PTYS 597a

PLANETARY FIELD GEOLOGY PRACTICUM

Field Trip 24-26 April 1992

The University of Arizona
Tucson, Arizona
# Table of Contents

## First Day: 24 April 1992
- **Oracle Junction to Globe**
  - John Stansberry and Jim Head

## Geology of the San Manuel Ore Body: A Classic Porphyry Copper Deposit
- Don Musselwhite

## The El Capitan Catastrophic Landslide
- Will Grundy and Mark Lemmon

## Salt River Canyon
- Lisa McFarlane and Jeff Johnson

## The Springer Volcanic Field: An Example of Plio-Pleistocene monogenetic volcanism in Arizona
- Randy Tufts

## Rim Gravels
- Mike Nolan

## Second Day: 25 April 1992
- **Petriified Forest**
  - Steffi Engel

## The Chinle Formation of the Painted Desert
- Bill Bottke

## Formation Processes of Sapping Valleys
- Goro Komatsu

## Comparisons, Mars and Venus

## Sapping Features: Morphology
- Valerie Hillgren

## Canyon de Chelly
- Erik Asphaug and Andy Rivkin

## Third Day: 26 April 1992
- **More Canyon de Chelly**

## Hopi Buttes
- Ellen Howell

## Reservation Country
- Kevin Garlow

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1. West.
2. Your helpful hosts.
3. May be moved to day 2, depending on time.
<table>
<thead>
<tr>
<th>ERA</th>
<th>PERIOD</th>
<th>EPOCH</th>
<th>AGE (mil yr)</th>
<th>DOMINANT LIFE FORMS</th>
<th>EVENTS IN ARIZONA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Holocene</td>
<td>0.01</td>
<td>Present erosion cycle gouges Pleistocene and Tertiary deposits. Basalt volcanism continues near San Francisco Peaks and at a few other sites.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pleistocene</td>
<td>2</td>
<td>Regional uplift accelerates erosion; cyclic erosion creates terraces. Basalt volcanism occurs in several areas; San Francisco Peaks grow, collapse, and are glaciated. Colorado River flows through Gulf of California. Fluvial lakes occupy some valleys.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pliocene</td>
<td>5</td>
<td>Colorado River turns west, initiates canyon cutting on Colorado Plateau. Little Colorado reverses in recurrent movements lift plateaus. In south, basin fill with streams and lake deposits.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Miocene</td>
<td>24</td>
<td>Basin and Range Orogeny 15 to 8 million years ago creates fault-block ranges with NW-SE grain. Basalt volcanism widespread.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oligocene</td>
<td>38</td>
<td>Mid-Tertiary orogeny 30-20 million years ago pushes up mountains with NE-SW grain. Metamorphic core complexes form. Colorado Plateau rises; Colorado River flows south, east of Salt River by Dinosaur. Verde Valley intercepts northerly drainage. Explosive volcanism common, with calderas in Chiricahua and Supersition Mountains.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eocene</td>
<td>65</td>
<td>Tension faulting in south is accompanied by volcanism and intrusion of dikes, stocks, laccoliths. Intermountain valleys fill with debris from mountains. Verde Valley begins to form.</td>
<td></td>
</tr>
<tr>
<td>CENOZOIC</td>
<td>Age of Mammals</td>
<td>Tertiary</td>
<td>50</td>
<td>Laramide Orogeny ends 50 million years ago, leaving uneroded intermountain valleys, some with lakes. No volcanism or intrusions mark &quot;Eocene magma gap.&quot; Northbound streams deposit ring gravels.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cretaceous</td>
<td>63</td>
<td>In south, Laramide Orogeny creates mountains with NE-SW trend; overthrusting may have occurred. Explosive volcanism occurs. Abundant small intrusions appear, some containing copper, silver, gold. In north, plateaus begin to form as large blocks are lifted or dropped.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Age of Reptiles</td>
<td>Jurassic</td>
<td>138</td>
<td>Seafloor briefly from west and south; volcanism widespread. Laramide Orogeny begins 75 million years ago as west-drifting continent collides with outlying plates.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Triassic</td>
<td>205</td>
<td>Deserts widespread; thick sand and dune deposits in north. Explosive volcanism in south and west is followed by erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Permian</td>
<td>240</td>
<td>Extensive coastal plain, delta, and dune deposits spread north from mountains in central and southern Arizona. Faulting, small intrusions, explosive volcanism occur in south.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Age of Fishes</td>
<td>Pennsylvanian</td>
<td>290</td>
<td>Dunes form across northern Arizona, then a western sea invades briefly. Alternating marine and non-marine deposition in south and west.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mississippian</td>
<td>330</td>
<td>Marine limestones deposited in south and south-central Arizona; floodplain and desert prevail in north.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Devonian</td>
<td>365</td>
<td>Widespread deposition of fossil-bearing marine limestone is followed by emergence and development of karst topography with sinks and caves.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silurian</td>
<td>410</td>
<td>Marine deposits form, then are removed from many areas by erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ordovician</td>
<td>435</td>
<td>No record.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cambrian</td>
<td>500</td>
<td>Brief marine invasion, then no record.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>570</td>
<td>A western sea advances across denuded continent, depositing conglomerate and sandstone, then shale and limestone.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Younger</td>
<td></td>
<td>1700</td>
<td>Great Unconformity — long erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Older</td>
<td></td>
<td></td>
<td>Several episodes of mount-building and intrusions of sills and dikes are followed by marine and near-shore sedimentation, faulting, and uplift.</td>
<td></td>
</tr>
<tr>
<td>PRE-CAMBRIAN</td>
<td></td>
<td></td>
<td></td>
<td>Sedimentary and volcanic rocks accumulate, then are compressed and altered into NE-SW-trending ranges extending beyond Arizona. 1.7 billion years ago granite batholiths intrude these older metamorphic rocks.</td>
<td></td>
</tr>
</tbody>
</table>

After Chronic. 1983.
PTYS 597a

PLANETARY FIELD GEOLOGY PRACTICUM

Field Trip 24–26 April 1992

Day 1
Tucson to Show Low
# Highway 77: Oracle Jct. to Globe

## Key to geologic map

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description / Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>highway</td>
<td></td>
</tr>
<tr>
<td>I-10</td>
<td></td>
</tr>
<tr>
<td>river</td>
<td></td>
</tr>
<tr>
<td>fault</td>
<td></td>
</tr>
</tbody>
</table>

### Intrusive Igneous

- **Oracle Granite** (1.4 Ga)
  - Diabase, Mescal Mtns
  - North of Globe

- **Pinal Mtns Granite**
  - Galindo Mtns Tertiary intrusives

### Volcanic

- **Galindo Mtns**
  - Tertiary Andesite
  - Cretaceous Andesite

- **Gila River Canyon**
  - Cretaceous Andesite

### Metamorphic

- **Pinal Schist**
Sedimentary

Black Hills
- Cretaceous Shales, Quartzite, Limestone

Camp Grant Wash & northward
- Apache Group, Precambrian
- Paleozoic Limestone

Gila River Canyon
- Naco Limestone, Pennsylvanian

Mescal Mountains
- Naco Limestone
  - Bolsa Quartzite, Cambrian
  - Martin Shale, Devonian
  - Escabrosa Limestone, Mississippian
- Mescal Limestone / Apache, P.C. Dripping Spgs. Quartzite
- Pioneer Shale
- Barnes Conglomerate
Spring 1992 Field Trip Experience

Hard rocks between Oracle and Globe along US 77, conducted by Jim Head (West)

We will be able to see rocks from nearly the entire sedimentary section on the way to Globe. The units visible from Route 77 and a sedimentary sequence are shown below. These compliment the geologic sketch map in John Stansberry's section. The rocks represented along the route are listed by age in the table and are marked by an asterisk in the sedimentary section. John will handle the sedimentary rocks and I'll discuss the igneous and metamorphic rocks. There will be considerable overlap. The hard rocks you should notice (in order of appearance) are

1) Oracle granite (1.55Ga), near Oracle. Note color and presence of zeoliths.
2) Fault contact of Precambrian granite and Cenozoic gravels, past San Manuel turnoff. Note that this granite differs from the Oracle granite.
3) Tertiary volcanics, west side of road, north of Aravaipa Creek.
4) Contact between Cretaceous volcanics and the Naco limestone, north of the big anticlinal arch.
5) Older Precambrian granite in contact with the Pinal Schist (1.6Ga) at Pinal Pass. Note dikes in the granite.
6) Younger Precambrian diabase and Tertiary dacite boulders north of Globe.

Table 5. Ages and geologic names of rock units encountered along State Highway 77

<table>
<thead>
<tr>
<th>AGES</th>
<th>ROCK REPRESENTATIVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENOZOIC</td>
<td>Not named sands, silts, clays, gravels and volcanics</td>
</tr>
<tr>
<td>Quaternary</td>
<td>Not named sedimentary and volcanic rocks; Dacite; Andesite;</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Bidahochi Formation; Not named high elevation gravels</td>
</tr>
<tr>
<td>MESOZOIC</td>
<td>Not named sedimentary rocks and, locally, volcanic rocks</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Not present</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Wingate Sandstone; Chinle Formation; Moenkopi Formation</td>
</tr>
<tr>
<td>Triassic</td>
<td></td>
</tr>
<tr>
<td>PALEOZOIC</td>
<td>Kaibab Formation; Coconino Sandstone; Supai Formation</td>
</tr>
<tr>
<td>Permian</td>
<td>Possibly basal Supai Formation; Naco Limestone</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Redwall Limestone and Escabrosa Limestone</td>
</tr>
<tr>
<td>Mississippian</td>
<td>Martin Formation</td>
</tr>
<tr>
<td>Devonian</td>
<td>None</td>
</tr>
<tr>
<td>Silurian</td>
<td>None</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Bolsa Quartzite</td>
</tr>
<tr>
<td>Cambrian</td>
<td></td>
</tr>
<tr>
<td>PRECAMBRIAN</td>
<td>Diabase; Troy Quartzite; Apache Group; Mescal Limestone,</td>
</tr>
<tr>
<td>Younger</td>
<td>Dripping Spring Quartzite, Barnea Conglomerate, Pioneer Shale</td>
</tr>
<tr>
<td>Older</td>
<td>Granitic rocks locally named, e.g., Oracle Granite; Pinal Schist</td>
</tr>
</tbody>
</table>
Figure 1. Diagrammatic column showing stratigraphic sections of the area.

Keith et al. (1960) in GSA Memoir 153
**Geologic History**

A summary of geologic events in the area includes:

- Precambrian quartz monzonite mass (the Oracle Granite);
- Intrusion by monzonite porphyry;
- Intrusion of both by diabase;
- Fracturing associated with regional compression;
- San Manuel ore body formed—its genesis related to the monzonite porphyry intrusion;
- Erosional cycle—oxidation begins;
- Cloudburst Formation deposited with concomitant intrusion of andesite dikes into the older rocks;
- Intrusion of rhyolite into the Cloudburst volcanics and all older rocks;
- Regional tilting of 20°–25° NE. and chloritic alteration;
- Erosional cycle—oxidation renewed;
- Gila (?) Conglomerate deposited;
- San Manuel fault developed;
- Further tilting to the northeast with development of N. 25° W. system of normal faults and renewed oxidation;
- Further faulting along N. 60° E. trend offsetting N. 25° W. system;
- Quaternary deposits.
SUMMARY

The San Manuel ore body is a disseminated copper deposit with ore mineralization localized in quartz monzonite, monzonite porphyry, and diabase. Deposition of ore is believed to be but one event in the igneous history of the area. The igneous epoch opened

with intrusion of monzonite porphyry, which was followed by diabase intrusion and regional compression that intensely fractured the rocks. Invasion by hydrothermal solutions of varying composition produced intense although variable alteration; primary ore minerals (chalcopyrite and molybdenite) were deposited at a time when potash content of the invading solutions was high. The broad zone of contact between quartz monzonite and monzonite porphyry rock was the most favorable zone for deposition of chalcopyrite; the quartz monzonite appears to have been a slightly better host rock. Ore localization is related to rock permeability, which varies with closeness of fracturing and density of the host rock. There is no evidence that chemical control played any significant part in ore localization.

Since its formation, the deposit has been intruded by minor dikes of andesite and rhyolite and has undergone at least three epochs of oxidation and enrichment. Oxidation was deep and pervasive, but enrichment was limited, and the ore body being mined today owes its economic significance mainly to primary mineralization.

With the attainment of full production in 1958, San Manuel took rank among the major copper mines in the western hemisphere. In 1961, as the world's largest underground operation, the mine ranked fourth in tonnage and sixth in metallic copper production among the hemisphere's major producers.

With a substantial reserve of sulfide tonnage remaining, the mine should continue as a first rank producer of copper for several decades.

Concentric alteration and mineralization zones from the type area of San Manuel-Salome, Arizona. (a) alteration zones (b) zones of mineralization (c) occurrences of sulphides.

SECTION 5-9

Idealized longitudinal section looking northwest.
The El Capitan Catastrophic Landslide

With your most catastrophic hosts

Will Grundy and Mark Lemmon

Vitally catastrophic statistics

Volume of rock: $4 \times 10^7$ m$^3$  
Max vertical drop: 1300 m  
Deposit thickness: 5 - 35 m  
Max exposed length: 3800 m  
Time of emplacement: Pleistocene (?)  
Max horizontal travel: 6800 m  
Width of deposits: 1500 m

Catastrophic references:


Figure 27.—El Capitan landslide and its source area on El Capitan Mountain. Reduced from geologic map of El Capitan Mountain quadrangle (Cornwall and Krieger, 1977).
Figure 17. Idealised morphology (not to scale) of large dry-climate rock-avalanche deposit showing internal features and associated substrate lithofacies in proximal, medial, and distal portions. Abbreviations are the same as in Figure 15. Approximate vertical scale is indicated for zonal stratigraphic columns.
FIGURE 1. Location map of the Salt River Canyon area

serious attention from geologists. Existing geologic maps of the Can-
an access to local strain-metering interferometric fracture (Fig. 13). Where the diaphragm defines a pre-existing fault, complex displacement of the fault itself would be expected to occur, and it is possible that this may have affected the behavior of the fault zone. Each fault serves as a partition between components of the salt. In some cases, the magnitude of the fault 24.

The initiation faults were not generally bounded for measuring flow. Rather, the faults accommodated vertical motions (Fig. 15).

Slide (1967) large scale section and interpretation. The progressive displacement is interpreted as follows: from to the east of the fault, the slide occurred. The effect of the slide is shown in the figure, with the west side of the fault and the east side of the fault.<br>

Wahulla Canyon at Milepost 46.6. Manzal (1964) showed that the local displacement on the fault is the same as the thickness of the slide. A complementary fault occurs below the western core forming slide, and is defined by dripping Spring Quartz at the fault-producing site (Fig. 17). The fault producing site is visible (Fig. 17). The fault producing site is visible (Fig. 17). The fault producing site is visible (Fig. 17).

Davis and Others: Salt River Canyon
rocks (Hayes and Drewes, 1968; Drewes and Finnell, 1968; Finnell, 1970; Drewes, 1971). The Cretaceous rocks in southern Arizona, unlike the Paleozoic and Triassic (?) Jurassic rocks, were flat lying and undeformed prior to Laramide tectonism and thus serve as an important guide to the style and kinematics of Laramide deformation (Davis, 1979).

The principal Laramide deformation of Arizona was strong northeast-southwest compressional deformation. Monoclines developed in the Colorado Plateau (Kelley, 1955a, 1955b). To the south, deformation belts of folding and thrust and reverse faulting were produced (Gilhuly, 1956; Sahins, 1957; Cooper and Silver, 1964; Drewes, 1978; Davis, 1979). The regional structural framework of which the folded and faulted strata were a part is not known for certainty. Drewes (1978) has interpreted the Laramide geologic framework in the context of low-angle, northeast-directed overthrusting. Davis (1979) considered the deformation style akin to Wyoming-type basement-cored uplifts. A highly speculative interpretation that has emerged recently is that all of southern Arizona, at a depth of about 10,000 to 15,000 ft, is underlain by a system of flat faults that separate Precambrian basement above from a repeated sequence of Cretaceous and older rock below. This interpretation has been offered by the Arizona Corporation as a working hypothesis for exploration for hydrocarbons in southern and western Arizona (Keith, 1980). In effect, the model suggests that a break-out zone of thrusting may cross part of the Transition Zone in the Salt River region, perhaps camouflaged by the effects of Basin and Range faulting. Alternatively, the inferred thrust zone may root underneath the Colorado Plateau tectonic province, in which case the Basin and Range Colorado Plateau boundary zone would be in an upper-plate position (Otten, 1981).

Following major crustal shortening, but still in Laramide time, the Basin and Range province of southern Arizona was invaded by abundant plutons of granitic and quartz monzonitic composition, many of which are copper rich. According to Rehrig and Heidrick (1972), the Laramide intrusions were formed at a time of crustal extension and differential uplift achieved under the influence of weak lateral compression.

A net effect of Laramide tectonism was northeast tilting of Cretaceous strata in the Transition Zone and along the southern boundary of the Colorado Plateau (Peirce and others, 1979). Tilling was a response to uplift in the region of the Transition Zone and of a yet undefined portion of the Basin and Range province. The gently tilted strata were subjected to Paleocene-Eocene erosion, beveling rocks in the region along a continuous surface. It was on this surface in slight angular unconformity with Cretaceous strata that the Eocene-Oligocene rim gravels were deposited along the southern edge of the Colorado Plateau (Peirce and others, 1979). This clastic sequence, now preserved in remnant patches at high elevations on the southern edge of the Colorado Plateau, was a product of northeastward transport and deposition on a concave-upward surface, which is now largely removed from the Mogollon Rim. Clasts within the rim gravels conclusively disclose that Precambrian crystalline rocks were exposed as major bedrock sources during the time of deposition of these gravels. In fact, Peirce and others (1979) have shown that Precambrian bedrock was exposed within 30 mi of the site(s) of deposition of some of the rim gravels. Furthermore, 50- to 60-m.y.-old Laramide volcanic rocks are represented as clasts in the rim gravels. Large boulders in the rim gravels disclose high stream gradients (Peirce and others, 1979).

"later in Oligocene(?) time, a generally unrecognized tectonic event induced erosion and downcutting that outlined an ancestral Col-

![Figure 8. Composite geologic column for the Salt River Canyon region](image-url)
Figure 3.—Outcrops of younger Precambrian strata and coextensive diabase intrusions in southeastern Arizona. Modified from county geologic maps published by Arizona Bureau of Mines, 1958–60.
Quartzite and Mescal Limestone of the Apache Group, and the diabase, which intrudes all the Precambrian units (Figs. 10b and 14b). Within this segment, products of the inferred rifting of the North American continent are exposed, including major diabasic intrusions and intrusion-related mineralization. Furthermore, the effects of probably Laramide deformation are revealed in beautifully exposed monoclinal and in a complexly reactivated ancient fault zone, the Canyon Creek fault (Fig. 18b).

The second segment (II, Fig. 9) cuts into middle Proterozoic rocks, namely the Redmond Formation, the White Ledges, Yankee Joe, and Blackjack Canyon Formations of the Hess Canyon Group, and the Ruin Granite (Figs. 18b, 26b, 28b, 37b, 38b, and 40b). The lithologies of the Hess Canyon Group and the volcanic Redmond Formation are typical of the 1.6- to 1.7-b.y.-old dominantly metasedimentary sequence. The northeast-trending Precambrian structural grain of folding so typical of Arizona is well displayed by the rocks along this segment of the river. Side canyons offer excellent exposures of folds, cleavages, and transposition structures. Additionally, the presence of the Ruin Granite provides an opportunity for a close look at part of the 1.42-b.y.-old anorthosite granite suite.

The third segment (III, Fig. 9) of the river (Figs. 38b and 40b) is dominated by Tertiary conglomerate and other clastic rocks, rhyolitic volcanic rocks, basalt flows, and Quaternary gravels. These rocks afford insight into mid-Tertiary and Basin and Range events of faulting, intrusion, and extrusion, as well as the geomorphic development of the region through which the Salt River flows.

**TABLE 2. Geological Column, Salt River Canyon**

<table>
<thead>
<tr>
<th>AGE</th>
<th>NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUATERNARY</td>
<td>Alluvium</td>
<td>River gravels, sands, and occasional silts.</td>
</tr>
<tr>
<td>QUATERNARY</td>
<td>Terrace</td>
<td>Gravels and sands stranded on benches cut by the Salt River as it downcut through the Transition Zone. Some of these terraces may be older than Pleistocene, but detailed work is needed to distinguish the ages.</td>
</tr>
<tr>
<td>UPPER TERTIARY</td>
<td>Basalt</td>
<td>This 10-m.y.-old basalt covers many of the plateaus in this region, including Black Mesa on the north side of the Salt River. It is seen at river level in Redmond Flat as a columnar jointed flow.</td>
</tr>
<tr>
<td>LOWER MIOCENE</td>
<td>Dacite and</td>
<td>Felic water-laid and air-laid tuffs, which are intercalated with Tertiary sediments. According to Peterson (1962), the top of the Whitetail Conglomerate is defined by the appearance of these dacitic tuffs. Age is 19.9 m.y. (Damon and Bikerman, 1964).</td>
</tr>
<tr>
<td></td>
<td>Rhyolite Tuffs</td>
<td></td>
</tr>
<tr>
<td>MID-TERTIARY</td>
<td>Basalts</td>
<td>Undated basalt flows and occasional hypabyssal intrusions; sometimes deposited on dacies, usually upon sediments.</td>
</tr>
<tr>
<td>OLIGOCENE TO MIOCENE</td>
<td>Tertiary</td>
<td>These sediments consist of conglomerates, siltstones, and sandstones. There are occasional interbeds of volcanic and volcanoclastic rocks.</td>
</tr>
<tr>
<td></td>
<td>sedimentary</td>
<td></td>
</tr>
<tr>
<td></td>
<td>rocks</td>
<td></td>
</tr>
<tr>
<td>OLIGOCENE</td>
<td>Apache</td>
<td>A prominent cliff-forming rhyodacite tuff within the Tertiary sediments. The Apache Leap completely blanketed the lower stretches of the Salt River region, and may have a source at the ignimbrite vent just upstream from Redmond Flat.</td>
</tr>
<tr>
<td></td>
<td>Leap Tuff</td>
<td></td>
</tr>
<tr>
<td>EOCENE TO OLIGOCENE</td>
<td>&quot;Whitetail</td>
<td>Generally referred to as &quot;Whitetail Conglomerate,&quot; these old gravels are poorly consolidated, well-rounded conglomerates, which are derived from uplifted areas of central Arizona, and consist of pebbles, cobbles, and boulders representing all the older rocks of the region. (Moore, 1968, p. 60)</td>
</tr>
<tr>
<td></td>
<td>Conglomerate</td>
<td></td>
</tr>
<tr>
<td>AGE</td>
<td>NAME</td>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>-----</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>PALEOZOIC AND MESOZOIC</td>
<td></td>
<td>Not seen in part of canyon that was traversed.</td>
</tr>
<tr>
<td>&quot;APACHE GROUP&quot; DIABASE 1.14 ±0.04 b.y.</td>
<td></td>
<td>Coarse- to fine-grained ophiitic to subophitic olivine diabase in sills. Weathers light olive gray to yellow-brown, typically a slope former. Chill margins of multiple intrusions and some differentiation are noted in the diabase. The diabase preferentially intrudes Apache Group rocks, especially the Mescal Limestone, but also intrudes the Troy Quartzite. Successive levels of sills are interconnected by dikes. Extensive thermal metamorphism is noted in the country rock. Asbestos mineralization is common at the Diabase-Mescal contact. The sills and dikes vary in thickness from inches to more than one thousand feet. The thickness of the Apache Group has been doubled as a result of all intrusion. (Shride, 1967)</td>
</tr>
<tr>
<td>TROY QUAZARTITE</td>
<td>Quartzite Member</td>
<td>Light-gray to grayish-pink medium-grained orthoquartzite with hematite-coated grains cemented by quartz overgrowths. Bedding is generally 2–30 in and is cross stratified. The quartzite is a steep bedded slope former. (Shride, 1967)</td>
</tr>
<tr>
<td></td>
<td>Chaledonic Sandstone 0–700 ft</td>
<td>Light-gray to pinkish-gray sericite sandstone. Coarse grained with pebbles of jasper, rhyolite, and quartzite. Thin bedded to massive, it is a ledge and cliff former in its more massive units. Cross stratification can be seen in the more thinly bedded units. (Shride, 1967)</td>
</tr>
<tr>
<td></td>
<td>Arkose Member 0–450 ft</td>
<td>A basal conglomerate with weathered, rounded clasts from the underlying basalt flows. Dominantly a pale-brown to red, fine- to medium-grained arkose, firmly cemented. Large-scale (10–100 ft) cross-stratification; interbedded with silty scabs. A cliff former with rounded ledges. (Shride, 1967)</td>
</tr>
<tr>
<td>Basalt Flows 0–375 ft</td>
<td>Grayish-red to brown, porphyritic, vesicular hematitic basalt. Intergranular texture of laths of plagioclase and apatite. Abundant alteration minerals are present: chlorite, serpentine, and albite. The basalt overlies the Argillite member of the Mescal Limestone and also separates the Algal and Argillite members of the Mescal. (Shride, 1967)</td>
<td></td>
</tr>
<tr>
<td>LIMESTONE</td>
<td>Argillite Member 0–100 ft</td>
<td>A yellow-brown, siliceous, dense argillite with intraformational chert breccias and conglomerates. Some thermal alteration minerals, micas and amphiboles, can be found in close proximity to the basalt flows. (Shride, 1967)</td>
</tr>
<tr>
<td></td>
<td>Basalt Flow 0–110 ft</td>
<td>“Hemispheric and vesicular” basalt. See entry above under Basalt Flows. (Shride, 1967, p. 26)</td>
</tr>
<tr>
<td>APERCHE GROUP</td>
<td></td>
<td>The Algal member is composed of two units. The upper is a grayish-red to yellowish-brown crystalline dolomite with lenses of chert. The lower is an algal unit. The upper dolomite is a slope former. The algal unit is a pale-red to reddish-brown dolomiticstromatolitic (Collenia frequent) limestone, typically thick bedded (6 ft) and is a cliff former. (Shride, 1967)</td>
</tr>
<tr>
<td></td>
<td>Algal Member 40–130 ft</td>
<td>A coarse-grained arkose to feldspathic sandstone forms the basal member of the Mescal a cliff former 5–6 ft thick. Above this is a thick dolomite sequence. Yellow-brown to grayish-red, thick- to thin-bedded crystalline limestone with abundant lenses of chert dominate the lower Mescal. Forms both ledges and slopes. (Shride, 1967)</td>
</tr>
<tr>
<td></td>
<td>Lower Member 150–270 ft</td>
<td>A fine-grained grayish-orange to yellow-brown siltsone with intercalated thin-bedded bedded arkose comprises the upper member of the Dripping Spring Quartzite. The siltsone is comprised of clay- and silt-sized material, dominantly feldspathic and micaceous with some fine-grained pyrite. Forms slopes with intermitten ledges. (Shride, 1967)</td>
</tr>
<tr>
<td>DRIPPING SPRING</td>
<td>Siltstone Member 200–370 ft</td>
<td>A fine- to medium-grained, pale-brown to orange arkosic quartzite, massively bedded. A prominent cliff and ledge former. When bedding is revealed by weathering, prominent cross-stratification may be seen. (Shride, 1967)</td>
</tr>
<tr>
<td></td>
<td>Arkose Member 200–350 ft</td>
<td>A gray-red basal arkosic conglomerate member of the Dripping Spring Fm. Well-rounded granules, pebbles, and cobbles of various quartzite, jasper, and some volcanic rocks in a poorly sorted, very coarse arkosic matrix. Bedding thickness is variable, typically a ledge and cliff former 5–30 ft thick. Contact is gradational with upper member of the Pioneer Shale (Shride, 1967)</td>
</tr>
<tr>
<td>550–700 ft</td>
<td>Barnes Conglomerate 0–40 ft</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 10a. Topographic map of the Mule Hoof Bend area.
hornblende (a) The commonest mineral of the amphibole group: \( \text{Ca}_2\text{Na}(\text{Mg,Fe}_2^+\text{Fe}^3+)\text{Al}_2(\text{Si}_3\text{O}_8)(\text{OH})_2 \). It has a variable composition, and may contain potassium and appreciable fluorine. Hornblende is commonly black, dark green, or brown, and occurs in distinct monoclinic crystals or in columnar, fibrous, or granular forms. It is a primary constituent in many acid and intermediate igneous rocks (granites, syenites, diorites, andesites) and less commonly in basic igneous rocks, and it is a common metamorphic mineral in gneisses and schists. Symbol: H. (b) A term sometimes used (esp. by the Germans) to designate the amphibole group of minerals. The term “Hornblende” is an old German name for any dark, prismatic crystal found with metallic ores but containing no valuable metal (the word “Blende” indicates “a deceiving”).—Obsolete: hornstone, hornblende andesite, hornblende,breccia, hornblendite.

hornblende-feldspar facies Rocks formed in the middle grades of thermal (contact) metamorphism at temperatures between 350°C and 550°C and at low pressures not exceeding about 2500 bars (Turner and Van Hoven, 1960, p.511). It is part of the hornblende facies: Cfs: pyroxene-hornblende facies; albite-plagioclase-hornblende facies.

hornblendite An igneous rock composed almost entirely of hornblende. The term has been equated incorrectly by some authors with the metamorphic rock amphibolite.

monocline A unit of strata that dips or flexes from the horizontal in one direction only, and is not part of an anticline or syncline. It is generally a large feature of gentle dip. Cfs: monocline; flexure. Adj: monoclinal. Obs. syn: unicline.

ophite A general term for diabases which have retained their ophiolitic structure although the pyroxene is altered to uravite. The term was originated by Palsson in 1819.

opholite Said of the holocrystalline, hypidiomorphic-granular texture of an igneous rock (esp. diabase) in which lath-shaped plagioclase crystals are partially or completely included in pyroxene crystals (typically augite). Also, said of a rock exhibiting ophiolitic texture (esp. ophiolite) or, rarely, of a similar texture involving other pairs of minerals. The term diabasic, although generally considered synonymous, was distinguished from “ophitic” by Kemp (1900, p.155-159) who considered the latter as having an excess of augite over plagioclase, while the former had a predominance of plagioclase, with augite filling the interstices. Cfs: ophiolitic; ophioliptic. Non-preferred syn: basaltophitic; granitophytic. Syn: doleritic; gabroïd.

olivine (a) An olive-green, grayish-green, or brown orthorrhombic mineral: \( \text{Mg,Fe}_2\text{SiO}_4 \). It comprises the isomorphous solid-solution series forsterite-fayalite. Olivine is a common rock-forming mineral of basic, ultrabasic, and low-alumina igneous rocks (gabbro, basalt, peridotite, dunite); it crystallizes early from a magma, weathering readily at the Earth's surface, and metabolizes to serpentine. (b) A name applied to a group of minerals forming the isomorphous system (Mg,Fe,Mn,Fe)_2SiO_4, including forsterite, fayalite, tephroite, and a hypothetical calcium orthosilicate. Also, any member of this system.—See also: peridot; chrysolite. Syn: olivinoid.

olivine basalts A group of basalts that contain olivine in addition to their other components; considered by some petrographers as a less-preferred syn. of alkali olivine basalt.

Paleozoic An era of geologic time, from the end of the Proterozoic to the beginning of the Mesozoic. Obs syn: Primary.

pegmatite An exceptionally coarse-grained (most grains one cm or more in diameter) igneous rock, with interlocking crystals, usually found as irregular dikes, lenses, or veins, esp. at the margins of batholiths. Although pegmatites having gross compositions similar to other rock types are known, their composition is generally that of granite: the composition may be simple or complex and may include rare minerals rich in such elements as lithium, beryllium, francium, niobium, tantalum, uranium, and rare earths. Pegmatites represent the last and most hydrous portion of a magma to crystallize and hence contain high concentrations of minerals present only in trace amounts in granitic rocks. The first use of the term “pegmatic” is attributed to Hauy (1822) who used it as a syn. of graphic granite. Cfs: pegmatoid; symplectite. See also: pegmatitic. Syn: giant granite.
peltite (a) A sediment or sedimentary rock composed of the finest detritus (clay- or mud-size particles); e.g. a mudstone, or a calcareous sediment composed of clay, minute particles of quartz, or rock flour. The term is equivalent to the Latin-derived term, lutite. (b) A fine-grained sedimentary rock composed of more or less hydrated aluminum silicates with which are mingled other small particles of various minerals (Twenhofel, 1937, p.50); an aluminous sediment. (c) A term regarded by Tyrrell (1921, p.501-502) as the metamorphic derivative of lutite, such as the metamorphosed product of a siltstone or mudstone. “As commonly used, a peltite means an aluminous sediment metamorphosed, but if used systematically, it means a fine-grained sediment metamorphosed” (Bayly, 1888, p.230). —Etymology: Greek pelte, “clay mud”. See also: psammitite; parspith. Syn. peylite.

peltite (a) Pertaining to or characteristic of peltite; esp. said of a sedimentary rock composed of clay, such as a “peltite silt” representing a consolidated volcanic ash consisting of clay-size particles. (b) Said of a metamorphic rock derived from a peltite; e.g. a “peltite gneiss”, a “peltite hornfels”, or a “peltite schist”, derived by metamorphism of an argillaceous or of a fine-grained aluminous sediment.—Cf. argillaceous: lutaceous.

plagioclase (a) A group of triclinic feldspars of general formula: (Na, Ca)Al[(Si, Al)]O. At high temperatures it forms a complete solid-solution series from Ab (NaAlSiO₃) to An (CaAl₂Si₂O₈). The plagioclase series is arbitrarily subdivided and named according to increasing mole fraction of the An component: albite (An 100), oligoclase (An 10-30), andesine (An 30-50), labradorite (An 50-70), bytownite (An 70-80), and anorthite (An 90-100). The Al/Si ratio varies with increasing An content from 1:3 to 1:1. Plagioclases are one of the commonest rock-forming minerals, have characteristic twinning, and commonly display zoning. (b) A mineral of the plagioclase group; e.g. albite, anorthite, peraluminous, and anorhinite feldspar. —The term was introduced by Breithaupt (1847, p.485) who applied it to all feldspars having an oblique angle between the two main cleavages. Cf. alkali feldspar; orthoclase. Syn: sodium-calcium feldspar.

pluton (a) An igneous intrusion. (b) A body of rock formed by metamorphic replacement. —The term originally signified only deep-seated or plutonic bodies of granitoid texture. See also: plutonism.

plutonism Var. of plutonic.

plutonic (a) Pertaining to igneous rocks formed at great depth. See also: plutonic rock. Ct: hypabyssal. (b) Pertaining to rocks formed by any process at great depth. —Syn: abyssal; plutonian; deep-seated; hypogene.

Polihipli An old term for the Permian and the Triassic. Polihite and of the texture of an igneous rock in which small crystals of one mineral (e.g. plagioclase) are irregularly scattered without common orientation in a larger crystal of another mineral (e.g. pyroxene); also, said of the enclosed crystal. The larger crystal is typically anhedral and exhibits optical and crystallographic continuity; in hand specimen, this texture produces lustrous patches (luster mottling) due to reflection from cleavage planes. Originally spelled poecilite. Ct: ophitic; enidioblastic. Nonrecommended syn: semipelmagnitic.


sealie [petrology] Said of certain light-colored silica- or magnesiurate minerals present in the form of igneous rocks; e.g. quartz, feldspars, feldspathoids. Also, applied to rocks having one or more of these minerals as major components of the norm. Etymology: a mnemonic term derived from silicon + aluminum + ion. Ct: ienic; mafic; felsic.
The Springerville Volcanic Field: an example of Pliopleistocene monogenetic volcanism in Arizona.

4/23/92
Randy Tufts

By turns hot embers from her entrails fly,
And flakes of mountain flame that arch the sky.—Virgil’s Aeneid

Some of the world’s most active volcanoes are near the centers of ancient civilization in the Mediterranean region: Mount Etna in Sicily and Vesuvius on the shore of the Bay of Naples. Thus it is not strange that classic literature contains many references to volcanoes and that many myths and legends are associated with them. This wealth of folklore is an important source of information on the activity of volcanoes in ancient times.

In Greek mythology Hephaestus is the god of fire, and the name, meaning “burning,” “shining,” or “flaming,” probably originally referred to the brilliance of lightning. In Roman mythology Hephaestus was identified with Vulcan, one of the three children of Jupiter and Juno. Vulcan was the god of fire, especially terrestrial fire, volcanic eruptions, and the glow of the hearth and forge. Vulcan was the blacksmith of the gods. His forge at Olympus was equipped with anvils and all the implements of the trade. Vulcan made the arrows for Apollo and Diana, the shield of Achilles, and the invincible breast-plate of Hercules. He was toolmaker to the gods, utilizing the power of his forge for their welfare. His wife, according to the Odyssey, was Venus. (See Gayley 1911, p. 26.)

Poets have identified Vulcan’s workshop with various active volcanoes in the belief that the smoking mountain was the chimney of Vulcan’s forge. The explosions in the eruption of a volcano were believed to be Vulcan pounding on his anvil, while the fire and smoke came from the forge. It was here that Vulcan made the thunderbolts which Jove threw about so recklessly. Most frequently in ancient writings Vulcan’s forge was located on the island of Vulcano, one of the Lipari or Aeolian Islands in the Tyrrenhian Sea, off the coast of Sicily (see Ch. 8). In fact, the name volcano is derived from the Latin name Vulcanus or Volcanus, applied to the island in ancient times because it was believed to be the location of the forge of Vulcan. From this association, the name volcano has been applied to all mountains which give off “smoke and fire” throughout the world.

There is a legend that, during the reign of Romulus, a temple to Vulcan was built in Rome, and a festival called Vulcanalia was held on August 23 of each year, the ceremony consisting of a sacrifice to Vulcan for the purpose of averting all mishaps that might arise from the use of fire or light.

After Bullard. 1984
After Chronic. 1983.

When lava flowed down Corduroy Creek it displaced the stream. Because rocks of the bordering ridges were weaker and eroded away, the lava now cape a long, narrow ridge adjacent to the stream's new course.

After Ulrich et al. 1989
Fig. 5.4 Schematic diagram of a cinder cone. Bedding of cinders at the flank of the cone is at the angle of repose (30°). A small welded spatter rampart is on the left side of the diagram.

After Smiley et al. 1984

Fig. 7-H. Von Wolff diagram for the rocks of Hawaii. Compositions are plotted in terms of the normative components “L” (leucocratic minerals, feldspar, and feldspathoids), “M” (mafic minerals, pyroxene, olivine, and iron oxides), and “Q” normative quartz above the line LM and normative Ne and Le below.

Hawaii

After McBirney. 1984

After Condit et al. 1989

Figure 9. — Topographic profile across the White Mountains showing the possible final configuration of the volcano.

After Merrill and Pewe. 1977
### Summary of Characteristics of Arizona's Pleistocene Volcanic Fields

<table>
<thead>
<tr>
<th>Location</th>
<th>Area (sq km)</th>
<th>Altitude (m)</th>
<th>Elevation (m)</th>
<th>Fallout (m)</th>
<th>Volcanic Types and Numbers</th>
<th>Rock Types</th>
<th>Nuclides</th>
<th>$^{26}Ar/^{39}Ar$ Age (Ma)</th>
<th>References</th>
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<tr>
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<td>1300</td>
<td>200</td>
<td>40</td>
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<td>0.0105-0.0180</td>
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<td>2000</td>
<td>320</td>
<td>80</td>
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<td>0.0105-0.0180</td>
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Figure 1. Fields of Pleistocene age volcanoes in the Arizona region. Units are San Francisco, Zuni-Banderas and Pinacate are potentially active. Convergences of Pleistocene basaltic rocks that are older than 3 Ma lack easily recognizable constructive landforms and are sorted. The general characteristics of each field are summarized in table 1.

After Lynch, 1989

Figure A.6. Root names for $\text{SiO}_2$-undersaturated volcanic felsic rocks.

Figure A.5. Root names for volcanic rocks corresponding to plutonic granitoid rocks.

After Plummer. 1988
Figure 4.10 Classification chart for the most common igneous rocks. Rock names based on special features are not shown.

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<td>RHYOLITE</td>
<td>ANDESITE</td>
<td>BASALT</td>
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Preliminary stages

- Potassium feldspar (orthoclase)
- Plagioclase feldspar

Increasing silica

- 75% SiO₂
- Increasing K₂O and Na₂O
- Increasing CaO, FeO, and MgO

FELISC INTERMEDIATE MAFIC ULTRA-MAFIC


Figure A.6. Root names for SiO₂ undersaturated volcanic felsic rocks.

Figure A.5. Root names for volcanic rocks corresponding to plutonic granitoid rocks.

29 After Plummer. 1988
Figure 4.10 Classification chart for the most common igneous rocks. Rock names based on special textures are not shown.


Figure A.5. Root names for volcanic rocks corresponding to plutonic granitoid rocks.

Figure A.6. Root names for SiO₂-undersaturated volcanic felsic rocks.

29 After Plummer. 1988
Problem: Why is there gravel on top of the hill, which is from rocks older than the ones it sits on? All of the water flows from the North, now, but they’re older than anything in that direction, and are more similar to the rocks far below. In fact, there’s even bits of basalt otherwise found only to the South.

Answer: The hill used to go farther South, the gravel rolled downhill, then the old hill went away.

Issues remaining:
Modern dating of some rim gravels yields 30-50 My. Stratigraphy is more complicated than pictured here. Perhaps an additional (pre- basin-and-range) faulting episode. Colorado River. Up to 80 km of scarp erosion.
PTYS 597a

PLANETARY FIELD GEOLOGY PRACTICUM

Field Trip 24–26 April 1992

Day 2
Show Low to Canyon de Chelly
Trilobite fossils will not collect fossils.

10 years ago

Today

Silicification
The Basics:

The Chinle Formation of the late Triassic age is composed of various rocks of continental origin, including claystone, sandstone, limestone, siltstone, and conglomerate. It extends over most of the Colorado Plateau province, where it varies in thickness from 200 ft to 1700 ft (typical depth of 1000 ft). It is not uncommon to see the exposed layers of this formation where erosional processes are significant. The mixtures of the depositional conglomerate lead to many colors (blue, gray, red, yellow, white, green) which give the painted desert its name.

The Chinle Formation rests uncomfortably on the underlying strata, where in most of the Colorado Plateau it overlies the Moenkopi Formation of the Early and Middle Triassic age. It is divided into a lower (bentonitic) part and an upper (red-beds) part. The lower part of the Chinle Formation is considered to be a continental deposit laid down in streams and lakes and on flood plains (this interpretation is based predominantly on the types of sedimentary structures and fossils). The upper part is likely a lake bed deposit, due to the grain size and composition of the depositional features. Fossils in these regions are much scarcer, but contact between the two units is gradational and difficult to find in some areas.
Origins of the Chinle:

The Triassic period (230 - 180 M.Y. ago) was a time of general emergence above sea level, following the late Permian withdrawal of the middle Permian shallow seas that covered most of Arizona. As high mountain ranges rose in central Arizona, all of central and southern Arizona was uplifted (Mogollon Highland) and deeply eroded with erosional debris spread northward in early Triassic times by sluggish streams to be deposited as mud and sand on the low coastal plain of a shallow sea that extended northward and westward into Utah and Nevada. Occasional volcanoes deposited fine volcanic ash into these flow features which mixed with the other debris and clay. Stream directions, as indicated by the orientation of the cross strata, were mostly N-NE, indicating a source area to the south of the Colorado plateau. This source, the Mogollon highland, was predominantly a volcanic terrain, as indicated by the abundance of volcanic debris in the lower Chinle. Fossil-bearing pebbles in conglomerate layers in the lower Chinle, on the other hand, indicate that some sedimentary rocks were exposed as well in the source region. Fallen trees were often caught up in this flow and eventually silicified, forming the "petrified trees" we see today (see Steffi's talk).

By late Triassic time the elevation of Mogollon Highland had increased enough that the slope gradient among the northward flowing rivers was allowing transportation of coarser sediments, such as sand and gravel, over the coastal plain. These gravels were spread uniformly and are now referred to the Shinarump Conglomerate. The widespread sandstone and conglomerate units of this feature are probably point-bar deposits produced by the lateral migration of meandering streams. Following this deposition, the Mogollon Highlands were evidently reduced in elevation, since the following deposition sediments were much finer in grain size. This material (volcanic ash, sand and clay) was spread over most of

The Lower Chinle; Composition and Characteristics:

The lower part of the Chinle formation is mainly composed of variegated bentonitic claystone (a reddish clay formed from volcanic ash), clayey sandstone, and thin widespread units and sandstone and conglomerate. Easily erodible, bentonite also swells up when its wet and shrinks when its dry, making life difficult for new plant growth as well as allowing the Chinle to form very distinctive landforms. It contains an abundant amount of fossil flora and fauna, attesting to the early violence surrounding the production of the volcanic sediments.

The Petrified Forest Member is the thickest and most wide-spread member of the lower Chinle Formation. Present throughout lower the southern part of the Colorado Plateau, it is generally 1000 ft thick and composed of brightly colored horizontally stratified claystone and clayey siltstone as well as cross-stratified clayey sandstone. These rocks contain montmorillonitic clay probably derived from the alteration of volcanic glass, and sand-sized material composed of volcanic debris. In some areas the member contains units of cross-stratified ledge-forming sandstone and conglomerate (i.e. the most conspicuous being the Sonsela Sandstone Bed, which covers a large part of NE Arizona and NW New Mexico).
The Upper Chinle; Composition and Characteristics:

The upper part of the Chinle consists of reddish horizontally bedded or structureless siltstone and generally minor amounts of sandstone, limestone, and siltstone. Fossils in these regions are much scarcer, but contact between the lower and upper Chinle units is gradational and difficult to find in some areas.

The upper part of the Chinle Formation may be mostly a lake deposit, as indicated by the fine texture and even bedding of the strata and by the type of fossils. Cross stratified sandstone layers, interpreted as stream deposits, are abundant locally and are most abundant in a narrow belt extending from SW Colorado to Central Utah. This belt of sandstone is considered to mark the location of a major river system. Highlands in W. Colorado and the Mogollon Highland in S. Arizona are considered to be the major source areas during deposition of the upper part of the Chinle Formation. Granitic and metamorphic rocks and some sedimentary rocks were exposed in the W. Colorado highlands, but rocks exposed in the Mogollon Highland were mainly volcanic.
Figure 1. — Nomenclature of the Chinle Formation and related strata in the Colorado Plateau region.
Figure 17. Horizontally stratified claystone in Petrified Forest Member of Chinle Formation near abandoned town of Paria, Utah. Cliffs in background are in units of the Glen Canyon Group.

Figure 11-3. Petrified logs of Araucariaceae in the Chinle Formation at Petrified Forest National
Figure 12. — Correlation of Chinle Formation in north-central Arizona and south-central Utah.

Figure 18. — Frothy weathering surface developed on claystone in Petrified Forest Member of Chinle Formation near Joseph City, Ariz.
Winslow to Petrified Forest

Terrace deposits north of the Little Colorado River are surfaced with Pleistocene sand and gravel.

Lithodendron Wash takes its name from the stumps (litho) trees (dendron) of Petrified Forest.

In the Painted Desert badlands Trisassic rocks change hue with every change in light and shadow.

The Bidahochi Formation caps a low plateau south and southeast of the highway.

Near its eastern limit the marine Kalabab Limestone grades into shore and dune sandstone similar to the Coconino Sandstone.

Petrified Forest to New Mexico

I-40

ROADSIDE GEOLOGY OF ARIZONA (CHRONIC), 1983
Planetary Field Geology Handout

Formation Process of Sapping Valleys

Figure 2. Factors important in valley morphology by sapping action at various times of geomorphic changes. Feedback relations are indicated by arrows pointing in opposing directions. Local processes involving hillslope and adjacent channels constitute an especially complex intermittent system (dashed lines).

Baker et al., 1990

Figure 11. Plan view of the perturbations of a ground-water flow net that lead to the extension of spring heads to form a drainage network. Solid arrows are low flow, dashed indicate evapotranspiration. (a) Concentration of flow at a broad area protected by an escarpment, (b) Concentration of flow caused by a small meander below controlled by a lithological heterogeneous, (c) lateral convergence of flow lines around neighboring spring heads that have creased lines. A local escarpment, tributary valleys form as a result of secondary perturbations of the flow field due to the same process or hydrologic factor. Convergence of the spring heads leads to divergence of flow between the valleys (After Dunne, 1990).

Dunne, 1990

Howard, 1987
Comparison, Mars and Venus

Marsian Valley Networks

1) Geologic settings

   a. cratered highland (Noachean, 3.8 - 3.9 billion years)

2) Morphology, particularly for the longitudinal valleys
   (Pieri, 1980, Baker, 1982)

   a. theater-shaped valley headwalls
   b. strong structural control of valley alignment and planform
   c. hanging tributary valleys
   d. long main valleys with short, stubby tributaries
   e. irregular angles of channel junction
   d. valley widths that remain nearly constant in a downstream direction

3) Origin

   a. surface runoff, particularly for the dendritic valley networks (Milton, 1973, Sagan et al., 1973)
   b. sapping (Pieri, 1980, Baker, 1982)
   c. valley glacier (Lucchitta et al., 1981, Lucchitta, 1982)

4) Implication

   a. warm, wet climate (Pollack, 1979)
   b. hydrothermal circulation (Brakenridge et al., 1985, Gulick and Baker, 1989)

Venusian Valley Networks

1) Geologic settings

   a. highland regions
   b. coronae
   c. novae

2) Morphology (Gulick et al., 1992)

   a. rectangular
   b. labyrinthic
   c. pitted or irregular

3) Origin

   a. lava sapping (Komatsu et al., 1992)

4) Implication

   a. gradual thermal erosion
   b. exotic low viscosity lavas (sulfur, carbonatite)
Sapping Features: Morphology
(V. Hillgren)

General Features:
1) Valleys have "theater" heads
2) Steep head walls
3) Constant valley width
4) Short tributaries
5) Size and orientation controlled by structure

Why the Colorado Plateau?
On the Colorado Plateau there are abundant sandstones with high porosity, permeability, and weak cement. In other words, groundwater flows easily through these units.
Figure 7. Canyon de Chelly and Spider Rock. Photo: S. Reynolds.


Erik Asphaug and Andy Rivkin, your helpful hosts
DEFIANCE UPLIFT

The Defiance uplift lies along the western part of the region, mostly in Arizona but extending locally a short distance into New Mexico. It is a north-trending uplift about 30 miles wide and 100 miles long. It is asymmetrical on the east as a result of the sharp, sinuous Defiance monocline which determines the eastern boundary. The staggered, broad crestal axes of the uplift have a maximum structural relief of 7,500 feet, some 3,000-6,000 feet of which is on the monocline. The monocline is only 1-2 miles wide between its monoclinal and synclinal bends, and dips along it range from 20°-90°. By contrast dips in the broad crestal area and along the wide, gentle western limb only very locally exceed three degrees.

Faults are uncommon and minor, with two notable exceptions: the Tsaiie graben and the Wide Ruins fault zone. The Tsaiie graben in the northwestern part of the uplift is 1-2 miles wide and 15 miles long. Its northeastern trending normal faults drop Triassic Chinle one or two hundred feet between Shinarump sandstones.

Despite exposures of Precambrian rocks in the Zuni and Defiance uplifts, the deformational history of pre-Paleozoic time as well as the early and middle Paleozoic is poorly or not at all known in the region. Lower Paleozoic beds probably covered all the region only to be stripped by late Devonian time.

Monoclines and related structures of the Colorado Plateau developed principally during Late Cretaceous to early Tertiary (Laramide) time, whereas epiregic uplift of the plateau as a whole probably took place later during Tertiary time. Minor doming related to injection of laccoliths and other intrusions occurred after Laramide time and modified some of the older structures.

A compressional origin for the monoclines has been proposed by Baker (1935) and by Kelley (1955a, 1955b) on the basis of geometry of the monoclines and the regional distribution of thrust faults of similar age in surrounding regions. Earlier workers, however, thought that vertically oriented forces had produced vertical faults in the basement with draping of overlying beds to form the monoclines (Powell, 1873; Dutton, 1880). It seems likely that primary horizontal compression deep within the crust beneath the Colorado Plateau resulted in local secondary stress fields near the surface having strong vertical components, perhaps similar to a mechanism proposed by Thom (1955) for wedge uplifts in the northern Rocky Mountain region. This implies a strong crust that was able to transmit horizontal stresses over long distances without intense deformation.
B Pennsylvania isopach and the Zuni-Defiance positive

A Bouguer Gravity Map (Modified from Woollard and Joesting, 1964)
In Canyon de Chelly, there are only three geological units visible, only two of which are encountered along the White House Trail. These units are the Shinarump Conglomerate, which is part of the Chinle Formation, the de Chelly Sandstone, which has its type section here in the canyon, and the Supai Formation, which is more sedimentary units. The latter is hidden from view even at the bottom of the trail.
DE CHELLY: De Chelly Sandstone is typically divided into a number of members. Three of these members, the White House, Hunter's Point and Oak Springs members are present in Canyon de Chelly. There is some controversy viz. the Oak Springs member, however, as most investigators don't actually consider it as related to the de Chelly formation, but a tongue from a different formation, like the Supai. The de Chelly Sandstone is Permian in age, and composes 240 meters of the 305 m depth of Canyon de Chelly.

The White House member is the most recently lain, dating back 260-275 million years to the Leonard Epoch of the Permian Period. Cross-bedding in this member seems to indicate an eolian origin. Paleogeographic studies suggest that this area was covered by sand dunes at the time, with the cross-bedding showing a prevailing north to northeasterly wind. A shallow sea was nearby, as the figure shows.

Going a little further back in time, we come to the Oak Springs member. As mentioned before, this seems to be a tongue of adjacent red bed units, perhaps the Supai. This unit and all further units are not visible from the White House Trail.

The Hunter's Point member shows evidence of an aquatic depositional environment: ripple lamination, even bedding and fine sand-sized grains. All these seem to indicate a medium-to-low energy area, such as a broad shelf. The aforementioned sea is thought to have intruded further in earlier times.

SHIPARUMP: This unit is of Upper Triassic age, laid down roughly 210 million years ago. The clasts seem to be Precambrian, eroded from the Mogollon Rim. However, there also appears to be some contribution from eroded de Chelly Sandstone as well. Shiparump Conglomerate is light gray, tan and brown, and coarse grained (obviously).

SUPAI FORMATION: This is dark, poorly resistant and slope forming. It seems to have been deposited in a mudflat with shifting stream courses.

The uplift of the plateau seems to have occurred in the last 10 million years, with the canyon itself only being cut in the last few million.

FIGURE 14—Hypothetical paleogeography during the later stages of deposition of the Schnebly Hill formation and DeChelly Sandstone.
SHINARUMP CONGLOMERATE MEMBER (of Chinle Fm.)—U. Triassic
abund. (0-225'). (5) Recog. as basal cgl. mem. of Chinle Fm. Disconfl. or unconf. on Moenkopi Fm.; conf. and gradat. with Monitor Butte Mem. of Chinle Fm. Acc. to J. H. Stewart, 1957, A.A.P.G. Bull., v. 41, p. 442-452, in Moab, Utah area, the so-called Shinarump cgl. of Baker (1933) and McKnight (1940) is a strat. higher unit at base of Chinle and is assigned to Church Rock Mem. of Chinle. The Shinarump was long regarded as a fm.

DE CHELLY SANDSTONE MEMBER (of Cutler Fm.) or DE CHELLY SANDSTONE (of Cutler Gr.)—L. Permian (Leonardian)
(1) NE Arizona, SE Utah, NW New Mexico. (2) H. E. Gregory, 1915, A.J.S., 4th, v. 40, p. 102. (3) Canyon de Chelly, Apache Co., Arizona. (4) Mass. x-bed., lt. red, buff, and br. ss. and cgl. (0-1,000'). Pale br.-red, tan, oran., even-gr. cse. x-bed. ss. with a few sh. (300'-800'). (5) Orig. a mem. of the Cutler Fm.; raised to fm. rank by J. A. Monar, 1957, Four Cor. Geol. Soc. 2d Gdbk., p. 90. In Monument Valley, overlies the Organ Rock Tongue; in places overlies Supai Fm.; overlain by Hoskinnini Mem. of Moenkopi Fm. In pt., equiv. to Supai Fm. and Coconino Ss. Prob. equiv. of White Rim Ss. in Utah and of Meseta Blanca Ss. Mem. of Yeso Fm. in New Mexico. In type area, H. W. Peirce, 1964, N.M.G.S. 18th Gdbk., p. 57-62, recog. five memms. (ascend.) Hunters Point, Oak Springs Cliffs, White House, Black Creek, and Fort Defiance (all not present at some locs.).

SUPAI FORMATION (of Aubrey Gr.)—Pennsylvanian-Permian
(1) Four Corners region to E California and SE Nevada. (2) N. H. Darton, 1910, U.S.G.S. Bull. 435, p. 21-25. (3) Supai Village, in Havasu (Cataract) Canyon, N Arizona. Supai is contraction of word "Havasuapi". (4) Red ss. and sh., purp. ls. (500'-1,000'; 1,700'-1,800' along Mogollon Rim, Arizona; 3,000' (?) in Confusion Range, Utah). (5) Conf. on Naco Ls. or unconf. on Redwall Ls.; overlain disconfl. or gradat. by Hermit Sh. or Rico Mem. of Cutler; or by Kainab Ls.; or by Coconino Ss. In Grand Canyon area, the Hermit Sh. sep. Supai from Coconino. In Defiance uplift and Toadlena area, Supai interfingers with overly. De Chelly Ss. Equiv. to Cutler Gr., and to Abo and Yeso Fms.
PTYS 597a

PLANETARY FIELD GEOLOGY
PRACTICUM

Field Trip 24–26 April 1992

Day 3
Canyon de Chelly to Tucson
via Flagstaff
HOPI BUTTES
Ellen Howell

Where they are (1-3)
and
What they are (4)

Figure 1. Index map of Navajo and Hopi reservations and vicinity showing the distribution of diatremes, sedimentary and volcanic rocks of Pliocene (?) age, and configuration of the pre-Bidahochi surface.

Figure 1. Bidahochi Formation. Subdivision and lithologies after Repenning and Irwin, 1954; and Shoemaker, et al., 1957.
Figure 1b.—ERTS photomosaic of Black Mesa Basin and adjacent areas, northeastern Arizona, showing the route of a 2-day field trip (NASA ERTS E-1103-17323-7, 1318-17265-7, 1318-17271-5, 1319-17321-5, and 1319-17323-7).
Figure 3. Geologic map and section of the diatreme at the Hosietsko claim showing distribution of mineralized rocks.
Aerial photograph looking north toward Coliseum maar (stop 4) asahad Wash. Part of the maar is still hidden beneath the Formation. The entire structure may have been buried by m during Jedidio time, as suggested by superposition of the The "coliseum" wall of bedded tuff breccia within the maar is a circular zone of faulting and drag folding caused by ositional subsidence within the crater. Fossil fish and bird have been found in lacustrine sediments of this maar.

Figure 1. Schematic diagram of a diatreme after the vent has collapsed, been filled with sediments, collapsed again, and undergone erosion. Sediments filling the diatreme consist of fine-grained sandstone and siltstone interbedded with volcanic tuff. Alluvium and soil fill the uppermost portion of the vent. Inner portions of the vent are filled with volcanic tuff, breccias, and agglomerates. A collapse ring, steeply dipping beds, and outwardly dipping faults are produced from collapse of the vent.
OLDEST BASALTS OF SAN FRANCISCO VOLCANIC FIELD (PLIOCENE AND MIocene)—Informally called rim basalts; in Volunteer Canyon unit includes four flows with K-Ar ages of 3.9 to 9.0 m.y. (Damon and others, 1974)

DACITE DOME (PLIOCENE)—Occurs on northeast flank of San Francisco Mountain stratovolcano. Age is 2.78 ± 0.13 m.y. (Damon and others, 1974)

RHYOLITE DOME OR FLOW (PLIOCENE)—Glassy, aphyric to porphyritic rhyolite. Associated with Sitgreaves Mountain and Kendrick Peak volcanoes and isolated domes between these centers and San Francisco Mountain stratovolcano

RHYOLITE PYROCLASTIC DEPOSITS (PLIOCENE)—Associated with Sitgreaves Mountain; predominantly air-fall deposits

ROCKS OF HOPI BUTTES VOLCANIC FIELD

BIDAHOCHE FORMATION (PLIOCENE AND MIocene)

Upper member—Sandstone, weakly consolidated, mostly fluvial in origin

Lower member—Calcareous mudstone, siltstone, sandstone, and minor rhyolitic ash. Mostly lacustrine in origin

Volcanic vent deposits—Includes tuff breccia, agglomerate, and lacustrine deposits in maar craters. Lava flows may cover vents and other deposits. Ages range from approximately 8.5 to 4.2 m.y. (P. E. Damon, unpub. data, 1979)

Monchique lavas—Alkaline lamprophyre containing clinopyroxene, olivine, biotite, and analcite. Extends beyond its source, in some cases as much as several kilometers. Ages are 7 to 6 m.y. (P. E. Damon, unpub. data, 1979)

Dike or neck—Monchique similar to lava flows (Tdb); commonly includes tuff breccia. Age range is same as for vent deposits (Tdv)

Bedded monchique tuff—Mostly lacustrine or air-fall in origin; may extend several kilometers from the eruptive source

SEDIMENTARY ROCKS OF THE COLORADO PLATEAU

WEPO FORMATION OF MESADERE GROUP (UPPER CRETACEOUS)—
Alternating beds of olive-gray siltstone, coal, and yellowish-gray sandstone. Thickness 0-350 ft (0-107 m)

TOREVA FORMATION OF MESAVERDE GROUP (UPPER CRETACEOUS)

Upper sandstone member—Yellowish-gray to grayish-orange-pink, fine-grained to very coarse grained sandstone. Thickness 0-80 ft (0-24 m)

Middle carbonaceous mudstone member—Variegated mudstone. Thickness 0-100 ft (0-30 m)

Lower sandstone member—Light-brown to pale-yellowish-gray, fine- to medium-grained sandstone. Thickness 0-120 feet (0-37 m)

Tongue of Toreva Formation—Sandstone. Intertongues with Mancos Shale. Mapped in the Padilla Mesa area. Thickness 0-250 ft (0-76 m)

MANCOS SHALE (UPPER CRETACEOUS)—Light- to dark-gray claystone and siltstone. Thickness 160-725 ft (50-220 m)

Upper tongue—Light- to dark-gray claystone and siltstone. Mapped in the Padilla Mesa area. Thickness 0-50 ft (0-15 m)

DAKOTA SANDSTONE (UPPER CRETACEOUS)—Tan, brown, and gray sandstone, conglomeratic sandstone, and conglomerate. Thickness 0-90 ft (0-27 m). Finches out to southeast

COW SPRINGS SANDSTONE (MIDDLE JURASSIC)—Greenish-gray to light-yellowish-gray, fine- to medium-grained, cross-stratified sandstone. Thickness 0-285 ft (0-87 m) where exposed; 470 ft (143 m) thick in well at Keams Canyon. Finches out to southeast