TRAINING FOR PLANETARY EXPLORATION IN ANALOG TERRAINS: THE VALUE OF NORTHERN ARIZONA AND THE COLORADO PLATEAU. L. A. Edgar[1], J. A. Skinner Jr.[1], J. E. Bleacher[2], C. A. Evans[3], T. G. Graff[4], J. M. Hurtado[5], K. E. Young[6], [1]USGS Astrogeology Science Center, 2255 N. Gemini Drive, Flagstaff, AZ (ledgar@usgs.gov), [2]NASA HQ, [3]NASA JSC, [4]Jacobs Engineering, NASA JSC, [5]Univ. Texas, El Paso, [6]NASA GSFC.

Introduction: Northern Arizona and the Colorado Plateau have long been used as training grounds for human and robotic planetary exploration due to their geologic diversity, environments analogous to planetary surfaces, and ease of access on federal and state lands. This region offers access to a wide variety of planetary analogs in close proximity, including multiple styles of volcanism, impact cratering, and diverse sedimentary sequences. The use of terrestrial analogs gained increased attention during the 1950s and 1960s in preparation for the geologic exploration of the Moon at sites including the San Francisco Volcanic Field, Barringer Crater (i.e., Meteor Crater), the Verde Valley, Hopi Buttes Volcanic Field, and the Grand Canyon, among others. Here, we review several key analog sites (Fig. 1), their historical and current use, and resources available to the community to optimize their use for facilitating planetary exploration.

Geologic Context: The geology of northern Arizona is defined by a major structural transition along the Mogollon Rim, from the extensional Basin and Range to that of the Colorado Plateau. North of this transition, the mostly flat-lying rock units that make up the regional plateau occur between approximately 5,000 to 7,000 feet elevation. The oldest rocks underlying this region are 1.7-1.8 Ga granite and schist, which are overlain by a thick sequence of Paleozoic sedimentary rocks (forming the stratigraphic section exposed in the Grand Canyon). A complex tectonic history resulted in both the uplift of this plateau and regional extension, which reactivated deeply-seated crustal faults, as well as stretching and thinning of the crust. Beginning ~10 Ma, magma migrated upward along these faults and erupted onto the surface, forming the numerous cones and lava flows of the San Francisco Volcanic Field (SFVF). The SFVF comprises nearly 600 cinder cones and lava domes, numerous lava flows, widespread cinder deposits, and the San Francisco Mountain stratovolcano. Collectively this field represents a wide range of eruption styles and terrain types, including excellent basaltic volcanic analogs for the Moon and Mars. The most recent geologic history of the region involves fluvial and eolian erosion and deposition.

Relevant Analog Sites: Widely used training sites include the following:

SP Crater is a 250-m-tall basaltic andesite cinder cone with an agglutinate rim that erupted between 7,000 and 71,000 years ago on top of slightly older, eroded basaltic cones and flows and Permian-age limestone. SP Flow, a blocky, levee-bound and minimally vegetated lava flow, emanates from the base of SP Crater and flows north for 7 km, partly filling a graben. SP Crater and Flow have been used as analogs for studies in radar roughness, basalt mineralogy and textures, and effusive eruption processes; training of NASA astronauts, engineers, and managers [1-3]; and flight hardware and communication tests. The ruggedness, youthful age and appearance, marginal levees and lobes, mineralogy, cone-flow timing, and location in topographically variable terrain make SP Crater and Flow an optimal location for a diverse range of science, technology, and training exercises.

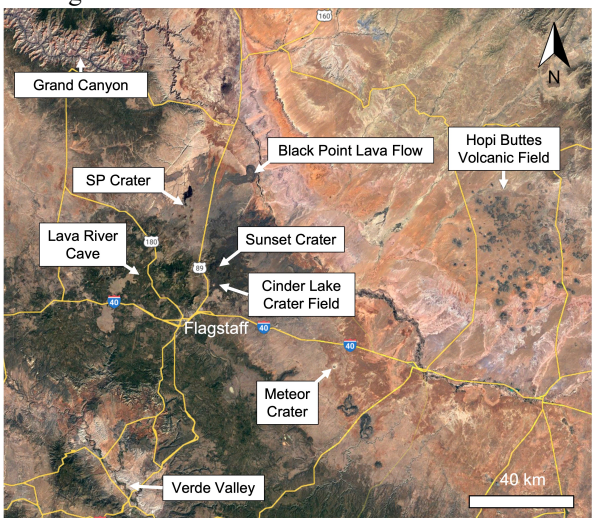

Fig. 1. Key analog study locations in northern Arizona.

Black Point Lava Flow is a basaltic, fissure-fed lava flow that erupted ~2.4 Ma and buried Triassic-age sandstone. The flow extends over 20 km and has up to 30-m-tall lobate margins and a blocky terminal lobe, the latter due to surficial faulting and sliding on weak subjacent clay-rich units. Outcrops of sandstone beneath the lava flow are evidence of significant vertical deflation since emplacement and superposing terrace gravels indicate periodic fluvial inundation. Black Point Flow was notably used as a base for the diverse portfolio of DRATS 2010 science and technology studies [4]. The marginal deflation, fissure-source, superposing gravels, terminal mass-wasting, broadly level surface, and ease of access make Black Point Flow an optimal location for investigating post-emplacement erosion and modification as well as mobility, suit, and tool testing.

Sunset Crater is a basaltic scoria cone and associated flow that represent the second (of three) eruptive phases from a 10-km fissure in ~1085 BCE.

The centralized eruption resulted in cone building, dispersed tephra units, and two main flows (Kana'a and Bonito), the latter of which extends 3 km from the source and includes rafted pieces of the cone. Subsequent erosion and remobilization of tephra units has resulted in dispersed basaltic dunes. The Bonito Flow was used extensively by NASA astronauts and engineers for suit mobility, observation, communication, and tool testing in advance of the Apollo missions [5]. The extreme youth, ruggedness of flow, tephra and aeolian components, accessibility, and historical nature make Sunset Crater an optimal location for investigating monogenetic explosive eruptions, aeolian transport, and historically comparative science and technical training.

Hopi Buttes Volcanic Field (HBVF) is located on the Navajo Nation in northeastern Arizona and is composed of over 300 maars and diatremes that erupted through older Paleozoic and Mesozoic sedimentary rocks. The diversity of sedimentary and volcanic environments in close proximity makes this a prime target for understanding past habitable environments. This area was historically used for Apollo suit and mobility testing, navigation, fly-over exercises, and scientific mission operations [6].

Cinder Lake Crater Field consists of two areas that were constructed in 1967 to replicate part of the Mare Tranquillitatis region on the Moon in preparation for the Apollo 11 landing. The cinder field is made up of tephra from Sunset Crater, and two fields of craters were generated using planned explosions. The craters range in size from 5 to 100 ft in diameter. This site provides an excellent analog for training in impact stratigraphy as well as navigation in complex terrain. During the Apollo program, the Cinder Lake Crater Field was used for traverse planning, instrument deployment, as well as to test lunar rover prototypes and hand tools [5-6].

Meteor Crater is one of the best-preserved impact craters on Earth. The 1.2 km crater formed 50,000 years ago and resulted in well-exposed inverted stratigraphy through the sedimentary sequence in which it impacted. The crater provides a world class analog for impact cratering processes and mobility considerations on other planetary bodies. Historically this site was used for distinguishing volcanic versus impact-generated craters, including detailed studies of overturned stratigraphy, ejecta deposits, and fallback units, and was part of training for Apollo astronauts to document and map these features on aerial photographs [6].

The *Verde Valley* is a lesser-known site but provides a great analog for volcanic and sedimentary processes. The Verde Valley is a structural basin in the transition zone of Arizona, exposing rocks from the Paleoproterozoic to Quaternary. Evidence for water-lava interactions serve as important analogs for the search for life elsewhere in the solar system. Historically, this region was also used for astronaut training in ground-truthing, geologic mapping, and distinguishing various lava flows [6].

Current Analog Activities: There has been renewed interest in terrestrial analogs in northern Arizona for training, testing, and research, in part due to increased human and robotic missions and the announcement of NASA's return to the Moon through the Artemis program. Recent analog activities have included astronaut training at SP Crater, Meteor Crater, and the Grand Canyon [e.g. 1,3] as well as geology bootcamp training for NASA engineers and managers to introduce the basics of field geology applied to a variety of exploration disciplines [2]. These local analog sites are also used for science operations tests and tool development [e.g. 7]. Several other science and exploration studies have planned investigations of the volcanic, sedimentary, and geophysical properties of the area, and used these sites for testing exploration strategies and mobility [e.g. 8-9]. Mission teams and undergraduate and graduate classes also frequent the area for studies of planetary surface processes.

Northern Arizona and the Colorado Plateau have long been a focal point of terrestrial analog studies, and resources are being made available to help support and facilitate research, training, and field testing in the area. Increased interest in terrestrial analog studies underscore a need for more cohesion among scientists and engineers, and the products and results that are generated through research and testing efforts. To support the continued focus on northern Arizona and the Colorado Plateau for analog research, the USGS Terrestrial Analogs for Research and Geologic Exploration Training (TARGET) program provides community support for analog activities, including logistical support, data archiving, sample collections, field guides, virtual field trips, and training in field methods and mapping [10-13].

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