CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Field Work at Sunset Crater, Arizona
Project Nos. 06002.01.312 and 06002.01.362
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DATE AND PLACE: June 4–July 9, 2006
Sunset Crater, Arizona

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SENSITIVITY: Non-Sensitive

PERSONS PRESENT:

All authors also served as members of the field team. Yasuo Tomishima, a visiting scientist from Advanced Industrial Science and Technology (AIST) in Japan, participated in the second week of field work and contributed as a regular member of the field team.

BACKGROUND AND PURPOSE OF TRIP:

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 post-eruption surface processes at Yucca Mountain, Nevada. Because few data relevant to airborne transport, dispersal, and subsequent redistribution processes are obtainable from the Yucca Mountain area, there are large uncertainties in applying models and data derived from analog areas with tephra deposition. To reduce these uncertainties, staff are conducting focused investigations for tephra transport, dispersal, and remobilization following a potential volcanic eruption. Field and laboratory analyses at Sunset Crater, the primary analog study site, improve current conceptual models of tephra deposition and redistribution. This investigation supports both the Airborne Transport of Radionuclides and Redistribution of Radionuclides in Soil Integrated Subissues.

Sunset Crater volcano is located in the San Francisco volcanic field 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, which oxidized bright red due to retained heat. Eruptive activity began in 1064 or 1065 A.D. (Smiley, 1958) and continued, probably intermittently, for about 150 years (Holm and Moore, 1987; Tanaka, et al., 1990). The basaltic pyroclastic sheet from the eruption of Sunset Crater volcano occurs as a widespread deposit of fresh black and subordinate red tephra that mantles the preexisting landscape. In the distal regions, the tephra may be present as a thin discontinuous mantle overlying other lithologic units.

The Strombolian-type eruption that created Sunset Crater is characterized by bursts of solidified and partly solidified fine-grained ejecta such as ash and lapilli (or cinders) to coarser-grained ejecta such as blocks and bombs. When transported through the air, this volcanic ejecta is collectively termed tephra. Strombolian eruptions may range from weak to violent, depending on the magnitude of mass-flow rate and tephra dispersal. 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. Staff have calculated an area of 2,800 km^2 [1,077 mi^2] encompassed by the 1 mm [0.04 in] isopach of Sunset Crater tephra, while the calculated volume of the tephra-fall deposit is 0.75 km^3 [0.18 mi^3] (Amos, 1986). An area of 1,500 km^2 [576 mi^2] has been selected for field investigations.

Strombolian eruptions are generally basaltic or near-basaltic in composition and may be accompanied by the discharge of relatively fluid lava spatter and the simultaneous effusion of lava. At Sunset Crater, 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 comprise Sunset Crater National Monument, while the Kana-a lava flow and the majority of the tephra-fall deposit lie within the Coconino National Forest.

The climate at Sunset Crater is semiarid, more comparable to Yucca Mountain than the climate of the Parícutin volcano in central Mexico, which was studied earlier by CNWRA. Mean precipitation is 435 mm/yr [17 in/yr] (Sellers and Hill, 1974). Proximal tephra thickness is greater than 5 m [16.4 ft], and traces of the deposit are still present 20 km [12.4 mi] from the vent (Amos, 1986), indicating that substantial tephra deposits can persist for 1,000 years in a semiarid environment. There is less gullying and overland flow on Sunset Crater tephra-fall deposits than at Parícutin due to a more permeable deposit and substrate. In this case, the substrate—the material beneath the Sunset Crater tephra deposit—is also relatively permeable.

The direction, thickness, and extent of the tephra-fall deposit; grain-size distribution; and the tendency of scoria cones to occur in groups all have important ramifications for understanding issues related to potential igneous activity at Yucca Mountain. Few data relevant to airborne transport, dispersal, and subsequent redistribution processes are obtainable from the Yucca Mountain area. For example, the youngest volcano in this area is 80,000-year-old Lathrop Wells, a scoria cone located near the southern end of Yucca Mountain, less than 20 km [12.4 mi] from the potential repository footprint. Therefore, Sunset Crater serves as a crucial analog, and any data obtained from this volcano contribute to our understanding of possible future volcanism at Yucca Mountain.

SUMMARY OF ACTIVITIES:

Field activities at Sunset Crater focused on three main tasks: (i) airborne particle concentration measurements; (ii) geological measurements, including both geomorphological and volcanological objectives; and (iii) spectroscopic measurements, including vegetative and lithologic classifications. Field activities were run concurrently as long as a sufficient number of staff members were present to support two field teams. During the first four weeks of field work in June, the primary focus was on airborne particle concentration measurements due to the substantial length of time required to prepare and maintain the equipment and to conduct a thorough sampling campaign. Highlighted by three Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite overpasses, spectroscopic measurements concluded field activities in July.

Airborne Particle Concentration Measurements

Staff from the Redistribution of Radionuclides in Soil Integrated Subissue measured airborne particle concentrations around the Sunset Crater analog volcanic site. Inhalation of airborne concentrations of resuspended volcanic ash has a high significance to waste isolation. The airborne particle concentration measurements will allow staff to increase realism and reduce uncertainties in estimates of potential consequences and risk from an igneous eruption that intersects the repository. When available, results of the field work will be integrated into evaluations of input parameter values for the Total-system Performance Assessment (TPA) code.

Airborne particle measurements were investigated over both volcanic (tephra) and nonvolcanic (e.g., sandstone) ground surface material. Measurements were acquired over six types of ground surface material:

- Primarily nonreworked tephra deposited from the Sunset Crater eruption about 900 years ago
- Fluvial deposits of redistributed tephra
- Eolian deposits of redistributed tephra
- Primarily nonreworked, nonvolcanic material
- Fluvial deposits of redistributed nonvolcanic material
- Eolian deposits of redistributed nonvolcanic material

For each of the six types of ground surface material, separate airborne particle measurements were performed for three different levels of surface-disturbing activity:

- Ambient measurements without human surface-disturbing activity
- Light disturbance measurements associated with walking or setting up equipment
- Heavy disturbance measurements associated with digging, hoeing, or collecting surface samples

Therefore, there are 18 measurement classes of acquired airborne particle concentrations based on the different combinations of ground surface material types and surface-disturbing conditions. Conducting the field work over a range of different ground surface material types and surface-disturbing conditions will allow staff to quantify the magnitude of airborne particle concentrations and their sensitivity to types of ground surface material and level of surface-disturbing activity. In addition to airborne particle measurements, surface samples were obtained from each of the six types of ground surface material for future analysis in the laboratory (e.g., granulometry).

Geological Measurements

Geologic tasks included measurements of tephra and alluvium thickness, sample collection for granulometric analysis, observations and measurements of fluvial processes, observations and measurements of erosional and soil-forming (pedogenic) rates and processes, and characterization of candidate sites for airborne particle concentration and spectroscopic measurements. Field work provides the means to identify and quantify the main effects of surficial transport processes as a function of time after an eruption with the intention of gaining fundamental insights into tephra redistribution and remobilization. The Sunset Crater tephra deposit is being eroded by creep and shallow landslides (mass-wasting processes), raindrop splash, and deflation (wind action). Staff observed that sheet wash and channel erosion (including rilling and gullying) occur primarily on older (pre-Sunset) surfaces because of the coarse grain size and highly porous nature of the Sunset tephra.

Tephra thickness was measured by digging numerous shallow pits, usually down to the substrate or pre-eruption surface. From these vertical sections, descriptions of soil, colluvium, and tephra were recorded for each pit. Geologic samples were collected as necessary and many tephra pits were associated with planned traverses across a portion of the field area. Results are being compared to the previously published isopach map of Amos (1986).

Additional thickness measurements were recorded for alluvium and eolian deposits of reworked Sunset tephra. Alluvial deposits are scattered across the San Francisco volcanic field, but the most relevant sites are those that directly drain from the Sunset Crater tephra deposit. The regional slope for the study area is to the east-northeast toward the Little Colorado River. Black, patchy eolian deposits are easily identified along the distal margins of the Sunset tephra deposit where wind action has transported or remobilized the tephra away from the site of initial deposition. Both alluvial and eolian deposits have been mapped by the U.S. Geological Survey as part of the geologic map of the eastern San Francisco volcanic field (Moore and Wolfe, 1976). Based on staff field work, this map has proven to be reliable.

Measurements pertaining to alluvial and eolian deposits are being utilized to assess fluvial and eolian remobilization, respectively, to provide new volume and rate estimates. Measurements of alluvium thickness and volume potentially contribute to calculations of post-eruption sediment yield of fluvially redistributed tephra (or ash in the TPA code) that discharges from the affected drainage basin. Estimates of transport rates for redistributed tephra will be useful for (i) refining parameter values in the TPA code, (ii) developing models for eolian redistribution processes, and (iii) refining fluvial redistribution process-level modeling.

Although dry washes are present, perennial streams do not exist in the area encompassed by the Sunset Crater tephra deposit. San Francisco Wash drains the southern portion of the study area, and the Sunset Crater-Wupatki loop road (Forest Road 545) follows Kana-a Wash in approximately the center of the study area. Antelope Wash and Deadman Wash to the north are hindered by inappropriate drainage characteristics and difficult access. Samples were collected from San Francisco and Kana-a Washes to measure downstream fining (e.g., diminution and comminution), tephra breakage, and fines enrichment/depletion processes. Both upstream and downstream locations were examined. Results will contribute to our understanding of grain-size characteristics in the fluvial system and the relationship to source areas. Furthermore, these data will be used to determine if fluvial and eolian processes have deposited a higher percentage of fine material in the depositional regions. Sunset Crater serves as a Yucca Mountain analog, and this approach may be applied to the Yucca Mountain region to support calculations of inhalation dose because they could record tephra particle abrasion or diminution as tephra fragments are transported down Fortymile Wash toward the location of the Reasonably Maximally Exposed Individual.

Granulometric analyses are used as 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. Numerous samples for grain-size analyses were collected from drainages, eolian deposits (coppice dunes), alluvium deposits, and along relevant hillslopes and transects as part of tephra thickness analyses. Most analyses are made with a set of sieves in the laboratory. Sieving is a practical approach for classifying samples in the range of ~16 to 0.064 mm [~0.6 to 0.0025 in], for which standard sieves are available. Above this grain size, hand counts of individual fragments are useful; below this grain size, a laser diffraction particle size analyzer can extend the range to approximately 1 μm [4×10^{-5} in]. Sieve analysis is presently being conducted and measurements for the finest grain-size fraction will be conducted by Division 1 at Southwest Research Institute. Results will be compared to similar analyses from Parícutin (Mexico), Cerro Negro (Nicaragua), Lathrop Wells, and Fortymile Wash (alluvium only).

Spectroscopic Measurements

Spectroscopy and analysis of satellite and airborne imagery offer the means to assess the complex relationship between tephra thickness, vegetation, elevation, soil moisture, lithology, and weathering. Field work serves as ground truth for remotely acquired data. Using a portable instrument, field spectroscopy includes studies of reflectance or radiance properties of vegetation, soils, rocks, and water bodies under solar illumination. Satellite and airborne imagery are useful for evaluating uncertainties in published tephra deposit patterns and distribution characteristics. Multispectral data is used to map mineralogic information while radar data is used to map surface morphology. Output consists of a collection of thematic maps that are being used to understand the geomorphologic evolution of the tephra deposit, including information on weathering and erosion.

A key component of the remote sensing data base is imagery from ASTER. This is an imaging instrument flying on Terra, a satellite launched in December 1999 as part of National Aeronautics and Space Administration's (NASA) Earth Observing System. ASTER is a cooperative effort between NASA; Japan's Ministry of Economy, Trade and Industry; and Japan's Earth Remote Sensing Data Analysis Center. ASTER captures high spatial resolution data in 14 bands from the visible to the thermal infrared (TIR) wavelengths. It is being used to obtain detailed maps of land surface temperature, reflectance, and elevation.

ASTER is an on-demand instrument, meaning that data is only acquired over a location if a request has been submitted to observe that area. Previously acquired data can be ordered. Staff had previously proposed and successfully been granted an ASTER data acquisition from NASA . Table 1 describes these three overpasses. Field work was planned in conjunction with the ASTER data acquisitions, and an intense field campaign was conducted with the intent of calibrating satellite data with field spectroscopic data. The spectral characteristics of ASTER data are valuable because the tandem day/night data set should provide improved understanding of the nature of lithologic units and geologic mapping of tephra deposits. Clouds affected the measurements for each overpass; however, from the ground it was difficult to estimate the percentage of cloud cover for each acquired image. The threshold for data acceptance is 10 percent or less for cloud coverage, but final data quality is not yet known.

Table 1. General Specifications of Requested ASTER Satellite Data

Date (UTC)	Nadir Time (UTC)	Peak Elevation	Visibility	Telescope
23 June 2006	18:19:56	87.9°	Day	Full Mode
8 July 2006	05:34:24	85.4°	Night	SWIR/TIR
9 July 2006	18:19:41	88.4°	Day	Full Mode

Other tasks involving spectroscopy and image analysis included (i) characterizing the candidate sites for airborne particle concentration measurements and sampling, (ii) characterizing vegetation and terrain types, and (iii) producing various types of classification maps based on spectral properties and statistics of known parts (training sites) within a digital image. Based on field work, major lithologic and vegetation types include:

- Sparsely vegetated patches of black tephra (cinder)
- Lava beds (Bonito and Kana-a lava flows)
- Agglutinate (patches of welded volcanic material)
- Patches of eolian-reworked tephra
- Sedimentary formations (nonvolcanic rocks including the Kaibab and Moenkopi Formations)
- Urban and residential
- Industrial (including mining)
- Solid-waste disposal sites (e.g., municipal landfill)
- Ponderosa Pine woodland
- Ponderosa Pine-Apache Plume woodland
- Pinyon Pine-Utah Juniper woodland
- Mixed shrublands
- Grasslands

Describing the intermixing of Sunset tephra with each of these units is a major task of the spectroscopic and remote sensing work.

OTHER ACTIVITIES:

Laboratory and data analyses will follow the collection of airborne particle concentration, geological, and spectroscopic measurements and samples.

CONCLUSIONS:

Field investigations at Sunset Crater volcano offer the opportunity to study a 900-year-old tephra deposit in a semiarid climate as a Yucca Mountain analog for both volcanic processes and post-eruption surface processes. Team members benefitted from directly observing an actual tephra-fall deposit. Data obtained from this important analog contribute to our understanding of possible future volcanism at Yucca Mountain because it will reduce uncertainties and improve realism in the modeling of consequences for the potential release of radioactive material directly into the atmosphere from a volcanic eruption intersecting the potential repository. Laboratory and data analyses from these field investigations have begun and will be reported on in the future. Results from these studies will be used to update process-level modeling, to refine model parameters for performance assessment calculations, to develop and refine risk insights, and to support staff review of the potential DOE license application.

PROBLEMS ENCOUNTERED:

The lower absolute air pressure at the high-elevation field site required additional steps for premeasurement checks of air flow rates with the airborne particle sampling equipment. Pump battery lifetime for operational air flow rates was also significantly reduced at high elevations. Staff overcame these equipment difficulties by purchasing new equipment and renting a generator.

Field work was nearly postponed due to increased fire danger in the Coconino National Forest of north-central Arizona. The first notable incident was the Woody Fire, which began about 4 p.m. MST on June 14, 2006, and was driven by wind gusts of over 40 mph. Fortunately, this fire was rapidly contained. It burned 100 acres on the west side of Flagstaff and 1,000 homes were evacuated, but no structures were lost. This fire was less than three miles from the hotel used by staff.

Because of a 3,000-acre fire near Sedona and the extreme fire danger, the Coconino National Forest closed to public access and use on June 23, 2006, at 8:00 a.m MST. Staff met with personnel from the National Park Service and U.S. Department of Agriculture-Forest Service. Staff used field maps created at CNWRA to locate specific field sites and explain in detail the research objectives and scope of the project. The National Forest Service granted two entry/activity permits (one for each field vehicle) with the agreement that staff would take all measures to prevent fires and report any fires that may be discovered. The permits were valid for the Peaks and O'Leary Districts in the Coconino National Forest around Sunset Crater. The forest closure lasted for one week. As moisture levels increased, the forest was opened again for the July 4th holiday weekend.

PENDING ACTIONS:

This work will be discussed in greater detail in the intermediate milestone due in September, 2006, entitled Status Report of Field Observations from Sunset Crater, Arizona.

RECOMMENDATIONS:

Additional field work should be conducted at the Sunset Crater analog site as part of CNWRA proactive items because this work provides critical data for both the Airborne Transport of Radionuclides and Redistribution of Radionuclides in Soil Integrated Subissues. Based on the scope of activities in Arizona, additional and complementary field studies should be conducted at Crater Flat, Big Dune, and Fortymile Wash in the Yucca Mountain region.

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