
Responses to Explosive Volcanic Eruptions by Small to Complex Societies in Ancient Mexico and Central America

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Solutions [to hazards and disasters] are not to be found primarily in new technologies or better use of existing ones. The difficulties . . . stem from social factors. Social problems can only be dealt with socially; technological improvements can only address technological problems.

QUARANTELLI 1991: 27

Gilbert White (1945), a cultural geographer, pioneered the initial serious social science studies of natural hazards, disasters, recoveries, and mitigation. The field of hazard-disaster studies has grown impressively since then (Alexander 1997; Burton, Kates, and White 1978). David Alexander (1995, 1997) surveyed the field and found thirty different disciplines studying hazards and disasters, from the social sciences through the natural sciences and engineering. Because hazard-disaster research began in the social sciences, one might expect, or hope, that it led the way to today and received the majority of research support. Ironically, the natural sciences and engineering now overwhelmingly dominate the social sciences in funding for research in the domain of natural hazards and disasters and in applied dimensions. In virtually all cases within the natural sciences and engineering and even including the social sciences, the focus of research is the immediacy of the hazard, the disaster, recovery, and mitigation. Rarely have long-term studies covering decades or centuries been conducted, and even less frequently have scholars looked into what sectors of

a society, or which competing societies, benefit from a disaster over long time spans. In addition, rarely have the creative aspects of disasters been explored, such as where native peoples with centuries of experience develop housing that is resistant to massive stresses, is relatively non-hazardous if it fails, and is easy to reconstruct. As societies “modernize,” they too often turn away from traditional and appropriate architecture as “backward” and thus increase the risk of injury and death when disaster occurs. Archaeology is uniquely positioned to explore these aspects of hazards and disasters. It is my hope that archaeologists, aided by other social and natural scientists, can explore the negative and creative-positive aspects of hazards and disasters over long time spans in all occupied areas of the globe and share their insights with people inside and outside their discipline.

Another under-researched and under-theorized domain is how non-literate societies convey disaster knowledge, hazard recognition, and proper behavior from one generation to the next, over very long time spans. Literate societies underestimate these accomplishments, often losing traditional extreme-environmental knowledge and thus putting themselves in danger. Kevin Krajick’s article “Tracking Myth to Geological Reality” (2005) summarizes a few cases, such as Northwest Coast native peoples believing that earthquakes and tsunamis can result from battles between the powerful sky deity, the thunderbird, and the ocean deity, the whale, and thus that they need to avoid low-lying coastal areas. Geoscientists have documented periodicities of a few hundred years between major earthquakes and tsunamis in the Seattle area. Similarly, when the massive Indonesian earthquake occurred in 2004, native peoples with long oral traditions in Thailand took to the sea and easily rode out the ocean swell. In contrast, about a quarter million literate people without this oral history drowned in the tsunami. Non-literate societies can maintain hazard perception for many centuries or even millennia by embedding knowledge in religious belief and through frequent repetition of the stories orally and in public performances.

In this chapter I explore the complex relationships between human agency and nature, particularly when nature changes suddenly. I have found thirty-six cases where explosive volcanism impacted ancient societies in what are now Mexico and Central America (Sheets 1999, 2008). What at first glance might seem like a reasonable sample size is actually quite limited, particularly because so few cases are amply researched in social and natural science domains. Few cases have had extensive investigations by volcanologists and archaeologists and thus are difficult to understand broadly and to use comparatively. Comparing explosive volcanic eruptions is rather complex, with significant variables including magnitude, speed of onset, volume of tephra (or dense rock equivalent), and geochemistry. When cultural factors are also considered, very detailed studies are required to seriously explore vulnerability, impacts, recov-

eries, social organizations, political orders, religion, traditional knowledge, and other important themes. Therefore this chapter is exploratory, in recognition of the formidable array of significant variables spanning the humanities, social sciences, and natural sciences.

SCALED VULNERABILITIES

A first step in examining these cases is to compare them volcanologically. Of course, natural scientists and engineers have emphasized the geophysical agency of a disaster—whether it be flood, earthquake, tsunami, hurricane, or volcanic eruption—and have documented the importance of the speed of onset, intensity, and magnitude as key factors. Scaling the magnitude of volcanic eruptions is a crucial component for comparisons, and the Volcanic Explosivity Index (VEI) developed by the Smithsonian Institution, Museum of Natural History, is used here (<http://www.volcano.si.edu/>). The VEI is an 8-point scale of increasing magnitudes, with anything over 4 being “cataclysmic” or worse, with more than 0.1 km³ of tephra volume emitted. For reference, the Mount Saint Helens eruption in 1980 consisted of 1 km³ of tephra. Underdeveloped in the literature are the social factors that render a society vulnerable to sudden massive stress, and each of them can be scaled. This chapter considers such social factors and provides a preliminary methodological framework to examine them. Thus I define five broad categories of social factors that affect a culture’s vulnerability to geophysical disasters. I also propose a scale with which to assess each domain of social vulnerability on a 5-point range: very low, low, moderate, high, and very high.

Societal Complexity/Political Organization

Societal complexity ranges from small bands of egalitarian hunter-gatherers through egalitarian villagers; to moderate-sized ranked societies, often called chiefdoms; to large, complex societies, often called states, with highly differentiated classes or castes. In political organization, societies range from egalitarian groups that make decisions by consensus to highly structured societies with centralized authority at the top and strong institutions of enforcement, with limited but extant power of commoners to effect changes. Societal complexity and political organization parallel each other sufficiently to be combined here.

Within the sample of three dozen cases where explosive eruptions affected ancient Mexican–Central American cultures, I have found that the most resilient were the egalitarian villagers of the Arenal area, Costa Rica (Sheets 2001, 2008) (figure 2.1). The ten ancient eruptions of Arenal Volcano documented by our project (Sheets 1994) have been given VEI magnitudes of 4 (0.1 to 0.9



2.1. *Map of Mexico and Central America, with archaeological sites and volcanoes indicated. Map by Payson Sheets.*

km³ of tephra) and were thus evaluated as “cataclysmic.” Volcanologists have documented many more eruptions of Arenal Volcano, and a total of thirty-two eruptions are listed by the Smithsonian, beginning 7,000 years ago and ending with the present ongoing eruption (figure 2.2). Some of them were from the adjoining cone of Cerro Chato. Cerro Chato and Arenal share the same magma chamber and for our purposes here can be considered the same source.

Of those thirty-two eruptions, twenty-three occurred during Precolumbian times. Presumably, the reason over half of them were not found in the archaeological record is that they were not of sufficient magnitude to deposit thick tephra layers at distances of 15 to 35 km eastward from the source, and they survived turbation and soil formation processes to preserve to today. The smaller of these eruptions surely caused less social and ecological disruption, but all of them served as reminders of the hazards the volcano posed and must have reinforced traditional knowledge, hazard awareness, disaster experience, and belief.

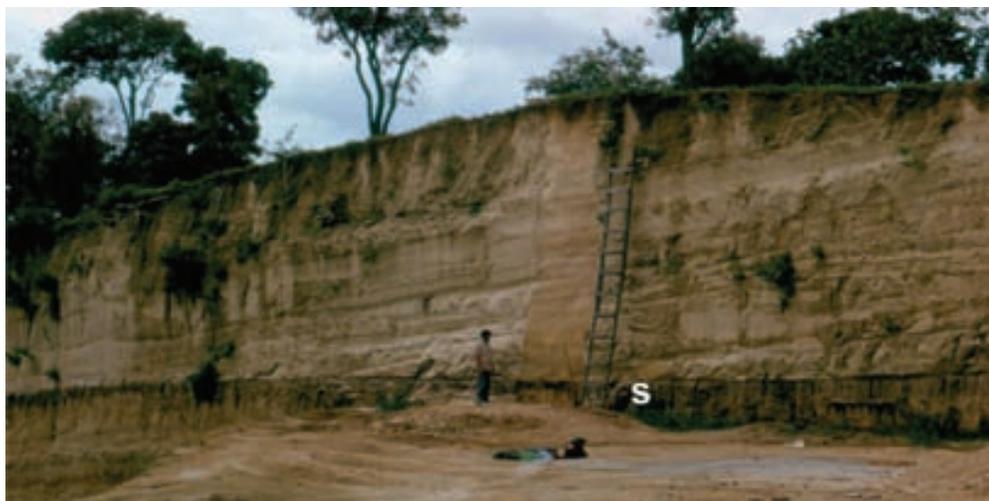
Presumably because Arenal egalitarian decision-making rested at the village or often at the household level, responses to an emergency could be rapid. Given the average periodicity of a big eruption every four centuries (and smaller



2.2. *Stratigraphy of air-fall volcanic ash deposits from Arenal Volcano, and soils developed on them, with Tom Sever for scale. Unit 65 is the soil that existed prior to Arenal erupting. Units 61, 55, 50, 40, and 20 were major eruptions that preserved even at this distance, 23 km away. Other ash falls have been incorporated into soils and are not visible. The thin Unit 10 is barely visible below the “U” and is the remains of the recent 1968 eruption. By Payson Sheets.*

ones more often), maintaining knowledge within an oral tradition would have been well within their capabilities. R. J. Blong (1982) discovered that Papua New Guinea natives passed extraordinarily detailed information about an eruption by oral history for a few centuries. Krajick (2005) documents the Klamath natives of Oregon maintaining generally accurate information about the eruption of Mount Mazama by oral tradition for 7,000 years. I scale the vulnerability of these Arenal villagers to the ten big eruptions of Arenal Volcano, in terms of social and political organization and adaptation, as very low.

Southeast Maya civilization and the early–fifth-century Ilopango eruption in El Salvador (Dull, Southon, and Sheets 2001) occupy the other end of the cultural and volcanological spectrum (figure 2.3). The eruption was so great it received a VEI of 6+ (71 km³ of tephra emitted), evaluated as “paroxysmal,” and thus was one of the greatest Central American eruptions in the past million years. The complex and hierarchical Miraflores branch of Maya civilization never recovered from the eruption (Sheets 2008). Not only was the society highly vulnerable because of hierarchical social stratification and a complex redistributive economy (ibid.), but the sheer magnitude of the eruption and its sialic (acidic, slow-weathering) chemistry stifled recovery in the central to eastern areas affected. While the eruption was devastating to local inhabitants,



2.3. *Ilopango volcanic ash 7 m deep burying a soil marked “S” that also contained a settlement before the eruption. This location, Ciudad Credisa, is ca. 12 km from the source. Mike Foster provides scale. Profile cleaned for recording. The Ilopango eruption was the greatest in Central America in the past 84,000 years. Photo by Payson Sheets.*

the magnitude of physical impact was lessened at more distant areas, such as Kaminaljuyu. However, the cultural effects at those distant locations were considerable, with a dramatic decline in population, abandonment of all ten previously occupied mound complexes, and intrusive Teotihuacan-style architecture (Michels 1979: 296)—which I suggest indicates outsiders taking advantage of local societal weakening. At even more distant localities, such as the Peten of northern Guatemala, a thin dusting of tephra could have been beneficial by adding porosity to tropical lowland soils, adding nutrients, and inhibiting insect pests. Crops in areas of eastern Washington State benefited from thin deposits of volcanic ash from the 1980 Mount Saint Helens eruption adding a mulch layer and killing insect pests by inhibiting their breathing.

Following the Ilopango eruption, natural processes of weathering, soil formation, plant succession, and animal reoccupation ensued. We estimate it took at least a half century for people to reoccupy the Zapotitan Valley, and the Ceren site is one of the earliest known settlements in that reoccupation (Sheets 2004) (figure 2.4). Ceren, a Maya village of commoners, thrived for almost another century until it was entombed by tephra from the Loma Caldera eruption shortly after AD 600. Loma Caldera is only 600 m north of the village, and the eruption occurred when magma moving upward came in contact with water of the Rio Sucio. Two warnings of the eruption occurred, the first of which was an earthquake of about magnitude 4 on the Richter scale, as evidenced by round-bottomed pots remaining on elevated surfaces and minor ground cracking in the eastern part of the site. But in a very tectonically active



2.4. *Structure 1 at the Ceren site, Zapotitan Valley, El Salvador. The valley and most of El Salvador were abandoned because of the fall of the Ilopango tephra ("T") and were reoccupied after a juvenile soil formed. Ceren residents lived and thrived for a few decades before being buried by 5 m of volcanic ash from the nearby Loma Caldera volcanic vent. Photo by Payson Sheets.*

area such as El Salvador, an earthquake of that magnitude would not cause alarm. The second warning would have caught people's attention, though, as this kind of eruption, a phreatomagmatic eruption, begins with a shrieking noise of steam. That sound is probably why we have found nobody in the village killed by the eruption, as everyone likely headed south in an emergency evacuation.

The Loma Caldera eruption was disastrous for Ceren and nearby settlements, but only within a diameter of 2–3 km from the epicenter. Most people living in the valley were not adversely affected by the eruption itself. But based on an estimated 30 km² area that would have had to have been evacuated and estimated population densities at about 200 per km² (Black 1983), around 6,000 people would have had to have resettled in other areas, which must have created strains on an already densely settled landscape. The stratigraphy at Ceren reveals two later explosive eruptions, both of which had greater regional impacts than did Loma Caldera. San Salvador (Boqueron) Volcano erupted (VEI 4) probably in the 900s, depositing a thick pasty wet tephra all across the valley but particularly thick in the southern and eastern portions. Those areas were abandoned for a generation or longer by an estimated 21,000 to 54,000 people (Sheets 2004: 116). The Boqueron eruption was more than an order of magnitude greater in impact than Loma Caldera but vastly smaller than Ilopango.

The most recent (uppermost) tephra layer at Ceren began falling on November 4, 1658, from the Playon eruption (VEI 3). Playon lava and tephra were devastating to Spanish Colonial agriculture, ranching, and indigo growing and processing (Sheets 2004) and to the natives' communal lands. Following the Spanish Conquest in the 1530s, native populations underwent severe depopulation as well as circumscription of their lands. The legal and adaptive hassles suffered by native Pipil Indians who were displaced by the Playon tephra and lava are described in detail by David Browning (1971). Prior to the eruption, the Pipiles utilized the shrinking lands around their town of Nexapa under the principle of communal property, but Spanish colonials operated under the principle of individual landownership. When both groups had their land taken away by the eruption, the Spanish administration discriminated against the Pipiles by denying them any land for almost eighty years but finally granted them legal title to a narrow strip of land up the slope of San Salvador Volcano. Colonial authorities looked after the economic well-being of the displaced Spanish cattle ranchers and indigo farmers promptly after the eruption because they were participants in the national economy and culture, to the detriment of the original occupants. Politically and economically disenfranchised groups are the easiest to ignore at times of stress or emergency by those in positions of authority, an unfortunate but almost universal phenomenon.



2.5. *Panama's Baru Volcano in the background and "no-man's land" in the middle ground. The petroglyphs on the boulder in the foreground mark the boundary of the Barriles chiefdom. Bruce Dahlin is excavating around the periphery of the boulder. The "V" shape at the top of the volcano resulted from the lake breaching the edge of the crater and scouring the side, creating large flood deposits below (not visible in this view). Photo by Payson Sheets.*

Societal Conflict

In the cases I have examined, the effects of the eruption of Volcan Baru in western Panama at about AD 700 best illustrate the effects societal conflict can have on increasing vulnerability to sudden great stress (figure 2.5). I assess this factor as high in this case. The tephra deposited at the Barriles chiefdoms was thin (Linares and Ranere 1980: 291), I am estimating about a half meter originally, weathered and compacted to ca. 10 cm at present. It did not receive a Smithsonian VEI rating, perhaps because it was so small. Deposits comparable to this in the Arenal area, at a good distance from the source, caused temporary abandonment because of damage to flora and fauna. Full cultural recovery with reoccupation at Arenal occurred fairly soon, probably within a few decades at most. In contrast to Arenal, this Baru eruption caused abandonment of the Barriles chiefdoms up and down the Rio Chiriqui and migrations over the continental divide into the humid Caribbean lowlands, requiring fundamental adaptive and cultural changes (Linares and Ranere 1980).

The Barriles society never recovered or reoccupied the area. Rather, a different culture group moved into the area following ecological recovery. Why were the effects on Barriles so severe from such a relatively small eruption? The apparent reason for such a drastic effect is that the chiefdoms were engaged in chronic warfare with each other (Sheets 2001) in a densely packed alluvial valley and thus were severely limited in areas in which to seek refuge. The Baru eruption and the Barrilles chiefdoms provide a case study that illustrates how societal conflict greatly increases vulnerability to even a relatively small unanticipated stress.

Demography and Mobility

The above-mentioned Barriles chiefdoms also highlight another major category of social factors that directly affect a group's susceptibility to geophysical stress. The chiefdoms had demographically filled in the valley along the Rio Chiriqui, exploiting the productive alluvial soils but hemmed in by the weak soils on the surrounding hills (Linares and Ranere 1980). Such dense populations could be sustained under usual conditions but perhaps barely, as population increase may have been pushing the threshold of sustainability. But when Baru erupted in a minor way, the additional stress it caused was sufficient to overload the system. Because of the densely occupied landscape in western Panama, other nearby river valleys offered no refuge, so the impacted chiefdoms were forced to move to a distant and very different environment (*ibid.*). In contrast, the villagers in the sparsely populated Arenal area moved easily to nearby locales beyond the tephra blankets until ecological recovery had occurred. It is possible that Arenal refugees revisited their abandoned villages to walk the prescribed paths to and from their cemeteries, even before they could actually reoccupy the villages themselves (Sheets and Sever 2007). Population densities in Mesoamerica were far greater than those in Panama or Costa Rica, thereby providing few or no under-populated areas to which immigrants could relocate and maintain their cultural traditions. Thus we can see a range of demographically caused vulnerabilities, from very low (Arenal) to high (Barriles) to very high (Mesoamerica).

Economy and Adaptation

Large, explosive volcanic eruptions that impact societies with complex redistributive economies and intensive agricultural systems with high degrees of vulnerability in Mesoamerica provide instructive contrasts to lower Central America. Claus Siebe (2000: 61) dates a "cataclysmic" eruption of Popocatepetl to slightly more than 2,000 years ago and ascribes a VEI of 6, thus approaching the Ilopango eruption in magnitude. His prediction of devastation of pro-



2.6. Cholula, Puebla, Mexico. The talud-tablero architecture of a one-tier platform was buried by a deep lahar from Popocatepetl Volcano. The lahar is labeled in the middle ground. Photo by Payson Sheets.

ductive lands in Puebla has been verified by excavations of the communities around Tetimpa by Patricia Plunket and Gabriela Uruñuela (Evans 2008: 250). Surely many immigrants headed downhill farther east to the big city of Cholula (ibid.: 251) and may have moved into that metropolis, likely at the lowest level of the social strata. The fact that talud-tablero architecture had been practiced for many decades in Tetimpa and then suddenly showed up in Teotihuacan at about the same time as the eruption suggests that many refugees may have fled from Puebla to that great Basin of Mexico city and perhaps introduced talud-tablero architecture there. Many of them may have become local construction workers. But this is curious, as one would not expect refugees to introduce an architectural style into their host settlement that became the religious form henceforth. Following ecological recovery, some farmers apparently traveled back up to their land at Tetimpa for agricultural purposes and then returned to safer locations below. But the later eruption of Popocatepetl, during the ninth century, again devastated the slopes around Tetimpa (Plunket and Uruñuela 1998, 2002). I believe Cholula was devastated by a massive *lahar*, that is, a huge mudflow of largely wet volcanic ash (Sheets 2008: 180), following that second eruption (figure 2.6).

In the middle and Late Formative, prior to Teotihuacan becoming a large city, Cuicuilco was the first community in the Basin of Mexico to develop



2.7. *Cuicuilco, highland central Mexico. The main pyramid is on the left and was partially buried by the lava from Xitle Volcano, on the right. The lava was excavated away from the base of the pyramid, down to the pre-eruption ground surface. Photo by Payson Sheets.*

a civic-ceremonial center with a large pyramid and perhaps 20,000 people (Evans 2008: 210). The eruption of Xitle Volcano (VEI 3) about 2,000 years ago deposited thick layers of tephra and lava, devastating and depopulating the southern basin for centuries (figure 2.7). Soils on top of the lavas have yet to recover, but they provide a scenic landscape for the modern Pedregal subdivision. Teotihuacan's rapid growth must have been, at least in part, a result of absorbing refugees from Cuicuilco and surrounding areas, in addition to those from Puebla. I suspect the refugees from both areas were absorbed into increasingly hierarchical Teotihuacan at the lowest level of society, as agricultural or construction workers or even as slaves.

The eruptions of Popocatepetl (Siebe et al. 1996), which affected Puebla (Tetimpa and Cholula); Xitle, which impacted Cuicuilco; and Ilopango, which affected the Miraflores Maya, impacted societies with complex redistributive economies and intensive agricultural systems. These societies relied on long-distance trade networks, centralized authority with occupational specialists, and markets for exchanges. A highly structured top-down economy is subject to disruption when a significant portion of that system is devastated. The agricultural system of all these societies was maize-based, supplemented by beans and squash, and likely manioc with the Maya. In these cases the economies and agricultural systems were highly developed, stretched somewhere close to their

limits, and therefore I would rate their vulnerabilities to unanticipated sudden stresses as high. In all cases the impacted societies struggled to recover; in two of these cases they never did recover.

Differential Impacts of Disasters: Of Course There Were Losers, but There Were Also Winners

The huge explosive eruption of Ilopango Volcano thoroughly eliminated the early vibrant Miraflores branch of Maya civilization in the southeast highlands in the fifth century AD (Dull, Southon, and Sheets 2001) or possibly the early sixth century, and it never recovered. However, at greater distances where a few centimeters of tephra fell, the benefits of increasing soil porosity—acting as mulch—and stifling of noxious insects would have been beneficial. For instance, the tephra should have had salutary edaphic effects on tropical soils in the Peten of Guatemala, including Tikal.

Tikal and other Maya sites in the tropical lowlands must have been impacted greatly by the worldwide atmospheric event of AD 536, which dramatically lowered temperatures for sixteen years and caused years without summers, crop failures, starvation, and political instabilities in Europe, Africa, and China (Gunn 2000). Hubert Robichaux (2000) argues that the event's dramatic dimming of sunlight and climatic effects must have caused agricultural difficulties for Tikal, leading to its weakening. Tikal showed no evidence of changing its adaptation and continued its reliance on exalted divine kingship. That weakening was exploited by Caracol, in alliance with Calakmul, to conquer Tikal in AD 562. Caracol, only 70 km away, would have been similarly impacted by the AD 536 phenomenon. However, Caracol developed extraordinarily extensive terracing systems that protected soils and maximized rainfall moisture retention, which buffered the effects of the event (Chase and Chase 2000). Also, Caracol was more heterarchical than Tikal, with more widespread distribution of preciosities and dispersed settlements of all social classes, integrated by a system of roadways. Then, 120 years later, Tikal revolted, defeated Caracol, and reestablished its independence.

The collapse of Classic Maya civilization in the ninth century, only in the Southern Maya Lowlands, was caused largely by anthropogenic factors of overpopulation, deforestation, soil damage, and nutritional difficulties (Webster, Freter, and Gonlin 2000), accelerated by drought (Curtis, Hodell, and Brenner 1996). Those who benefited from the collapse lived north and south of the depopulated area and benefited at least in part by seizing control of trade routes that used to go through the Peten. Thus sites in the Maya highlands prospered and even attracted immigrants such as the Pipil from central Mexico (Fowler 1989). The Putun (Chontal) Maya thrived after the Maya collapse, as they already had established trade routes linking central Mexico with coastal

communities around the Yucatan Peninsula from their heartland in the southern Gulf Coast. By about AD 850 they were robustly expanding and took on a major political-economic role in Chichen Itza (Evans 2008: 386–390).

I believe it is important to explore the antecedents of the collapse of the Classic Maya civilization from the different perspectives of humanities and sciences. If we look at Tikal from a humanistic perspective, the apex of artistic achievement occurred during the reign of Jasaw Chan K'awiil I, from AD 682 to 734 (Martin and Grube 2008: 44), when Temples 1 and 2 were constructed, magnificent stela and lintel carving was done, and large twin-pyramid complexes were built every twenty years on a katun cycle. In contrast, a scientist exploring land use, subsistence, diet, population, and other infrastructure factors involved with sustainability would perceive an apex about two centuries earlier. In spite of crossing the threshold of sustainability, the arts and architecture thrived for perhaps a couple of hundred years until the collapse process began in earnest. William Haviland's analyses (1967) of human burials at Tikal revealed the dramatic decline in stature—an indication of poor nutrition—of elites and commoners from the Early to the Late Classic. In fact, the stature of both classes in the Late Classic was inferior to that even of the Preclassic period.

Tikal was not alone in experiencing an apex of humanistic accomplishment well after the threshold of sustainability had been crossed. At Copan the apex of art and architecture was reached under the thirteenth ruler, Waxaklajuun Ubaah K'awiil, AD 695–738 (Martin and Grube 2008: 203). As patron of the arts, more stelae were carved for him than for any other ruler, and they are in magnificently high relief. He began the Hieroglyphic Stairway, as well as numerous pyramids and temples, and built one of the largest and most elaborate ball courts of any in the Maya area during the Classic period. Webster and his colleagues (2000) document the deforestation, soil erosion, and other infrastructure difficulties of the Late Classic. Perhaps the construction of “Rosalila” around AD 550 (Martin and Grube 2008: 198) as the last building to use abundant stucco decoration, requiring huge amounts of firewood, marks the crossing of the threshold of sustainability.

SUMMARY AND CONCLUSIONS

The “ceremonial centers” of complex societies were the loci of centralized political, economic, and religious authority. Where authority was highly centralized and severely impacted or destroyed by explosive volcanism, recovery of that culture did not occur, as exemplified by the Miraflores Maya and Cuicuilco and perhaps the Tetimpa area of Puebla (Plunket and Uruñuela 1998, 2002). Refugees were often absorbed at the lowest social level of receiving societies and had to adapt to their servitude. Where the magnitude of the eruption was

not as great, complex societies have shown impressive resilience in the long run, such as San Andres and surrounding settlements impacted by the ninth- to tenth-century eruption of Boqueron (VEI 4) and the Loma Caldera eruption in the fifth or sixth century (VEI 3), both in El Salvador (Sheets 2002, 2008).

Decentralized egalitarian societies, such as those in the Arenal area, could react particularly rapidly to an emergency. Most decision-making occurred at the household level, presumably in the context of traditional oral knowledge, and evacuations could be effected at a moment's notice. Because only a tiny fraction of the diet came from domesticated foods and regional population densities were very low, refuge areas beyond the devastation could readily support refugees. Repopulating the disaster areas were the descendants of the pre-eruption villagers (Sheets and Sever 2007), and no culture changes could be attributed to any of the eruptions and dislocations. Of course, I am not recommending that worldwide populations change their cultures and adaptations to emulate Arenal villagers, as the time when that could be done was passed many millennia ago. However, there is a clear lesson for present-day complex societies to instill nodes of authority dispersed among populations inhabiting hazardous areas. The thousands of stranded Katrina victims in New Orleans standing still and looking upward at TV cameras in helicopters, passively waiting for government assistance, provide a compelling case. They did not know what to do and waited for top-down authority. Unfortunately for them, the authority was as woefully unprepared as they were.

Along with centralized authority in complex societies go redistributive economies. States are characterized as having high degrees of occupational specialization, and the products made by those specialists require elaborate systems to redistribute them. Such complex systems can function well under usual conditions but are subject to failure under unanticipated stresses. Further development of this topic could be done by modeling network structures with nodes and links, but that is beyond the scope of this chapter.

One of the smallest eruptions in the sample, the eighth-century eruption of Baru in Panama, had surprisingly severe consequences on the Barriles ranked societies (chiefdoms). They had to completely abandon the area, and they never reoccupied it even after full ecological recovery. Rather, they had to migrate over the divide and down into the much more humid tropical rainforest on the Caribbean side and fundamentally change their adaptation, settlement pattern, and other culture elements. I believe this is primarily because the chiefdoms were in a state of chronic warfare and thus made themselves vulnerable to a sudden unanticipated stress, even a very small one when compared with the other eruptions under consideration here.

Earlier in this chapter I gave some thought to encoding hazard and disaster information into myth and religion. That encoding can give societies templates for behavior and can often save lives, such as the traditional peoples

heading out to sea after they felt the large 2004 Sumatra earthquake and the tide receded (Krajick 2005). Many lives were saved through recognition of the early warnings of a tsunami. Similarly, Northwest Coast societies encoded earthquakes and tsunamis into beliefs about battles between the thunderbird and the whale, both powerful deities, and would therefore head to high ground (*ibid.*). Where disasters were not similarly encoded and thus exceeded ideological understandings, explanation fails, and people can severely question their beliefs.

Another aspect of the relationships between disasters and religion is under-theorized and under-researched. Today we are comfortable explaining the origins of disasters in terms of plate tectonics, evacuating magma chambers, releases of stresses along fault planes, or other geophysical or climatic factors. However, cultures around the world consistently ascribed the sources of disasters to the supernatural domain prior to the development of Western empirical science in the past few centuries. Commonly, the elites in non-Western societies were primarily responsible for interceding between their people and the deities. Under usual conditions the elites could demonstrate their successes in communicating with the supernatural domain, thus strengthening their religious authority. But a truly great disaster must call into question religious belief as well as confidence in elite religious efficacy. Archaeologists would do well to explore the relationship between mega-disasters and significant change in religious belief and practice. Long-term worldwide suffering caused by an atmospheric phenomenon—probably a high altitude dust layer—in AD 536 was documented in many areas (Gunn 2000), such as about 75 percent of the people in a northern Chinese kingdom dying (Houston 2000). Margaret Houston (*ibid.*) suggests that the 536 impact could have contributed to the collapse of the Wei Empire and the loss of the mandate of heaven and facilitated the shift toward Buddhism. A disaster of this magnitude could have undermined confidence in religion, thus facilitating the emergence of a new religious order.

The AD 536 phenomenon was recorded in Europe and the Near East. In Italy the Roman senator Cassiodorus wrote that for a year the sun was so dimmed it cast no shadow at noon, and crops were not maturing because of perpetual frost and drought, causing famine (Young 2000: 36). The Byzantine historian Procopius reported similar conditions at Carthage, North Africa, as did historians in Mesopotamia and Constantinople (*ibid.*: 37). Bailey Young argues that the event contributed to the end of classical civilizations and the beginning of the Middle Ages. Although the event was not recorded as precisely in Britain, Elizabeth Jones (2000) believes it caused political chaos and spiritual disillusionment and perhaps contributed to epidemics in England, Europe, and the Near East.

The prophet Muhammad lived and developed Islam a few decades later than the phenomenon, and conversion spread astoundingly rapidly. The inex-

plicable climatic stresses and the disenchantment with extant belief systems may have facilitated that spread. Considerable research needs to be done before this could be considered compellingly demonstrated.

Demographic factors, of course, are major components in people making themselves less or more vulnerable to disasters. The single most important element is the spectacular population explosion of recent centuries, so it is not surprising that the tolls in deaths and destruction increase annually. Obviously needed are population control and zoning to restrict habitation in known hazardous areas. Within this study sample there is only one area where population did not increase dramatically to near carrying capacity, and that was the Arenal area. In spite of carefully examining the cultural inventory (artifacts, features, architecture, subsistence, economy, political organization, and pattern of settlement) for any evidence of volcanically induced change, we could find none. And that was not because of a paucity of eruptions. In our archaeological-volcanological research we documented ten large eruptions (VEI 4) in almost 400 years, and the Smithsonian website documents evidence of many other eruptions over a longer time period. Arenal peoples must have generated considerable traditional knowledge about eruptions, societal responses, and reoccupations, in spite of—or more likely because of—their frequency.

Are there lessons from the past that could inform us today? Native peoples in so many areas of the world, over centuries or millennia, developed architecture that was appropriate to the perceived hazards and experienced disasters. Pole-and-thatch structures or those of bajareque (wattle and daub) withstand strong winds and major earthquakes. Such bajareque structures can be quite sizable and ample, with two stories and easily 2,000 to 3,000 square feet (186–279 m²) in floor area. Even when the stress leads to strain that cannot be withstood and the walls shed the mudding, it causes little harm to inhabitants. However, with modernization, traditional architecture acquires an aura of backwardness, and people shift to unreinforced adobe or cinderblock architecture. Under usual conditions it survives and looks fine, but when it fails under earthquake stress it causes great injury and death. The reintroduction of traditional architecture under the guise of a new label with mystique, such as “Ceren architecture,” can provide protection. Such reintroduction into El Salvador has begun.

We cannot encourage more than 6 billion people to revert to hunting and gathering or an Arenal-style sedentism and adaptation so they can maintain mobility in the face of disaster. But with the perspective furnished by archaeology, it appears to me that some of the great tragedies of the human experience in the past millennium are unfettered population explosion, loss of traditional environmental knowledge, and authorities' irresponsibility. Packing more and more people onto the earth's surface inevitably increases the tolls of death and destruction when disasters occur, in part by reducing the available options for

successful mitigation. The need for birth control is patently obvious but tragically ignored. Given today's dense populations, at a minimum land-use planning to decrease residence in known hazardous areas needs to become policy throughout the world, and it needs to be done in concert with family planning so future generations are not squeezed back into those dangerous zones. Dispersed nodes of experience and authority for decision-making need to be created in hierarchically organized societies. Thus when the centralized authority is either incapacitated or unable to assist, local groups can take over in disaster assistance and recovery.

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UNDERSTANDING HAZARDS, MITIGATING IMPACTS, AVOIDING DISASTERS**Statement for Policy Makers and the Disaster Management Community**

Hazards from volcanic eruptions, especially explosive eruptions, abound in Mexico and in every Central American country. Explosive eruptions can be damaging to vegetation, animals, and people, as the fine volcanic ash falling from the air can cause significant damage and, in large amounts, death.

Volcanologists can detect the early signs that a volcano is building toward an eruption with a moderate degree of accuracy. They can perceive when a warning needs to be issued and thus when people with their animals and prized possessions need to evacuate the hazard zone. They pay particular attention to earthquakes, which indicate that magma sources are moving close to the surface as well as an increase in sulfur gases being emitted. Warnings should be initiated by well-trained experts because a premature or inaccurate warning that leads to an unnecessary evacuation makes evacuees less likely to heed the next order to evacuate.

I suggest that planning and educational programs in schools and for adults be initiated in known hazardous areas so people know what to do in an emergency. Local nodes of decision-making need to be established so people are not waiting for information from the central government in the country's capital.

For example, Costa Rica's Arenal Volcano has been very active in ancient, historic, and recent times and continues to emit lava, volcanic ash, and sulfur gas today. Pyroclastic flows (huge clouds of volcanic ash, gases that kill everything in their paths because they have temperatures in the range of hundreds of degrees Celsius) have rushed down the north side of the volcano in recent decades. Against volcanologists' recommendations, resort lodges with hot spring pools have been built in those areas, and the only suggestion that acknowledges risk is for everyone to park their cars pointing outward toward the highway. This proposal is not smart, for if everyone rushed for their cars they would create a traffic jam, and the death rate would be extremely high. Rather, if people were told to simply climb the sides of the valley, most of them could reach relative safety within a few minutes.

In this chapter volcanic eruptions that have been encountered in archaeological sites are documented in Costa Rica and other countries. Because of the nature of preservation, only the largest eruptions, those that caused the deepest burial and greatest consequences for both nature and people, are found. Our work around Arenal Volcano found ten large eruptions during the past 4,000 years, an average of one per 400 years. It would be a mistake to think that figure is an accurate representation of how often eruptions occur. I suggest that anyone interested in Arenal's eruptions and thus risks to nearby

people today should consult the easily accessed website of the Smithsonian Institution's Global Volcanism Program at <http://www.volcano.si.edu/world>, where they can find a more complete record of eruptions for individual volcanoes as well as eruptions by region. The more complete eruptive history of Arenal documents twenty-eight separate eruptions, almost three times as many as we found doing archaeological work.

As earthquakes routinely accompany volcanic eruptions, a note on earthquake hazards and mitigations is appropriate here. Millennia of experience with earthquakes by natives living in Mexico and Central America have led to the development of an architecture appropriate to seismically active areas. Called "wattle and daub," or "bajareque" in Central America, this architecture consists of a series of vertical poles firmly anchored into buildings' foundations—creating reinforcement for the walls—and tied tightly to the roof beams. The lower portions of walls are mudded, plastered, or both to provide privacy and solidity but not to the point that the structure lacks flexibility. Homes can be substantial, of two stories, and large. Any structure has limits, though, and if an extremely strong earthquake causes damage, the wall fails in small pieces that at most cause bruising and minor cuts. In contrast, the Spanish introduced unreinforced adobe brick architecture, and when a wall fails, it often kills people. Unfortunately, bajareque architecture gained a sense of being backward, so we renamed it "Ceren architecture" because the importance of that site to the Salvadoran people gave it prestige. People are now adopting Ceren architecture in the area.