Effects of scoria-cone eruptions upon nearby human communities

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ABSTRACT

Scoria-cone eruptions are typically low in volume and explosivity compared with eruptions from stratovolcanoes, but they can affect local populations profoundly. Scoria-cone eruption effects vary dramatically due to eruption style, tephra blanket extent, climate, types of land use, the culture and complexity of the affected group, and resulting governmental action. A comparison of a historic eruption (Parícutin, México) with prehistoric eruptions (herein we primarily focus on Sunset Crater in northern Arizona, USA) elucidates the controls on and effects of these variables. Long-term effects of lava flows extend little beyond the flow edges. These flows, however, can be used for defensive purposes, providing refuges from invasion for those who know them well. In arid lands, tephra blankets serve as mulches, decreasing runoff and evaporation, increasing infiltration, and regulating soil temperature. Management and retention of these scoria mulches, which can open new areas for agriculture, become a priority for farming communities. In humid areas, though, the tephra blanket may impede plant growth and increase erosion. Cultural responses to eruptions vary, from cultural collapse, through fragmentation of society, dramatic changes, and development of new technologies, to little apparent change. Eruptions may also be viewed as retribution for poor behavior, and attempts are made to mollify angry gods.

Keywords: Scoria cones, geoarchaeology, volcanic risk, agriculture, Sunset Crater, Parícutin.

INTRODUCTION

Scoria-cone volcanoes are the most abundant volcanic landform on Earth (Wood, 1980). About 20 volcanoes per year erupt basaltic magma, some producing scoria cones, and basaltic volcanoes occur in all tectonic settings (Walker, 1993). Most scoria cones are monogenetic centers; therefore, each eruption produces a new volcano. However, these cone-forming eruptions are less frequent, less dramatic, and their environmental effects less widespread than eruptions at stratovolcanoes (Simkin and Siebert, 1994), whose effects on human populations are comparatively well documented (e.g., Sheets and Grayson, 1979; Blong, 1982, 1984; Sheets and McKee, 1994). Thus, the hazards of scoria-cone eruptions have largely been overlooked. Scoria-cone eruptions, however, commonly occur in areas where people live and farm; therefore, their effects can be profoundly life altering. This paper describes the effects of scoria-cone eruptions on human populations, filling in a significant gap in our understanding of these potentially catastrophic events.

A scoria-cone eruption can produce a cone (up to ~500 m tall) of unconsolidated to welded basaltic to andesitic scoria lapilli and ash. The eruption may also produce one or more lava flows, emitted near the base of the cone, and a blanket of scoriaceous lapilli and ash fallout covering tens to thousands of square kilometers (Vespermann and Schmincke, 2000). A variety of models explain scoria cones and their deposits (e.g., McGetchin et al., 1974; Heiken, 1978; Valentine et al., 2006). The height of the eruption column, which largely determines the extent of the scoria blanket, and the effusion rate, which largely determines how far lava flows reach, are the two most important features that control their effects on humans. Recent work has shown that many scoria cones were not formed only by Strombolian explosions and Hawaiian fountaining, and "violent Strombolian" eruptions with sustained eruption columns are common in the volcanic record (e.g., Gutmann, 2002; Valentine et al., 2005). Scoria cones commonly form volcanic fields, especially in intra-plate environments, that consist of tens to hundreds of individual volcanoes (e.g., Hasenaka and Carmichael, 1985). These fields

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are active over millions of years and long periods between eruptions (100s to 10,000s of years) can result in a lack of awareness of volcanic risks. Lava flows tend to level the topography between the cones. Weathering of lava and scoria produces a soil in which agricultural activities can be carried out. This leads to human populations living in areas with moderate to high potential for scoria-cone eruptions.

In southwestern North America, human populations have lived and farmed within scoria-cone fields for over 5000 yr (Piperno and Flannery, 2001), a period during which more than a dozen scoria cones erupted, with the most recent eruption occurring in the mid-twentieth century (Fig. 1) (Wood and Kienle, 1990; Simkin and Siebert, 1994). Comparisons of the effects of these eruptions upon nearby populations are instructive. The people who lived near where the new volcanoes formed were mostly subsistence farmers who primarily grew corn, beans, and squash. Nonetheless, each eruption affected local populations in different ways. Choices made by affected groups, and by individuals within these groups, resulted in different adaptive responses. These choices were both predicated upon, and constrained by, a complex mix of variables, which include the nature of the eruption, features of the surrounding environment, and the culture and complexity of the affected group.

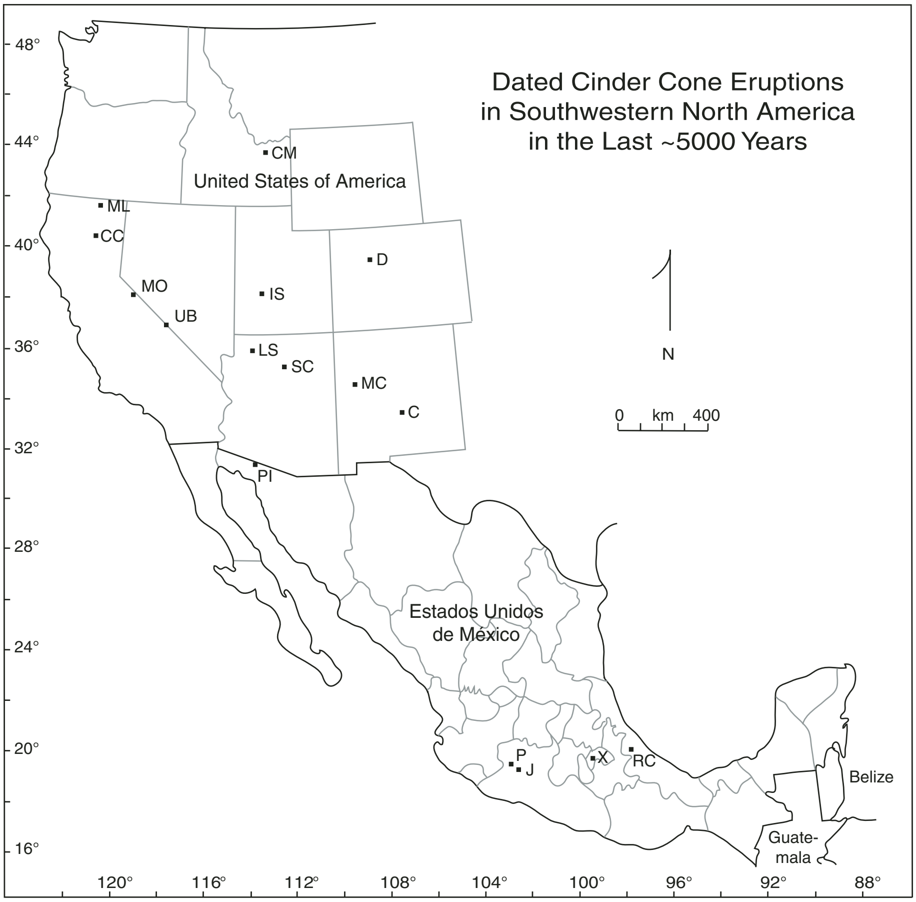

Figure 1. Location of the scoria-cone volcanoes that have erupted in the past 5000 yr in southwestern North America. C—Carrizozo (5.2 ka; Dunbar, 1999); CC—Cinder Cone at Lassen (1630–1670 CE; Clynne et al., 2000); CM—Craters of the Moon (126–>5000 ybp; Simkin and Siebert, 1994); D—Dotsero (4150 ybp; Wood and Kienle, 1990); IS—Ice Springs (1280 ybp; Simkin and Siebert, 1994); J—Jorullo (1759–1774 CE); LS—Little Springs (1050–1200 CE; this study and references cited herein); MC—McCarty's Flow (3180 ybp; Laughlin et al., 1994); ML—Medicine Lake (Callahan and Paint Pot, 1000–1100 ybp; Donnelly-Nolan et al., 1990); MO—Mono-Inyo Craters, Coso and Big Pine Volcanic Fields (Holocene to several hundred years old, rhyolitic and basaltic; Simkin and Siebert, 1994); P—Parícutin (1943–1952 CE)—note that at least four other scoria cones in the Michoacán-Guanajuato volcanic field are <5 ka; 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 scoria cones; Simkin and Siebert, 1994); X—Xitle (1670 ybp; Siebe, 2000), as well as Chichinautzin (1835 ybp) and Guespalapa (2835–4690 ybp; Siebe et al., 2004).

In this paper, we focus on the effects of two scoria-cone eruptions on human populations, and the various responses of those populations. The two volcanoes, for which both geological and anthropological data are available, are Parícutin in Michoacán, México, which erupted between 1943 and 1952 CE, and Sunset Crater in north-central Arizona, which erupted sometime between 1050 and 1100 CE (Colton 1946; Holm and Moore, 1987; Elson et al., 2002; Ort et al., 2002). Two other prehistoric eruptions—Little Springs in northern Arizona and Xitle in modern Mexico City—are discussed as additional examples of the diversity in human response and adaptation. These particular eruptions were chosen because they represent a spectrum of the variability observed in scoria-cone eruptions and in the social complexity of the affected human populations. All four volcanoes had distinct eruptive styles and affected populations with different levels of cultural complexity. The style and magnitude of eruption are, of course, critical controls on the eruptive impacts, but sociocultural variables are also important. A better understanding of these cultural factors can help affected populations and authorities plan for future responses to scoria-cone eruptions.

A spectrum of eruptive styles affecting groups with different cultures and levels of social complexity (ranging from groups with limited hierarchical structure to state-level societies) presents clear examples of the variability of human adaptation to catastrophic volcanic events. Little Springs was the smallest eruption and affected a small, possibly seasonal population. These people adapted easily to the emplacement of the cone and flow. The small amount of data from Little Springs suggests that the lava flows were used primarily for shelter, defense, and, based on modern Paiute Indian data, possibly for rituals (Stoffle et al., 2004; Ort et al., 2008). Sunset Crater was a larger eruption than Little Springs and affected a larger population with numerous permanent habitation sites and agricultural fields. The adaptive response of these people was to abandon the immediate area and move a few kilometers away into a dramatically different environment that necessitated technological changes but where, by all appearances, they thrived. Volcano ritual appears important at Sunset Crater, based on both the archaeological record and on accounts from modern Hopi Indians. Parícutin, somewhat larger in size than Sunset Crater, affected an even larger population within a state-level society, and with a modern federal system overseeing its "adaptation" to the event. Predictably, the responses by local groups varied, with some quite successful stories and others less so. At Xitle, a highly complex, prehistoric state-level society already showing signs of decline may have been pushed over the edge by the devastating effects of the eruption (Gonzalez et al., 2000).

ERUPTIONS

Parícutin

Parícutin is a well-studied scoria cone in the Michoacán-Guanajuato volcanic field of west-central México. This volcanic field contains ~1000 vents in a 200 × 250 km area (Hasenaka and Carmichael, 1985). Parícutin erupted from 1943 to 1952, covering an area of 24.8 km^2 with 0.7 km^3 of lava, and producing a 424-m-high scoria cone (Fig. 2). Scoria fallout (1.3 km^3) covered an area of ~300 km^2 to depths of >15 cm (Luhr and Simkin, 1993). Volcanic ash dusted Mexico City 320 km away, and the eruption column exceeded 6 km in height several times. Scoria fall killed nearly all plant life within 5–8 km of the cone within the first year, but immediate famine was averted because the eruption began two months after the corn harvest, just as farmers were preparing their fields for the next year. The eruption proceeded slowly enough for groups to be evacuated and for important religious relics to be saved from destruction before the lava flows arrived at their towns. The eruption was widely blamed on the desecration of a religious shrine a few years before (Nolan, 1979). The residents of the Parícutin area erected a row of 2-m-high wooden crosses in front of the advancing flow to prevent it, unsuccessfully, from encroaching upon their village; other religious rites, such as pilgrimages and supplications, were also undertaken to stop the lava (Foshag and González-Reyna, 1956; Luhr and Simkin, 1993). No one died in the eruption itself (three people were killed by eruption-related lightning), but about one hundred people died due to land disputes, diseases, and loss of will to live (Nolan, 1979; Luhr and Simkin, 1993).

Agriculture was severely affected by the deposition of more than 25 cm of ash around Parícutin. Of the 233 km^2 within the 25-cm isopach (Fig. 2), ~50 km^2 were potentially arable prior to the eruption (Rees, 1979). Farming of areas covered with between 10 and 25 cm of tephra was dependent on local topographic conditions and scoria erosion rates, rendering much of this area also unusable immediately following the eruption. The denuded landscape covered with unconsolidated tephra was ideal for large-scale erosion, particularly during the high rain-

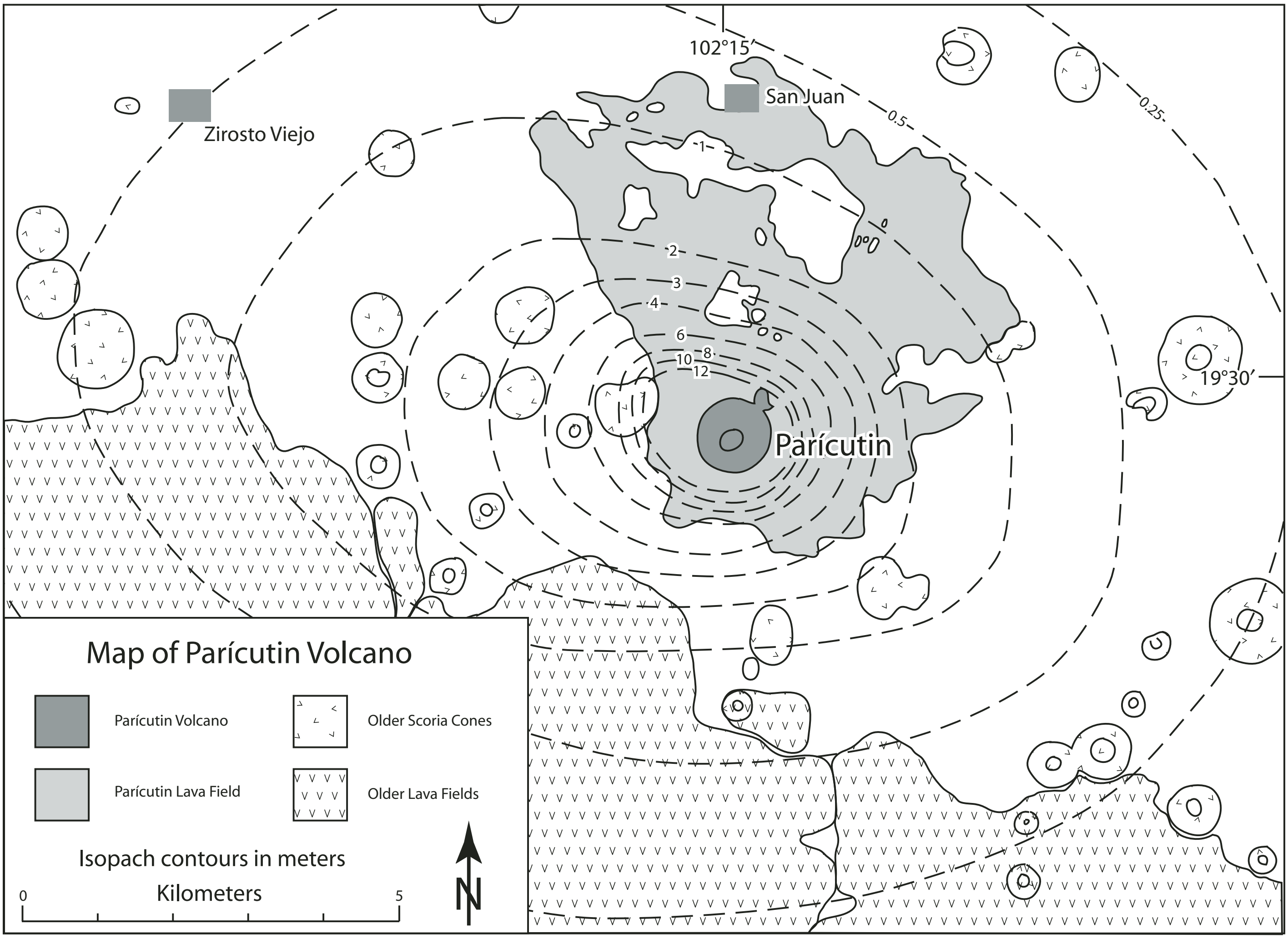

Figure 2. Map of Parícutin volcano and its eruptive products. Fallout thicknesses (in meters) were measured in 1946, after most of the fallout had been deposited. Modified from Segerstrom (1950).

fall months of 1943. The scoria filled streams and covered hills to produce a smoothed, hummocky topography. Drainage patterns were disrupted, causing streams to flow out of their channels and across the landscape in large, destructive floods (Segerstrom, 1950). The easily transported loose scoria created massive debris flows, further burying farmed fields and destroying irrigation systems. Rilling and gullying created new, deeply incised drainages. After the eruption, farmers returned to the area and once again attempted to grow crops. They found a bleak landscape of unfamiliar terrain and sediments of poor agricultural quality. The fertile soils that once supported crops were either eroded or buried. Eventually, and with variable success, areas with between 10 and 25 cm of scoria became farmland once again. Attempts were made to wash away the thick tephra by rerouting rivers, which only resulted in more incision and gullying. Bulldozers were brought in to scrape to the original soil surface, but the immensity of the project, the continuous redistribution of scoria by wind and water, the lack of a place to put the scoria, and high financial costs caused the farmers to abandon this method (Rees, 1979). The most practical method of reclaiming agricultural lands under 10–25 cm of tephra was to manually remove or rework the scoria into the underlying soil. Furrow plowing that mixed the scoria with the underlying soil and nitrogen-containing weeds was the most successful technique, although crop production remained uneven across single fields and from one farming community to another. Fertilizer was also needed to continuously supply nutrients due to the poor quality of the primary scoria, which only has ~55 ppm nitrogen compared with 350 ppm for the underlying soil (Rees, 1979). Our data indicate that the scoria is relatively rich in soil phosphorus (P), with ~17.4 ppm, while the underlying soil has 3.3 ppm. P decreases in abundance and availability with time, particularly in the allophane-rich soils of weathered volcanic substrates; therefore, older soils in the area tend to have low P contents and availability. Although post-eruptive P increases might have benefited crops, the eruption-related increase in P does not negate the limiting effects of very low N and thick (>25-cm) tephra layers.

Five Purépeche (Tarascan) Indian communities, comprising several thousand people, had to be abandoned under governmental order (Nolan, 1979, 1993). Some of these communities moved en masse to form new villages, while others were relocated into existing villages and urban centers. Those who were moved to larger urban centers found their way of life dramatically altered. Reactions to the evacuations ranged from complete cooperation to absolute resistance, and some communities divided into those who left and those who stayed. These divisions continue to the present day. Those evacuated to different environments had some difficulties in learning new agricultural techniques, and encountered considerable resistance from previous residents, resulting in land disputes and violence. The people who moved to the outskirts of the closest city (Uruapan) soon became urbanized and lost connection with their past lifestyles. Those who were able to stay in their old towns or in nearby communities have maintained their culture to a greater extent. These areas were not strife-free, however, because land disputes occurred where the lava flows and heavy tephra fall buried border markers and topographic indications of territorial boundaries.

Sunset Crater Eruption

Sunset Crater, ~25 km northeast of Flagstaff, Arizona, is the youngest vent in the San Francisco volcanic field, which contains at least 600 scoria cones ranging in age from ca. 6 Ma to recent (Wood and Kienle, 1990). Archaeological investigations in the early 1930s discovered pit structures filled and buried by Sunset Crater tephra, indicating that the eruption occurred during the prehistoric occupation, although the date of the eruption was unknown at that time (Colton, 1932a, 1946; Downum, 1988). Amos (1986), Holm and Moore (1987), and our fieldwork show that the Sunset Crater eruption began along a fissure (Fig. 3). Eruption soon localized to form the Sunset Crater cone during a major cone-building phase that also produced widespread tephra fallout. Two lava flows, Kana'a (to the northeast) and Bonito (to the west), with a total volume of ~0.1 km^3 (Amos, 1986), were emplaced concurrently with fallout that underlies and overlies the lava flows. Both lava flows remained active for a limited period of time after tephra fall had ceased. Spatter agglutinate around the rim of Sunset Crater appears to record the end of pyroclastic activity. The eruption produced a >300-m-high scoria cone and basaltic lava flows that cover ~8 km^2, with a total erupted volume of ~0.9 km^3 (Fig. 3). Tephra from the volcano clearly impacted prehistoric inhabitants over a wide area, with depths greater than 1 cm covering ~2300 km^2 (Fig. 4; Hooten et al., 2001). This caused population movement and dramatically altered settlement, subsistence, economic, and ritual systems (Colton, 1936, 1946, 1960; Sullivan and Downum, 1991; Elson and Ort, 2003; Elson et al., 2002, 2007).

The time and duration of the eruption are not accurately known. No evidence of any eruptive hiatus (e.g., erosion, soil horizons, buried ripple or dune forms, and bioturbation) occurs within the eruptive sequence; therefore, the long eruptive episode proposed by some researchers (e.g., Pilles, 1979; Holm and Moore, 1987) does not seem likely. Archaeological dating of contexts with and without Sunset scoria suggests eruption between ca. 1050 and 1125 CE. New paleomagnetic secular variation data, augmenting and including the data of Champion (1980), combined with lava and tephra stratigraphy, constrain the eruption to a brief (months to years) period between 1040 and 1100 CE (Ort et al., 2002). An eruption date of 1064–1065 CE was proposed by Smiley (1958) based on suppressed and complacent tree rings from beams recovered from the prehistoric site of Wupatki, a 100-room masonry pueblo located ~20 km northeast of Sunset Crater. Although this date is entrenched in both the geological and archaeological literatures, it is inconclusive for a number of reasons (Boston, 1995; Elson et al., 2002). A reexamination of Smiley's set of eight affected tree-ring samples revealed that most are duplicates from the same tree, and that beams from only two Douglas firs (*Pseudotsuga menziesi*) and one Ponderosa pine (*Pinus ponderosa*) show altered rings. The original provenance of the beams is unknown, and Wupatki, at 1500 masl, is ~20 km from the nearest current stands of these high-elevation species. In addition, hundreds of tree-ring samples that span this period have been examined since Smiley's work, and none contain this unique signature, a signature unlike those reported from eruptions elsewhere. Typically, thin rings are produced for a few years after an eruption, and then the tree resumes a normal growth pattern. Sheppard et al. (2005) showed that rings similar to the unusual ones found by Smiley can be formed in nonvolcanic contexts. Thus, although the Wupatki beams date an event that caused narrow and then complacent ring formation, a causative link to the Sunset Crater eruption is unknown.

Another way to estimate the duration of the eruption is to calculate the discharge needed to obtain the observed length of lava flows, using the technique of Walker (1973). This technique relies upon the observation that the distance a lava flow reaches from its source is controlled by the discharge at the vent. A slower discharge leads to stalling of the flow front and inflation of the flow body, whereas a higher discharge results in greater advance of the flow front. The total length of time required for the eruption can then be calculated by dividing the volume of erupted lava by the discharge. At Sunset Crater, this can be calculated for the Kana'a lava flow, but the Bonito lava flow ponded on the uphill side of the volcano, and thus the flow length is not directly related to discharge. For the 10- to 11-km-long Kana'a lava flow (it is difficult to determine its exact point of origin), discharge

Figure 3. Map of the Sunset Crater eruption, adapted from Moore and Wolfe (1987).

plots at 4–20 m^3s^{-1} on Walker's Figure 4. Slope does not appear to affect flow length very much, but Walker (1973) states that many lava flows reach their full length in the first days of the eruption, so that average discharge may be much lower than the peak discharge calculated from flow length. In the case of Kana'a flow, though, the lack of scoria covering the distal end of the flow indicates that this was emplaced late in the eruption, after scoria fall ended, and the low height of the flow and lack of lava breakouts or other evidence of multiple lava pulses is consistent with one flow lobe lengthening over time. Thus, this discharge range may represent average conditions. The total Kana'a flow is $\sim 4 \times 10^7$ m^3 (Amos, 1986); therefore, it would have taken ~23–115 days to produce the lava flow at the estimated discharge. This very rough estimate of eruption duration does not include the (likely short) portions of the eruption prior to the effusion of the Kana'a flow (during the fissure eruption) and the (again likely short) period when Bonito and the end of Kana'a lava flows were erupted after scoria fall had ceased.

At the time of the eruption, the area around Sunset Crater was densely occupied by small, relatively independent human groups that subsisted largely on the cultivation of corn and a few other crops, supplemented by hunting and gathering. The great majority (>98%) of habitation sites in the area that date earlier than 1050 CE are above 1900 masl, and the average pre-eruption site elevation is ~2100 masl, about the elevation of the base of the Sunset Crater cone (Elson et al., 2007). This restricted range reflects temperature and precipitation controls. Growing corn at higher elevation is risky, with both early fall and late spring freezes common in the tree-ring record, and the growing season can be shorter than the 75- to 120-day corn maturation period. Without irrigation, corn in the southwestern United States needs ~250 mm of annual precipitation, 150 mm of which must fall as rain during the growing season (Muenchrath and Salvador, 1995). Below 1900 masl in the Sunset Crater area, this requirement is not met today and probably was not met at the time of the Sunset Crater eruption (Elson et al., 2006). Thus, the people who inhabited the Sunset Crater area prior to the eruption were making use of a limited viable agricultural zone.

To evaluate the effects of the Sunset scoria upon agriculture in the area, corn was planted at various soil depths under different tephra blanket thicknesses in fields near Sunset Crater at 2100 masl and near Wupatki at 1740 masl (Fig. 5; see also Waring, 2007). The results agree with observations from Parícutin (Rees, 1979), as well as from simpler experiments carried out in the Sunset Crater area by Colton (1965) and Maule (1963). These data show that more than ~15–20 cm of scoria results in significantly reduced corn germination, as well as heavy damage to crops already in the field (Sheets, 1980; Blong, 1982; Waring, 2007). Scoria could be manually thinned to reach this thickness, but high winds characteristic of the region (Acker et al., 2007) would return the scoria quickly, and at some point, removing scoria becomes inefficient and impractical. We use 30 cm as a conservative measure of the tephra depth greater than which prehistoric agriculture could probably not have been undertaken. An isopach map of Sunset Crater tephra, produced by combining Amos's (1986) data with our mapping (Hooten et al., 2001), shows that ~400 km^2 was covered to depths greater than 30 cm. About 265 km^2 of that area is above 1900 masl (Fig. 4), and therefore within the area that was potentially farmable prior to the eruption. We argue that this area must have been abandoned at the time of the eruption.

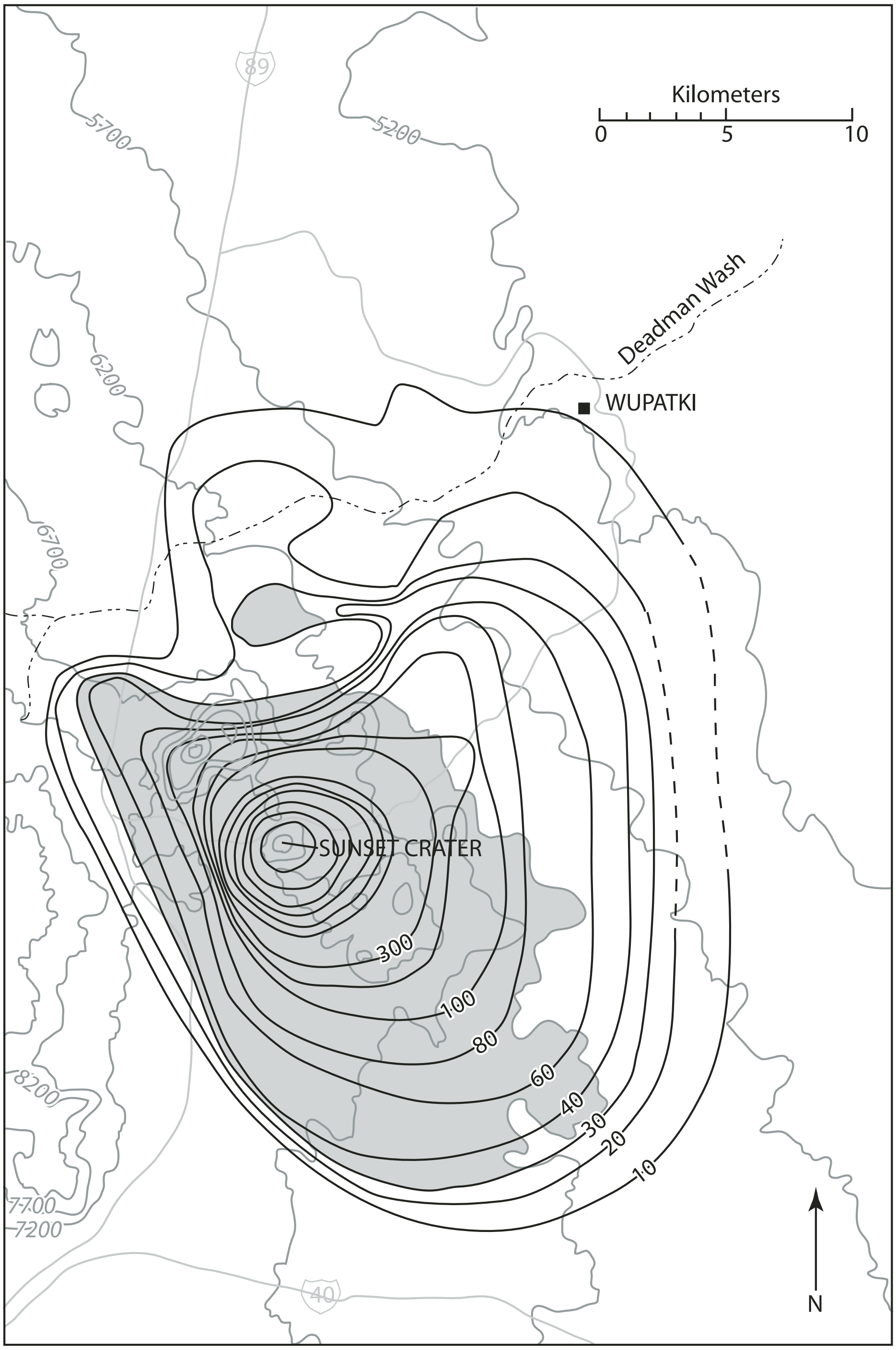

Figure 4. Isopach map of Sunset Crater tephra deposits. Isopach contour lines are in centimeters, topographic contour lines are in feet above sea level. Paved roads shown for geographic reference. Shading denotes area of probable population abandonment above 1900 m (6200 feet) asl with greater than 30 cm of tephra deposition.

Archaeological data from the Coconino National Forest site files suggest that there were ~200 pre-eruption habitation sites in the area above 1900 masl that were subsequently covered by >30 cm of Sunset Crater tephra (Elson, 2006; Elson et al., 2007). Determining population from numbers of sites is imprecise because it is difficult to know how many people lived at a site at any given time. However, archaeological remains from the general Flagstaff area suggest that, prior to the eruption, an average of 1–2 households for each habitation site is reasonable, with perhaps six people per household (Colton, 1946; Elson, 2006). This suggests a population of 1800 people (±50%) potentially inhabiting the area where the eruption would have significantly impacted corn agriculture.

The corn growth experiments also confirm Colton's (1932a, 1936) hypothesis that a thin layer of scoria functioned as a lithic "mulch," retaining water and slowing evaporation enough to allow crops to grow in areas previously too dry for agriculture. The beneficial aspects of tephra-mulch agriculture have also been recorded in other areas; at Parícutin, barley and wheat crops were reported to be excellent from areas with 3 cm of tephra fall (Segerstrom, 1950; Rees, 1979), while in Papua New Guinea, higher crop yields following the eruption of Tibito Tephra are still recounted in oral histories 300 yr after the eruption (Blong, 1982). The deposition of scoria mulch in the lower elevations north of Sunset Crater may have opened up new areas for agriculture. In our plots, as well as in the earlier experiments, corn germination was enhanced with a 3–8 cm tephra thickness (Fig. 5; Maule, 1963; Colton, 1965; Waring, 2007). Wupatki National Monument, located ~20 km north of Sunset Crater, was covered by 1–10 cm of tephra (Fig. 4; Hooten et al., 2001). The entire Wupatki area is at an elevation below minimum precipitation limits for corn growth, yet the monument contains some of the largest and most complex archaeological sites in the Flagstaff area, with ~2400 sites in total within the 243-km^2 monument (Anderson, 1990). In an area where only 0.1% of the 977 dated sites were inhabited prior to 1050 CE, with most post-dating 1100 CE, it is a reasonable inference that the Sunset Crater tephra blanket improved the agricultural environment to encourage this new settlement. A combination of lost arable land at higher elevations and newly farmable land at lower elevations, plus periods of higher-than-average precipitation with little interannual variation during the late eleventh century and first half of the twelfth century CE (Salzer and Dean, 2007), likely contributed to

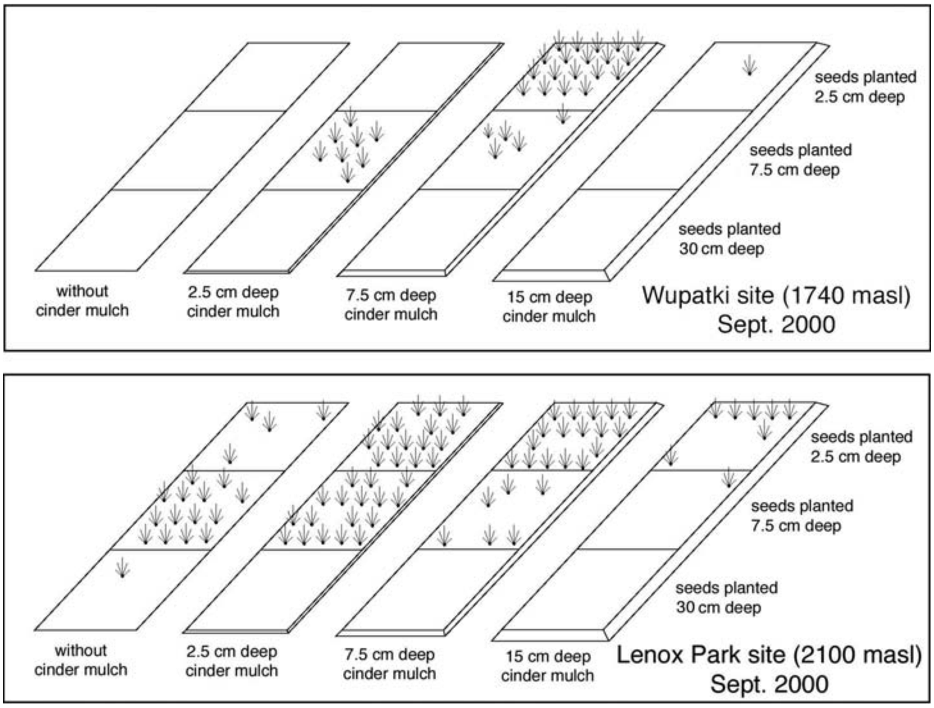

Figure 5. Cartoon showing corn germination in an experimental agricultural plot just south of Wupatki National Monument (1740 m asl) and at Lenox Park, near Sunset Crater (2100 masl), September, 2000. Modern Hopi corn agriculture uses a 30-cm planting depth.

this migration. Although the creation of new viable agricultural lands probably resulted in immigration by groups previously living outside of the Sunset Crater area, as suggested by Colton (1946), Downum and Sullivan (1990), and others, the majority of new settlers could have simply been those displaced by the eruption itself.

The Sunset Crater eruption was an awe-inspiring event for the local people, which may also have been reflected in ritual practices. Elson et al. (2002) describe corn impressions in Sunset Crater spatter agglutinate fragments found at a prehistoric habitation site ~4 km from the Bonito lava flow. These "corn rocks" contain impressions of corn ears, including lava septa between kernels, as well as individual corn kernels and pieces of corn husk. The physical characteristics of the corn rocks, along with attempts to reproduce the features (Elson et al., 2002), are consistent with the corn rocks being made at hornitos on the surface of the Sunset Crater lava flows. Apparently, people placed ears of corn on the lip or base of the hornito, where spatter then covered them. The resulting corn molds in the agglutinate were retrieved during a quiescent phase and carried to the habitation site >4 km away, where at least some were incorporated into the walls of masonry structures. Similar spatter agglutinates, but containing pot sherds instead of corn, are found in structures near the Little Springs volcano (Ort et al., 2008). Corn is a sacred plant in all Pueblo cultures of the southwestern United States (Parsons, 1936; Ford, 1994), and the corn rocks may represent a ritual offering, perhaps to appease the forces responsible for the eruption. Some 900 yr later, Hopi accounts of the Sunset Crater eruption—which is generally blamed on divine punishment for immoral behavior—are part of traditional clan histories, underscoring the significance of this event to those who witnessed it (Colton, 1932b; Malotki and Lomatuway'ma, 1987). The Hopi religious figure most closely associated with the eruption, the Kana'a katsina, wears a bandolier of corn cobs.

DISCUSSION

The two scoria-cone eruptions described above demonstrate a diversity of human responses to eruptions that varied in style and in the extent of damage to the local communities. This diversity increases if other scoria cones are examined, specifically Little Springs, situated just north of the Grand Canyon, and Xitle, situated on the southern edge of what is now Mexico City. Little Springs probably erupted in the late eleventh or early twelfth centuries CE and is a ~100-m-high spatter rampart with little scoria deposition. Two blocky basaltic lava flows cover ~5 km^2 (Ort et al., 2008). Xitle covered an area of ~70 km^2 with lava and produced a 140-m-high scoria cone (Siebe, 2000). This eruption occurred at 280 ± 30 CE in a heavily urbanized area containing Cuicuilco, a large prehistoric city with pyramids, habitation areas, and other public structures (Adams, 1991; Gonzalez et al., 2000).

All four of these eruptions were near where people lived and farmed, a common feature of scoria-cone volcanic fields. Scoria-cone eruptions are significant because the affected areas, although small (100s to 1000s of km^2), are often moderately to densely populated. Population displacement—that is, the creation of volcano refugees—is a likely consequence of any scoria-cone eruption. Lava flows and fallout blankets thicker than 10–15 cm are the chief causes of population displacement. New lava renders the land unfarmable for extended periods (hundreds of years in semiarid environments, although perhaps less than a century in tropical rainforests) and thus can be regarded as a multi-generational effect. The refugees from these areas are permanently displaced. At Little Springs volcano, the lack of widespread tephra resulted in relatively little impact upon the agricultural people in the area. A preliminary investigation (Ort et al., 2008) found over 150 prehistoric structures on top of the lava, which may have been used thereafter as a defensive retreat.

Effects of Scoria Blankets

The net effect of thick scoria blankets depends upon a variety of environmental factors and the types of subsistence practices carried out. Deposits thicker than 10 cm can cause roof collapse, particularly when wet, as well as render agricultural fields at least temporarily unusable (Rees, 1979; Sheets, 1980; Blong, 1984; Elson et al., 2007; Waring, 2007). In scoria deposits thicker than 30 cm, agriculture is impossible at first. Eventually, the scoria can work into the pre-eruption soil or be blown into drifts, allowing some of the near-vent pre-eruption soil to be used again. Deep-rooted plants, such as trees, can survive in the scoria deposits and help add organic material for new soil formation, especially in a moist environment, and, over time, an area can revert to its pre-eruption conditions. In semiarid areas, this process can take more than 1000 yr, because soils today are at best described as "incipient" in thick Sunset Crater scoria deposits (Holzschuh, 2004). In warmer, more humid environments, such as at Parícutin, which receives almost one meter of annual rainfall, incipient soils can develop in a few decades (Rees, 1979; Bocco et al., 2005).

The agricultural effects of the scoria deposition in the semiarid to arid climate of Sunset Crater differed from those in the humid climate of Parícutin. Agriculture in semiarid and arid climates can benefit greatly from the deposition of a relatively thin "mulching" layer of scoria, whereas in humid climates such benefit is negligible. Because water is generally the limiting factor for crop production in the arid southwestern United States, the positive influence of tephra on soil water conservation is enormous. A tephra mulch on agricultural soil plots helps to decrease runoff, increase infiltration, decrease evaporation, and regulate soil temperature. This is strongly supported by a wide body of literature on pebble-mulching, practiced along the Rio Grande in both prehistoric and historic times (Maxwell and Anschuetz, 1992; Lightfoot, 1994; Lightfoot and Eddy, 1995; Dominguez, 2002), as well as by experimental data on pebble-mulching (Alderfer and Merkel, 1943; Choriki et al., 1964; Corey and Kemper, 1968; Fairbourn, 1973; Hakimi and Kachru, 1978). Although the Sunset Crater tephra is typically finer grained than the pebbles used in the above studies, similar processes would still have been in operation (Ort et al., 2008). The smaller grain size is important because of the eolian redistribution of the Sunset scoria blanket and the consequent management techniques developed to deal with this.

The benefits of the Sunset Crater scoria mulch on prehistoric agriculture are shown by the dramatic increase in population following the eruption, and the numerous post-eruptive agricultural features in the low-lying, arid environs near to and within Wupatki National Monument (Anderson, 1990). There, the population apparently flourished only after the scoria mulch covered the landscape and conserved soil moisture. Average yearly precipitation at Wupatki today (and probably 900 yr ago) is just over 200 mm, with only 100 mm falling during the growing season. Because this is below the threshold needed for corn agriculture (Muenchrath and Salvador, 1995), the scoria mulch was probably a critical variable in prehistoric settlement of this area. However, in areas where the tephra served as mulches for farming, as at the prehistoric sites in the Wupatki area, such benefits are probably short-lived, with scoria blowing away or being worked into the pre-eruption soil in a period of decades to perhaps a century or two. Keeping a consistent 3–10 cm layer of scoria across agricultural field areas would have required active management involving the construction of some type of brush or rock scoria-migration barriers, which are found throughout the area (Elson et al., 2007). The Wupatki area was largely abandoned by 1200 CE, or around 100–150 yr following the eruption, and this may be the temporal limit for scoria-mulch agriculture in this area.

Whereas agriculture in arid climates benefits from a thin layer of tephra, an adverse effect is noted in a humid climate, such as that of Parícutin. Added moisture retention is of little benefit where water is abundant. The scoria does not add significant soil nutrients, with the possible exception of phosphorus. Also, in areas with high rainfall, destructive erosion of loose surface scoria is a risk. Gullying was a problem near Parícutin; the scoria-covered fields require constant anti-erosion maintenance. Interviews with farmers in the nearby town of Angahuan indicate that the scoria does not benefit the soils and requires the application of a fertilizer, which is costly and often prohibitive in these subsistence economies (Segerstrom, 1950). A few towns, including Corupo, near the 10-cm scoria isopach, however, experienced increased crop productivity after the eruption (Segerstrom, 1950).

Differences between Volcanoes

Comparisons of scoria cones help elucidate some of the variables controlling the severity of impacts upon local populations. Parícutin had an eruption volume roughly the same as that of Sunset Crater, and the aerial extent of its scoria fall is similar. In spite of this, the Sunset Crater eruption appears to have had a more profound effect on human populations in the area. One important difference between Parícutin and Sunset Crater is that Parícutin, at ~1500 mm/year, receives approximately three times the rainfall at Sunset Crater and four times that of Wupatki. Our examination of the soils indicates that new soil is better developed at Parícutin after 60 yr than it is at Sunset Crater after >900 yr. Another important difference is that Sunset Crater erupted in an area that had a limited amount of prime agricultural land, due primarily to precipitation limits, and the lava and >30-cm-thick tephra deposit rendered much of this land inarable. Seasonal (dominantly spring) winds buffet northern Arizona (Acker et al., 2007) and mobilize scoria lapilli up to >1 cm in diameter. Simply digging a small hole down 30 cm to the underlying native soils and planting seeds, as the Hopi do in sand dunes today (Ford, 1994), was not practical because the wind-blown scoria would quickly bury the planting hole, and also likely abrade the growing plant. People were forced to move tens of kilometers and develop new agricultural practices, such as the construction of rock barriers, to keep a consistent thickness of tephra across agricultural areas and reduce the abrasion on the plants. At Parícutin, while some significant land disputes occurred, most displaced farmers either moved to new land and employed similar techniques to those they had used prior to the eruption, or they moved to urban centers and changed their lifestyle completely. For a given eruption, the more marginal or scarce the pre-eruption land is for agriculture, the greater the effects of the eruption are likely to be on an agrarian people.

A comparison of Sunset Crater and Little Springs volcanoes, situated less than 200 km apart, is instructive because both erupted in similar environments, near the ponderosa pine/piñon-juniper life-zone boundary, which was the most agriculturally productive zone in their semiarid environments (Altschul and Fairley, 1989; Elson, 2006). Whereas the Sunset Crater eruption caused migration and development of new agrarian techniques, the Little Springs eruption appears to have had little effect on population distribution and subsistence systems (Ort et al., 2008). This difference appears to be due to the virtual absence of a tephra blanket at Little Springs, so that only the sites within the ~5-km^2 area covered by lava flows had to be evacuated. Although the evacuation process and size of evacuated area at Little Springs are unknown, it is clear that the affected area was much smaller than the several hundred square kilometers that were evacuated in the Sunset Crater eruption due to thick fallout. After the eruption, people returned and built structures and trails atop the Little Springs lava flows. These were apparently used for defensive purposes as a type of rarely occupied fortified retreat because only a few artifacts were found in association with the >150 recorded masonry rooms. Sites containing typical prehistoric artifact assemblages occurred off of the lava right up to the flow edges and were presumably used for day-to-day habitation and farming. The Sunset lava flows were not reoccupied, probably because local populations had to move farther away due to the heavy scoria fall around the flow areas. Data from the National Park Service site files and our own fieldwork indicate that the only evidence of prehistoric use of the Sunset lava flows is for water collection (ceramic jars under drips), caching water jars for travelers, or for ritual purposes (prayer sticks and other offerings).

Eruptive volume, as well as the aerial extent of the scoria blanket and lava flows, controls the extent of the area affected by the eruptions. Hazards may be greater from the generally larger volume arc scoria-cone eruptions than from intraplate scoria-cone eruptions. The effects on local populations near new volcanoes, however, are only partially controlled by the eruption volume. The duration of an eruption does not appear to have a strong influence on the level of the effects on local human populations. The hazards-significance of the eruption length of two of the longest-lived scoria-cone eruptions known, Parícutin and Jorullo (Gadow, 1930), is not obvious when compared to the probably shorter-lived Sunset Crater and Little Springs eruptions.

Cultural Management of Scoria-Cone Eruptions

Given that about twenty scoria-cone eruptions occurred in the past 5000 yr in southwestern North America, it is worth discussing the potential implications of this work for hazards in the area. Environmentally induced disasters and catastrophes cause nearby humans to act or suffer (Oliver-Smith and Hoffman, 1999; Bawden and Reycraft, 2000; McCoy and Heiken, 2000; Hoffman and Oliver-Smith, 2002). As previously noted in the archaeological and geological literatures, the characteristics of a volcano eruption are important in determining its effects, but the sociocultural structure and, in high-complexity groups, governmental actions, control much of the resulting human response (Pilles, 1979; Sheets and Grayson, 1979; Sheets, 1980, 1983; Blong, 1982, 1984; Sheets and McKee, 1994; Chester, 2005; Plunket and Uruñuela, 1998; Luongo et al., 2003). Most of this work is based on huge, catastrophic stratovolcano eruptions, which can kill thousands of people, cause tsunami, and make extremely large areas uninhabitable for generations. The much smaller and slower scoria-cone eruption poses much less threat to human lives and tends to proceed at a pace that allows time to plan for evacuation. Therefore, governmental response should (1) create the fewest evacuees, (2) affect the fewest number of residents elsewhere, (3) change the lifestyle and ethos of the evacuees as little as possible, and (4) allow for as much free choice by the evacuees as is safe. A perceived lack of free choice was a major source of dissatisfaction in the response by the Mexican government to the Parícutin eruption, where “loss of a will to live” by displaced elderly residents was a significant factor in psychological breakdown and a number of deaths (Nolan, 1979, p. 330).

Management of the risks associated with scoria-cone eruptions may be problematic, as people are unlikely to flee until conditions (scoria fall or lava flows) are life threatening. At Parícutin, evacuees tended to stay at home until lava flows were within sight or the thickness of scoria deposits became too great. Such behavior helps maintain territorial rights and prevents looting while personal danger is low, but it complicates the orderly relocation of villages. When only some residents relocated, the sociopolitical structure of a town was fragmented. Populations that relocated as a group to form a similar-sized town elsewhere, such as San Juan Parangaricutiro, did better collectively. Other populations, such as the town of Parícutin, which left part of the community in the hills near the volcano while the rest moved to Caltzontzin, on the outskirts of the city of Uruapan, lost much of their social and political identity and were prone to becoming dysfunctional evacuee camps. Zirosto, another small community near Parícutin, fragmented into Zirosto Nuevo, populated by evacuees who moved 2 km away, and Zirosto Viejo, populated by those who stayed behind. The latter group suffered because the government did not provide the same level of services (schools, electricity, roads, etc.) that it provided to the new town (Nolan, 1979, 1993). The need for relocations caused by a scoria-cone eruption must be openly acknowledged and dealt with evenhandedly by the government.

The detailed character of the evacuations caused by the prehistoric eruptions discussed in this paper is not known. However, the tendency for people to stay at home as long as possible, combined with the gradual colonization and development of the post-eruption lower elevation settlements, suggests that people did not move en masse directly from the Sunset Crater area to Wupatki and other nearby settlements. Whether they moved in with kin in unaffected areas or, as the Hopi say, left the region completely (Ferguson and Loma’omvaya, 2008), prehistoric decision-making in the Sunset Crater area was probably at the family or extended-family level, rather than at a higher-order, non-kin level (Kamp and Whittaker, 1990, 1999). Although the lower-elevation settlements, such as Wupatki, were apparently quite successful, changes in architecture, technology, and exchange networks suggest that affected groups had to learn new techniques and behaviors when they left the Sunset Crater area. The Wupatki sites contained much greater population sizes and densities than earlier sites near Sunset Crater; therefore, newly arriving migrants also had to learn to cooperate and live within a significantly larger social group, one that was not entirely based upon kinship. The opening up of large areas of newly fertile land may also have brought an influx of migrants from areas outside of the region, further introducing new customs and techniques, as well as the potential for intergroup conflict and/or cooperation (Colton, 1946; Downum and Sullivan, 1990).

Reycraft and Bawden (2000) list environmental and social variables that affect how humans respond to environmental disasters (Table 1). The frequency, duration, and magnitude of the event are critical variables in determining the effects of a disaster. Other important variables include the extent, speed, timing, extent of prior knowledge, and periodicity of the event, as well as the social complexity of the affected group(s). Combinations of the above variables determine the destructive level of the disaster, with each event likely being highly idiosyncratic because the variables combine in different ways. Therefore, each disaster must be understood on its own terms.

In the cases discussed in this paper, Xitle is the eruption that occurred in an area with the highest level of concentration of resources, capital investment, technological efficiency, and likely population density, wealth, and social complexity. It also appears to have caused the most profound effects, with the subsequent collapse of the Cuicuilco community, as would be expected from Reycraft and Bawden’s (2000) analysis of critical factors. The people of the Sunset Crater area appear to have had a fairly high population density, but their less complex and more flexible social structure allowed them to react to the eruption in an efficient way. Sunset Crater inhabitants also did not have nearly the same investment in housing, religious structures, and agricultural facilities as the Cuicuilco population, allowing for a much more rapid recovery. Similar conclusions can be drawn for the Little Springs and Parícutin eruptions, but this also assumes a fairly low level of sophistication on the part of disaster-response entities. In the modern world, cultures

TABLE 1. SOCIAL VARIABLES THAT AFFECT HUMAN RESPONSE TO ENVIRONMENTAL DISASTERS

Social variable	How it affects human response to disaster
Resource distribution	Whether resources are concentrated and intensive or dispersed and extensive will affect damage to social system.
Level of capital investment in resource exploitation	Greater investment in capital (e.g. irrigation canals) causes greater damage.
Level of technological efficiency	More advanced technology provides greater capacity for response—but greater reliance on capital investment provides greater damage potential.
Type of economic system	Increased risk with market system and dependence on cash monocropping versus diversity and buffering of traditional economy
Experience with event	Experience, directly or via oral tradition, may affect response.
Population density	Greater population density yields greater potential damage. As population density increases, more people are forced into areas of greater risk.
Wealth	Related to population density; poorer individuals often forced into risk-prone areas to survive. They have less capacity to recover, and are less likely to experiment with response measures.
Level of sociopolitical complexity	Determines political capacity of response, and amount of energy (labor and resources) available for disaster avoidance and relief
Areal extent of a given polity	Determines geographical extent *from* which labor and resources may be taken for response

Note: After Reycraft and Bawden (2000) still vary in complexity, but most would be classified as more complex than the examples discussed in this paper. A lesson for future response teams is, if possible, to attempt to respond in a manner that encourages decisions to be made at a lower level, perhaps at the level of the family, neighborhood, ward, or small village. With smaller and less hierarchical decision-making groups, directly affected individuals can also have greater input into what happens to them, which also serves to empower those taking part in the decision-making process.

Volcanic eruptions are almost always incorporated into local traditional histories, and ritual behavior on the part of affected groups should be expected (Nolan, 1979; Kirch, 1985; Plunket and Uruñuela, 1998; Scarth, 1999; Sigurdsson, 1999; Duffield, 2001; Chester, 2005). Many eruptions are seen as responses to spiritual transgressions, and offerings are made in an attempt to remediate these "sins" and avert the ongoing destruction (Scarth, 1999). Hopi accounts of the Sunset Crater eruption cite various offenses, including gambling, immoral behavior, and the cuckolding of a spirit-being (Colton, 1932b; Malotki and Lomatuway'ma, 1987; Ferguson and Loma'omvaya, 2008). At Parícutin, the Purépeche villagers blamed the eruption on the desecration of a shrine and "the wrath of God on a sinful people" (Nolan, 1979, p. 301), and residents erected crosses in front of the moving flow (Foshag and González-Reyna, 1956; Luhr and Simkin, 1993). Perhaps most important for volcanic hazards response, studies of catastrophic events have shown that religious or cultural mechanisms for coping with a natural disaster, such as a volcanic eruption, are highly adaptive, enabling affected individuals and groups to more readily accept the event and begin the recovery process (Nolan, 1979). Therefore, the religious and cultural spheres also need to be considered by those managing the effects of catastrophic events. More work is clearly needed to understand what techniques work best at empowering individuals and small communities to respond effectively to scoria-cone and other types of eruptions.

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