

Planetary Geology
Dr. Greeley

NAME _____

PLANETARY GEOLOGY FIELD TRIP EXERCISE

ANSWER KEY

This field trip introduces some basic geologic principles and emphasizes those facets that are important in planetary geology. We will visit several localities, shown as numbered "STOPS" on the cover of this exercise.

One of the objectives of this trip is to gather criteria that will aid in the identification of various types of craters. At each of the "crater" stops, be sure to record **critical** data and make sketches on the back of the page that will help to distinguish one crater type from another. A second objective is to note the **form** of each of the several types of volcanoes that will be seen. Questions regarding **craters** and **volcanoes** will be asked at a future time.

In order to obtain credit you must turn in this completed exercise at the end of the trip. All of the answers will be provided during the trip.

While driving to Stop 1:

1. Examine the geologic map of Arizona (cover). What are the age and type of the youngest rocks we will drive across (or near) on the trip?

Quaternary; sedimentary rocks, alluvium

What are the age and type of the oldest rocks we will drive across (or near) on the trip?

Younger Precambrian; sedimentary, intrusive diabase, metamorphic rocks

2. What do the pink and red units on the map represent?

Pink = Quaternary and upper Tertiary volcanic rocks; red = Tertiary and Cretaceous volcanic and intrusive rocks

3. Many rocks in the lower desert show white, chalky surfaces; other rocks show shiny, dark surfaces. What are these? Would a fresh exposure of these rocks be dark? Why or why not? What is the significance to planetary science?

White surfaces = caliche (secondary carbonate deposits); dark surfaces = "desert varnish," a surface veneer that is composed of manganese compounds formed by interaction of dust and desert "dew," perhaps enhanced or facilitated by biological activity. Caliche and desert varnish can form on any rock and, therefore, a fresh exposure would have the appearance of the host rock.

Remote sensing is commonly used in planetary science (including Earth) for mapping surface compositions; caliche and desert varnish can influence the "signatures" from some remote sensing detectors, and might not indicate the composition of the host rock.

4. What are the physiographic provinces we will visit on the trip?

- a) *Basin and Range (correlates with the predominantly yellow units on the geologic map in the south and southwest part of Arizona).*
- b) *Colorado Plateau (correlates with the blue, green, and pink units in the northeast part of Arizona).*
- c) *Transition zone (correlates with the olive green units between the other two provinces).*

5. Notice the basalt flows exposed in road-cuts between mileposts 247 to 250. What is the range of thickness of the flows? *3 to 10 m.*

What is the origin of the red zones between some flows?

Paleo-soils that were heated ("baked") and oxidized when the overlying lava flowed over them.

Stop 1 (Sunset Point Rest Area):

1. What is the rock type here?

Basalt with vesicles

2. Look eastward toward **Joe's Hill**, the rounded mound toward the horizon. In the space below, draw a simple profile and cross section of Joe's Hill, and give a short description of its origin.

Joe's Hill is a classic shield-shaped volcano built from relatively thin, fluid lava flows of basaltic composition. The flows with "baked soils" seen in the near-by road cuts were derived from this volcano.

3. Compare and contrast the morphology of flood basalt regions, Hawaiian shield volcanoes, and shield-field volcanism.

Flood basalts produce thick flows (~100 m thick) of large volumes that typically bury their own vent structure (which are long fissures, while shield volcanoes, like Joe's Hill, involve smaller volumes of lava that produce thinner flows erupted from "central" vents (e.g., craters); "shield fields" consist of multiple small coalesced shield volcanoes with vents that are often aligned.

4. The **Bradshaw Mountains** are to the west on the horizon. What are their age, composition, and economic significance?

They are composed of Precambrian metamorphic and intrusive rocks; some of the first mining in Arizona occurred in the Bradshaw Mountains, and currently week-end "hobby prospectors" pan for gold in the local streams.

While driving to Stop 2:

Notice the terrain between Mileposts 258 and 259; how does this terrain and the exposed rocks differ from the basaltic surface of Black Mesa? Explain what this terrain and rocks might be.

The terrain is characterized by large rounded boulders that are granite, shaped by exfoliation.

Stop 2 (Verde Valley Overlook):

1. What "caps" the Colorado Plateau, visible from here?

Basaltic lava flows

2. What underlies the "cap"?

Paleozoic layered sedimentary rocks

3. What is the origin of Verde Valley?

The valley formed by faulting on the south side and erosion on the north side. The highway to this stop descended the scarp zone of the Verde Fault.

4. What are the age and origin of the whitish beds in Verde Valley?

Pliocene; fresh-water limestone and marl (limestone with clay). Eruptions from the Hackberry Mountain area to the southeast (down-river direction) repeatedly dammed the ancient Verde River to form paleo-lakes.

5. What is the origin of the white strata visible to the south in the cliffs?

Volcanic silicic ash erupted from the Hackberry Mountain area.

Stop 3 (Montezuma Well):

We will take the trail to Montezuma Well, just past the ranger shack.

1. Explain the origin of the pits and hollows on the surfaces of the rocks.

These are solution pits resulting from "carbonation" in which weak carbonic acid forms from surface water and carbon dioxide from the atmosphere.

2. What is a possible origin for the "raised rim" around the well?

These are travertine deposits ("tufa") from ancient springs around the sink hole when the water table was higher.

3. Take the trail down to the creek. Explain why the level of the lake in the well remains ~constant.

The lake is the source for the spring at the end of the trail, and the spring drainage keeps the lake level fairly constant.

4. Are the deposits exposed in the cliff above the spring all of the same composition? Explain your answer.

There is a large block of basalt incorporated in the limestone; it was washed into the paleolake from eroded lava flows that "cap" the plateau to the north northeast. Such rocks are called "xenoliths," meaning "strange rocks" because they are out of place.

Stop 4 (Stoneman Lake):

1. What is the rock type here? *Basalt* What **phenocrysts** can be identified in the rock? *Olivine*
2. Examine the air photo of Stoneman Lake. How does the shape of the lake compare with that of the crater-depression?

The lake is kidney shaped, while the depression containing the lake is circular.

3. Consider the origin of the depression containing Stoneman Lake. Record your observations as to rim morphology, evidence of faulting, evidence that there was (or was not) a volcanic vent here. What underlies the rock units? What volcanic term could be applied to this crater?

No raised rim, no indication of over-turned stratigraphy; no indication that this was a volcanic vent (no spatter, cinders, oxidized lavas, or fumarolic materials), no evidence of faulting. The near-by hills are volcanic; the underlying rocks are sedimentary and include limestone. The Stoneman Lake depression is thought to be a collapse feature, in which the basalts collapsed into an underlying karstic feature; alternatively the collapse could have resulted as magma chamber(s) emptied as they fed the surrounding volcanic centers; in either case, the feature would be called a "pit crater" similar to those seen in Hawaii along the "chain of craters" of Kilaueu volcano. Some pit craters are not vents.

4. Describe briefly the differences and similarities among the **Black Hills**, **Mormon Lake**, and **San Francisco** volcanic fields, especially as to age, rock types, and volcanology.

All three are composed principally of basaltic lava flows with local eruptive centers that include small volumes of silicic materials, including dacite and rhyolite. The Black Hills VF, which includes Joe's Hill and Black Mesa, is oldest (10-16 Ma), Mormon VF is intermediate in age (5-10 Ma), and San Francisco VF is the youngest (<5 Ma), suggesting a trend in magmatism toward the north. Volcanic styles include Hawaiian eruptions (relatively quiet effusion of basaltic lava flows, including construction of small shield volcanoes), mild explosive eruptions (Strombolian style) to form cinder cones, eruption of andesites to form composite volcanoes (San Francisco Mountain), eruption of viscous dacite and rhyolite to form volcanic domes, and explosive silicic eruption to produce sheets of ash.

Stop 5 (Mormon Lake Overlook):

1. What is the rock type here?

Basalt

2. Examine the hill (**Mormon Mountain**) west of the lake, and the hill at the south end of the lake. Compare and contrast their profiles and general morphology and explain their similarities/differences.

Mormon Mountain has steeper slopes, a reflection of the viscous dacite lavas that formed this "dome volcano;" the feature to the south is a small basaltic shield volcano built from more fluid basalt flows; it has been cut by a graben (part of the fault system at this stop), and has been further modified by the superposition of a late-stage cinder cone.

This stop affords a good view of San Francisco Mountain, a composite volcano with a summit elevation of 3850 m (12,633 ft.), the highest point in Arizona.

3. Explain the possible origin for the basin containing Mormon Lake.

Faulting (the parking area is on the up-thrown side of a prominent north-south trending fault), and possible collapse over a magma chamber(s) that emptied to "feed" the eruptive centers, such as Mormon Mountain. This feature is a "volcano-tectonic depression." Mormon Lake is the largest natural lake in Arizona, and is intermittent, dependent on precipitation and ground water levels.

While driving along Lake Mary (milepost 336.8)

1. Notice the sedimentary rocks in road-cuts on the east side; what sedimentary structure(s) do you recognize?

Sedimentary cross-beds

2. What is the origin(s) of these features?

Bedding structures in sand dunes and/or near-shore deltaic deposits

3. Explain the significance of these features as related to Meridiani Planum, Mars.

Cross-bedded sediments were documented by the Mars rover, Opportunity, and are thought to reflect near-shore deposits, as might form in lagoons.

Stop 6 (Meteor Crater):

1. We will go straight to the crater rim overlook through the Visitor Center. When did Meteor Crater form?

40,000 to 50,000 years ago

What happened to the impacting object that formed the crater?

It was fragmented and partly vaporized.

What type and size object formed the crater?

An iron object about 30 m in diameter

2. How much erosion has occurred on the surrounding ejecta blanket?

About 1 m

What is the maximum size ejecta block?

About 5-8 m across

3. What mineral(s) have been found in the Coconino Sandstone and what is their significance?

Coesite and stishovite, which are impact metamorphic forms of quartz.

4. Examine the air photo of Meteor Crater and compare its planimetric form to the depression containing Stoneman Lake. How do you account for the difference between the two crater shapes?

Stoneman Lake depression resulted from collapse and is circular, whereas the excavation of Meteor crater was partly controlled by an orthogonal set of joints.

5. Notice the buttes visible to the north and northeast; what are these features called and what is their origin(s)?

These are the Hopi Buttes and Navajo Buttes; they are diatremes, resulting from deep explosive eruptions.

6. Return to the Visitor Center for the exhibits. On the trail back to the Visitor Center search for evidence of over-turned stratigraphy in the rim.

The red Moenkopi formation has dips that show the overturning strata; it is both underlain and overlain by the tan Kiabab Formation, showing the inversion of stratigraphy.

Stop 7 (Rattlesnake Crater):

1. What is the morphology of this depression, which is a *maar crater*?

Raised rim crater, with east rim higher; outline is semi-circular; floor is smooth.

2. What is the composition of the rim material?

Basaltic granular material ("tuff"). Note the presence of small pieces of white sandstone (xenoliths) in the rim material. These were carried to the surface by the rising magma and were ripped from the underlying sedimentary formations.

3. Why is the east rim higher than the west rim?

It is likely that prevailing winds from the west blew pyroclastic material toward the east during eruptions from the vent; directed eruptions might also have been involved.

4. What is the age relationship between the crater and the hill to the east?

The hill to the east is a cinder-and-spatter cone superposed on the maar crater and is younger.

5. Explain the origin of Rattlesnake Crater.

It is a maar crater, resulting from phreatomagmatic explosions; these tend to be "point-source" releases of energy similar in some ways to impacts; thus, maar craters typically most-closely resemble impact craters with raised rims, circular outlines, and floors that are often below the surrounding terrain. Maars do not, however, have over-turned rim stratigraphy.

Stop 8 (Elden Mountain overlook):

1. What is the composition and age of this volcano?

Dacite, erupted at 0.5-0.6 Ma

2. What type of volcanic landform is Elden Mountain?

Volcanic dome

3. What are the dimensions of the flow lobes?

Various sizes, up to 2 km long by 0.5 km wide

4. Was the extrusion of lava the only volcanic activity at Elden Mountain? Explain.

No, there were also explosive eruptions, as evidenced by ash deposits found in the surrounding terrain. This part of the dome is "exogenous," formed by lava flows; the north side of the dome is "endogenous," formed by dacite intrusions that uplifted Paleozoic sedimentary rocks.

Stop 9. Cinder Lake:

1. What is the origin of the cinders here?

Sunset Crater, which is a few km to the north (Stop 10)

2. Examine the small craters. Are they all the same size and shape?

No, they have a variety of sizes and shapes

3. What is the yellowish material on the rims?

Clay deposits excavated from below the cinders

4. Explain the significance of these craters.

These were produced artificially by explosions to create a simulated lunar impact-cratered mare surface for astronaut training during the Apollo program. Unfortunately, off-road vehicles have degraded most of the craters.

Stop 10a (Sunset Crater Visitor Center):

Examine the displays in the Visitor Center and answer the following questions.

1. Identify the largest earthquake that occurred in the western United States today and its magnitude.

(see interactive display)

2. View the interactive panoramic images taken at the summit of Sunset Crater; match the aerial photograph in the exercise to the panoramic image and describe the crater as part of the "hole" assignment.

The summit crater has an irregular outline; there are light-colored materials around the rim, and lava appears to be present, in addition to the cinders.

3. Describe the shape and size of the largest volcanic bomb on display.

It is a "football" shape elongated feature, with tapered ends, "bread crust" texture, and surface striations; it is ~65 cm by 25 cm.

4. Can fossils form from volcanic eruptions? Explain your answer.

Yes, molten lava can encase plants and animals, forming molds that preserve the form; numerous molds of ears of corn have been found in the lavas from the Sunset Crater eruption.

5. What is the age and basis for the age-dating of the eruptions at Sunset Crater? Be specific.

Eruptions were around 1064 (contemporaneous with the historic Battle of Hastings), and lasted 150-200 years. Dating is based primarily tree-ring dates from roof beams in Native American dwellings buried by the eruption.

6. Is there any pattern in the eruptions in the San Francisco Volcanic Field? Explain.

Yes; there appears to be a general shift in eruptions toward the east.

7. What is the **style of eruption** for Sunset Crater; how high were the **fire fountains** and the **ash cloud**?

Mild explosive eruptions (Strombolian style), accompanied by effusive activity to produce lava flows, and some fire fountains to produce spatter cones.

8. What is the range in thickness of the ash deposits from the Sunset Crater eruptions from the base of the cinder cone north to **Waputki**? From the ash **isopachous map**, what is the inferred wind direction at the time of the eruption?

~1200 cm thick at base of the cinder cone to ~10 cm thick at Waputki (~12 miles to Waputki). The inferred wind direction was generally from the west toward the east.

Stop 10b (Bonito Lava Flow parking area):

1. Orient the aerial photograph to the terrain. What is the rock type here? **Basalt**
2. Take the trail across the flow northward to the cliff. Describe the surface of the flow (texture, vesicularity, relief, flow structures, etc.). What kind of flow is this?

This flow is rugged, with a rough, clinker, vesicular surface of several m relief; this is a basalt a'a lava flow, which was of relatively high viscosity during emplacement; a'a is a Hawaiian term used for this type of surface.

3. What formed the cliff?

It is the flow margin, the edge of which has collapsed to expose the flow interior.

4. How thick do you estimate the clinkery texture to be? **1-2 m**
5. Describe the interior of the flow.

Massive crystalline basalt; vesicles present, but fewer than in the clinkery upper zone.

6. Describe the probable manner in which this flow advanced.

A'a flows advance much like a tank-tread in which the top of the flow is over-ridden as the flow advances and the clinkery flow top become the bottom of the flow.

Stop 10c (Sunset Crater Nature Trail):

We will take the trail; orient the aerial photograph to the terrain and proceed to Station 1 (instructor will guide you)

Station 1. This feature is a **lava tube**. What is the lava type (texture) that makes up the roof of the tube? Is this the primary surface of the flow? Why or why not?

The flow here is pahoehoe lava, a Hawaiian term and typified by the smooth non-clinkery surface. This is not quite the original surface; pahoehoe flows that are fresh typically have a glassy rind on the surface that is ~mm thick, which is quickly lost from weathering; otherwise, the flow features, etc. seen here primary flow textures.

How do lava tubes form?

Lava tubes form by more than one process. Many form from roofing over of an open lava channel, others develop within flows that advance by budding of "lava toes" fed by conduits of lava within the overall flow, with some conduits evolving into focused feeder tubes.

Do lava tubes typically form in a'a flows? *No* Why or why not?

Generally, lava tubes form in low-viscosity lavas, although there are rare occurrences in a'a flows. This is a reflection of the viscosity of the flows and differences in the modes of emplacement between pahoehoe and a'a.

Station 2. What features identify this as a *vent*?

Spatter deposits and oxidized lavas are typical of volcanic vents. However, this is a "hornito" (Spanish for "little oven"), one type of "rootless vent," meaning that it did not form directly over the magma conduit. This particular feature probably formed over a rupture in the roof of a lava tube.

What is the origin of the whitish deposits?

Minerals precipitated from fumarolic outgassing; fumaroles are also typical of volcanic vents.

Station 3. Two lava flows are visible here, the relatively lower-level greenish-black aa flow, and a second reddish flow that forms the higher unit and which the trail in the distance climbs. The Park Service (and C.A. Hodges) tells us that the lower flow is younger. Do you agree? Give the evidence for your position (use superposition, geometric relations, etc.). Also use the air photo. You may want to reserve a final opinion until after you examine the surface of the reddish flow.

The upper, reddish flow is the older, as evidenced by the presence of ash that is mostly absent on the lower greenish flow, indicating that the reddish flow was present when the ash was erupted, but that the greenish, lower flow was not present. The difference in timing could be a matter of only hours. The presence of ash on the upper flow is evident in the aerial photograph as the light grey surface, showing that remote sensing as well as in situ field evidence is important in solving planetary problems.

What was the vent for the older lava flow?

The flow emerged from the base of Sunset cinder cone; the lower flow apparently extruded from the base of the upper flow.

Station 4 (top of trail). Several light-toned rocks are found in the lava here. What are these features called? What kinds of rocks are they, and how did they get there?

These are xenoliths of sandstone ripped from the conduit walls as the magma squeezed through the underlying sedimentary rocks. The xenoliths were carried into place in the lava flow.

Station 5 (viewing platform). How did this crack form and what are the features marked here?

Pressure exerted by lavas beneath the flow crust fractured the crust, followed by extrusion of these features called "squeeze-ups," the features with the golden sheen seen from the viewing platform. Squeeze-ups form much like toothpaste oozing from a tube.

Stop 10d (Cinder Hills Overlook):

There is a good view of Sunset Crater cinder cone and other small volcanoes from this stop.

1. What is the maximum slope on the various cones? Why is there an upper limit?

The maximum slope is about 30 degrees, which is close to the angle of repose (~34 degrees) for loose materials such as cinders, which are ballistically emplaced.

2. Is Sunset cinder cone composed solely of cinders?

No, lava is visible near the summit, formed by “spatter.”

3. Would you expect cones to have a different form on the Moon? Mercury? Venus? Why or why not?

Cones result from the ballistic emplacement of cinders, the trajectories of which are governed mostly by gravity and the presence or absence of an atmosphere. On the Moon in the low g environment and in the absence of an atmosphere the trajectories are longer (all other factors held equal), with pyroclastics spread over a wide area (thus cinder cones are absent or rare on the Moon). The higher g on Mercury might result in cinder cone formation, but none have been found so far in its exploration. The very dense atmosphere on Venus and its high g would lead to cinder cone formation.

4. Are all the cones of the same age? Why or why not?

Not quite, some show different degrees of erosion.

5. How many of the cones show signs of erosion?

A few do, but most are relatively young, and exhibit little erosion.

6. Is water an effective agent of erosion here? Why or why not?

The water soaks into the loose cinders without cutting channels.

7. Trees appear to grow predominantly on the north slopes; why is this?

Snow lasts longer into the spring and summer, which provides moisture to vegetation.

8. Describe the appearance of O'Leary Peak. How is it different from the other hills in this area? Why?

Its slopes are somewhat steeper and more heavily vegetated than the other hills in the area. O'Leary peak is a volcanic dome composed of rhyodacite lavas, and is much older than the cinder cones, providing a longer time for vegetation growth.

Stop 11 (San Francisco Peaks Overlook):

1. Examine San Francisco Mountain and identify the principal summits and features (Agassiz, Doyle, Humphrey, Dry Lake Hills, Sugarloaf, North Sugarloaf, etc.). Is the current profile the pristine shape for San Francisco Mountain? Explain.

No, it was probably a much higher volcano (reaching perhaps 4,900 m, or 16,000 feet) prior to the formation of the inner valley, visible from here.

2. What is the principal composition (by volume) of San Francisco Mountain? *Andesite*
3. What is the relationship between sequence/evolution of San Francisco Mountain and silica content?

No apparent sequence.

4. What is the oldest feature identified with the Mountain?

North Sugarloaf Peak, dated at 2.78 Ma

5. What is the origin of the inner valley?

It formed from massive landslides, perhaps accompanied by some collapse. Some analogies have been drawn between the inner valley and the recent eruptions at Mount St. Helens and the formation of its equivalent inner valley.

Stop 12. Robinson Crater / O'Leary Peak, west flank

1. Collect the variety of rocks at this exposure; identify the mineral(s) present and the texture of the rocks. Name the rock(s).

This stop is at the locked gate to an operation at Robinson crater, where pumice is being commercially mined. Minerals include quartz, feldspar, and small amounts of biotite. The rocks are microcrystalline rhyodacite, pumice, and obsidian.

2. Explain the differences among the samples.

The dark obsidian, the white pumice, and the light-colored rock (rhyodacite) all have the same composition (silicic), and demonstrate the role of texture in the appearance of rocks (obsidian = glassy; pumice = glassy with abundant vesicles; light colored rock rhyodacite = crystalline).

3. Return to the vehicles and drive a couple of hundred meters back down the hill. Examine the outcrop on the left and explain the mode of growth for O'Leary Peak.

Road cuts a short distance from the gate exhibit "crumble breccia" that results from rock that is sloughed from the steep flanks of the dome as intrusion/extrusion occurs.

4. What is the age for O'Leary Peak, and what is the age based upon?

It has been dated at 233 Ka, based on radiogenic ages of the mineral sanidine in the rocks.

5. What is the origin of the black cinders?

These are basaltic cinders from the pyroclastic eruptions of Sunset Crater.

Stop 13. Lava River Cave (also called Government Cave):

1. What is the average thickness of the tube roof?

This is difficult to determine without an accurate survey, but 10-15 m is a good estimate from the observations near the entrance to the tube. The entrance formed by collapse of the roof.

2. What is the role of the lava tubes in the emplacement of long flows? Explain.

Lava tubes are effectively extensions of the vent; basalt is an excellent insulating medium. Measurements of temperatures in active lava tubes in Hawaii show a drop of only 2° C/km.

3. What is the significance of lava tubes in the planetary context?

Many of the channels and elongate chains of craters (but not chains of secondary impact craters) on the Moon, Mars, and Venus appear to be collapse lava tubes which emplaced the extensive basaltic lavas.

The return from Flagstaff to Tempe will be on US Highway 89A south to Sedona, then Arizona Highway 179 (turn left in Sedona) back to I-17.

Stop 14 (Oak Creek canyon overlook): US Forest Service "pullout" east of the highway.

1. This position marks the headward zone of Oak Creek Canyon. Explain the reason for the difference in elevation between the west side and east side of the canyon.

Oak Creek Canyon is partly cut along a fault, with the west wall of the canyon being the up-thrown side of the Oak Creek Fault.

2. The "Red Rock" of the drive from here to I-17 is composed of what formation(s) and age(s)? What was the environment(s) of deposition for the rock(s)? To answer these questions, sketch a geological column showing the rock(s), age(s), and environment(s) below.

Cenozoic basalt flows = volcanic

Permian { *Kaibab Limestone = marine environment*
Coconino Sandstone = dunes
Supai-hermit = near-shore, muddy environment

The drive to the interstate will be on narrow, winding mountainous roads. Be patient; enjoy the scenery/geology (except the driver!). Do not try to "caravan" from now to Tempe. There is a road-side rest area with rest rooms on I-17, just south of the junction of AZ 179 and I-17.