibab. The sandstone is interbedded with red claystone and siltstone which form an impervious layer beneath the sandstone. The perched water table is only 5 meters beneath the surface at the site of the well. Recharge occurs from local runoff and from direct precipitation on the out-crop belt of the sandstone. This well provided water for the original home-stead at the ranch headquarters. Water is currently produced for stock at the rate of about 4,000 liters a week. Similar lenses of sandstone are scattered through the red clastic units of the Alpha Member. Many of these sandstone lenses may be local aquifers, which could constitute an access-ible source of ground water for the ranches on the Coconino Plateau.

In order to explore this possibility, the distribution of sandstone in the uppermost unit of clastic rocks in the Kaibab Limestone was mapped over an area of about 130 square kilometers in the vicinity of the Globe Ranch (Fig. 11) as a part of our ERTS-I investigation. This area can be identi-fied readily on the color combined ratio image discussed above. A series of very shallow test holes was then drilled in areas that appeared favor-able for recharge of ground water in the sandstone. Two out of eighteen exploratory holes encountered water. The distribution of the water is controlled by variation in the permeability of the clastic rocks as well as by conditions of recharge. The two waterbearing holes are currently being monitored and tested to determine potential production of water from the local sandstone aquifer. The results at this study show that ground water supplies in the Alpha Member of the Kaibab Limestone can be found at depths as shallow as 6 to 15 meters by an inexpensive program of drilling guided by geologic mapping.

Water is so scarce on the Coconino Plateau that the development of even small additional supplies at sites convenient for watering of stock is a matter of importance to the ranching industry. At some ranches, the water obtained from a single existing well is distributed through an expensive system of pipes to strategically located storage tanks and watering tanks. Elsewhere, water is hauled by trucks. In some cases shallow wells that are capable of producing as little as 400 liters of water per day can be and are being utilized. One of the purposes of this investigation is to find additional widely distributed shallow sources of water.
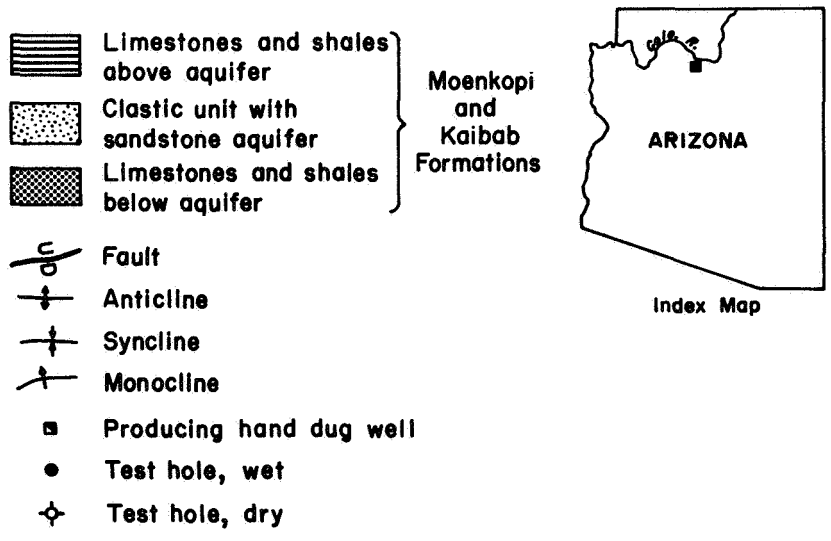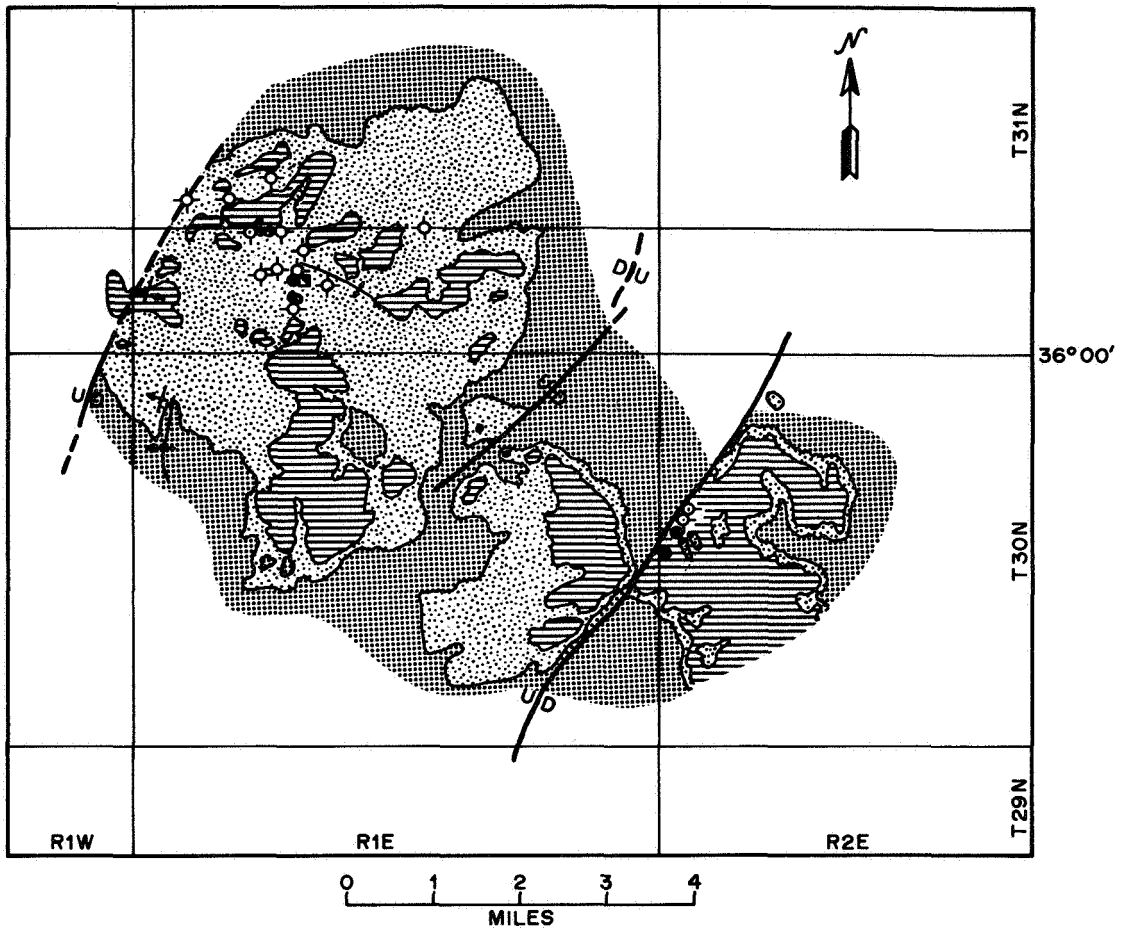
Figure II. Simplified geologic map of the Globe Ranch area, Coconino County, Arizona, with test hole locations.

SHIVWITS PLATEAU

The Shivwits Plateau is at the western boundary of the Colorado Plateau in northwesternmost Arizona and is seen in the upper center of Figure 12. The southern edge of the Plateau is marked by the Grand Canyon and the western margin by the Grand Wash Cliffs, which are a fault-line scarp along the Grand Wash fault. The eastern edge is at the Hurricane fault. The exceptional sharpness of the structural boundary between the plateau and the Basin and Range province makes the Shivwits critical for understanding the relations between the two provinces and the history of their common boundary. Because of its proximity to the mouth of the Grand Canyon and to the edge of the Colorado Plateau, the Shivwits Plateau also is very important for understanding the physiographic development of the region in general and the history of the Colorado River in particular. All these characteristics are being used in the present study, which is intended to combine conventional geologic techniques with the special advantages of ERTS photographs. During the course of this study an improved understanding of the geology of the Shivwits Plateau has resulted in practical applications that were not foreseen when the project was started. These applications are discussed below.

Structural Evolution

The Shivwits Plateau and adjacent parts of the Colorado Plateau differ from the Basin and Range terrane to the west in physiography, amount and kind of deformation, crustal properties, and geologic history. Many of these differences go back as far as Paleozoic time. Parallelism of the structural grain of the Plateau with that of the adjacent Basin and Range Province indicates that the two crustal blocks have been subject to the same stress field, but the more subdued deformation of the Plateau indicates that it has behaved as a competent, buttress-like block. Deformation of the Plateau has been controlled by the basement. Fractures in the basement -- some probably very old -- have repetitively localized and focused deformation occurring in response to varied stress fields. Thus, the Laramide compressive field resulted in deformation expressed at the surface by folding and warping; the subsequent extensional stress field related to basin-range deformation resulted in normal faulting along the same lines of weakness. The tectonic map of the western Plateau probably is a map of basement fractures. Shear stresses are reflected by transcurrent faults in the Basin and Range, and by sets of fractures with anomalous trends on the Plateau. These fractures have no transcurrent displacement, but were utilized by block faulting. Intersection of these anomalous fracture sets with the more common north-trending structures seems to have localized the only mineralization of commercial value in the area.

Physiographic Evolution

The physiography of the Shivwits Plateau has been controlled by these factors: (a) ancient uplift and erosion southwest of the present margin of the Plateau; (b) gentle structural dip to the northeast; (c) interlayering of hard and soft strata; (d) faulting; (e) effusion of lava; (f) incision by the Colorado River. These factors have resulted in the following physiographic elements: (a) cuesta scarps formed wherever hard layers lie over soft ones. These scarps originated from the ancient uplift southwest of the Plateau, and
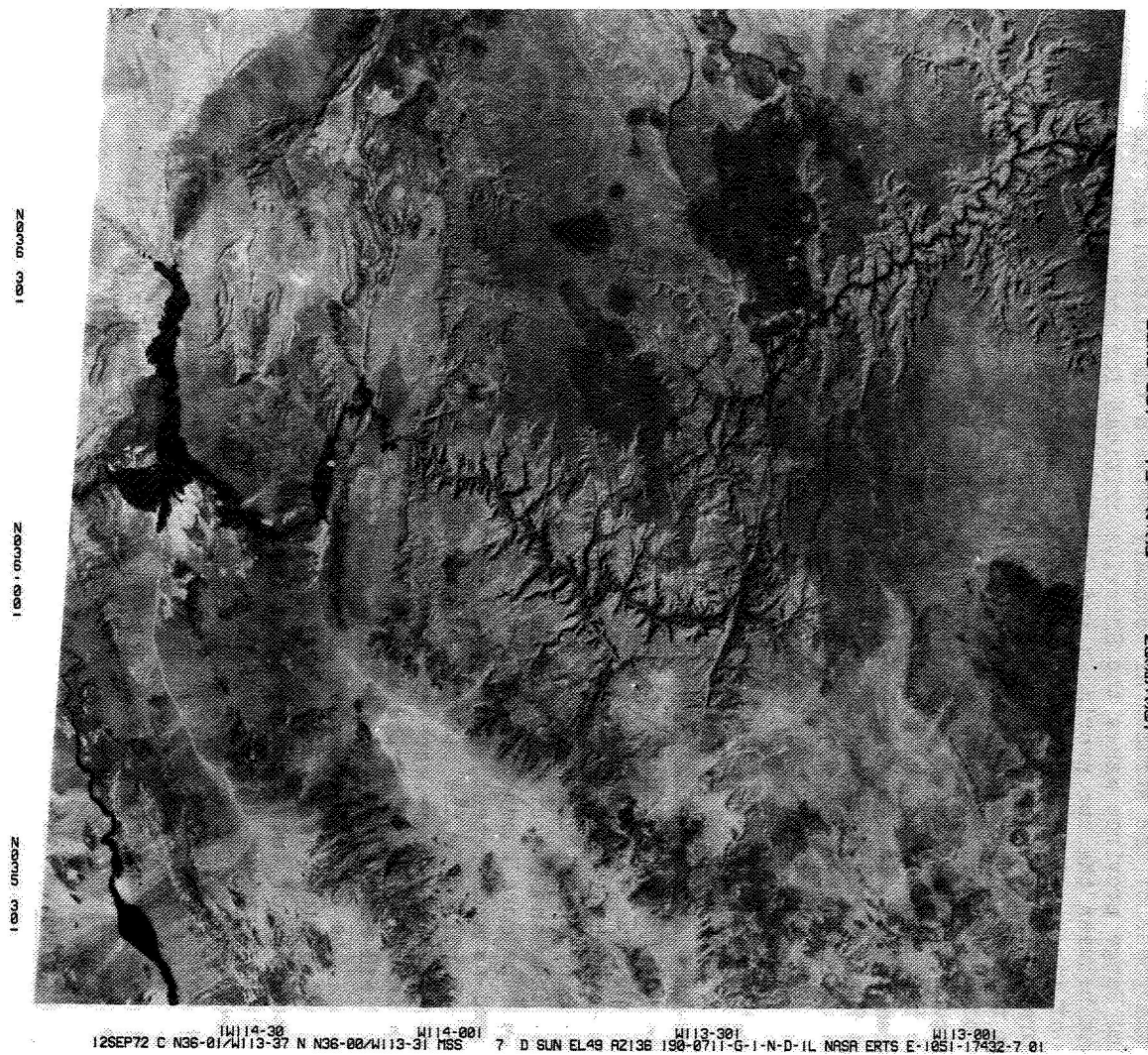
Figure I2. Frame EI05I-I7432-7 showing the Shivwits Plateau area in the upper center. The Shivwits lava is the dark material trending toward the upper left of the image.

have been retreating northeast down the structural slope; (b) cuesta troughs
(strike valleys) at the foot of the cuesta scarps. They trend northwest
to north-northwest and have been the major factor in controlling drainage
directions; (c) stripped surfaces following particularly resistant strata;
(d) erosion surfaces bevelling strata approximately equally resistant to
erosion; (e) lava plateaus; (f) canyons. These are a relatively recent and
minor, though impressive, element formed in response to incision by the
Colorado River; (g) fault scarps produced by relatively recent movement on
major faults.

Ancient drainages flowed mostly north-northwest along broad cuesta troughs.
These drainages represent the pre-Grand Canyon drainages in northwest
Arizona. In part, they may represent an ancient northerly trend of the
Colorado River before the river established its westward course through
the western Grand Canyon. One of these valleys was followed by the Shiv-
wits lavas, which rest on a surface of low relief that is incompatible
with a canyon landscape in the vicinity. If the 6 m.y. radiometric age for
the lavas is correct, the western Grand Canyon must have been cut more
recently than that date.

Ground Water

Water is extremely scarce on the Shivwits Plateau, and is the single most
important factor in controlling the usability of the area. In the course of
this study, it has become apparent that the few known shallow water resources
on the Shivwits occur where the lavas rest on impermeable shales of the
Triassic Moenkopi Formation. The lava is fractured, and serves as an aqui-
fer. Where the lava rests on the Moenkopi Formation, the water percolating
through the lava is trapped at the base of the lava, and flows down the axis
of the ancient valley that had been partially filled by the lava. Where the
lava and the Moenkopi are cut by faults transverse to the old valley, the
down-valley flow is interrupted and ground water ponds up on the upstream
side of the fault. These are the most favorable places for exploration and
development of new shallow-water resources.

Value of ERTS

ERTS photographs have proven indispensable for providing the regional per-
spective in the Shivwits area, without which it would have been much slower
and more difficult -- perhaps even impossible -- to reach an understanding
of the structural and physiographic development of the Shivwits Plateau area.
Thus, for example, the ERTS photographs have illustrated very clearly the
structural grain of the Shivwits Plateau, its relation to the grain of the
Basin and Range Province, and the location and alignment of anomalous struc-
tural features. In some instances, ERTS photographs have permitted extension
of faults that were difficult to map on the ground because of poor exposure
or difficult access. ERTS photographs have also pointed out the physiographic
grain of the region, the importance of cuesta scarps in controlling drainage,
and the relation between lava flows and ancient valleys. It is doubtful
that any of these would have been understood without the perspective pro-
vided by the photographs. No large scale attempt has yet been made to use
computer enhanced images.

SUMMARY

ERTS image data has been applied to three related geological provinces with diverse individual problems. The scale of ERTS has been shown to be valuable for reconnaissance geologic mapping and the synoptic view has proved to be invaluable.

Subtle reflectivity differences among rock units can be detected by computer enhancement techniques. These differences have been shown to be valuable for locating possible perched aquifers on the Coconino Plateau. However, intensive groundwork must be carried out to identify logical points for shallow test drilling in these areas.

Numerous faults and fractures have been identified for the first time. Their relative activity is important for seismic hazard evaluation. The fractures have an important bearing on where the drilling for water in the Flagstaff and Sedona areas should be attempted. The general orientation of this ERTS study toward applications results has been fruitful.

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