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Variable effects of cinder-cone eruptions on prehistoric agrarian human populations in the American southwest

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ABSTRACT

Two ~900 BP cinder-cone eruptions in the American Southwest affected prehistoric human populations in different ways, mostly because of differences in the eruption styles and area affected. Primary pre-eruption cultural factors that may have led to successful adaptation to the eruptions include decision-making at the family or household level, low investment in site structures, dispersion of agricultural sites in varied environments, and settlement spread over a large area so that those who were less affected could shelter and feed evacuees.

Sunset Crater, near Flagstaff, Arizona, produced about 8 km^2 lava flow fields and a ~2300-km^2 tephra blanket in an area that had been settled by prehistoric groups for at least 1000 years. Local subsistence relied on agriculture, primarily maize, and >30 cm tephra cover rendered 265 km^2 of prime land unfarmable. This area was apparently abandoned for at least several generations. A >500-km^2 area was probably marked by collapsed roofs and other structural damage from the fallout. If the eruption occurred during the agricultural season, the fallout would also have significantly damaged crops. The eruption did have some benefits to local groups because lower elevation land, which had previously been too dry to farm, became agriculturally productive due to 3–8 cm of tephra 'mulch' and some temporary soil nutrient improvements. This previously uninhabited land became the site of significant year-round settlement and farming, eventually containing some of the largest pueblo structures ever built in the region. New agricultural techniques were developed to manage the fallout mulch. The eruption also affected ceramic production and trading patterns, and volcano-related ritual behavior – the production of maize-impressed lava-spatter agglutinate – was initiated.

Little Springs Volcano, about 200 km northwest of Sunset Crater, is a small spatter rampart around a series of vents that produced about 5 km^2 of lava flow fields, about 1 km^2 of land severely affected by ballistic fall, and no significant tephra fall. The small area affected resulted in much less disruption of human activities than at Sunset Crater. Farming was still possible right up to the edge of the lava flows, which became attractive sites for settlements. Most sites along the lava flows have habitation and storage structures at the base of the flow and a series of small, apparently little-used, structures on the blocky lava flow above. These lava surface structures may have been defensive in nature. In addition, trails were constructed on the blocky lava flow surface. These trails, whose access points are difficult to recognize from below, appear to have been used for rapid movement across the flows, and may also have been defensive in nature. Spatter-agglutinate blocks containing ceramic sherds within them, similar to the maize-impressed spatter agglutinate at Sunset Crater, were made at Little Springs and carried to a nearby habitation site.

In arid and semiarid lands such as northern Arizona, tephra fall is a mixed blessing. Thick cinder blankets (>20–30 cm) render land uninhabitable, but thinner (3–8 cm) deposits can serve to conserve soil moisture, regulate soil temperature (thus lengthening the growing season), and, by lowering soil pH, provide a temporary (decades to a century or two) increase in available phosphorus, an important nutrient for growth. The mulch opened up new lands for settlement but likely only lasted for a century or two before reworking reduced its effects.

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1. Introduction

Almost all human populations living in volcanically active areas have oral histories of what can be interpreted as volcano eruptions, generally involving fires and molten rock coming from deep within Earth. How far back eruption accounts go in human memory is unknown. One of the earliest unambiguous representations of a volcano is dated at 6200 BCE from the wall of a shrine at Çatal Hüyük, Turkey (Sigurdsson, 1999), but volcano memories of some cultures likely extend back much further in time. As humans, we have been reacting and adapting to volcano eruptions for a very long time, sometimes successfully, sometimes not. In this paper we discuss two successful adaptations that occurred around 900 years ago in the Southwest United States.

The prehistoric period in the Southwest United States began around 13–15 ka with the arrival of Pleistocene big-game hunters, but little evidence of agricultural settlements exists prior to 2000–3000 BCE. About eighteen cinder-cone eruptions occurred in all of southwestern North America during the past 5000 years (Fig. 1), and other types of eruptions, such as dome eruptions in eastern California and stratovolcano eruptions in the southern Cascades and Mexican Volcanic Belt of central Mexico, occurred far from the area of interest in this paper. The temporal and geographic spacing of these events suggests that local prehistoric populations did not have active memories of eruptions or first-hand knowledge of how to deal with them. Any eruption memories of these groups were as oral traditions, which almost certainly assigned a supernatural or religious origin to the features (Sigurdsson, 1999). These were likely important factors in adaptation to the two cinder-cone eruptions, and may help predict how modern groups will adapt to similar eruptions.

In this paper, we discuss the eruptions and resulting human adaptations at Sunset Crater and Little Springs volcanoes in northern Arizona (Fig. 1). Both were basaltic eruptions that resulted in very different responses by local human populations residing near the volcanoes, even though these groups had a similar social organization and subsistence system. Differences in the resulting adaptation were largely due to contrasts in the nature of the two eruptions and the sizes of the devastated areas. In both cases, though, the adaptations were successful. Our discussion makes use of all available data on the eruptions and prehistoric cultures, but much more geologic and archaeological data are available from Sunset Crater than Little Springs Volcano.

Fig. 1. Location map of cinder-cone eruptions in the past 5000 years in southwestern North America, including Sunset Crater and Little Springs. C = Carrizozo (5.2 ka; Dunbar, 1999); CC = Cinder Cone at Lassen (1630–1670 CE; Clynne et al., 2000); CM = Craters of the Moon (130 BCE—5000 BP Simkin and Siebert, 1994); D = Dotsero (4150 BP, Wood and Kienle, 1990), IS = Ice Springs (1280 BP; Simkin and Siebert, 1994); J = Jorullo (1759–1774 CE; Gadow, 1930); LS = Little Springs (1050–1200 CE; this study and references cited herein); MC = McCarty's Flow (3180 BP; Laughlin et al., 1994); ML = Medicine Lake (Callahan and Paint Pot, 1000–1100 BP; Donnelly-Nolan et al., 1990); P = Parícutin (1943–1952 CE; Luhr and Simkin, 1993) — note that 14 other cinder cones in the Michoacán–Guanajuato volcanic field are <10 ka (Hasenaka and Carmichael, 1985); PI = Pinacate volcanic field (Simkin and Siebert, 1994); RC = Rincón de Chapultepec (2980 BP) and El Volcancillo (870 BP; Siebert and Carrasco-Nuñez, 2002); SC = Sunset Crater (1050–1100 CE; this study and references cited herein), UB = Ubehebe Crater (a maar complex, but similar in impact to cinder cones, Simkin and Siebert, 1994); X = Xitle (1670 BP; Siebe, 2000), as well as Chichinautzin (1835 BP) and Guespalapa (2835–4690 BP; Siebe et al., 2004).

Archaeological research in the Sunset Crater area over the past 70 years has resulted in the subsurface excavation of hundreds of sites containing thousands of structures (Colton, 1946; Downum, 1988; Elson, 2006). Survey data (from surficial studies) are also much more complete at Sunset Crater. In contrast, the archaeological understanding of the Little Springs area is almost entirely based on the results of an archaeological investigation of a 3640 ha area north of the Grand Canyon (Moffitt and Chang, 1978) and our own survey of a portion of the lava flow (Elson and Ort, 2006). No subsurface excavations have taken place in this area.

2. Eruption descriptions

2.1. Sunset crater eruption

Sunset Crater is a >300-m-high cinder cone located about 25 km north of Flagstaff, Arizona. It is the youngest of about 600 cinder cones in the San Francisco volcanic field, which covers an area of approximately 5000 km^2 along the southern margin of the Colorado Plateau (Tanaka et al., 1986). Sunset Crater erupted into a volcanic landscape marked by abundant cinder cones with flat areas, mostly underlain by lava flows, between them (Fig. 2). Elevations in this area range between 1800 and 2200 masl and contain ponderosa pine (*Pinus ponderosa*) forest at elevations above 2040 masl (6700 ft), piñon–juniper (*Pinus edulis*/*Juniperus monospermae*) woodlands between 1890 and 2040 masl (6200–6700 ft), and desert grasslands below this. Vegetation is directly correlated with precipitation and temperature: the low elevation desert grassland habitat receives less than 150 mm/yr of rainfall but has a long frost-free growing season; the pine-forested highland area receives over 500 mm/yr of rainfall, but has a very short growing season. Sunset Crater and its lava flows blocked a significant stream valley that drained part of San Francisco Mountain, a nearby large stratovolcano. This stream is ephemeral now, but

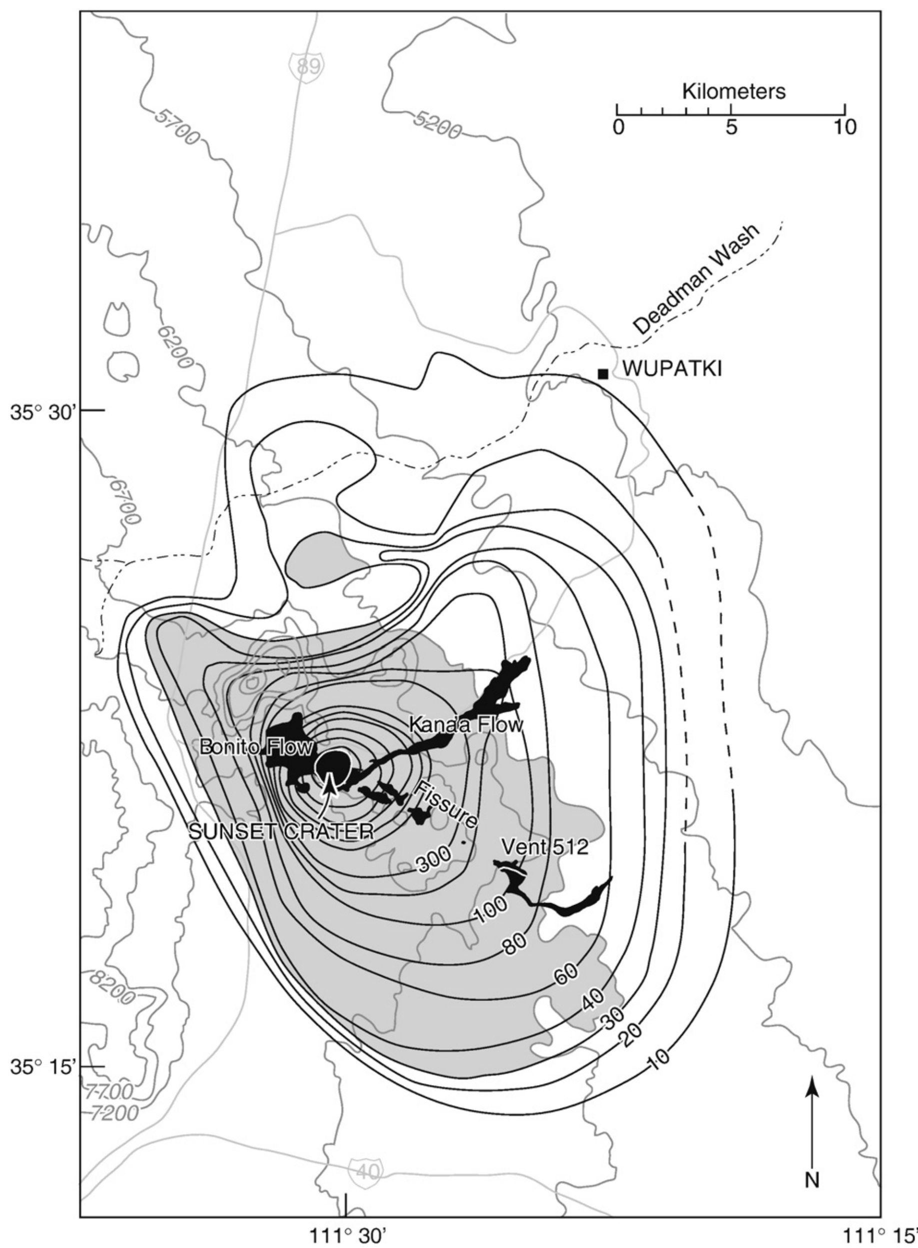

Fig. 2. Map of Sunset Crater area. Lava fields and vent areas of the Sunset eruption are shown in black. Topographic lines (gray) are in 500-foot contours. Isopach contours (black) are in centimeters. The area with more than 30 cm of fallout and at an elevation above 1890 masl (6200 ft) is shaded in gray to show the area of prime agricultural land and high density prehistoric settlement that had to be abandoned.

groundwater likely came to the surface prior to the eruption, especially during wet periods.

We use Amos (1986), Holm and Moore (1987), Holm (1987), and our own work to describe the Sunset Crater eruption sequence. Sunset Crater began with the opening of a 10-km-long fissure stretching from where Sunset Crater is now southeast to Vent 512 (Fig. 2). This fissure eruption deposited two distinct ashfall layers. The fissure is clearly traced, even where the spatter ramparts are not apparent, because it oxidized later cinder-fall to a red-brown color. It appears to have been discontinuous, with breaks of tens of meters to 2 km, and in some places, the breaks separate en-echelon fissure alignments. The eruption soon localized to the two ends of the fissure, at Sunset Crater and Vent 512. No fissure extends southeast of the Vent 512 area, but it is not certain where it stopped at the Sunset Crater end. This is partly because of the growth of Sunset Crater, which covers the fissure, but also because a small spatter rampart extends northwest of Sunset Crater. This rampart is younger than the fissure, but it may trace the initial fissure, which could extend under Sunset lava flows. Vent 512 is a complex 1.6-km-long series of fissures and spatter ramparts, many several meters high, and one section of the fissure erupted a roostertail jet about 100 m up the side of a nearby older cinder cone. Vent 512 was also the source for a 6.5-km-long spatter-fed lava flow. After Vent 512 ceased activity, Sunset Crater became the remaining vent for the rest of the eruption.

The Sunset Crater phase of the eruption began with a period of strombolian activity, during which at least six additional ashfall layers were deposited. After this, two lava flow fields were established while cinder fall continued. The Kana'a lava flow field is on the downhill side of the volcano, and follows a stream drainage almost 10 km to the northeast, with multiple flow lobes. The Bonito lava flow field is on the uphill side of the volcano, so the lava ponded against the volcano and spread out, filling the valley. At least three separate main phases of lava flow production can be distinguished (Holm, 1987). The last lava phase in each field has no overlying cinders, indicating that both flows were active until the end of cinder deposition. The Bonito lava field has more total lava without cinders on it then the Kana'a field, but it is unclear whether this has any significant time implication. The lava flows show evidence of inflation (Hon et al., 1994), with surficial features, such as ropy textures, tilted to near-vertical orientations along the flow lobe edges. The later, non-cinder-covered flows emanated from cracks in the margins of the earlier flows, likely during inflation. Squeezeups associated with this inflation are also common, with one on the Bonito flow being more than a kilometer long. Portions of the cinder cone were rafted away on the Bonito flow and are present as isolated bedded cinder and spatter agglutinate mounds on the lava flow surface (Holm, 1987). The eruption may have ended with small explosions at the summit, but these deposits are limited and difficult to interpret.

In estimating the effects of an eruption upon local populations, it is important to know what areas were affected at which stages of the eruption. Amos (1986) carried out a study of the tephra units that underlie the lavas. His fallout units I and II are related to the fissure eruption and their isopachs show a limited distribution centered along the fissure. Fallout units III and IV are the first to indicate a central vent at the current location of Sunset Crater itself and together were deposited over the entire area that Sunset cinders eventually covered: unit III has a southeast dispersal direction, while unit IV has a nearly circular coverage of a large area. After the emplacement of unit IV, there would have been little additional area to be covered by later ash fall; the ash fall extent, although not its total thickness, was set by the end of unit IV's deposition. Units V–VIII were also emplaced rapidly and account for most of the rest of the total fallout thickness.

2.1.1. Sunset eruption duration

The overall length of the Sunset Crater eruption is critical in understanding the resulting prehistoric response. This is because adaptation to a single, short-term event will be different from adaptation to a long-term event with multiple phases. No evidence for erosion within the Sunset cinder sequence nor of a hiatus within the lava flow sequence has been found. All of the cinder fall units, including Amos' (1986) units I–VIII and the additional units overlying the lavas, which he did not differentiate, are reddened where they overlie the fissure. The continuity of the reddening along the fissure suggests that it was not just late-stage fumarolic activity, which would have led to a reddening only around the fumaroles. Cinders overlying the Kana'a lava flow field are reddened also, and this reddening was used by Holm (1987) to map the course of the flows where cinder cover is thick. Surficial temperatures on lava flows and fissure spatter ramparts drop rapidly (hours to days) to near-ambient temperatures (Keszthelyi and Denlinger, 1996), so continuous lava flow beneath the lava crust is probably required to maintain the heightened heat flow (above the glass transition temperature; Burkhard, 2005) needed for the oxidation of the cinders (which would also act somewhat as an insulating blanket). This suggests that all of the tephra layers were deposited while the lavas were hot, so the entire eruption likely lasted for weeks to at most several years.

Amos (1986) estimated the volcano erupted about 0.58 km^3 (DRE) of magma. He calculated that the tephra deposits could have been emplaced in about 25–30 h of eruption, but the variety of different fallout plume directions indicates that eruption was not continuous and that enough time passed for different weather patterns to have been active during the eruption. The lava flows total about 0.1 km^3, and moderate extrusion rates of 1–3 m^3/s would allow this to be emplaced in weeks to months.

2.1.2. Date of the sunset eruption

The date of the Sunset Crater eruption is important in archaeological reconstruction of the prehistoric Southwest United States. This is because the eruption serves as both a temporal marker within the fallout zone and as a major catastrophic event to which local populations had to adapt. Various methods have been used to date the eruption, including dendrochronology (Smiley, 1958; Elson et al., 2005; Sheppard et al., 2005), paleomagnetic secular variation (Champion, 1980; Ort et al., 2002), and archaeological association (McGregor, 1936; Colton, 1946; Breternitz 1967). Data from archaeological contexts – comparing the dates of structures buried by Sunset Crater cinders with the dates of structures without cinders – indicate the eruption occurred sometime in the middle-to-late 11th or early 12th century CE (Colton, 1946; Breternitz, 1967; Downum, 1988; Boston, 1995). ^{14}C dating has not been undertaken for either Sunset Crater or Little Springs eruptions because no suitable samples have been recovered. No carbon has been found within the cinder sequence, and, because dead trees can remain intact for centuries in the arid environment, any carbon underlying the tephra would be suspect. In addition, the error bars on a ^{14}C date from this time period would be larger than those provided by the archaeological dates.

Smiley (1958) proposed that thin (or suppressed) tree rings in beams from the ruins of the 100-room Wupatki pueblo, situated in the desert grasslands about 20 km north of Sunset Crater, could be used to date the eruption. The thin rings began during the winter of 1064–65 CE and continued for over 70 years until the time the tree was cut down, so Smiley interpreted this as the date of the eruption. The original provenance of the beams is not known, other than that they are not local to Wupatki, which is 15–20 km from the nearest potential source areas. Although Smiley reported that eight beams showed this unusual pattern, five of these were duplicates from the same tree, and the sample actually consists of only one ponderosa pine (*Pinus ponderosa*) and two Douglas fir (*Pseudotsuga menziesii*) trees (Robinson et al., 1975), the latter of which are very rare within the area affected by Sunset cinders. Similar rings can be produced in non-eruptive contexts, with possible causes including localized drought, proximity to a forest fire, tornados, earthquakes, changes in the water table, extreme cold, mycorrhizal anomalies, and insect infestation (Boston 1995; Sheppard et al., 2005). Champion (1980) carried out paleomagnetic secular variation studies on the lava flows and found that the eruption could have taken place any time between 1064 and 1250 CE. A later secular variation study combining data from Champion's seventeen original sites with thirteen new sites shows that the eruption took place over a short time period (<10 years) in 1075 ± 25 CE (Ort et al., 2002).

The data thus best support a date for the Sunset Crater eruption between 1050 and 1100 CE, with a duration of a few years at most. During this time, the Sunset Crater area was inhabited by small groups of subsistence farmers and the Sunset Crater eruption was likely one of the most significant events that occurred in their lives. This is underscored by accounts of the eruption from the modern Hopi (a Native American tribe whose ancestors likely lived in the Sunset Crater area), which are still passed from generation to generation as a part of traditional knowledge (Colton, 1932; Malotki and Lomatuway'ma, 1987; Ferguson and Loma'omvaya, in press).

After the eruption, an area of >2300 km^2 was covered by >1 cm of fallout (Fig. 2), with around 400 km^2 beneath at least 30 cm of cinders (Hooten et al., 2001). Another 8 km^2 was underneath 2–30 m of lava. The cinders blew in the winds, making dune forms still visible today. By reducing evaporation, they probably led to increased groundwater supply and the appearance of new springs. Some spring deposits are present along now-dry portions of washes in the Wupatki area. Other springs may have dried up or been altered due to earth tremors and cinder deposition.

2.1.3. Post-eruption geomorphological changes at Sunset Crater

Since the eruption, the loose cinders on the ground surface have been redeposited by water, wind, and hillslope processes. Fifteen km from Sunset Crater at Grand Falls, where the cinder layer was 5 cm thick, stratigraphic exposures contain nearly clean but eolian reworked Sunset cinders overlying a weakly developed soil forming on the 19 ka Merriam flow (Fig. 3). Overlying the primary cinder layer is a layer of mixed Sunset cinders and reworked soil and eolian sands (Spurr et al., 2003). In the thicker tephra zone, Anderson (in press) described 1.5 m of hillslope and sheetflow material containing Sunset cinders filling a small alluvial channel that was eventually used for prehistoric agriculture. Hooten et al. (2001) described numerous profiles in Sunset cinders with the uppermost layers commonly showing evidence of sheetflow and eolian reworking.

Agricultural soils along an elevational gradient within the Sunset Crater tephra zone show increases in pH, nitrogen, and phosphorus with increasing elevation. Lower elevation areas near Wupatki and Grand Falls have significantly poorer soil nutrient availability than the higher elevation areas at Sunset Crater and Walnut Canyon National Monuments (Anderson, 2001; Spurr et al., 2003). The pH values at the lower elevation sites show alkaline conditions, in the 7.5–9 range, and have very low available P, generally less than 4 mg/kg. Nitrate–nitrogen is also low, generally less than 10 mg/kg. At higher elevations, available P can be as high as 31 mg/kg and nitrate–nitrogen 23 mg/kg, with pH values of 6.6–7.7. Therefore, along with insufficient precipitation, the lower elevations also have soil nutrient deficiencies, making agriculture in this area difficult.

2.2. Little Springs

Little Springs volcano is the youngest vent in the Uinkaret volcanic field, north of the Grand Canyon in northern Arizona. The field contains over 200 volcanic vents with ages <3.6 Ma (Billingsley et al., 2001). Prior to the eruption, the Little Springs area was a valley between volcanic highlands, with a north-to-south (downvalley) elevation gradient from about 2000 masl to 1850 masl and valley sides that reach 2200–2300 masl. Vegetation is mixed ponderosa pine (*Pinus ponderosa*) and juniper (*Juniperus monospermae*) forest in the upper areas and piñon/juniper (*Pinus edulis*/*Juniperus monospermae*) forest in the lower areas, with abundant grassy clearings. Average

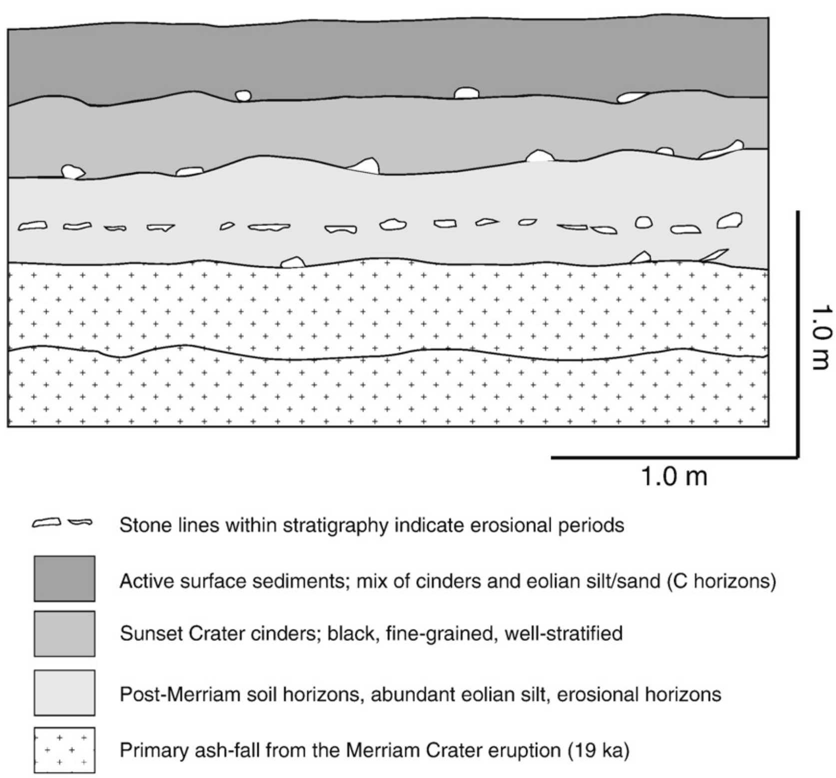

Fig. 3. Cross-section of 'typical' soil developed on Merriam Crater fallout about 15 km from Sunset Crater. As soil develops, stone lines indicate horizons from periods of erosion. Sunset Crater ash will likely develop a similar soil over time, but is currently lacking in the fine-grained eolian sediments that inflated the Merriam soils.

precipitation is around 300 mm and the agricultural growing season is usually long enough for successful corn agriculture. Surface water occurs only as small springs near the northern and southwestern termini of the flows.

The Little Springs eruption was very different from that at Sunset Crater and its effects on local populations were also distinct. The principal difference between the eruptions is that Little Springs was Hawaiian in nature, producing spatter ramparts and lava flows but no significant fallout deposits. The tallest volcanic landform is a 100-m-high, 400-m-long spatter rampart, with a vent complex on its west side that fed a northern and a southern lava lobe, the latter then flowing down a steep valley and spreading around two sides of a pre-existing cinder cone (Fig. 4). A small spatter rampart marks the southern edge of the vent area, but the western and northwestern borders are marked only by gentle hills covered with loose blocks.

The eruption appears to have initiated from a north-northwest-trending fissure that extended from the current main spatter rampart area to within 100 m of the northern edge of the north lobe, a distance of about 2 km. This fissure is now only visible as isolated spatter ramparts that fed lava flows that plunge under and then underlie the main northern lava lobe. Quaquaversal (radially outward) dips on these ramparts indicate that they are not fragments, but are the entire landform. No evidence of fissure vents south of the main spatter rampart has been found. Eruption from at least the north end of the fissure must have been short-lived, as no lava flows from it are seen at the edge of the main flow only 100 m north of the fissure's end.

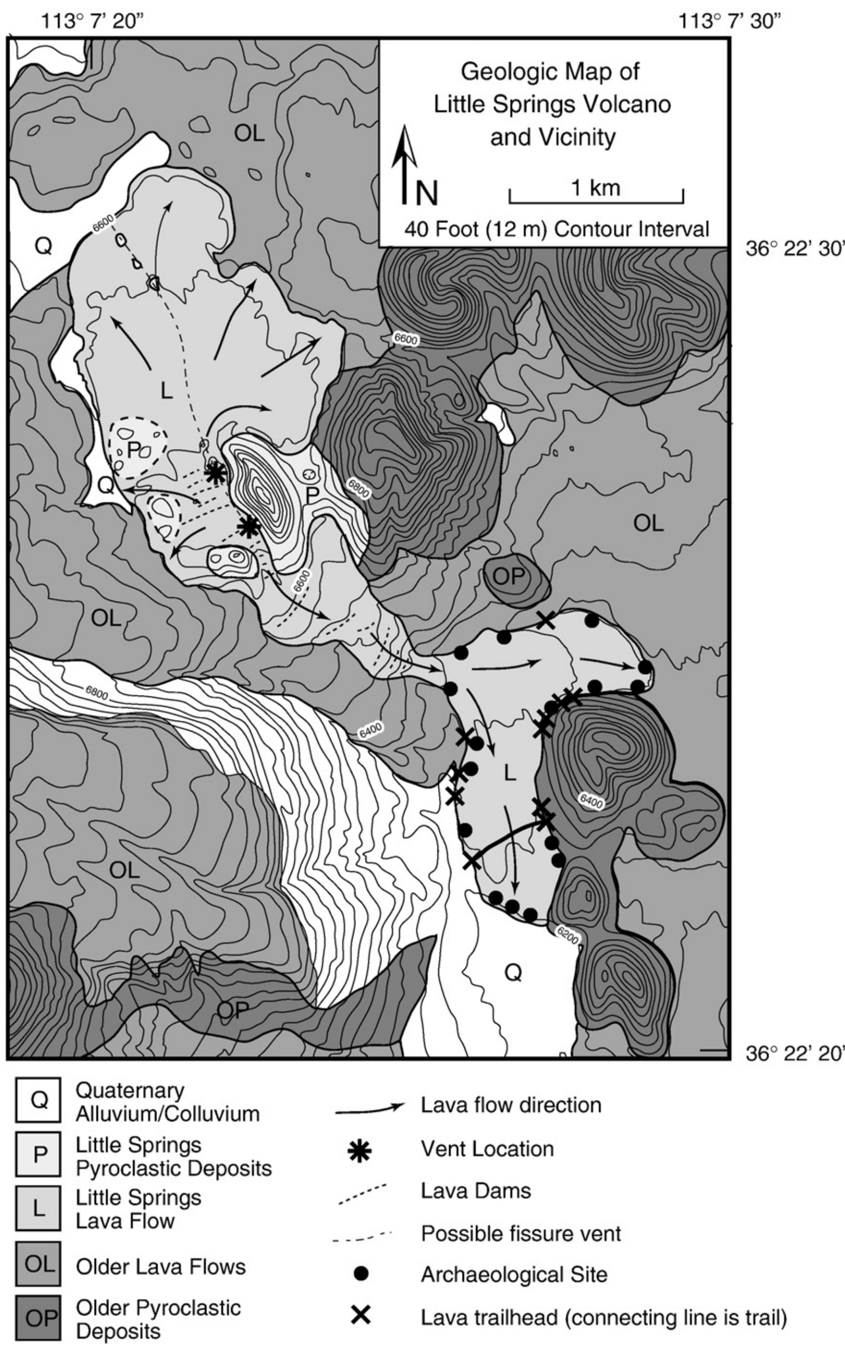

Fig. 4. Map of Little Springs volcano and surrounding area. Geology from Billingsley et al. (2001) and this work. Archaeological sites and trails were only mapped on the southern lobe. Others were found on the northern lobe but were not mapped as part of this project.

Most of the eruption then localized on an area at the southern end of the fissure. This location is at a significant break in slope that appears to have existed before the eruption, with most of the 150 m elevation difference between the northern and southern lava lobes occurring within about 1.5 km south of the main vent. Many small spatter ramparts occur within this vent area, but two areas appear to have been the main vents for at least the latter portion of the eruption, forming embayments in the main eastern spatter rampart. Although these embayments are probably largely constructional, the poor development of ramparts to the west of the vent areas suggests that at least some rafting of vent edifices occurred. The northern vent fed most or all of the northern flow lobe, which spread over a 1-km-wide valley and formed a broad blocky lava field. The southern vent fed the southern lobe, which flowed down the steep slope toward a lower open valley about 1 km away. Many rafted spatter-agglomerate complexes occur on the slope, many appearing to have dammed the flow and caused it to break through small gaps. Hornitos, resulting from breakouts of overpressured lava through the lava flow surface, are common along this section of the flow. Once the flow reached flat land, it spread out, partially surrounding a pre-existing cinder cone. The flat and fertile nature of the land it covered is visible in the approximately 1-km^2 area just south of the end of the flow.

The eruption covered about 5 km^2 with lava flows and spatter deposits. Another ~1 km^2 of land east of the main spatter rampart was heavily impacted by deposition of bombs and blocks. Outside of this area, few permanent effects are likely. Fires and acid rain may have affected vegetation for a year or two but the forest in this area evolved in a fire regime and likely recovered quickly.

2.2.1. Duration and date of the eruption

The Little Springs eruption probably lasted for a period of weeks to a year or two. This is based upon the lack of stratigraphically distinct lobes. Both the northern and southern lava fields are marked by a lack of breakout lava flows or over-riding lava flows, with remarkably consistent flow-top heights. Using a 5 km^2 aerial extent and an average flow thickness of 5–10 m, the total eruption volume was about 0.025–0.05 km^3 ($2.5–5\times10^6$ m^3). Using a low average discharge of 1 m^3/s, this would take 7000–14,000 h (0.75–1.5 yr) to erupt. A more normal discharge would result in a much shorter eruption time.

Several dating techniques have been applied to Little Springs volcano. Fenton et al. (2001) used cosmogenic He to obtain a 1300± 500 BP date. Ceramic sherds encased within lava-spatter blocks, similar to maize-impressed spatter blocks found at Sunset Crater (Elson et al., 2002), were recovered from a small masonry pueblo about 0.7 km from the lava flow. Several of the sherds are Hurricane Black-on-gray (Fig. 5), a ceramic type that conservatively dates to between 1025 and 1200 CE, with a possible tighter range between 1050 and 1150 CE (Altschul and Fairley, 1989). A recent paleomagnetic secular variation study (Elson and Ort, 2006) determined a virtual geomagnetic pole of latitude 71.8° and longitude 323.4°, virtually identical to one obtained by Champion previously (Duane Champion, personal communication, 2003). This location is near the secular variation curve of Hagstrum and Champion (2002) at 2380 and 7870 BP, but it does not match with the dates of the sherds incorporated into the lava spatter nor with the cosmogenic-He date. With the large amount of basalt in the area, it is possible that the lava flow was affected by magnetic fields from these other sources. However, no systematic difference in remanence was noted from north to south along the flow or with different aspects to slopes, as might be expected if a local field were important. Urrutia-Fucugauchi et al. (2004) show that, at Parícutin, paleomagnetic directions are systematically 10° too shallow, and suggest that this is due to internal sub-Curie point deformation of the flow and may be an uncommon occurrence at other cinder cones. Although we prefer the younger date, which matches the morphological youth of the flow, we cannot say with certainty that the flow occurred then. The only viable method

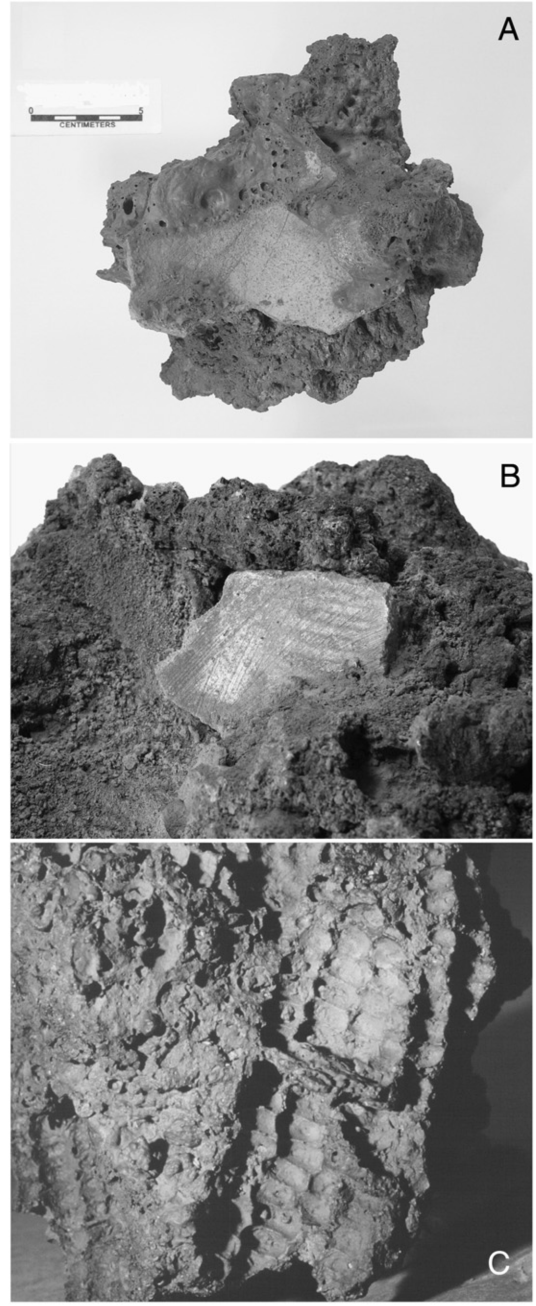

Fig. 5. Photographs of "sherd rock" from archaeological site 0.7 km from Little Springs lava flow and "corn rock" from a site 4 km from the Sunset Crater lava flow. A) Non-decorated sherd showing molten, vesicular nature of the lava that fell onto the sherd. B) Close-up view of decorated sherd embedded in lava. Ceramic type "Hurricane Black on Gray" is dated to 1050–1200 CE. Sherd is 7 cm in longest dimension. C) Maize-impressed spatter agglutinate. Rock is about 10 cm in diameter.

we have found to produce the sherd-containing spatter agglomerate blocks involves access to an hornito or spatter vent, so we believe this is the best date of the eruption. In any case, most of the interpretations of human interaction with Little Springs volcano do not require that humans were there at the time of the eruption, as our evidence is primarily for post-eruption activities.

The eruption altered the landscape by the addition of the lava flows, spatter ramparts, and bomb field to the east of the main spatter rampart. However, outside of this area, the landscape was largely unaltered, and no surface stream drainages were disrupted. Agriculture and habitation were still possible up to the edge of the flows. The flow surfaces are nearly devoid of vegetation today, except the west side of the northern lobe and the 'lava cascade' that leads from the southern vent to the southern flatlands. There, soil has developed in areas with smaller (2–10 cm) blocks on the lava surface. Much of the soil in this region consists of dust blown in from the west, and this dust, along with organic matter as vegetation gained a foothold, filled cavities between the clasts and allowed incipient soils to develop.

3. Discussion

The eruption of Sunset Crater dramatically and permanently altered the physical and cultural landscapes of northern Arizona. The smaller Little Springs eruption also permanently affected these landscapes, but in a less dramatic manner. Both of these volcanoes were almost certainly known and discussed throughout the greater prehistoric Southwest United States (Elson et al., 2007). Digital elevational modeling indicates that the Sunset Crater fire fountain (260–660 m high) and ash plume (4–6 km high) were visible from distances as far as 100 km and 400 km, respectively, increasing the volcano catchment area (Elson et al., 2002). Cinder-cone eruptions rarely directly cause deaths in the local population but psychological impacts are common and dependent on a number of variables, including the severity, proximity, and type of the eruption, and the nature or cultural practices of the affected group (Nolan, 1979; Reycraft and Bawden, 2000). Eruptions also damage agriculturally productive land, habitation structures, and storage features. In a marginal agricultural environment, such as the northern Southwest United States, destruction of field crops and even a portion of stored resources could be a major catastrophe, potentially leading to migration and even starvation. Understanding the changes in both the natural and human realms brought on by these eruptions has significant implications for reconstructing the prehistoric settlement of the greater Southwest United States.

3.1. Post-eruption geomorphic processes and agricultural implications

The volcanic event and the subsequent re-sculpting of the landscape by surficial processes provide the template upon which the prehistoric inhabitants had to adapt. Water and wind erosion and mass wasting affected the landscape following the eruption. Surface and ground water, as well as spring activity, were affected by the lava flow and tephra. In addition, soil formation processes and their soil-agricultural implications are important to understanding prehistoric adaptation to the eruption.

The volcanic activity resulted in two significant periods of landscape alteration. The first was the constructional phase of the volcanic features, lasting between a week and a few years. The second period of change is the erosion and redistribution of the volcanic material, which would have been at a high rate immediately after the eruption but continues today. Unconsolidated tephra on the ground surface provided a ready source of easily eroded and transported sediment during high rainfall events (e.g., during the Southwest summer monsoon). The following discussion draws on observations of post-eruptive landscape processes following the 1943–1952 CE Parícutin eruption (Segerstrom, 1950, 1960, 1966; Luhr and Simkin, 1993). Climatic differences between semi-arid northern Arizona and humid Michoacán led to different rates of erosional processes, but the processes are similar. Most of the following discussion relates more to Sunset Crater than Little Springs because Little Springs had a very sparse tephra deposit.

3.1.1. Erosion

Landscapes composed of cinder cones and unconsolidated cinders are prone to dramatic erosional processes. After the eruption, the landscape is covered with fine-grained material suitable for rapid re-deposition by wind and water, and cone slopes are steep and unstable. In addition, the landscape is denuded of much of its vegetation, further increasing the potential for erosion. Cinders from Sunset Crater were subjected to erosion and redeposition during the annual monsoon rains. In one rainstorm at Parícutin (20 September 1946), a large gully, several hundred meters long, 7–8 m wide, and as much as 5.8 m deep, formed. Three weeks later, the gully was 20 m wide and 12.4 m deep and had cut about 1.6 m into the underlying soils (Segerstrom, 1950). This is an extreme example that resulted when impounded water breached the cinder barrier, but it demonstrates cinders' susceptibility to erosion. At Sunset Crater, rills and gullies developed on cinder-covered hills, mass wasting occurred along the steep flanks of the new cone and other hills in the area, and sheet-flooding and channeling were undoubtedly common.

According to Segerstrom (1966), the highest rate of erosion occurs immediately following the volcanic activity, when unconsolidated material covers the denuded landscape. Rates of erosion decrease over time as the cinder layer is reworked and re-vegetation occurs. Segerstrom (1966, p. 307) observed after a return trip to Parícutin in 1965, 13 years after the eruption ceased, that "an approach toward stability was evident in all the devastated area: the cinder cone, the lava field…and the surrounding ash-covered terrain." Due to the drier climate in Arizona, the redistribution of Sunset cinders would occur much more slowly, although the slow rate of re-vegetation would expose cinders for a longer period of time. The maximum period of erosion would have been during the first significant episodes of monsoonal rains.

Sunset Crater tephra was reworked by eolian processes (Hooten et al., 2001; Spurr et al., 2003) and ash dunes are described by Berlin et al. (1977). Large areas of Wupatki National Monument are covered by eolian reworked tephra, and modern wind ripples can commonly be found in Sunset Crater National Monument. Wind-transported ash and lapilli can abrade plants, particularly important crops such as maize. The need for windbreaks to protect prehistoric crops resulted in the construction of post-eruptive rock alignments that are oriented transverse to the prevailing southwesterly winds (Brown, 1996). These rock alignments are probably the remains of brush windbreaks with rock weights holding them down.

3.1.2. Ground water

The emplacement of volcanic deposits can significantly affect drainage patterns, springs, and water sources. Lava flows generally move down drainages, blocking them and creating new patterns for surface flow. At Sunset Crater and Little Springs, the flows filled portions of valleys, permanently altering the surface hydrology. At Parícutin, lava flows and thick cinder deposits dammed perennial drainages and created new stream patterns. Because the cinders and lava are very permeable, they can act as recharge areas and provide a valuable reservoir of stored water. At Parícutin, some springs and wells increased their discharge between 1943 and 1957. Other springs and wells, however, experienced decreases in discharge, with some drying up and others being buried by up to 15 m of re-deposited cinders (Segerstrom, 1966). The shallow water table can produce new springs at the contact between the new, highly permeable cinder layer and the underlying pre-eruptive soils. The insulating nature of the lava tubes also allows for the formation of ice caves, which developed in both the Sunset Crater and Little Springs flows, and ice remains in these caves today.

3.1.3. Soil formation

In general, soils in volcanic deposits can be quite productive. Many of the world's richest agricultural areas for subsistence agriculture are in volcanic terrain. Volcanic soils tend to have high cation exchange capacity, high % base saturation, and good water-holding capacity. However, in the semi-arid landscapes of northern Arizona, volcanic soils commonly have low availability of important soil nutrients, such as nitrogen and phosphorus. Nitrogen is generally low due to the high temperature and low organic matter turnover, whereas P can be low because the high pH soils fix P within calcium carbonate.

Soil formation processes in cinders and on lava flows are distinctive. The addition of eolian dust, including clay, carbonate, iron oxides, and numerous nutrients adhering to clay surfaces, is important (Wells et al., 1987; Anderson et al., 2002; Spurr et al., 2003). Initial phases of soil formation include the addition of aerosolic dust, and its redistribution by rainfall and rainsplash (Anderson et al., 2002). Soil profiles in the 19 ka Merriam flow, a lava flow ~15 km ESE of Sunset Crater with about 5 cm of Sunset ash (Duffield et al., 2006), show soil horizons with Av (silty) soils underlying a desert pavement (Spurr et al., 2003). These soils did not develop *in* the basalt flow, but are a result of dust deposition *on* basalt flow surfaces and the formation of a soil horizon in the dust. Similar soil formation processes are expected in the Sunset Crater tephra and on the lava flows, but little has occurred yet.

3.1.4. Agricultural studies

The net effect of thick cinder blankets depends upon a variety of environmental factors and the types of subsistence practices. In deposits deeper than 20–30 cm, agriculture is impossible at first (Rees, 1979; Blong, 1984; Elson et al., 2007; Waring, 2007). Eventually, some of the cinders work into the pre-eruption soil or are blown into drifts, allowing much of the pre-eruption soil to be used again. At Parícutin, cinders were removed from agricultural fields, but much of this effort was either unsuccessful or caused more extensive erosion (Luhr and Simkin, 1993). The loss of soils is detrimental to subsistence economies, and this loss can be permanent on a human time scale. Soil formation in semi-arid areas can take more than 1000 years, as soils are best described as 'incipient' in thick Sunset Crater cinder deposits. In warmer, more humid environments, such as at Parícutin, which receives almost 1 m of annual rainfall, incipient soils can develop in a few decades, even on thick cinder deposits.

The agricultural effects of the cinder deposition in the semi-arid to arid climate of Sunset Crater differed from those in the humid climate of Parícutin. Agriculture in semi-arid and arid climates can benefit greatly from the deposition of a relatively thin layer of cinders that acts as a mulch (a protective covering, such as leaves, bark, or crushed rock, spread on the ground to reduce evaporation and erosion, improve the soil, and control temperature variations), whereas in humid climates such benefit is negligible. Water is generally the limiting factor for crop production in the arid southwestern United States. A mulch of cinders on agricultural soil plots decreases runoff, increases infiltration, and decreases evaporation. Experiments by Choriki et al. (1964) using pebble mulches indicate that evaporation from non-mulched ground was 0.88 cm/day while under pebble mulch it was 0.18 cm/day. After a two-year period, 30–40% more soil moisture would be retained under mulched soils. Fairbourn (1973) estimated that, under pebble mulch, 60% of winter moisture is stored compared to 40% for non-mulched ground. With 380 mm of mean annual precipitation, a pebble-mulch soil will retain approximately 40 to 60 mm more rainfall than non-mulched ground (Corey and Kemper, 1968), enough to make the difference between crop success or failure in many environments. In addition, Alderfer and Merkel (1943) determined that 40–60% runoff occurred on bare ground while only 3–10% runoff occurred on pebble-mulch areas for a 75 mm/hr rainfall event. Decreasing runoff would help retain soil nutrients adhering to sediments. Cinder mulches can also trap organic matter, thus adding to soil nitrogen. Increased infiltration may also lead to development of new shallow-sourced springs.

Lithic mulches also help regulate soil temperature, which lengthens the growing season and decreases diurnal temperature fluctuations. Experimental data from maize grown in pebble-mulch fields indicate that the combined effects of higher soil moisture, longer growing season, and higher rate of water and nutrient uptake allows plants to emerge two to three days earlier and begin tasseling four to seven days earlier than maize grown in fields without a lithic mulch (Fairbourn, 1973; Hakimi and Kachru, 1978). In the Sunset Crater area, the temperature moderation property of the cinder mulch is important at higher elevations and the moisture retention property is critical at lower elevations.

Little Springs and Sunset Crater are at the margins of the zone where maize agriculture is reliably successful (Elson et al., 2006; Elson and Ort 2006). Successful cultivation of maize requires at least 250 mm of annual precipitation, 150 mm of which must come during the growing season (Muenchrath and Salvador, 1995). In the Sunset Crater area, areas below 1890 masl, which include all of the prehistoric sites in Wupatki National Monument, do not receive sufficient rainfall during the growing season for maize agriculture (Elson et al., 2006, 2007). Little Springs, at an elevation around 1900 masl, receives an average of 180 mm of precipitation during the growing season (as extrapolated from Mt. Trumbull climate data in Sellers and Hill, 1974). Most types of maize mature in 115–120 days, although some short-season varieties grown by pueblo Indians in the Southwest United States mature in as few as 75–90 days (Muenchrath and Salvador, 1995). In the Flagstaff area, there is a 70% probability of 83 consecutive days with temperatures above 0 °C and 106 consecutive days with temperatures above −2.0 °C (a 'hard' freeze) at an elevation of 2,040 masl, close to the elevation of Sunset Crater's base (Elson et al., 2006). Although Little Springs has a long enough growing season on average, temperature varies greatly and early or late killing frosts are not uncommon, making crop success unpredictable. Interannual variability in both precipitation and temperature also add to agricultural uncertainty (Salzer and Kipfmueller, 2005). Due to these factors, microenvironmental differences in precipitation and temperature are extremely important and could mean the difference between success and failure in cultivation.

3.1.5. Soil nutrients

Soil nutrient studies (Berlin et al., 1990; Anderson, 2001; Spurr et al., 2003; Edwards, 2007) suggest that soils in the Sunset Crater–Wupatki National Monuments area are suitable for maize growth, but may be subjected to water and nutrient limitations. The mulching effects of the Sunset Crater tephra may have alleviated some of the soil moisture problems, as did the common placement of fields in areas with shallow depth to an impermeable rock or soil layer (Edwards, 2007). This would have trapped infiltrating water at the level of the rooting zone, thereby allowing shallow stored water to be available for plant uptake. The tephra mulch may also have positively influenced soil nutrient availability because the pH of the tephra and the increase in soil moisture would likely have increased nutrient availability.

Spurr et al.'s (2003) description of greater P and N availability with increasing elevation are intriguing. At high soil pH values (7.5–9), such as those in the alkaline soils of the Wupatki area, P adsorbs to the abundant calcium carbonate to form Ca-phosphate. The acidic cinders may lower the soil pH enough (ideally to 6–7) to free up the P in the calcium phosphate, forming orthophosphate, the form available for plant uptake. The change in pH and increase in rainfall are the controlling factors. At the lower elevations, high pH values of 8.4–9 limit P availability whereas at the higher elevations, pH values between 6.6 and 7.7 increase P availability. This increase in available P would likely have been temporary, though, as the overriding control on the soil pH would be climate. Over time, the soil pH would re-equilibrate with the alkaline conditions of the lower elevation soils and the available P would decrease.

3.2. Human adaptation to the eruptions

Similarities in settlement, subsistence, and social organizations of the pre-eruptive groups living in the Sunset Crater and Little Springs areas allowed for successful adaptation to the eruptions. Even though habitation sites and agricultural field areas were destroyed in both areas, after a short period of adjustment, the affected populations appear to have thrived. What is significant is that after the initial response, which involved migration out of the areas beneath lava and heavy cinder cover and reliance on kin and other established social networks for shelter and subsistence, the two groups differed in their long-term adaptations. While social differences between the groups may have contributed to the use of these different adaptive strategies, differences in the nature of the two eruptions were likely the primary causal factor.

3.2.1. Pre-eruption adaptive factors

The Sunset Crater and Little Springs volcanoes erupted within less than 150 years of each other and are approximately 200 km apart (Fig. 1). The 150 years estimated between the two eruptions is the maximum temporal separation; the eruptions could have been contemporaneous or within a single human generation, but the data necessary to refine the dating are not available. Whereas Sunset Crater contained a larger prehistoric population than Little Springs, the prehistoric peoples who lived and farmed in these areas were similar. At the time of the eruptions, both areas were occupied by small groups of farmers subsisting largely on maize agriculture, along with the cultivation of beans, squash, and cotton. Hunting of small game (e.g., rabbits) and deer, and gathering of wild foodstuffs (e.g., amaranth seeds, pine nuts, cactus fruit) supplemented the crops. Agricultural fields were small, generally encompassing no more than 10–20 ha, with most around 1–5 ha. Irrigation was not practiced, due to the lack of large streams with a dependable flow. Instead, minor water-control features, such as linear rock terraces or rock-and-brush check-dams across small drainages, were used to slow water flow and entrap soil. The small size of the fields was partly due to environmental parameters. Because Sunset Crater and the Little Springs are located at the fringes of the viable maize agriculture zone, farmers sought to minimize risk. Small agricultural plots were placed in a number of microenvironments, varying in elevation, slope, exposure, substrate, soil type, and water source, thereby ensuring that in all but the very worst years some crop would be harvested.

Most habitation sites were small, sufficient for 1–2 families (likely kin-related) living in semi-subterranean pit structures and surface masonry rooms built from local materials (Elson, 2006). Depending on the site, one structure was generally used for storage, while the others were for sleeping, cooking, and other domestic activities. A few larger sites were also present, containing from 10–20 structures, which were probably inhabited by several unrelated families. Although the larger sites do not appear to be appreciably wealthier or contain higher status individuals than the smaller sites, they may have served more of an integrative function by being the focal point for the larger community.

The social organization of the prehistoric groups who inhabited the Sunset Crater and Little Springs areas was in many ways pre-adapted to successfully deal with and manage the eruptions. Both areas were occupied by small groups of subsistence-level agriculturists with decision making occurring at the household or extended family level, although the few larger sites may have contained several unrelated families necessitating at times more structured or hierarchical decision making. Larger multi-site social groups (or communities) may have been recognized, particularly for religious ceremonies, marriage networks, or defensive purposes, but the archaeological data suggest that most sites contained one or two relatively independent families, living for the most part in a non-hierarchical social system (Kamp and Whittaker, 1999). This contrasts markedly with the post-eruptive period, when groups aggregated into large, multifamily pueblos with a more complex social structure.

The low complexity, non-hierarchical social organization of Sunset Crater and Little Springs groups was advantageous in dealing with the eruptions because: 1) Small group or family-level decision-making allowed for a rapid response; evacuation was not predicated on directions coming from the top of the social hierarchy; 2) Minimal energy was invested in architecture and site structure — construction of a new pit structure or small masonry pueblo could be accomplished in days or weeks with materials at hand; 3) The small size of agricultural plots meant that less energy was invested in each individual field; the risk-reduction strategy of multiple plots spread over varied environments also meant that some field areas may have received less damage from the eruption; 4) The overall settlement system was focused on dispersed, small sites, meaning that kin likely lived in a wide area, so that those who were not affected by the eruption could feed and shelter those who were, and 5) The Sunset Crater and Little Springs eruptions were relatively small when compared to other eruptions, and areas without tephra deposition were present within 10–20 km at Sunset Crater and 1–2 km at Little Springs, allowing for migration into known areas.

3.3. Sunset Crater

Sunset Crater was by far the more significant of the two eruptions, affecting a large area with deep tephra fall (~400 km^2 was under >30 cm of fallout). At modern eruptions, crop yield is significantly reduced with cinder depths greater than 15–20 cm, and agriculture is not possible in depths over 30 cm (Sheets and Grayson, 1979; Luhr and Simkin, 1993). Ten to fifteen centimeters of ash, particularly when wet, can cause moderate to heavy damage to modern structures (Blong, 1984), suggesting that prehistoric pit structures and masonry rooms at sites as distant as 10–15 km from Sunset Crater may have sustained significant damage. The archaeological data indicate four primary responses made by Sunset Crater inhabitants to the eruption: (1) population movement; (2) use of new agricultural methods; (3) changes in ceramic production and exchange networks; and (4) initiation of volcano-related ritual behavior.

3.3.1. Population movement and new agricultural technology

Agricultural experiments by Maule (1963), Colton (1965), and Waring (in press) support the importance of cinder mulch for local agriculture. At an experimental plot planted by Waring near Wupatki National Monument at approximately 1735 masl, no maize germinated without a cinder mulch cover, similar to results obtained by Maule at Wupatki Pueblo. These experiments indicate that a cinder cover of 3–8 cm is beneficial to maize growth. Conversely, the experiments also indicate that >15 cm cinder cover is detrimental to agriculture, and that maize will not grow in cinders deeper than 20–25 cm. Cinders continue to harm agriculture at Parícutin; 40 years after the eruption, vegetation in the areas with >15 cm fallout had still not recovered (Rees, 1979). The 30-cm isopach, which encloses about 400 km^2 (Fig. 2), is a very conservative measure of the area around Sunset Crater that was not farmable. Structures within and beyond this area were also heavily damaged by tephra fall, with most probably sustaining roof and wall collapse.

Archaeologists have long known that the higher elevations in the Flagstaff area were occupied earlier (Colton, 1946; Pilles, 1979); the average elevation of sites prior to 1050 CE was over 2000 masl (Elson et al., 2007). As described above, precipitation limits make 1890 masl the lower limit for most pre-eruptive settlement in the area because maize could not reliably be grown below that altitude. Of the 400 km^2 of land covered by >30 cm tephra, about 265 km^2 was above 1890 m in elevation and received, prior to the eruption, enough rainfall for maize growth, making it prime agricultural land that had to be abandoned after the eruption (Elson et al., 2007). Conversely, lower elevation areas with cinder deposits between 3 and 8 cm would now have become suitable for farming, due to the beneficial effects of the cinder mulch.

Archaeological data from the general Sunset Crater area indicate that an average of 10 prehistoric sites per km^2 is a conservative estimate for the 265 km^2 of abandoned agricultural land. Estimates of the number of sites buried and no longer inhabitable following the eruption indicate that there were around 2650 sites, of which close to 1700 were habitation sites (Elson et al., 2007). This number is similar to that found in Wupatki National Monument, where a comprehensive survey inventory of the 143 km^2 park revealed about 2400 prehistoric sites (Anderson, 1990). At ~1580 masl, Wupatki National Monument averages around 180 mm of precipitation per year and therefore did not regularly receive enough rainfall to support agriculture prior to the deposition of a cinder mulch. The beneficial effect of the cinder mulch is strongly supported by the observation that, of the 977 sites that could be dated, only 2 (0.2%) were definitively occupied prior to the eruption, indicating enormous migration into the lower elevations after this time (Downum and Sullivan, 1990). Based on these data, it is clear that many, if not most, of the new lower elevation settlements were made by the same people who had lived near Sunset Crater (Elson et al., 2007). It is also possible that migrants from neighboring regions were attracted to this newly fertile area as well (Colton, 1946; Sullivan and Downum, 1991). Groups displaced by the eruption and migrants from outside the area may also have moved to the region south of Sunset Crater, which had a similar increase in population at this time (Colton, 1946).

Settlement of the lower elevations may also have been aided by a moister climatic regime in 1050–1090 CE (Salzer and Kipfmueller, 2005; Salzer and Dean, 2007). During this period, precipitation was average or above average nearly 80% of the time, with over 60% of years having above average rainfall. In the normally arid and often unpredictable Southwest, this rainfall increase represents particularly favorable conditions for dryland farming.

Groups that moved into newly fertile areas would have needed new agricultural technology for 'cinder management.' This strategy would involve keeping a consistent layer of cinders, 3–8 cm deep, over agricultural areas, which would not have been easy in a region buffeted by strong seasonal winds. Although some of the numerous agricultural features found throughout this area, such as linear rock alignments, likely functioned as soil or water traps, or to protect young plants from the wind (Downum and Sullivan, 1990; Travis, 1990), we suspect that many were used to trap and manage cinders.

3.3.2. Ceramic production and exchange

Data from the petrographic analysis of ceramic temper indicates that great majority of non-decorated (plainware) ceramic pots used in the Sunset Crater/Wupatki area were made in a relatively small area just south and west of Sunset Crater (Elson et al., 2007). Significant changes in ceramic production and exchange occurred following the eruption because about 50% of this area was covered with 20–40 cm of tephra, likely causing abandonment of numerous sites and disruption of ceramic production areas. It is probable that the eruption significantly reduced local ceramic production, at least until erosion had reduced the cinders to a depth in which occupation and farming were possible again. The petrographic data further confirm that, following the eruption, another ceramic ware, probably made in an unaffected area 50–60 km west of Sunset Crater, replaced the local wares. It is possible that these outside producers increased ceramic production to fill the gap left by the disruption in local manufacture. What was exchanged for these ceramics is unknown, although it may have involved foodstuffs and other goods from the newly settled areas.

3.3.3. Ritual behavior

The Sunset Crater eruption may also have led to the initiation of volcano-related ritual behavior. This is demonstrated by the recovery of over 50 pieces of Sunset Crater basalt with prehistoric maize cob and stalk impressions, termed 'corn rocks' (Fig. 5), from the surface of a site 4 km from the nearest lava flow (Elson et al., 2002). Another 950 pieces of Sunset Crater basalt without corn impressions were also recovered from the site, and these likely represent pieces of lava that were brought to the site and then cracked opened to expose the corn casts. Elson et al. (2002) argue that the characteristics of the corn rocks, along with experimental data, suggest that the rocks were made deliberately through placement of maize cobs as an offering around an *hornito*. Maize is a sacred plant to all Pueblo groups in the Southwest United States and it is likely that it served a similar purpose in this region during prehistory. Why over 40 kg of rocks with maize casts were transported to a habitation site 4 km from the lava flow is unknown, but the effort required in collecting, carrying, and then exposing the corn remains in these pieces strongly argues against the casual transport of a volcano souvenir; it can be speculated that the corn rocks themselves may have been seen as a source of power or, given that one was found embedded in the wall of a structure, as protection from the malevolent forces of the volcano. Although both prehistoric and modern offerings are commonly associated with volcanoes in other parts of the world (Luhr and Simkin, 1993; Plunket and Uruñuela, 1998a, 1998b; Scarth, 1999; Sigurdsson, 1999), this is the first evidence from the southwestern United States of possible ritual behavior related to volcanism.

3.4. Little Springs volcano

The response to the eruption by Little Springs inhabitants was distinct from that at Sunset Crater, because Little Springs had little cinder deposition and only the 6 km^2 area directly beneath the spatter rampart, lava flow, and lava bomb areas had to be abandoned (Elson and Ort, 2006). Although archaeological investigations in the Little Springs area are limited, Moffitt and Chang (1978) interpret a relatively high site density, similar to that around Sunset Crater. Extrapolating from these data, 45 habitation sites may have been buried by the eruption. This is significantly fewer than the close to 1700 habitation sites estimated to have been impacted by Sunset Crater, clearly showing the differences in magnitude between the two eruptions.

Unlike Sunset Crater, where the thick cinder deposit made living anywhere near the lava flow untenable, occupation at Little Springs continued on and near arable land right up to the flow edge. Masonry structures, built out of lava blocks, were constructed abutting the lava face at the base of the flow and on top of the flow itself. Our preliminary archaeological survey of just the southern lava lobe recorded 16 sites containing a total of around 150 structures on the flow top and 50 structures at the base (Fig. 4; Elson and Ort, 2006). The largest sites contained structures on both the flow top and at the base; for example, one site has >45 structures on top of the lava, with another ~10 structures at the base. Structures around the base of the flow have associated low density artifact scatters, but only a small number of artifacts – a few pieces of broken pottery and flaked stone debris – were found with the structures on top of the flow, suggesting that they were not long-term habitations and may have been used largely for defensive purposes.

The defensive nature of the top of the flow is further supported by an intricate and extensive network of trails that trend both north–south and east–west across the lava (Elson and Ort, 2006). The trails were constructed by using small lava blocks to fill in holes and smooth the rough surfaces, which remain difficult to traverse without trails today. The trails are smooth enough to run on and their construction required significant labor and engineering; more labor was put into trail construction than into construction of the flow-top masonry structures. Ceramic sherds and a few rock cairns occur scattered along the trails, perhaps marking the routes. The building of these trails suggests a concern with rapid movement, which might be necessary in defensive situations. The trails cannot be seen from the base of the flow and all have rough, and somewhat hidden, access; someone who knew the lava flow and the trails and fortifications would have a tremendous advantage over any invader. The utility of lava flows as defensive retreats is amply demonstrated by the Modoc Indian War in the early 1870s, in which the U.S. Army estimated that they would need at least 1000 troops to defeat the 100–200 Modoc hiding in the lava beds along the shores of Tule Lake in northern California (Beck and Hasse, 2004).

Eleven prehistoric ceramic sherds embedded in Little Springs lava spatter agglutinate (Fig. 5) were recovered from a small masonry pueblo situated about 0.7 km east of the lava flow (Elson and Ort, 2006). The lava-embedded sherds, which represent at least two different ceramic types, were found clustered on the surface of the site, most within a single room, and may represent pieces of the collapsed room walls. The largest piece of spatter is approximately 25 cm by 25 cm by 10 cm, requiring a moderate amount of determination on the part of the carrier to bring it to the site from the place of origin. The sherd-embedded rocks may have been made in a similar way to the corn rocks at Sunset Crater (Elson et al., 2002; Elson and Ort, 2006). In this case, instead of maize, sherds, or possibly whole vessels, were placed on the spatter rampart of an hornito. Spatter then covered the ceramics, which were later retrieved and carried to the habitation site, where they may have been placed in the walls of the structures. Like the corn rocks, the reasons for this behavior are unknown, but the effort required to make and transport the sherd-embedded lava implies that, like the corn rocks, these were more than just a curiosity or volcano souvenir, and may have had some kind of ritual meaning. These are the only sherds encased in lava known from the American Southwest, and, to our knowledge, in all of North America.

After the eruption, the Little Springs lava flows were used for defensive purposes as a type of fortified retreat, while farming and settlement occurred right up to the flow edges. Use of Little Springs as a “hide-out” continued into the modern period, with fugitives from the Mountain Meadows Massacre of 1857 retreating into the lava flow (Hunt, 1978). The Sunset lava flows were not reoccupied and only sporadically used, almost certainly because local populations had to move tens of km away due to the heavy cinder fall around the flow areas. The only documented use of the Sunset lava flows was for water collection (ceramic jars found under drips), caching water jars for travelers (in small caves and lava block bins), or for ritual purposes (prayer sticks and other offerings).

4. Conclusions

Sunset Crater and Little Springs volcanoes, situated less than 200 km apart, erupted around the same time and in similar environments — near the ponderosa pine/piñon–juniper life-zone boundary, which was the most agriculturally productive and most densely settled portion of their semiarid environments. The effects of the eruptions on local populations, however, were markedly different. Whereas Sunset Crater caused large-scale migration, development of new agrarian techniques, and alterations in ceramic production and exchange systems, Little Springs had little effect on population distribution and subsistence systems, outside of the displacement of perhaps a few hundred people by the lava flow itself. Much of this difference is due to the lack of a significant cinder blanket at Little Springs, so that only the sites within the 6 km^2 area covered by the spatter rampart and lava flows had to be abandoned. Groups living around Little Springs may have delayed evacuation as long as they could, in order to preserve their crops or maintain territories, or they may have abandoned a somewhat larger area during the eruption due to forest fires and perceived danger, but the area was significantly smaller than the 400 km^2 (or 265 km^2 with high-density settlement) that were evacuated early in the Sunset Crater eruption due to the thick cinder and ash fallout.

The distance needed to leave the volcano-impacted zone at Little Springs Volcano may have been as small as a few km, whereas the heavy tephra fall from Sunset Crater probably necessitated a move of as much as 10–20 km, potentially placing the volcano refugees into the territory of other groups. Based on data from modern cinder-cone eruptions, it is likely that very little loss of life occurred directly from the lava flows or tephra fall because the absence of a hierarchical social organization meant that decisions to leave the area were probably made at the family level, allowing for a very rapid response. Violence could occur, however, if displaced groups were forced into territory claimed by others. Land wars and not the eruption itself accounted for the greatest loss of life associated with the eruption of Parícutin (Nolan, 1979). Archaeological evidence of prehistoric violence is known from the Sunset Crater–Wupatki area (Smith, 1952; Turner and Turner, 1990, 1999; Elson, 2006), but it is not known if this violence is related to the eruption.

Differences in the nature of the two volcano eruptions are reflected in the different adaptive mechanisms employed by the two groups. The deposition of a thick cinder blanket at Sunset Crater beneath which agriculture was no longer possible likely forced the migration of over a thousand people. At the same time, deposition of a thin layer of cinders acted as a mulch and opened up a previously arid unfarmable area to agriculture. This necessitated the adoption of new agricultural technology – cinder management – to ensure that a 3–8 cm layer of cinders remained across agricultural fields. However, such benefits were probably short-lived, with cinders blowing away or being worked into the pre-eruption soil within decades to perhaps a century or two. Keeping a consistent thin layer of cinders across agricultural field areas would have required the construction of some type of brush or rock cinder barrier, perhaps represented by the rock alignments described above (Elson et al., 2007; Brown, 1996). The Wupatki area was occupied for around 150 years, which may be the maximum time that human management could keep a thin layer of cinder mulch atop the agricultural field systems. Soil depletion by intensive farming may also have affected fertility.

At Little Springs, the lack of significant cinder deposition allowed post-eruption occupation to continue as it had prior to the eruption, with the only difference being that 6 km^2 were under lava or lava bombs and no longer accessible for occupation. While the lava flows may have displaced at most several hundred people, the small size of the flow suggests that territorial boundaries were probably not a factor in resettlement. Settlement occurred at the base of the flow, with the flow top being used as a defensive retreat.

Groups living near active volcanoes commonly incorporate eruption accounts into traditional histories, and ritual behavior by affected groups should be expected (Nolan, 1979; Plunket and Uruñuela, 1998a, b; Scarth, 1999; Sigurdsson, 1999). Many eruptions are seen as signs of spiritual and moral transgressions and offerings are made in an attempt to rectify these “sins” and avert the ongoing destruction (Scarth, 1999). Hopi Indian accounts of the Sunset Crater eruption, for example, cite various offenses, including gambling, immoral behavior, and the cuckolding of a powerful supernatural being (Colton, 1932; Malotki and Lomatuway'ma, 1987; Ferguson and Loma'omvaya, in press). Perhaps most important for understanding prehistoric (and modern) eruptions, religious or cultural mechanisms for coping with a natural disaster, such as a volcanic eruption, can be highly adaptive, enabling affected individuals and groups to more readily accept the event and begin the recovery process (Nolan, 1979). While it is probably impossible to know if religious adaptive mechanisms were occurring at these volcanoes, the recovery of spatter agglutinate blocks impressed with corn (Sunset Crater) and containing sherds (Little Springs) is suggestive of these processes.

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