FINAL STATUS REPORT OF FIELD OBSERVATIONS FROM SUNSET CRATER, ARIZONA

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ABSTRACT

Sunset Crater Volcano, Arizona, is serving as an analog site for tephra transport, deposition, redistribution, and resuspension. Field work activities include measuring tephra thickness and erosion, geologic sampling for granulometric analysis, spectral and remote sensing measurements of lithology and vegetation, and airborne particle concentration measurements. Some initial field analyses are presented in this status report, but the analysis of the majority of field data and subsequent laboratory analyses are in process. Data acquired from this field work may reduce uncertainties and improve realism in modeling consequences for the potential release of radioactive material directly into the atmosphere from a volcanic eruption intersecting the potential repository at Yucca Mountain. Data from this site may also be used to update process-level modeling, to refine model parameters for performance assessment calculations, to develop and refine risk insights, and to inform the review of the potential U.S. Department of Energy license application.

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The coauthors are grateful to all participants in the field work at Sunset Crater. Field team members included Donald Bannon, James Durham, Ronald McGinnis, and John Roseberry. Each coauthor also served as a major member of the field team. Denise Giles (graduate student, Oregon State University) and Yasuo Tomishima (visiting scientist, National Institute of Advanced Industrial Science and Technology in Japan) provided additional field support. Brittain Hill (NRC) was a member of the field reconnaissance team in 2004. Laboratory support was provided by Donald Bannon, Denise Giles, Marla Roberts, John Roseberry, Scott Rubio, Mark Silver, and Sandra Watson. Paul Bertetti and Bradley Werling provided additional laboratory support. The authors are grateful to Lauren Mulverhill for conducting the editorial review and Sharon Odam for assisting with the word processing and preparation of the final report. This report was improved from reviews by H. Lawrence McKague, Gordon Wittmeyer, English Pearcy, and Nancy Adams.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated original data contained within this report were collected and analyzed to meet quality assurance requirements as described in the CNWRA Quality Assurance Manual. Sources for all other data should be consulted to determine the level of quality of these data.

Field and laboratory analyses for Sunset Crater field work are documented in CNWRA Scientific Notebooks 747E, 748E, 818, 819E, and 880.

ANALYSES AND CODES: Calculations were checked as required by Quality Assurance Procedure (QAP)–014, Documentation and Verification of Scientific and Engineering Calculations, and recorded in a scientific notebook. Geologic samples were analyzed in the laboratory using the ASD FieldSpec® 3 spectroradiometer and Spectral Analysis and Management System Software (SAMS) 3.2. Generation of figures was aided by the use of controlled versions of ArcGIS 8.3 (Environmental Systems Research Institute, Inc., 2004), Arc/Info 7.0.2 (Environmental Systems Research Institute, Inc., 2003), and ArcView 3.2 (Environmental Systems Research Institute, Inc., 1999).

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1 INTRODUCTION

1.1 Background and Objectives

Sunset Crater in Arizona is a 900-year-old scoria-cone volcano with a surrounding deposit of tephra. Located in a semiarid climate of the Desert Southwest, it is a suitable analog for volcanic processes and posteruption surface processes at Yucca Mountain, Nevada. Lack of data relevant to airborne transport, dispersal, and subsequent redistribution processes in the Yucca Mountain area produces model uncertainties. To reduce these uncertainties, staff are conducting focused investigations for basaltic tephra transport, dispersal, and remobilization at Sunset Crater in the San Francisco Volcanic Field (SFVF)[1], Arizona.

Field and laboratory investigations involving the direction, thickness, extent, and grain-size characteristics of the tephra-fall deposit at Sunset Crater Volcano are being used to update process-level modeling, refine model parameters for performance assessment calculations, develop and refine risk insights, and prepare staff for the review of the potential U.S. Department of Energy (DOE) license application. Field activities have focused on three related tasks: (i) geology, (ii) remote sensing and spectroscopy, and (iii) airborne particle concentrations. This research supports both the Airborne Transport of Radionuclides and Redistribution of Radionuclides in Soil Integrated Subissues (NRC, 2005, 2003). When available and as appropriate, results of the field work will be integrated into evaluations of input parameter values for the Total-system Performance Assessment (TPA) code (Mohanty, et al., 2005).

Sunset Crater is located in the SFVF of north-central Arizona. The cone stands 314 m [1,030 ft] in height and measures 1,630 m [5,348 ft] in average diameter. It is named for the topmost cap of red scoria, whose oxidized bright red color is due to slow cooling. Eruptive activity began in 1064 or 1065 A.D. (Smiley, 1958) and continued, probably intermittently, for about 150 years (Holm, 1987; Holm and Moore, 1987; Tanaka, et al., 1990). It is interpreted to have been created by a Strombolian-type eruption with ejecta that includes scoriaceous ash {<2 mm [0.08 in]}, lapilli (or cinders) {2–64 mm [0.08–2.5 in]}, and blocks and bombs {>64 mm [2.5 in]}. When transported through the air, these volcanic ejecta are collectively termed tephra. After an eruption, tephra could be deposited over hundreds to perhaps thousands of square kilometers [tens to perhaps thousands of square miles] around and downwind from the vent. At Sunset Crater, the pyroclastic sheet from the eruption occurs as a widespread deposit of fresh black tephra that mantles the preexisting landscape (Figure 1-1). In the distal regions, the tephra may be present as a thin, discontinuous cover over older lithologic units.

During the course of the Sunset Crater eruption, two lava flows issued from the base of the cone: the Bonito flow to the west and the Kana-a (or Kana'a) flow to the northeast. The scoria cone and the Bonito lava flow are within Sunset Crater Volcano National Monument, while the Kana-a lava flow and the majority of the tephra-fall deposit lies within the Coconino National Forest. Sunset Crater Volcano National Monument is located approximately 20 km [12.4 mi] north of Flagstaff, Arizona (Figure 1-2).

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[1] San Francisco Volcanic Field is used frequently in this document; therefore the acronym SFVF has been used.

Figure 1-1. Sunset Crater Scoria Cone Viewed From the South. A Deposit of Black Tephra Covers the Surrounding Landscape.

1.2 Risk Significance

Quaternary basaltic volcanoes exist within 20 km [12.4 mi] of the potential radioactive waste repository at Yucca Mountain, Nevada. If radioactive waste was entrained in the conduit of a future volcanic event and transported in the resulting eruption plume, contaminated volcanic ash or tephra could be deposited over hundreds to perhaps thousands of square kilometers [tens to perhaps thousands of square miles]. In this potential scenario, ash particles from a basaltic eruption are assumed to be the carriers of the radionuclides. Depending on eruption and atmospheric conditions (e.g., wind direction), significant to negligible amounts of tephra could be deposited directly at the location of the reasonably maximally exposed individual or receptor. Additionally, tephra deposited on surrounding hillslopes would be eroded and transported by water and wind, with the potential for later deposition at or near the location of the receptor.

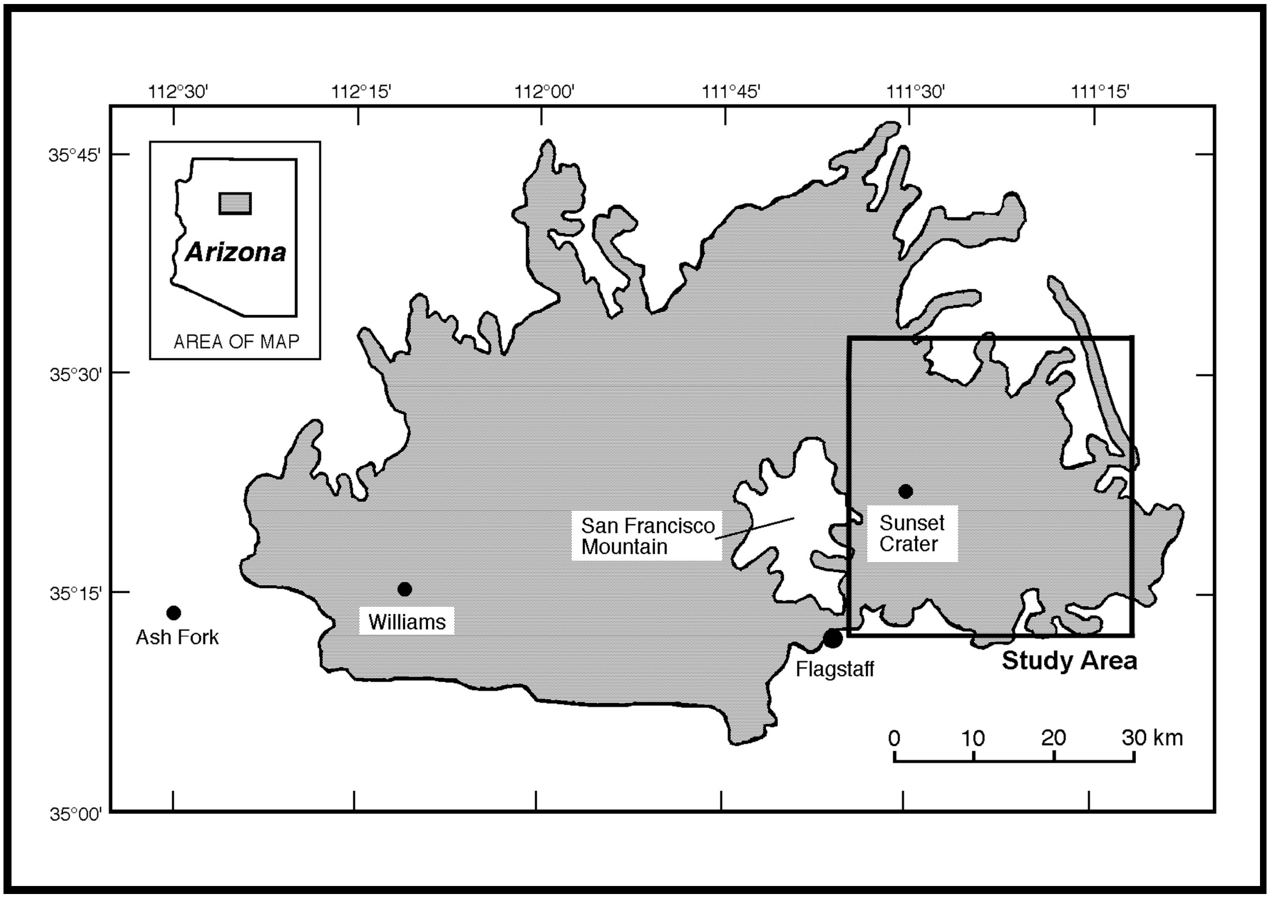

Figure 1-2. The San Francisco Volcanic Field of Arizona. Predominantly Basaltic Volcanic Rocks Younger Than 5 Million Years Are Shaded. San Francisco Mountain Is a Stratovolcano With a Silicic Composition. The Study Area Is Outlined.

An influx of redistributed tephra could affect the airborne radioactive particle concentrations at the receptor location, depending on the rate of remobilization of radioactive tephra and dilution with nonradioactive sediments. Resuspension of fine-grained tephra particles by surface disturbances or wind action may produce increased concentrations of ash and high-level waste. Airborne mass load for the years following a potential volcanic eruption is a high sensitivity parameter in total-system performance assessment estimates (Mohanty, et al., 2005, 2004), and uncertainties in this parameter strongly affect estimates of expected annual dose. For extrusive volcanism, remobilization is directly related to the four risk insights presented in the Risk Insights Baseline Report (NRC, 2004):

- Inhalation of resuspended volcanic ash (high significance to waste isolation)
- Remobilization of ash deposits (medium significance to waste isolation)
- Wind vectors during an eruption (medium significance to waste isolation)
- Volume of ash produced by an eruption (medium significance to waste isolation)

Although most deposits from basaltic volcanoes in the Yucca Mountain region are poorly preserved, sufficient information exists to conclude that the range of past activity at these volcanoes is analogous to that observed at volcanoes such as Sunset Crater (Hill and Connor, 2000; Hill, et al., 1998; NRC, 1999). Modeling investigations with new data resulting from this field work may reduce uncertainties and provide more realistic estimates of the airborne transport and deposition of radionuclides in volcanic ash plumes, including inhalation and remobilization after initial deposition.

Field investigations at Sunset Crater Volcano pertain to physical volcanology, tephra distribution, and tephra redistribution, as well as conceptual models for eruptive processes. This information relates to the features, events, and processes of disruptive events (Bechtel SAIC Company, LLC, 2005, 2004, 2003) and include eruption style, tephra volume, tephra particle size distributions, pyroclastic characteristics, tephra deposit density, and tephra redistribution and dilution.

1.3 San Francisco Volcanic Field

The SFVF of north-central Arizona is comprised of more than 600 volcanoes with associated lava flows or pyroclastic deposits. Although volcanic landforms with a basaltic composition are dominant, several intermediate to silicic volcanic centers have been recognized. Late Miocene to Holocene volcanic rocks cover approximately 4,800 km^2 [1,850 mi^2] and rest upon Permian and Triassic sedimentary rocks. The SFVF is centered at latitude 35°22'N–longitude 111°12'W and extends approximately 100 km [62 mi] east-west and 70 km [44 mi] north-south. It is bordered on the south and southwest by a group of Miocene–Early Pliocene volcanic rocks informally referred to as rim basalts (e.g., Tanaka, et al., 1990, 1986) because they occur along the Mogollon Rim—the physiographic feature that defines the southern margin of the Colorado Plateau. An area of 1,500 km^2 [577 mi^2] in the eastern portion of the SFVF has been selected for Center for Nuclear Waste Regulatory Analyses (CNWRA) field investigations (Figure 1-2). This area was selected because of climate, age, accessibility, and location of the continuous pyroclastic sheet from Sunset Crater.

San Francisco Mountain, a large composite volcano rising to an elevation of 3,851 m [12,633 ft], is the most prominent physiographic and volcanic feature in the field. Sunset Crater and its associated eruptive products are the youngest volcanic features in this field. Colton (1967) divided the basalt flows and scoria cones of the SFVF into five stages based on the degree of weathering and erosional modification. Moore, et al. (1976, 1974) redefined the sequence of Colton on the basis of established stratigraphic mapping, physiographic relations, and petrologic studies. They divided the basaltic flows and cones into five informal age groups: (i) Sunset age (Holocene); (ii) Merriam age (<0.1 million years); (iii) Tappan age (0.2 to 0.7 million years); (iv) Woodhouse age (0.8 to 3.0 million years); and (v) Cedar Ranch age (5.5 to 6 million years).

An eastward migration of volcanism in this field was identified by Luedke and Smith (1978) and Tanaka, et al. (1986).

In 1976 the U.S. Geological Survey (USGS)[2] began a geothermal research program to study the San Francisco Volcanic Field. The remanent magnetism of volcanic rocks was determined for over 650 sites (Tanaka, et al., 1990, 1986). In addition to the polarity of remanent magnetization, they examined K-Ar ages, spatial and petrographic associations, stratigraphic relationships, and the state of preservation of lava flows and scoria cones. These data were compiled into five 1:50,000-scale geologic maps covering the San Francisco Volcanic Field: (i) eastern sheet (Moore and Wolfe, 1987); (ii) central sheet (Wolfe, et al., 1987a); (iii) northwest sheet (Wolfe, et al., 1987b); (iv) southwest sheet (Newhall, et al., 1987); and (v) SP Mountain sheet (Ulrich and Bailey, 1987). Moore and Wolfe (1976) also published a geologic map of the eastern region of the volcanic field, which includes Sunset Crater and its associated volcanic deposits.

1.4 Climate

The plateau encompassing the SFVF is situated at an average elevation of 2,135 m [7,000 ft]. Mean annual precipitation at this elevation is approximately 500 mm [20 in], and temperatures are characteristic of high altitude climates (Sellers and Hill, 1974). Summer temperatures are pleasant and winters are cold, and all seasons have considerable diurnal temperature change. From early July until early September, afternoon thunderstorms develop almost daily over the higher terrains. These storms are usually short-lived and are triggered by moist, tropical air flowing into Arizona from the Gulf of Mexico. Additional precipitation is provided by winter storms that enter the state from the west after picking up moisture from the Pacific Ocean. Most of this precipitation falls as snow. The climate is semiarid, supporting pine forests at higher elevations and pinyon–sagebrush communities at lower elevations where precipitation amounts are lower. Peltier (1950) utilized mean annual temperature and precipitation to predict relative intensities of mechanical and chemical weathering. According to these climate-process diagrams, a semiarid climate experiences slight mechanical weathering and weak to moderate chemical weathering.

1.5 Field Campaigns

CNWRA staff conducted three separate field campaigns in the eastern SFVF over three consecutive years beginning in 2004. Reconnaissance was the primary objective of field work conducted in May 2004. Numerous sampling pits were dug to accurately characterize the Sunset Crater tephra-fall deposit. Sunset Crater was determined to be an acceptable analog for basaltic volcanism in Crater Flat and the Yucca Mountain region.

Field work was expanded in August 2005 to include (i) geological measurements with both geomorphological and volcanological objectives, (ii) spectroscopic measurements for mapping lithologic and vegetative units, and (iii) airborne particle concentration measurements. Tasks conducted in August 2005 with an emphasis on geologic investigation included (i) additional reconnaissance work, (ii) measurements of tephra and alluvium thickness, (iii) sample

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[2] U.S. Geological Survey is used frequently in this document; therefore the acronym USGS has been used.

collection for granulometric analysis, (iv) observation and characterization of the fluvial system, (v) observations and preliminary measurements of surface processes, and (vi) characterization of candidate sites for airborne particle concentration and spectroscopic measurements

Field spectral measurements in 2005 were performed using a system based on two USB2000–UV–VIS spectrometers. The spectral range of these detectors is limited and covers only a few bands on typical satellite imagery. Subtle absorption features found in many rock and soil samples cannot be analyzed because of this limited spectral range. A new instrument would be acquired after the 2005 field season.

Initial airborne particle concentration measurements in 2005 utilized the Institute of Occupational Medicine Personal Inhalable Sampler by SKC Incorporated with a MultiDust™ filter and foam disc. A conductive sampling head houses a reusable 25-mm [1-in] filter cassette assembly that is clipped near a worker's breathing zone and traps particles up to 100 μm [3.9×10^{-3} in] in aerodynamic diameter. This simulates the manner in which airborne particles are inhaled through the nose and mouth. The Institute of Occupational Medicine Sampler was judged to be unsatisfactory for Sunset Crater objectives because recommended procedures for processing and analyzing collected samples result in large measurement uncertainties. Follow-on investigations did not use Institute of Occupational Medicine Samplers.

The most recent field campaign at Sunset Crater was conducted in June and July 2006. With additional personnel, field activities were run concurrently as long as a sufficient number of staff members were present to support two field teams. During this campaign, the search, selection, and characterization of candidate sites for both airborne particle concentration and spectroscopic measurements was a high priority. Geologic tasks emphasized eolian and fluvial processes with sample collection for granulometric analysis.

A new field optical spectrometer was purchased for the 2006 field campaign. The new instrument is a FieldSpec® 3 produced by Analytical Spectral Devices and is designed to collect reflectance (solar or built-in light source), radiance, and irradiance measurements. This high spectral resolution spectroradiometer provides a solution to the previously mentioned limitations by collecting a high volume of quality data in a short time interval. It performs contact and noncontact National Institute of Standards and Technology-calibrated reflectance measurements of soil, vegetation, and rock samples over a wide spectral range.

The Model 8522 RespiCon™ Particle Sampler by TSI Incorporated was employed in 2006 for measuring airborne particulates. The RespiCon is a multistage virtual impactor that traps airborne particles onto three individual collection filters (TSI Incorporated, 2006). A conventional personal sampling pump draws air and airborne particles into the sampler through a ring-gap inlet. The lower absolute air pressure associated with the high elevation of the Flagstaff–Sunset Crater area required additional steps for premeasurement setup and checks of airflow rates with the airborne particle sampling equipment.

Appendices attached to this report provide location information and detail regarding survey (tephra) pits dug at the study site, samples used in granulometric analysis, geologic samples used for spectroscopic analysis, and site characteristics for samples used in airborne particle concentration measurements. Maps throughout the report show key locations, major tephra pit sites, field spectroscopy sites, and airborne particle concentration sampling locations.

2 GEOLOGIC MEASUREMENTS AND ANALYSES

2.1 Introduction

Field investigations at Sunset Crater Volcano provide an opportunity to study a 900-year-old tephra deposit in a semiarid environment as a Yucca Mountain analog for volcanic processes, posteruption surface processes, and risk insights. Geologic tasks primarily centered upon activities related to volcanology and geomorphology and included

- Excavation of survey pits to measure tephra thickness, evaluate vertical and lateral variations of the fall deposit, assess paleotopography, and aid with the interpretation of eruption and posteruption history
- Excavation of survey pits to measure the thickness of eolian, fluvial, colluvial, and alluvial deposits
- Observation, characterization, and measurement (when available) of surficial transport processes and their impact on erosion and estimates of erosion rate
- Field sample collection for granulometric analysis in the laboratory
- Field inspection and observation of the fluvial system in the Sunset Crater area as an analog for Fortymile Wash, Nevada
- Search and selection of candidate sites for both airborne particle concentration and spectroscopic measurements
- Geological characterization of candidate sites for both airborne particle concentration and spectroscopic measurements

2.2 Tephra Deposits

The fall deposits from the Sunset Crater eruption are widespread blankets of fresh black and subordinate red tephra. Pyroclasts are typically vitreous, highly vesicular, and achnelithic in morphology. Fall units are unconsolidated, well sorted, and demonstrate both reverse and normal grading. Grain size range is typical of Strombolian style eruptions (i.e., coarse scoriaceous ash to lapilli). Granulometric analyses are described in Section 2.4. Unlike the older scoria cones of Crater Flat, Nevada, secondary mineralization of Sunset Crater pyroclast surfaces by carbonate and/or silica is rare. Lithic fragments within the tephra are uncommon. When lithics are present, they make up an extremely low percentage (~ <0.5 percent) of their associated tephra package (Amos, 1986; Hooten, et al., 2001). Amos reports occasional carbonate lithic fragments from the Kaibab Formation.

Amos (1986) identified eight discrete tephra-fall units associated with the Sunset Crater eruption with an estimated total volume of 0.75 km^3 [0.18 mi^3] {dense rock equivalent volume of 0.41 km^3 [0.10 mi^3]}. Each unit ranges in thickness from millimeters to over 1 meter [0.4 in to 3.3 ft] and represents a separate phase of the eruption.

Tephra dispersal from the Sunset Crater eruption can be divided into a continuous and discontinuous deposit (Amos, 1986; Colton, 1967, 1932). The continuous fall deposit mantles the preexisting landscape (even after 900 years of erosion) and extends in an east to northeasterly direction for approximately 10 km [6.2 mi] along the main axis of deposition—an indication of prevailing wind direction and for approximately 4 km [2.5 mi] along the west axis. Proximally, this deposit is often greater than 1 m [3.3 ft] in thickness.

The discontinuous deposit is also most extensive to the east and northeast, reaching a distance of 20 km [12.4 mi] along the main axis of deposition. Where the covering is discontinuous, or at distances greater than approximately 10 to 15 km [6.2 to 9.3 mi] from Sunset Crater, tephra may exist only as a lag deposit with a thickness of one or two pyroclasts. This lag deposit ranges from 2 mm to 1 cm [0.08 to 0.4 in] in thickness. Throughout the distal regions of the deposit and in some instances beyond 20 km [12.4 mi] from the scoria cone, tephra may be present as black patches of sand-size particles reworked by eolian processes.

Amos (1986) measured tephra thickness and plotted the lines of equal thickness on an isopach map, reproduced in Figure 2-1 and superimposed upon an Enhanced Thematic Mapper Plus (ETM+)[3] Landsat scene. As expected, tephra thickness decreases away from the volcano in an elliptical pattern. Amos (1986) states that the Sunset Crater scoria fall deposit presently covers approximately 500 km^2 [192 mi^2], but this includes both the continuous and discontinuous ejecta deposits. From his general map of the deposit (Amos, 1986, Figure 9), the area of the continuous deposit is approximately 260 km^2 [100 mi^2], which is in agreement with the value calculated by Colton (1967). Hooten, et al. (2001) supplemented the Amos study with additional data points and generated a new isopach map (Figure 2-2). Hooten, et al. (2001) is the full technical report, but a general discussion of tephra dispersal, complete with an isopach map, can be found in Elson and Ort (2003). Although in general agreement, Hooten's map shows the pattern of fallout north of Sunset Crater is much less organized than in the earlier isopach map of Amos. Hooten, et al. (2001) propose that preexisting local topographic features played a significant role in the distribution and thickness in the proximal zone. Rapid decreases in thickness likely correspond to older volcanic edifices acting as a topographic barrier to tephra deposition.

Survey pits were dug for exploratory purposes, to measure the thickness of tephra or other geologic materials, and/or to examine the changing vertical section within the stratigraphic sequence. Some pits were excavated to examine alluvium, colluvium, fluvial deposits, or eolian material, although Sunset Crater tephra was usually present in at least minor amounts. Geologic samples were collected when deemed necessary or critical to the various aspects of this study. A large number of survey pits were excavated during each year of field work. Appendices A–C list these pits, their location, and a brief description of significant information. Although these data supplement the Amos (1986) and Hooten, et al. (2001) isopach maps, generating a new or revised isopach map was not a primary objective for the field and laboratory teams considering time and resources. This task could be pursued in the future. Field teams observed that topographic effects and local erosion produced the most significant discrepancies between tephra pit results and interpolating between contours on the previously published isopach maps.

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[3] Enhanced Thematic Mapper Plus is used frequently in this document; therefore the acronym ETM+ has been used.

The top of the tephra sequence, especially in the proximal region, is exposed directly on the surface without an overlying distinguishable soil horizon and is subjected to active surface processes. Because of the potential for erosion after 900 years since the time of emplacement, the initial thickness of tephra is unknown and the amount present today is only a measure of the minimum thickness at the time of the eruption. Careful inspection of the sequence reveals a topmost layer of bioturbated, disturbed tephra mixed with eolian fines (or potentially colluvium). This horizon is a surficial layer of scoria (cinder) with mixed sandy particles ranging from 8 to 15 cm [3.2 to 5.9 in] in thickness as measured in numerous pits. In other locations, the primary tephra is covered by a protective layer of alluvium—usually mixed with Sunset scoria—of the same thickness.

Sunset Crater tephra drapes preexisting scoria cones, and the older pyroclasts are noticeably more weathered and oxidized. When pits were dug to the base of the scoria-fall deposit, a substrate of oxidized, cohesive material usually was encountered. This is the preeruption surface (or paleosol) comprising a red-colored, clay-rich layer that sharply contrasts with the black, fine-grained and coarse-grained tephra layers (Figure 2-3).

2.3 Fluvial and Eolian Deposits

Primary tephra is recognizable in the field because it is glassy, vesicular, and unconsolidated. In contrast, fluvially reworked tephra is abraded, rounded, and often mixed with older sediment. Tephra that has been reworked by eolian processes is finer grained, well sorted by wind transport, and often remobilized into dune forms.

The USGS has mapped areal distribution of alluvial and eolian deposits as part of the geologic map of the eastern San Francisco Volcanic Field (Moore and Wolfe, 1976). As is typical for this semiarid region, the drainage system is ephemeral or intermittent and is characterized by dry, flat-floored channels (i.e., washes or arroyos). The regional slope for the study area is to the east-northeast toward the Little Colorado River. This river and some of the washes loosely serve as analogs for Fortymile Wash, Nevada. However, the coarse and porous nature of the Sunset Crater tephra deposit prohibits significant overland flow and runoff. Overland flow is more significant in the distal portion of the Sunset Crater fall deposit where the tephra covering is thin or intermittent and a weathered, preeruption surface dominates. Measurements were taken along a length of a small wash to calculate downstream fining (e.g., coefficient for diminution or comminution) and tephra breakage, but this analysis is not complete.

The most relevant fluvial and alluvial deposits are those related to the drainage directly from the Sunset Crater tephra deposit. The nonvolcanic substrate in the eastern San Francisco Volcanic Field consists of a sandy carbonate called the Kaibab Formation and a calcareous sandstone to shale called the Moenkopi Formation (Moore and Wolfe, 1976). Unconsolidated fragments of these formations are present, but the alluvium is primarily volcaniclastic in nature and is composed of basaltic material from the Sunset Crater eruption, basaltic fragments from other scoria cone eruptions, and nonbasaltic volcanic material such as the andesite, dacite, and rhyodacite associated with O'Leary Peak volcanism (Figure 2-4). Footslope colluvial deposits within the study area are dominated by tephra from the Sunset Crater eruption.

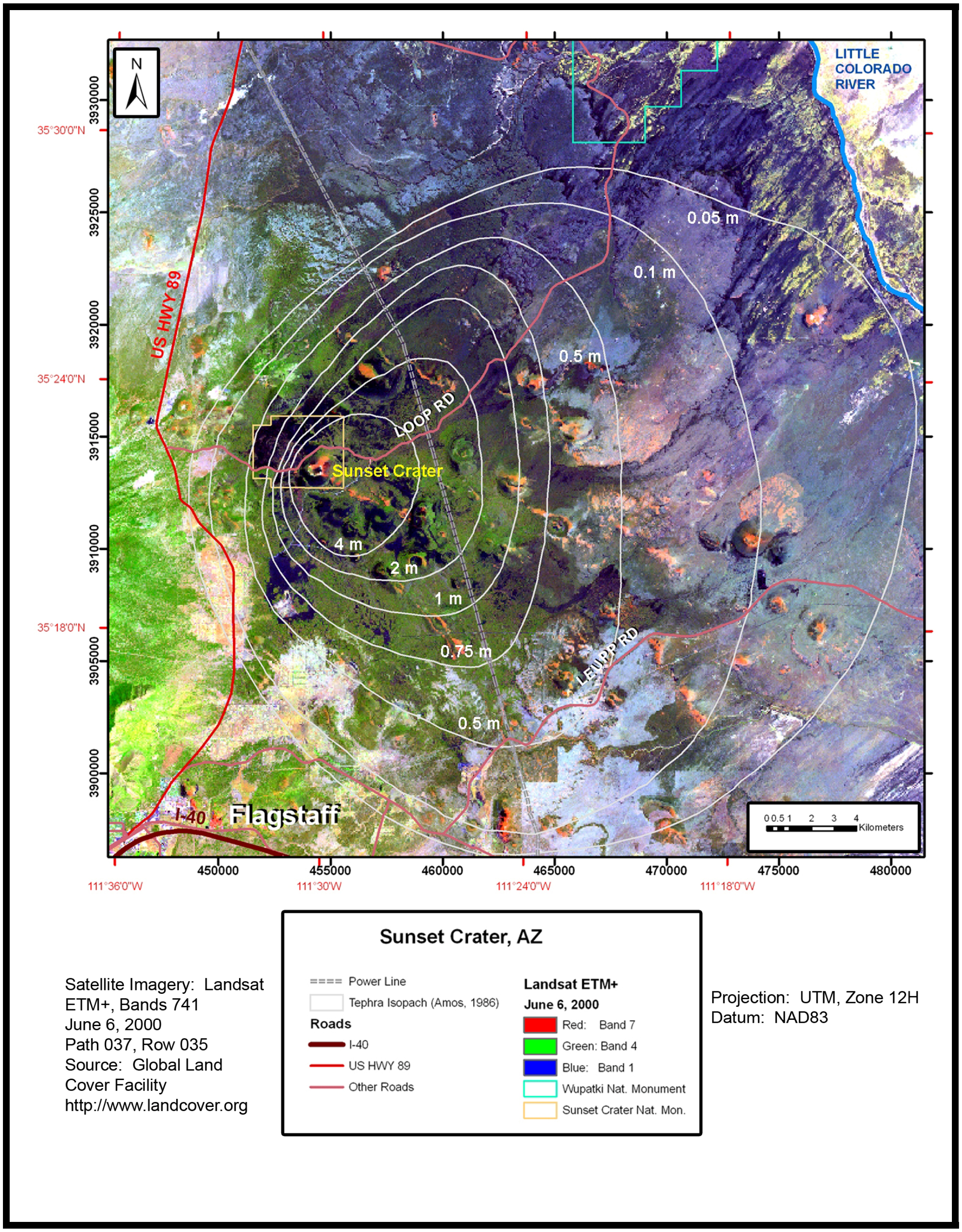

Figure 2-1. Map of Tephra Thickness Reproduced From Amos (1986) and Superimposed Upon Landsat ETM+ Satellite Data of the Study Area

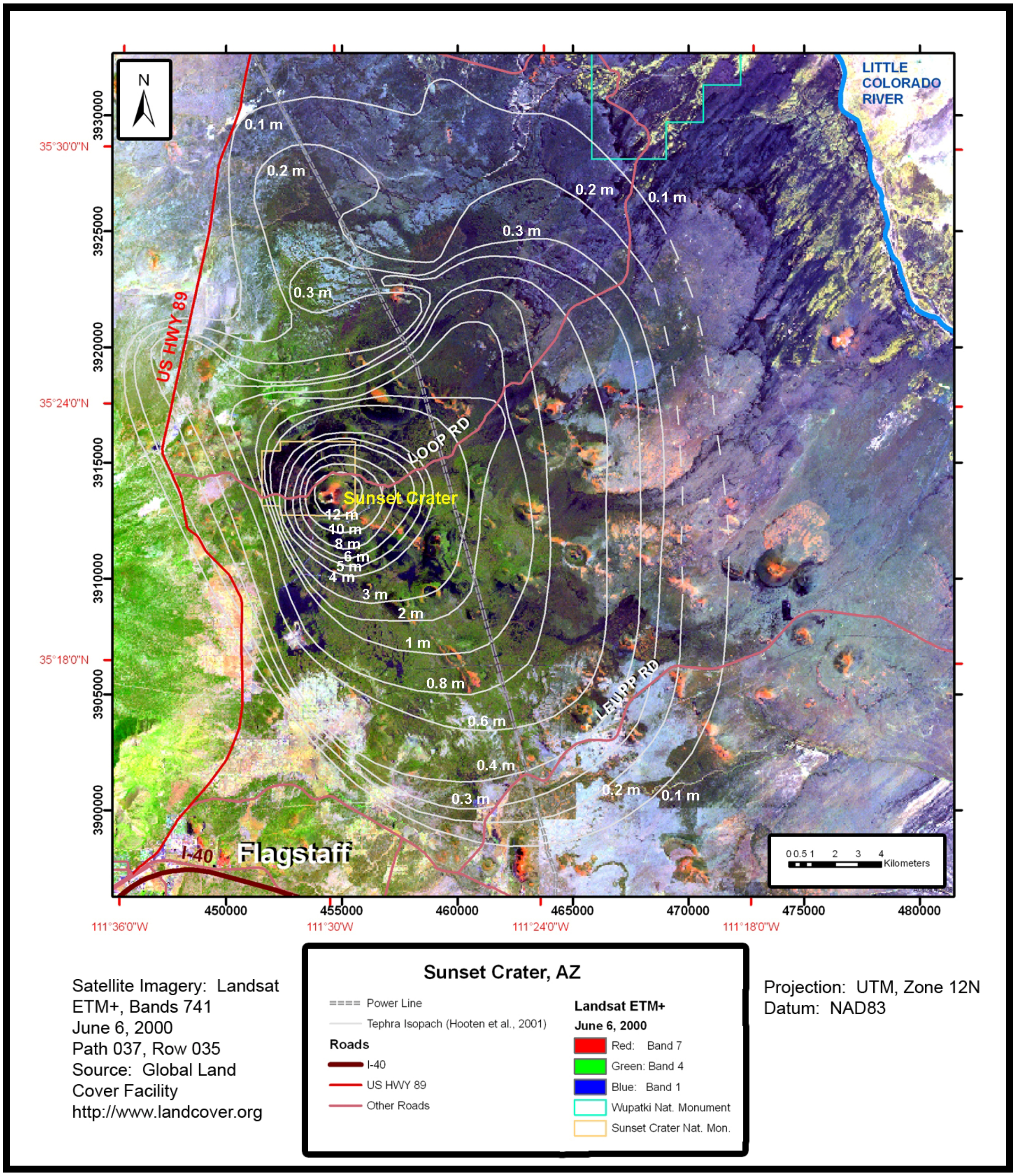

Figure 2-2. Map of Tephra Thickness Reproduced From Hooten, et al. (2001) and Superimposed Upon Landsat ETM+ Satellite Data of the Study Area

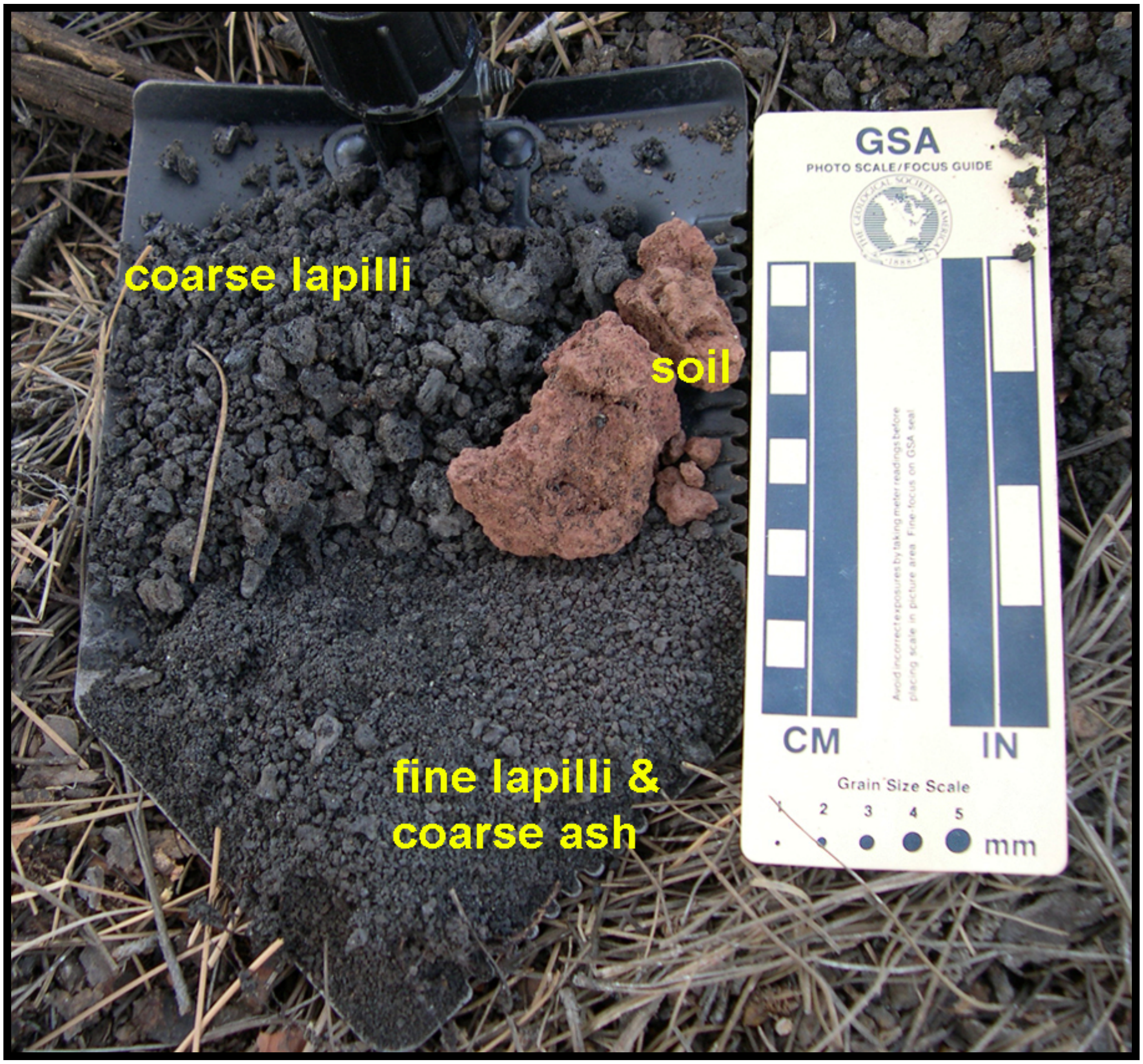

Figure 2-3. Representative Samples of Coarse Lapilli or Cinder, Fine Lapilli and Coarse Ash, and Oxidized Preeruption Soil

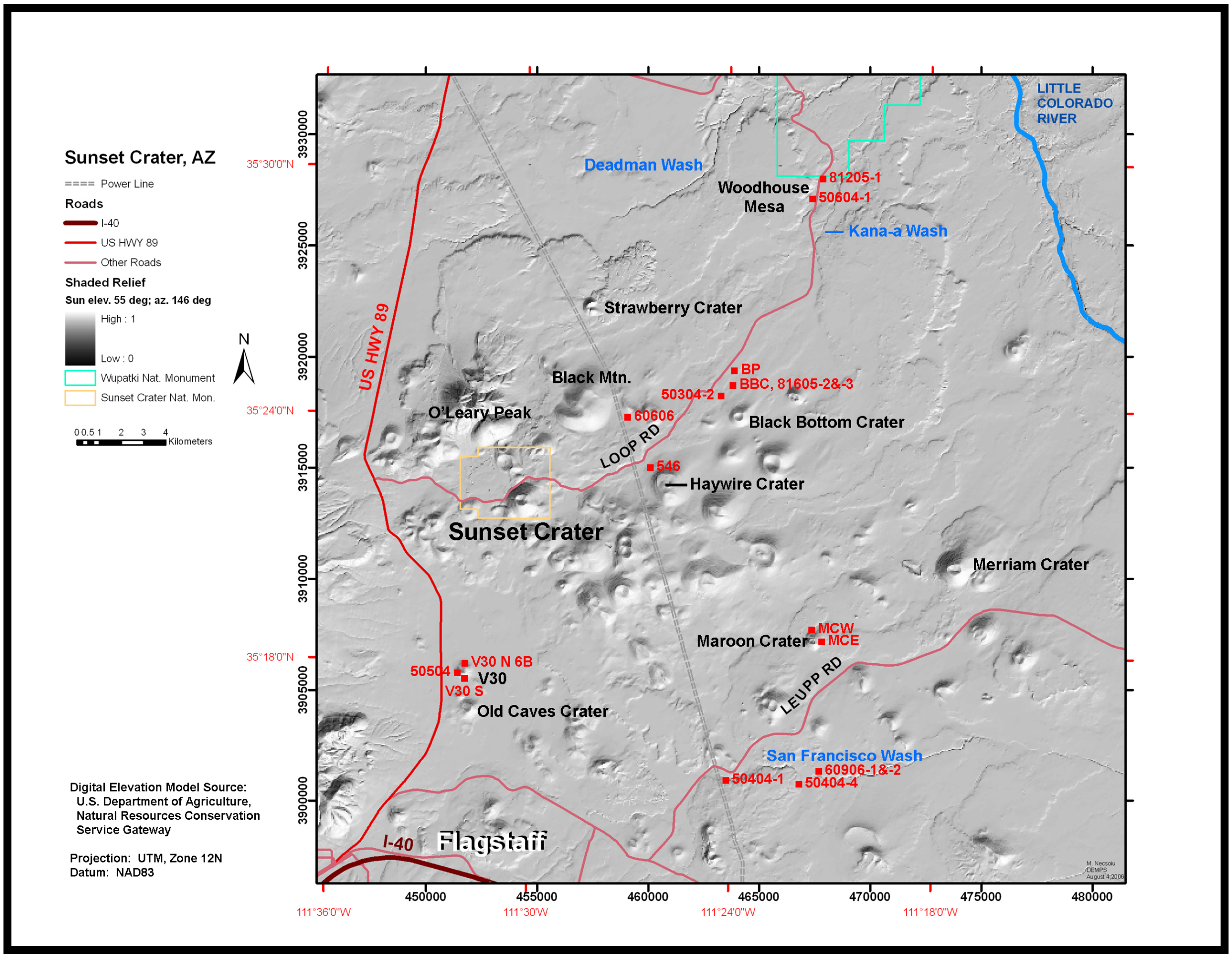

Figure 2-4. Shaded Relief Map of the Study Area Showing Relevant Topographic Features, Washes, and Sample Collection Areas Mentioned In the Test. This Map Is Based on a National Elevation Dataset 10 m [32.8 ft] Product and Complements the Landsat Satellite Data in Previous Figures.

Five pits were dug in 2006 to measure alluvium thickness, but each pit revealed a thick carbonate horizon at depths from 0.7–1.1 m [2.3–3.6 ft] (Appendix C). These alluvial deposits certainly predate the Sunset Crater eruption and could be as old as late Pleistocene to early Holocene.

Black, patchy eolian deposits of reworked Sunset tephra are easily identified along the distal margins of the fall deposit where wind action has transported or remobilized the tephra away from the site of initial deposition. These volcaniclastic deposits of wind-blown tephra are often characterized by coppice dunes (also known as nebkhas), which develop where sand-sized particles are trapped by clumps of vegetation and create small sand hummocks or mounds (McKee, 1982). Dune heights measured from 0.5–2.5 m [1.6–8.2 ft], but each eolian deposit thins considerably between clusters of vegetation in the interdune corridors causing the thickness to be highly variable (Figure 2-5). The margins of the deposit may appear continuous, but are very thin and measure less than 1 cm [0.4 in] in thickness. A local gradation from coarse-grained primary tephra fall deposit to fine-grained eolian reworked tephra deposit was observed around Black Bottom Crater and at other locations during field work. Other eolian deposits are related to local topographic effects, which may trap the moving tephra particles and form sand ramps or similar deposits (Figure 2-6).

In addition to the distal deposits of eolian-reworked Sunset Crater tephra, there are also eolian bedforms in the proximal region. Here the smaller particles of tephra have been blown into wind ripples and small transverse dunes {< 1 m [3.3 ft] in height}. These bedforms are most noticeable on open expanses of bare tephra.

2.4 Granulometric Analyses

2.4.1 Introduction

Granulometric analyses are the main source of data when examining the grain-size variations in unconsolidated pyroclastic (tephra) deposits. Systematic measurements of maximum particle size are also used to analyze the energetics of pyroclastic fall eruptions. Sieving has been completed for 41 samples collected from drainages, eolian deposits (coppice dunes), and along relevant hillslopes and level topography (Appendix D). Bulk *in-situ* density measurements are also listed in this appendix.

Samples were first dried and then placed in a set of stacked sieves that matches those the National Institute of Standards and Technology used in Reference Material 8010 (sand for sieve analysis). Because of the coarse grain size of Sunset tephra, 32 and 25-mm [1.25 and 1-in] sieves were used when necessary to complete the stack. The finest sieve used was a U.S. Standard Sieve No. 325 with a mesh opening of 4.5 phi units or 0.045 mm [0.0018 in]. The stack of sieves was placed on a shaking machine for 10 minutes. Mechanical analysis of resistant quartz sand may use longer sieving times, but 10 minutes was selected because of the fragile and friable nature of the vesicular pyroclasts.

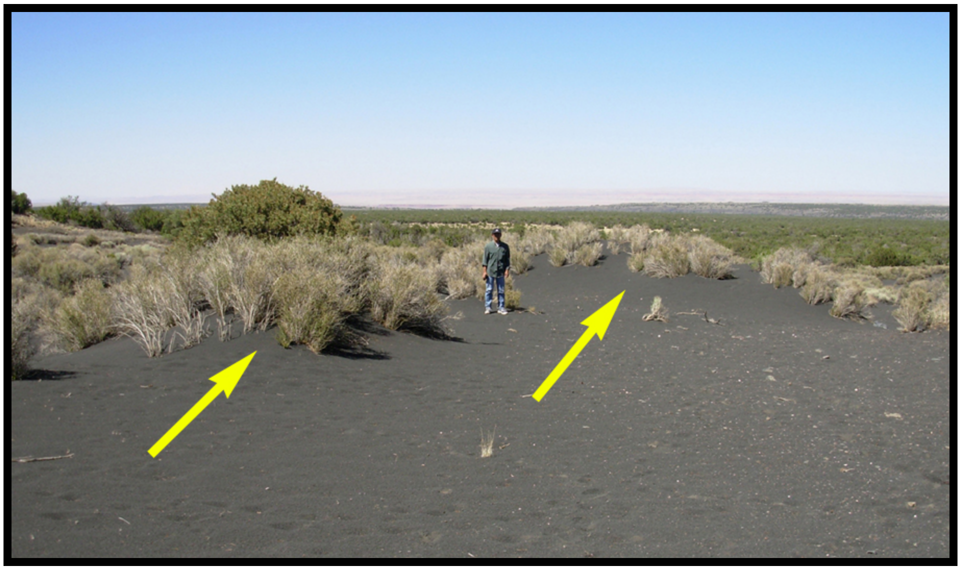

Figure 2-5. Coppice Dunes Are Composed of Tephra From the Sunset Crater Eruption. These Dunes Are Near Black Bottom Crater (Figure 2-4), 10 km [6 mi] Northeast of Sunset Crater.

Figure 2-6. Eolian-Reworked Sunset Crater Tephra in the Distal Area. Black-Colored Tephra, Which Has Been Remobilized by the Wind, Drapes the Red-Colored Moenkopi Formation. The Sedimentary Rock Is Capped by an Old Basaltic Lava Flow. Kana-a Wash Is in the Foreground.

Because of the broad distribution of grain sizes found in many geologic materials, it is common to use a logarithmic transformation of grain diameters called the phi (Φ) scale (Wentworth, 1922)

$$\Phi = -\log_2(d_{mm}) \tag{2-1}$$

for which d_{mm} is the grain diameter in millimeters [1 mm = 0.04 in]. For example, −4 Φ is equal to 16 mm [0.63 in], −2 Φ is equal to 4 mm [0.16 in], 0 Φ is equal to 1 mm [0.04 in], 2 Φ is equal to 0.25 mm [0.01 in], and 4 Φ is equal to 0.062 mm [0.0024 in].

2.4.2 Coarse- and Fine-Grained Tephra-Fall Units

Tephra samples were collected from the slopes of an older, unnamed scoria cone 8 km [5 mi] south-southwest of Sunset Crater. This older scoria-cone volcano is just north of Old Caves Crater (Figure 2-4) and is designated V30 in Moore and Wolfe (1976) and V2815 in Moore and Wolfe (1987). Samples were collected on the north and south flanks of this cone as part of short transects. Multiple horizons of coarse- and fine-grained black Sunset tephra mantle the oxidized, clay-rich substrate at location V30 N6B on the north flank: (i) a fine-grained horizon (with some colluvium) from a depth of 24–30 cm [9.4–11.8 in] (0 = top), (ii) a coarse-grained horizon (with some colluvium) from a depth of 70–80 cm [27.6–31.5 in], (iii) a coarse-grained horizon from a depth of 146–150 cm [57.5–59 in], and (iv) a fine-grained horizon from a depth of 170–174 cm [67–68.5 in] (Appendices B and D). A photograph of pit V30 N6B is shown in Figure 2-7, and sieving results from this sampling location, which clearly display the difference in tephra grain size, are presented in Figure 2-8. The beds are well sorted, typical of Strombolian volcanic activity. Matching discrete tephra-fall units was beyond the scope of this report.

2.4.3 Tephra Pit 60606

A tephra pit designated 60606 (June 6, 2006) was dug 5.5 km [3.4 mi] northeast of Sunset Crater near Black Mountain (Figure 2-4). Although the concentration of fines is subtle, this pit has a light-colored upper layer with a thickness of 15 to 17 cm [5.9 to 6.7 in] (Figure 2-9). Beneath this surface layer is a horizon of fine- to medium-grained tephra with a thickness of 45 cm [17.7 in]. A layer of slightly coarser tephra lies beneath this to the base of the pit at 89 cm [35 in] (Appendices C and D). This pit was not dug to the pre-Sunset surface.

Samples were collected every 8 cm [3.1 in] to a depth of 24 cm [9.4 in] to examine this surface layer. A fourth sample was collected at the base of the pit. Granulometric results displayed in Figure 2-10 show that finer grained particles are concentrated in the 8 to 16 cm [3.1 to 6.3 in] layer. This layer reflects an accumulation of finer pyroclasts, silt, clay, carbonates, and soluble salts that most likely have an eolian origin rather than being attributable to the chemical weathering of the parent basaltic tephra. The process of eluviation, which is the movement of insoluble particles such as clay minerals down the soil profile, could account for the accumulation. A possible local source of nonvolcanic eolian particles includes the Painted Desert, which is east of the Little Colorado River along the eastern margin of the study site.

Figure 2-7. Tephra Pit V30 N6B on Scoria Cone V30 Located South-Southwest of Sunset Crater. Loose Surface Soil and Some Colluvium Obscure Portions of the Pit Walls. Pit Depth is 194 cm [76.4 in].

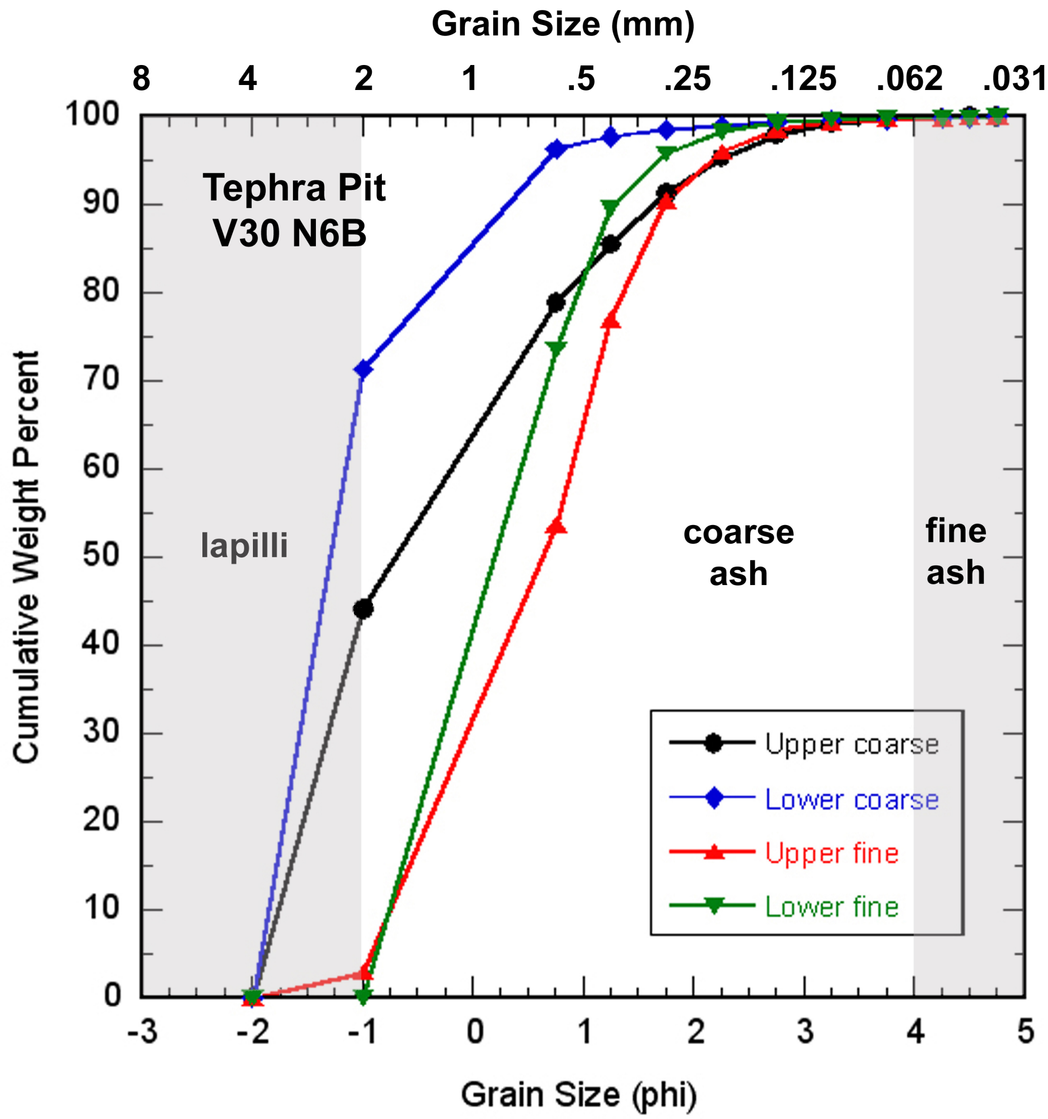

Figure 2-8. Grain-Size Distribution for Alternating Beds of Coarse to Fine Tephra From the Same Tephra Pit on Scoria Cone V30 Located South-Southwest of Sunset Crater. Negative Phi Values Represent Coarser Grain Sizes, While Positive Phi Values Represent Finer Grain Sizes. Standard Grain Size Intervals Are Also on the Figure With Coarse Ash Ranging Between −1 Φ [2 mm] and 4 Φ [0.062 mm].

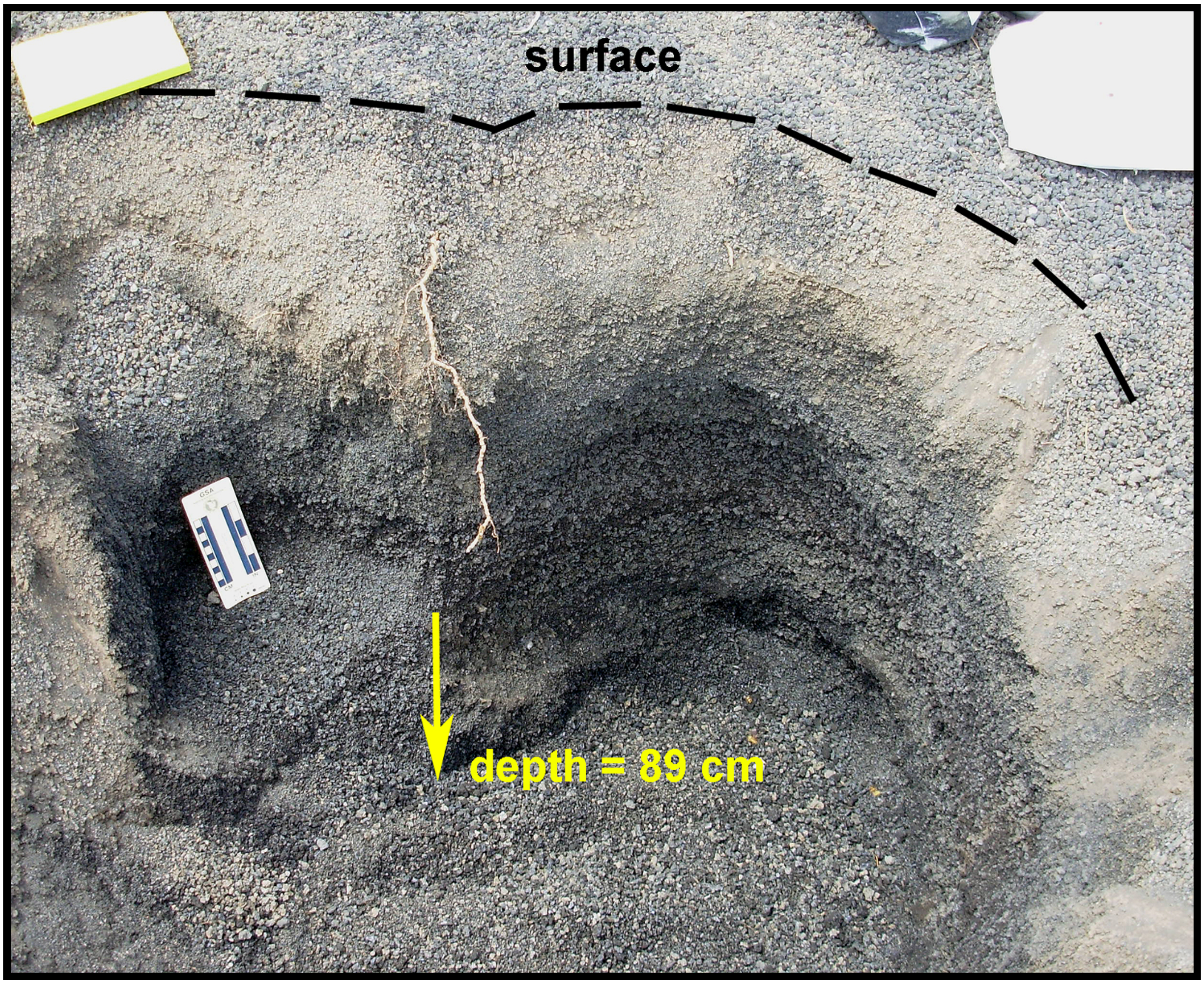

Figure 2-9. Tephra Pit 60606 Located Northeast of Sunset Crater

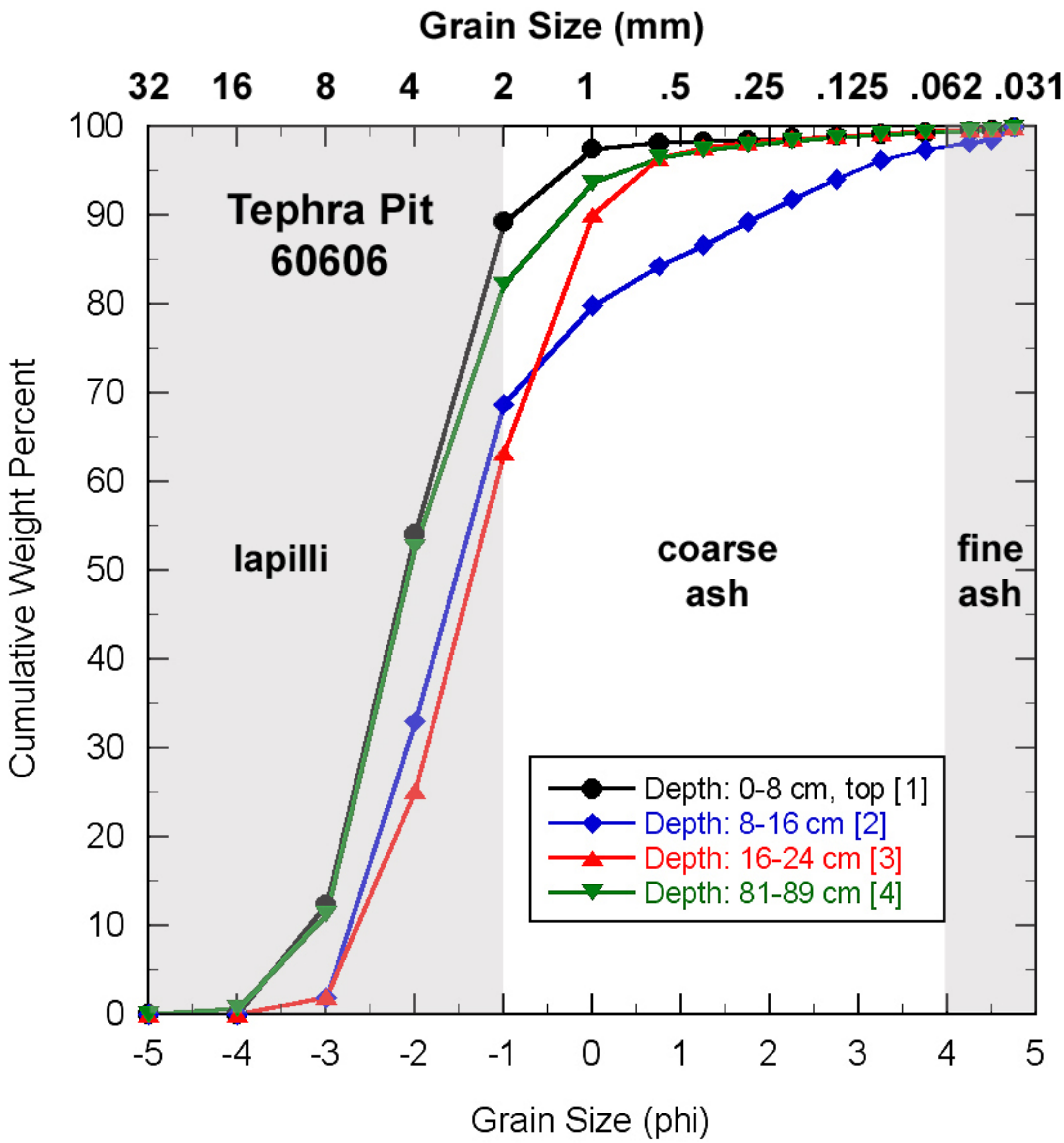

Figure 2-10. Grain-Size Distribution for Tephra Pit 60606

2.4.4 Coppice Dunes

Coppice dunes in the distal region of the Sunset Crater fall deposit form when small mounds of wind-blown tephra accumulate about a clump of vegetation. Wind is an effective agent for sorting material by size during transport. This transport is mostly achieved through saltation: the bouncing or leaping movement of rock particles carried by wind currents (or water currents in a fluvial system). Saltation most commonly transports particles from 0.06 to 1.0 mm [2.4×10^{-3} to 4.0×10^{-2} in] in diameter (e.g., Greeley and Iversen, 1985; Lancaster, 1995). This grain-size range extends from very fine sand (4 Φ) to coarse sand (0 Φ) (Wentworth, 1922). Figure 2-11 shows the unimodal grain-size distribution from two different coppice dunes. The approximate mean grain size for the samples in this figure is about 2 Φ {~0.25 mm [~9.8×10^{-3} in]}. This is between a fine- and medium-grained sand.

2.4.5 San Francisco Wash

Four samples were collected from bar deposits of fluvially reworked Sunset tephra. Each sample was from the San Francisco Wash (Figure 2-4), and the granulometric results are shown in Figure 2-12. The grain-size distribution for these samples reflects a mixture of fluvial sediment, tephra particles, and tephra particles that have begun to undergo downstream fining. The collection site for sample 60906-1 is shown in Figure 2-13.

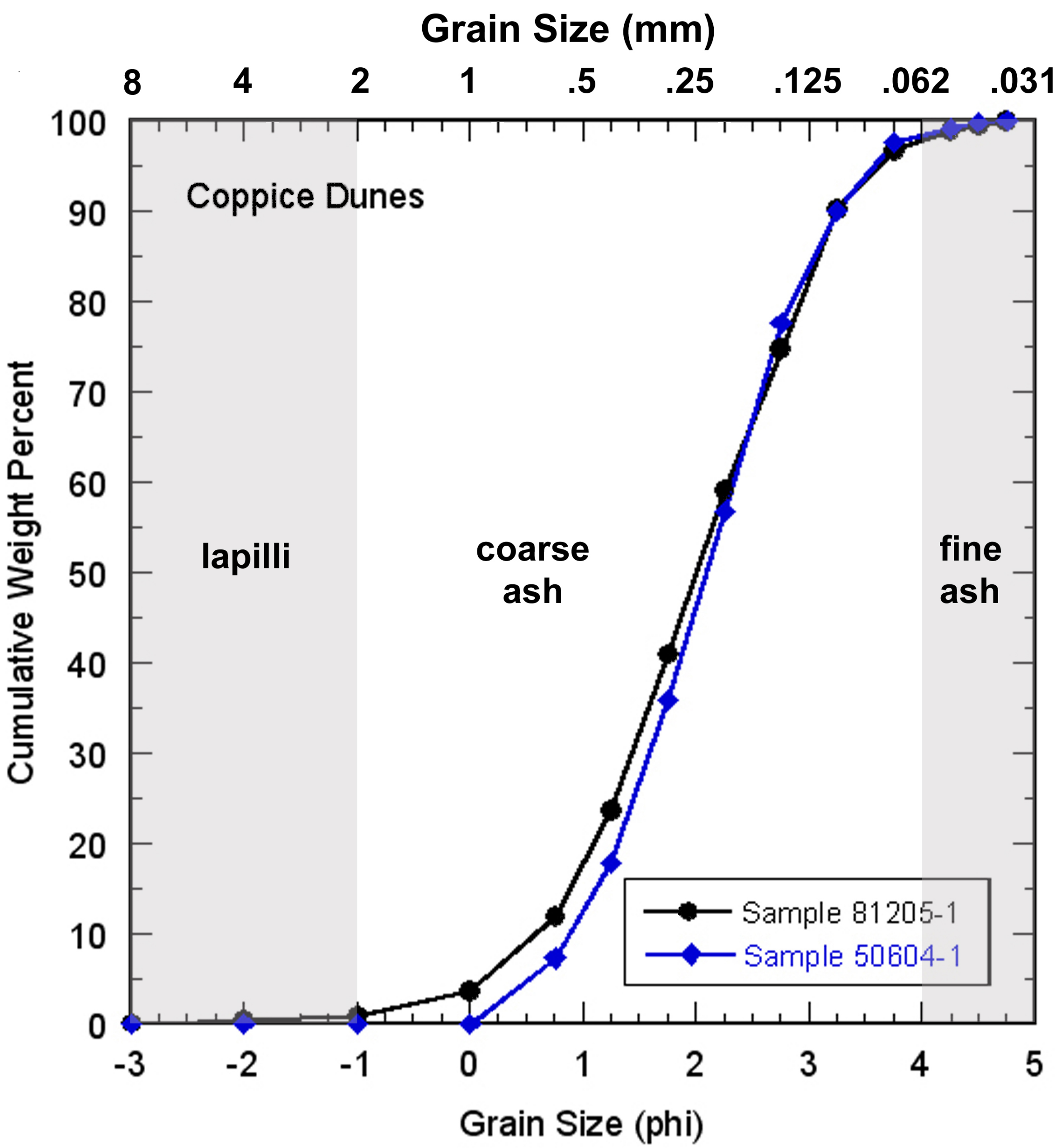

Figure 2-11. Grain-Size Distribution for Two Coppice Dunes Composed of Tephra From the Sunset Crater Eruption

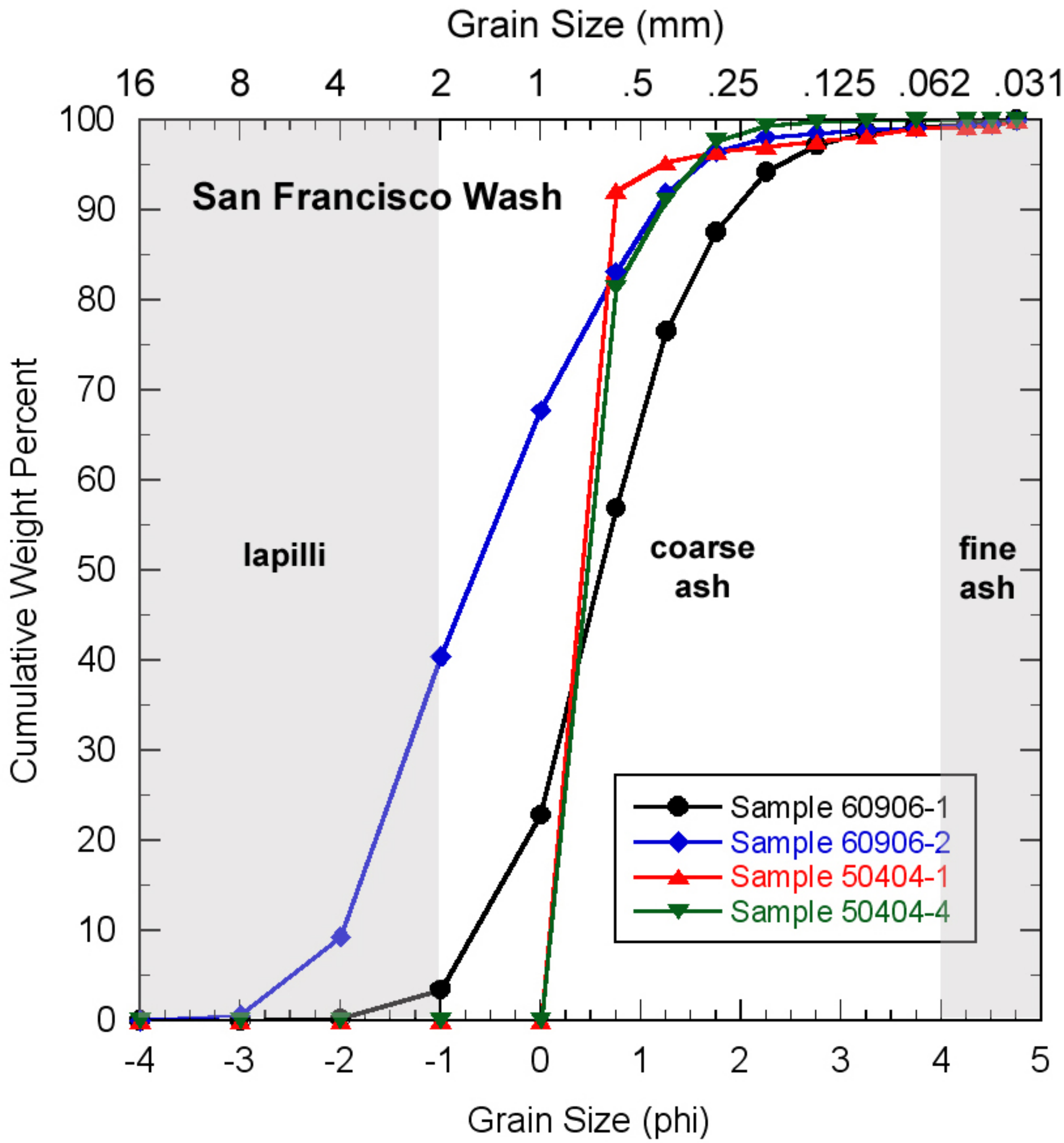

Figure 2-12. Grain-Size Distribution for Four Tephra Samples Collected in Bar Deposits in San Francisco Wash

Figure 2-13. Field Photograph of Fluvially Reworked Sunset Crater Tephra (Sample 60906-1)