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VOLCANISM AND MESOAMERICAN ARCHAEOLOGY

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Abstract

Drought and drought-induced famine are recurring phenomena in Mesoamerica that have devastated populations in the region repeatedly during the past two millennia. Although it is counterintuitive to conceive of the idea that volcanic eruptions anywhere in the world might affect the lives of people in Mesoamerica, we examine the reports of drought and famine during the period A.D. 1440 to 1840 and compare them with known, large volcanic eruptions. We then apply non-parametric statistical techniques to determine whether the coincidences seen between worldwide volcanic eruptions and Mesoamerican drought within the following two years were due to random chance or whether there was a direct, mathematically verifiable correlation. We find a direct correlation to a probability of 56 in 100 million. We conclude that due to its unique geographical position, Mesoamerica was repeatedly devastated by drought and subsequent famine between 1440 and 1840 due to the indirect climatic effects of large volcanic eruptions that could be located anywhere in the world.

Who would believe that the eruption of a volcano in Indonesia would cause death and devastation in Mesoamerica? It is counterintuitive to expect that volcanic eruptions around the world would have specific, measurable effects in one confined and limited part of the Earth such as Mesoamerica. It seems beyond the limits of what would be reasonable, but look at the evidence of what happened between A.D. 1440 and 1840.

Mesoamerica occupies a special geographic location that may make it particularly vulnerable to the worldwide climatic aberrations induced by large volcanic eruptions. These eruptions can occur anywhere in the world and need not be limited to Mesoamerica itself. The effects felt in Mesoamerica are not the primary effects of erupting lava, ash, or hot poisonous gases; rather, they are secondary climatic effects caused mainly by the injection of large quantities of sulfur into the stratosphere by large, explosive volcanic eruptions.

The meteorological effects are the result of volcanic sulfur's effect on the movement and position of the North Atlantic High in the North Atlantic Ocean. To better how this happens understand, we need to detour for a moment into the workings of weather in the North Atlantic weather system.

Air at the equator is warmed by sunlight and rises until it reaches the tropopause, at which point it encounters warmer air above it and can rise no farther. As it rises, the air cools, and the water vapor it contains condenses and precipitates as rainfall. Once the air reaches the tropopause, it moves toward the poles in each hemisphere and gradually sinks toward the surface at about 30° latitude. The sinking air is very dry, having lost its water vapor on the way up, and the area under the descending air is generally arid. Most of the world's deserts are located under the sinking air (Ahrens 1988:321).

This organized circulation regime is known as the Hadley cell, named for George Hadley, the eighteenth-century English meteorologist who first proposed it. Due to the dynamics of the Earth's circulation, the flow aloft is actually to the northeast, and the return flow at the surface is toward the southwest. The Hadley circulation is generally best developed over water, where there are no surface features to interfere with the flow. In the Atlantic, then, the descending branch of the Hadley-cell circulation is identified by the North Atlantic High, a cell of high pressure found in the Atlantic Ocean and also known as the Bermuda High or the Azores High (although it is rarely located directly over either Bermuda or the Azores) (Nieuwolt 1977:43).

The Hadley cell is a thermodynamic convection cell driven by solar radiation. Although some theorists believe that the boundary between the Hadley cell and the Ferrell cell, a secondary cell that lies poleward between 30° and 60°, is relatively fixed by the physics of the Earth's rotation and atmospheric dynamics, others have pointed out that the location of the boundary seems to have been displaced toward the equator during past glacial maxima (Haigh 1996:983; Sawyer 1966:222).

Research done by Richardson Gill (1994, 2000) on the position of the North Atlantic High during the twentieth century shows that it generally moves in a channel from the southwest to the northeast, as would be expected if the Hadley cell were expanding and contracting due to changes in incoming solar radiation. As the North Atlantic High moves to the southwest, closer to Mesoamerica, it affects the weather in the region. As it moves to the northeast, toward Europe, its effects are felt more in Europe and less in Mesoamerica (Gill 1994, 2000:138–143).

Many meteorologists have proposed that rainfall in Mesoamerica and the Caribbean is directly linked to the position of the

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North Atlantic High. A position far to the southwest, then, is conducive to drought in Mesoamerica, whereas a position far to the northeast is propitious for ample rainfall (Hewitson and Crane 1992:1837).

THE SHIFTING FOCUS OF DROUGHT

Drought is not a uniform, homogeneous weather pattern. Maps of drought that have been prepared in recent years based on solid meteorological data show that the areal extent of drought can be almost random, with areas of moderate dryness in the middle of broader areas of severe drought. To say, for example, that Texas suffered a devastating drought during the 1950s, which it certainly did, does not mean that every point in Texas was equally affected. For some places the drought was brutal, whereas for others it was merely unpleasant. Some areas of moderate drought were completely surrounded by areas of severe devastation.

During the late 1980s and early 1990s, San Antonio and South Texas suffered drought while Houston and southeastern Texas endured very heavy rainfall. Over the past century, recurring regional drought has afflicted the Great Plains, the Southwest, and northern Mexico repeatedly. In the 1930s, the focus of the most intense drought was North Texas, Oklahoma, and parts of Kansas; in the 1950s, it was central and East Texas; in the 1990s, the worst-hit areas were Chihuahua, Coahuila, and West Texas, although the total area affected by drought was much more extensive in each case.

The manifestation of drought in Mesoamerica appears to be similar. One time the focus of drought might be the Valley of Mexico, the next time, Yucatan, and perhaps the next, Tabasco or Veracruz. At times, especially for Yucatan and Mexico City, there are Colonial historical records. At other times, however, for less populated regions of the country, the Colonial records may not exist. As we move closer to the present, of course, the reliability of the records increases.

A ROLE FOR VOLCANOES

How can volcanoes play a role? For a volcano to be able to affect worldwide weather, it must meet certain conditions. First, the eruption must be explosive enough to inject eruption products into the stratosphere, the part of the atmosphere above the troposphere. The stratosphere is the region of the upper atmosphere lying above the weather of the lower atmosphere. Aerosols and gases injected into it, therefore, tend to remain there for extended periods of time, up to several years. The height of the eruption column is a critical factor (Goodman 1984:25).

Second, the explosiveness of a volcano generally depends on the quantity of silica contained in its magma, although the presence of water and other factors can also effect explosivity. Unfortunately, as the percentage of silica increases, the ability of the magma to incorporate sulfur decreases. A delicate balance must be struck between enough silica to be explosive and not too much so as to decrease the sulfur content of the erupted magma (Sigurdsson 1990:280).

Third, therefore, the magma must be very sulfurous. Many explosive eruptions, such as that of Mt. St. Helens in 1980, do not contain large quantities of sulfur and, as a result, have little climatic effect. Other, less explosive eruptions that are highly sulfurous can have much greater climatic impact.

Fourth, the location of the volcano can be important with regard to how severely it will affect Mesoamerica. A significant percentage of those volcanoes located between 20°N and 20°S can be related to severe drought in Mesoamerica, as will be shown. In fact, all of the droughts in Yucatan severe enough to have caused famine between 1440 and 1840 followed large, tropical eruptions.

Extratropical eruptions can also be related to drought in Mesoamerica although they do not appear to have been as responsible for famine. It is reasonable to conclude, however, that particularly large, climatically effective extratropical eruptions would have had worldwide effects. The possibility that they may also be linked to events in Mesoamerica seems reasonable.

Other factors surely play a role, as well, such as the direction of the blast, whether it is vertical or horizontal, and the time of year in which it occurs. An eruption whose major impact is felt during the Mesoamerican dry season may not affect people as much as would an eruption whose major impact is felt during the wet season.

When sulfur is present in the magma, the largest percentage of it is erupted as SO_2, or sulfur dioxide. Driven by the energy of solar radiation, it combines with water to form sulfuric acid, H_2SO_4, which settles into a layer of the lower stratosphere located at about 20 km (12.4 mi or 65,000 ft) known as the Junge layer, named for C. E. Junge, who discovered it with his colleagues in 1961. It takes about twelve months to convert the sulfur dioxide to sulfuric acid. Once the conversion is complete, atmospheric removal processes begin to eliminate the sulfur from the atmosphere. For large eruptions, sulfur can remain in the Junge layer for three to four years. By contrast, the solid tephra particles or ash decrease to virtually undetectable levels within three to four months. According to one study, the mass of sulfur compounds erupted during the 1970s from Fuego in Guatemala were 10 to 100 times greater than the mass of volcanic dust (Goodman 1994:10; Kondratyev 1988:22).

While the sulfur aerosols are in the Junge layer they are very effective at absorbing and reflecting sunlight. A principal climatic result of volcanic eruptions, therefore, is a cooling of the troposphere, the atmosphere below the Junge layer, and a warming of the stratosphere containing the sulfur aerosols. The effect is to deprive the Hadley cell circulation of the incoming energy that drives it. We propose that, as a result of the decreased energy available, the Hadley cell contracts to the southwest, bringing the North Atlantic High closer to Mesoamerica and affecting rainfall in the region (Kondratyev and Galindo 1997:319).

After El Chichón's 1982 eruption, the aerosol cloud was restricted to the tropics for nine months before it began to spread to the rest of the world, a very unexpected result. It would seem, then, that the primary effect would have been in the tropics, the principal area of Hadley cell circulation. Furthermore, El Chichón's aerosol cloud appears to have spread uniformly throughout the tropics, which would explain why eruptions in any part of the world between 20°N and 20°S seem to affect weather in Mesoamerica. A large tropical volcano would produce an aerosol cloud that spreads throughout the tropics, blocking incoming solar radiation and affecting the Hadley cell circulation. A contraction of the Hadley cell circulation could move the North Atlantic High to the southwest, bringing drought conditions to Mesoamerica (Rampino and Self 1984:54).

It is Mesoamerica's unique position at the southwestern corner of the Atlantic weather area and the North Atlantic High channel,

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then, that makes it vulnerable to volcano-induced changes in circulation and susceptible to volcano-induced drought.

The initial position of the North Atlantic High at the time of the eruption could be very important. If the High is already located far to the southwest at the time of the eruption, a farther movement caused by an eruption could have a much greater and more devastating effect on Mesoamerica than if the High were located initially far to the northeast. The High tends to be located to the southwest during periods of hemispheric cold and to the northeast during hemispheric warmth. We will look at eruptions that occurred between A.D. 1440 and 1840, roughly the time known as the Little Ice Age, and see that there was a remarkable correlation between large volcanic eruptions and drought in Mesoamerica. During the warm twentieth century, large volcanic eruptions do not appear to have had the same effect they did during the Little Ice Age—except during the cold first decade.

How, then, can we try to get a handle on what distinguishes a large, climatically effective eruption from a smaller, less effective one? Unfortunately, there is no precise way to study past eruptions and determine their climatic impact. The best we can do is measure the quantity of erupted magma. The Volcanic Explosivity Index (VEI) is a measure of the size of eruptions according to the volume of material they ejected. It does not tell us anything about the eruption's mechanics, the direction of the blast, the height of the eruption column, the quantity of sulfur, whether the eruption was explosive or effusive, the time of year, or any other factor that might be important in determining the climatic effects of the eruption. But it is all we have, so we might as well use it (Handler 1989:234).

COLONIAL ERUPTIONS AND DROUGHT

In examining volcanic eruptions during the years A.D. 1440 to 1840 against droughts known from historical records for the same period, there appears to be a breaking point between VEI magnitude 3 eruptions (10^8 m^3 of erupted material) and magnitude 4 eruptions (10^9 m^3). There are so many magnitude 3 eruptions that the percentage of correlation with Mesoamerican drought is small. For eruptions at magnitude 4 and higher, however, the percentage of correlation is quite noticeable. It is important to emphasize that not all eruptions at magnitude 4 and higher can be correlated with Mesoamerican drought, nor can all Mesoamerican drought be correlated with large eruptions, but a significant percentage of each can be tied to the other. Clearly, there is a relationship between Mesoamerican drought and large volcanic eruptions, as we will show.

We will look first at the historical record from Yucatan. During the period 1440–1840—-roughly, the Colonial period—24 famines were reported in historical documents such as Spanish colonial reports, native chronicles, or reports by travelers. Of the 24 famines, 13 were attributed to drought; 11 were attributed to other causes, such as locusts, hurricanes, excessive rainfall, or plant disease, or simply were not attributed to anything. Of the 13 famines attributed to drought, 11, or 85%, followed tropical volcanic eruptions at magnitude 4 or higher within two years. Of the 11 famines attributed to other causes, none followed a major tropical eruption within two years. This is a startling correlation.

In examining the droughts serious enough to have caused historically reported famine in Yucatan and the Valley of Mexico during 1440 to 1840, we found that 85% of the Yucatecan drought/famines and 87% of the Valley of Mexico drought/famines followed large eruptions within two years (see Table 1).

Table 1. Historically reported Mesoamerican droughts between A.D. 1440 and 1840 severe enough to have caused famine tabulated by region and by the number that followed large volcanic eruptions within two years

Area	Drought/Famines	Following Eruptions	%
Yucatan	13	11	85
Valley of Mexico	15	13	87

If we turn to the drought records from the Valley of Mexico, compiled in a study prepared for the Secretaría de Agricultura y Recursos Hidráulicos (Department of Agriculture and Hydraulic Resources) by Guadalupe Castorena and colleagues, about 30 drought episodes were reported during the years 1440–1840 that lasted three months or more (Table 2). Some, of course, lasted for years. Of the 30 droughts, 18, or 60%, followed tropical eruptions at magnitude 4 and higher within two years. Fifteen droughts were severe enough to have caused famine, and 11 of them, or 87%, followed large eruptions within two years. The fact that most drought/famines followed large eruptions at tropical volcanoes may show that tropical volcanoes are more deadly than those farther to the north or south (Castorena et al. 1980:76–87).

If we turn our perspective around and look at the tropical volcanic eruptions at magnitude 4 and higher between 1440 and 1840, as listed in the 1994 edition of *Volcanoes of the World*, the compilation of the Smithsonian Global Volcanism Project, we find 45 eruptions are known from that time period, as listed in Table 3. Of those, 32, or 71%, were followed within two years by known drought in some part of Mesoamerica, one time focused in Yucatan, the next time, the Valley of Mexico, or the Bajío. If we eliminate the matches based on more tentative radiocarbon dating, we are left with 41 eruptions, 28, or 68%, of which were followed by drought in Mesoamerica within two years (Simkin and Siebert 1994).

Further, *Volcanoes of the World* lists 689 volcanoes that are believed to have erupted over the past 10,000 years or so, during

Table 2. Reported Mesoamerican droughts occurring between 1440 and 1840 tabulated by region and number that follow large volcanic eruptions within two years

Area	Total Droughts[a]	Following Eruptions	%
Valley of Mexico	45	23	51
Yucatan	19	10	53
Guatemala	19	7	37
Bajío	15	3	20
Coahuila	6	1	17

[a]Droughts in the Bajío are from the states of Michoacan and Guanajuato. Note that the percentage of droughts correlated with volcanic eruptions drops off as one moves away from Yucatan and the Valley of Mexico. Not all of the drought records from each region cover the entire period. The length of the reported droughts range from one month to years.

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Table 3. A listing of large, tropical eruptions (magnitude 4 and higher on the VEI) between 1440 and 1840, followed within two years by drought in Mesoamerica, as reported by historical sources

Year	Volcano	Year	Drought Location and Event
1446[b]	Arenal, Costa Rica[4]	1446–1448	V Mexico drought
1450	Kelut, Java, Indonesia[3↑]	1450–1454	V Mexico drought, cold
1451	Kelut, Java, Indonesia[3↑]	1453	famine of 1 Rabbit
1452	Kuwae, Vanuatu[6]	1453–1454	Yucatecan drought, famine, cold
1459[a]	unknown volcano	1460/1464[c]	V Mexico drought
1460[a]	unknown volcano		
1486[d]	Billy Mitchell, Bougainville, SW Pacific[6]	1502	V Mexico drought
1534	Cotopaxi, Ecuador[4]	1535–1538	V Mexico drought, dearth
		1535–1541	Yucatecan drought, famine
1570	unknown volcano	1571	Yucatecan drought, famine
1580	Galeras, Colombia[4]	1579–1581	V Mexico drought, dearth
1581	Fuego, Guatemala[4?]		
1585	Colima, Mexico[4]	1587	V Mexico drought, famine
1586	Kelut, Java, Indonesia[5?]		
1593	Raung, Java, Indonesia[5?]	1594	V Mexico drought, famine
1595	Ruiz, Colombia[4]	1597–1598	V Mexico drought, frosts
1600	Huaynaputina, Peru[6?]		
1605	Momotombo, Nicaragua[4]		
1606	Colima, Mexico[4]		
1622	Colima, Mexico[4]	1623	Guatemalan drought
		1624	V Mexico drought, famine
1638	Raung, Java, Indonesia[4?]	1639	V Mexico drought
1640[e]	Long Island, northeast of New Guinea[6]	1641–1642	V Mexico drought, famine
1641	Kelut, Java, Indonesia[4?]		
	Awu, Sangihe, Indonesia[5?]		
1646	Makian, Indonesia[4?]	1648	Yucatecan drought, famine
1660	Guagua Pichincha, Ecuador[4]	1660	Yucatecan drought, famine
	Teon, Banda Sea, Indonesia[4?]	1661–1663	V Mexico drought, famine
		1661	Bajío drought
1673	Gamkonora, Halmahera, Indonesia[5?]		
1680	Tongkoko, Sulawesi, Indonesia[5?]		
1693	Serua, Indonesia[4?]	1693–1696	Michoacan drought
		1694	Guatemalan drought
		1695	V Mexico drought, dearth
1716	Taal, Luzon, Philippines[4?]		
1717	Fuego, Guatemala[4?]		
1720[f]	Cerro Bravo, Colombia[4]	1720	V Mexico drought
		1720	Guatemalan drought
1737	Fuego, Guatemala[4?]	1736–1739	V Mexico agricultural crisis, famine[g]
		1739	Guatemalan drought
		1739	Bajío drought
1744	Cotopaxi, Ecuador[4]	1746–1747	Bajío drought
		1746–1748	Guatemalan drought
1754	Taal, Luzon, Philippines[4]	1755	V Mexico drought
1759	Jorullo, Mexico[4]	1761–1762	V Mexico agricultural crisis, famine[h]
1760	Makian, Indonesia[4?]		
1764	Jorullo, Mexico[4]	1764–1765	V Mexico drought
		1765	Guatemalan drought
		1765–1768	Yucatecan drought, famine[g]
1768	Cotopaxi, Ecuador[4]	1768–1773	V Mexico drought, famine[i]
		1769–1773	Michoacan drought
		1769–1774	Yucatecan drought, famine
1793	Volcán de San Martín, Mexico[4]	1793	V Mexico drought
		1794–1795	Yucatecan drought, famine
1809[a]	unknown volcano	1808–1811	V Mexico drought, frosts
		1809–1810	Yucatecan drought
		1809–1810	All Mexico drought
		1810	Guatemalan drought
1812	Awu, Indonesia[4?]	1813	V Mexico agricultural crisis, famine[i]
	Soufrière, St. Vincent, West Indies[4]		

continued

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Table 3. *Continued*

Year	Volcano	Year	Drought Location and Event
1814	Mayon, Philippines[4]	1816	Coahuiltecan drought
1815	Tambora, Indonesia[7]	1817	Yucatecan drought, famine
1817	Raung, Java, Indonesia[4?]	1818	V Mexico drought
1818	Colima, Mexico[4]		
1822	Galunggung, Java, Indonesia[5]	1822–1823	Yucatecan drought, famine
		1822	Guatemalan drought
1826	Kelut, Indonesia[4?]		
1831	Babuyan Claro, Philippines[4?]	1831	V Mexico drought
1835	Cosegüina, Nicaragua[5]	1834–1835	Yucatecan drought, famine[j]
		1836	V Mexico drought
		1836	Veracruz drought

Note: Not all series of historical records cover the entire 400-year period. Years in italics are radiocarbon dates, as noted later, and therefore only tentative matches to droughts. The superscript beside the volcano's name shows the magnitude on the VEI: 4 is large, 5 very large, 6 huge, and 7 colossal; ? indicates uncertainty in the original magnitude attribution; ↑ shows an explosive eruption; V Mexico = Valley of Mexico. Sources for droughts: Castorena et al. 1980; Claxton 1986; Cook and Borah 1974; Craine and Reindorp 1979; Farriss 1984:61–62; Gill 2000:306–307; Landa 1975 [1566]; Molina Hübbe 1941; Stephens 1963 [1843]. Sources for volcanic eruptions: Bradley and Jones 1992:612–613; Dai et al. 1991:17, 361; Simkin and Siebert 1994:184–210.

[a]Ice core date ± 2 years.
[b]Radiocarbon date 1441–1467.
[c]Reported as 1460 and/or 1464.
[d]Radiocarbon date 1473–1516.
[e]Radiocarbon date 1635–1645.
[f]Tephrochronology date ± 150 years.
[g]The mortality reported during this famine was 50%.
[h]The mortality reported during this famine was 25%.
[i]The mortality reported during this famine was 10–15%.
[j]The drought intensified drastically (*desarollóse duramente*) in 1835.

the Holocene era, that have not yet been studied and whose eruption histories have not yet been determined. Additional volcanic eruptions may remain to be determined that can be tied to drought in Mesoamerica (Simkin and Siebert 1994).

The frequency with which drought follows large volcanic eruptions is far greater than can be expected from random chance. We will look closely at the statistics shortly.

Multiple Eruptions

We posit that large volcanic eruptions contaminate the stratosphere with eruption products, principally in the form of sulfur aerosols, which absorb or reflect incoming solar radiation, resulting in weather changes on a global scale and drought in Mesoamerica. Because of the inadequate nature of the Volcanic Explosivity Index for our purposes, it is difficult to tell what the exact nature of each eruption was and whether it in fact changed the weather. Thus, single eruptions in single years may or may not have been the kind of volcanoes needed to affect the worldwide climate.

Years in which two or more volcanoes erupted, however, would increase the chances of getting enough debris into the stratosphere to have a real climatic effect. One would expect, then, that if there were a genuine tie between sulfurous volcanic activity and drought in Mesoamerica, the correlation between years of multiple eruptions and Mesoamerican drought would be greater.

We found 13 years in which two or more volcanic eruptions had been definitely confirmed. In other words, there is no uncertainty in the dates. We know for a fact the eruptions occurred when they did. Every one of those cases, 100%, was followed by drought in Mesoamerica. There are two additional years in which the second volcano was of uncertain date and, in one case, of uncertain magnitude. Those were not followed by drought in Mesoamerica, and one can conclude that the tentatively assigned eruption dates are off the mark. It seems clear, then, that getting enough volcanic aerosols into the stratosphere will have serious consequences for Mesoamerica.

One instance of multiple volcanic eruptions for which we have recorded meteorologic observations occurred in the twentieth century: The year 1902 was really terrible for natural disasters in Mesoamerica and the Caribbean. A tidal wave hit the coast of El Salvador; there were numerous serious earthquakes, including two to which C. F. Richter assigned a magnitude of 8.3, in which thousands of people were killed; and there were five volcanic eruptions, three of which were magnitude 4 or greater. Following the eruptions, the years 1902–1904 saw severe drought in Yucatan. In 1903, the summer rains failed, and the total rainfall for the year was only 43% of the normal amount. As we can see, the one episode of multiple eruptions followed by drought for which we have good meteorological records confirms the pattern of the 13 years of multiple eruptions from the Colonial period (Gill 2000:160–164, 223–226).

STATISTICAL EXPLANATION OF DROUGHT FOLLOWING VOLCANIC ACTIVITY

The most serious difficulty in analyzing the relationship between eruptions and drought and famine during the Colonial period is

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that so many eruptions and so many droughts have been reported that, when looking at the data, it would initially appear as if random correlations must be occurring throughout the years. The credibility of our study, therefore, depends on a rigorous statistical analysis of the data, clearly separating random chance from true correlation, which we will now do.

The following tables of worldwide volcanic activity and drought in Mesoamerica were analyzed using time-honored statistical techniques. The data were made binary, under several different scenarios, to explore many questions pertinent to the concurrence of volcanic activity and drought in Mesoamerica. For each year, we created the indicator variable VIND of 1 if a major volcanic eruption occurred and 0 if otherwise. We also created the indicator variable DIND, which was coded as 1 if a drought had occurred in Mesoamerica in that year and 0 if otherwise.

Contingency Tables

Our primary objective was to examine whether Mesoamerican drought and major volcanic eruptions occurred independently of each other or whether their occurrences were *significantly* correlated. Specifically, we wanted to examine the presence of drought following a major volcanic eruption for a period of two years. To investigate this question, we used 2×2 contingency tables to test for independence between major volcanic activity and Mesoamerican drought. The null hypothesis contained herein is that the phenomena are independent against the stated alternative that they are dependent (or correlated).

The first hypothesis we wanted to test was the occurrence of drought in the same year of a volcanic eruption. In Table 4, we tallied the number of years in which drought and major volcanic eruptions occurred within the same year. In the 401 years covered in this study, spanning A.D. 1440 to 1840, there were:

- 60 years in which both drought and major volcanic activity occurred;
- 56 years in which major eruptions occurred but drought did not;
- 89 years in which no major eruption occurred but drought did occur;
- 196 years in which neither eruptions nor drought occurred.

We examined these data using a chi-square test for independence. If major volcanic activity and Mesoamerican drought in the same year are independent events, then the italicized numbers in Table 4 are the values that we would expect for each contingency. The empirically observed numbers (bold) and the expected numbers (italics) are then compared through a chi-square test statistic, which gives a value of 14.83.

For a chi-square test statistic to demonstrate statistical significance, which allows us to reject the null hypothesis at the 5% level, the result should be greater than the threshold of 3.841, which our results clearly are. We are therefore able to reject the null hypothesis—that drought is not dependent on volcanic eruptions—in favor of the alternative that drought is indeed dependent on volcanic eruptions, at least during the time period studied.

The chi-square test statistic measures the difference between the observed and the expected phenomena for each of the four cells in the table. The drought and eruption contingency made the largest contribution to the test statistic, whereas the no-drought and no-eruption contingency made the smallest contribution. The concurrence of these two variables produces the finding of significance.

The probability, known as the *p* value, that the observed numbers would occur due to chance alone is .000118, or 118 in 1 million, assuming that the phenomena are acting independently. This probability calculation is based on the chi-square distribution. We are once again led to the conclusion that the correlation we see is not due to random chance.

The second hypothesis we tested was the occurrence of drought in the year following volcanic activity. In Table 5, we list the number of years in which there were major volcanic eruptions followed by drought in the next year. In the 400 years spanning A.D. 1440 to 1839, there were:

- 63 years in which drought occurred in the year after major volcanic activity;
- 53 years in which drought did not occur in the year following a volcanic eruption;
- 86 years in which no major eruption occurred and drought did occur in the following year; and
- 198 years in which neither eruptions nor drought occurred in the following year.

We examined these data using a chi-square test for independence, as well. If major volcanic activity and Mesoamerican drought in the following year are independent events, then the italicized numbers in Table 5 are the values that we would expect for each contingency. The observed and expected numbers are then compared as before, producing a chi-square test statistic of 20.34, substantially above the significance threshold of 3.84. The probability, or *p* value, that the observed numbers would occur due to chance alone is .000006, or 6 in 1 million, assuming that the phenomena are acting independently. At this point, the evidence

Table 4. Major volcanic activity and drought in the same year

	Major Eruption		No Major Eruption		Total
Drought	**60**		**89**		149
		43.1		*105.9*	
No drought	**56**		**196**		252
		72.9		*179.1*	
Total	116		285		401

Bold = empirically observed numbers; italics = expected numbers.

Table 5. Major volcanic activity and drought in the following year

	Major Eruption		No Major Eruption		Total
Drought	**63**		**86**		149
		43.21		*105.79*	
No drought	**53**		198		251
		72.79		*178.21*	
Total	116		284		400

Bold = empirically observed numbers; italics = expected numbers.

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begins to mount that these phenomena are acting in concert with one another.

This paper's third hypothesis proposes the occurrence of drought two years after volcanic activity. In Table 6, we recorded the number of years in which major volcanoes erupted and drought occurred in the second following year. In the 399 years spanning A.D. 1440 to 1838, there were:

- 53 years in which drought occurred two years after major volcanic activity;
- 63 years in which major eruptions occurred but drought did not occur two years later;
- 96 years in which no major eruption occurred and drought did occur two years later;
- 187 years in which neither eruptions nor drought occurred two years later.

If major volcanic activity and Mesoamerican drought two years later are independent events, then the italicized numbers in Table 6 are the values that we would expect for the four contingencies. The observed and expected numbers are then compared producing a chi-square test statistic of 4.87, once again above the significance threshold of 3.84. The probability, or *p* value, that the observed numbers would occur due to chance alone is .0273, or 2.73 in 100, assuming that the phenomena are acting independently. Notice that the effect is still statistically significant at the 5% level but that the magnitude of the effect has begun to attenuate. Although this occurrence is not as impressive statistically, it concurs completely with the hypotheses set out.

As we expected, the phenomenon ceased to be significant when volcanic activity was compared with drought conditions three years later. The hypotheses of this paper included the occurrence of drought two years after volcanic activity, but not three. In Table 7, we again tallied the number of years in which major volcanic eruptions occurred and drought occurred in the third following year. In the 398 years spanning A.D. 1440 to 1837, there were:

- 48 years in which drought occurred three years after major volcanic activity;
- 68 years in which major eruptions occurred but drought did not occur three years later;
- 101 years in which no major eruption occurred and drought did occur three years later; and
- 181 years in which neither eruptions nor drought occurred three years later.

If major volcanic activity and Mesoamerican drought three years later are independent events, then the italicized numbers in Table 7 are the values that we would expect for each contingency. The observed and expected numbers for this scenario are then compared producing a chi-square test statistic of 1.09. The *p* value that the observed numbers would occur simply due to chance alone is .2973 (29.7 in 100), assuming that the phenomena are acting independently. Notice that the effect is *not* statistically significant at the 5% level. As we expected, the phenomenon ceased to be significant when volcanic activity was compared with drought conditions three years later.

Much to our surprise, however, the phenomenon was significant based on a lagged comparison of drought conditions four years later. As expected, the following 20 years showed no significance. The hypotheses of this paper did not include the occurrence of drought four years after volcanic activity. In Table 8, we again recorded the number of years, in which major volcanic eruptions occurred and drought occurred in the fourth following year. In the 397 years spanning A.D. 1440 to 1837, there were:

- 53 years in which drought occurred four years after major volcanic activity;
- 63 years in which major eruptions occurred but drought did not occur four years later;
- 96 years in which no major eruption occurred and drought did occur four years later; and
- 185 years in which neither eruptions nor drought occurred four years later.

If major volcanic activity and Mesoamerican drought four years later are independent events, then the italicized numbers in Table 8 are the values that we would expect for each contingency. The observed and expected numbers are then compared producing a chi-square test statistic of 4.65, which is above the significance threshold of 3.84. The *p* value that the observed numbers would

Table 6. Major volcanic activity and drought two years later

	Major Eruption		No Major Eruption		Total
Drought	**53**		**96**		149
		43.42		*105.68*	
No drought	**63**		**187**		250
		72.68		*177.32*	
Total	116		283		399

Bold = empirically observed numbers; italics = expected numbers.

Table 7. Major volcanic activity and drought three years later

	Major Eruption		No Major Eruption		Total
Drought	**48**		**101**		149
		43.43		*105.57*	
No drought	**68**		**181**		249
		72.57		*176.43*	
Total	116		282		398

Bold = empirically observed numbers; italics = expected numbers.

Table 8. Major volcanic activity and drought four years later

	Major Eruption		No Major Eruption		Total
Drought	**53**		**96**		149
		43.54		*105.46*	
No drought	**63**		**185**		248
		72.46		*175.54*	
Total	116		281		397

Bold = empirically observed numbers; italics = expected numbers.

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occur simply due to chance alone is .0310 (3.1 in 100), assuming that the phenomena are acting independently. Notice that the effect is statistically significant at the 5% level. We will examine this finding again in a moment and see that it is the result of recurring eruptions rather than a direct correlation of eruptions and subsequent drought.

As can be seen in Table 10, chi-square test results and *p* value calculations for all droughts lagging volcanic eruptions by five to twenty years do not show any statistical significance, as we would expect.

Meta-analysis

We can actually combine information from the volcanic activity and drought in the current or following year. In statistical studies, combining information from different independent studies is accomplished through meta-analysis. However, the data from the two 2×2 tables are highly correlated and must be combined into a common table for valid statistical inference. If we assumed independence of the probabilities from the contingency tables, we would obtain a result that is falsely optimistic. The evidence is overwhelming as it is.

In Table 9, we recorded the number of years in which major volcanic eruptions occurred and drought occurred in the same or in following years. In the 400 years spanning A.D. 1440 to 1839, there were:

- 81 years in which drought occurred in the same or following year after major volcanic activity;
- 35 years in which major eruptions occurred but drought did not occur in the same or following year;
- 120 years in which no major eruption occurred and drought did occur in the same or following year; and
- 164 years in which neither eruptions nor drought occurred in the same or following year.

If major volcanic activity and Mesoamerican drought in the same or following year are independent events, then the italicized numbers in Table 9 are the values that we would expect for each contingency. The observed and expected numbers were then compared producing an extremely large chi-square test statistic of 25.05, far above the significance threshold of 3.84. The probability, or *p* value, that the observed numbers would occur simply due to chance alone is .00000056 (56 out of 100 million), assuming that the phenomena are acting independently. While this result does not remove doubt, it does remove all *reasonable* doubt that major volcanic activity and Mesoamerican drought in the same or following year are acting independently.

For completeness, we list the test statistics and attendant *p* value for each comparison of volcanic activity with drought conditions *k* years later where *k* is the lag in Table 10. Notice that the *p* values fall above 5% after four years and only one lag (18) is even close to being statistically significant. A plot of the *p* values, from a 5-year lag to a 20-year lag, shows considerable variation across the interval (0,1) that is consistent with randomness.

We must question, however, whether our chi-square test was sensitive enough to detect a more modest correlation. The validity of chi-square tests is based on asymptotic (large sample) theory. Are the sample sizes of approximately 400 years adequate? In this case, we are able to detect a correlation as small as 10%, which makes the test very powerful in detecting even a modest correlation. The tests employed here are known as non-parametric tests, which make no assumptions about the underlying distributions of the number of volcanic eruptions or the number of occurrences of drought in Mesoamerica.

Notice that by simply realigning the drought data *k* years later with the major volcanic eruption data, we did not observe a correlation as high as 10% once the volcanic eruption had occurred more than four years earlier.

Time-Series Analysis

We can examine the binary major volcanic eruption data and the binary Mesoamerican drought data using methods known as time-series analysis. In mathematical terms, we examine the data for cycles, or periodicity, using methods of Fourier transforms. In this

Table 9. Major volcanic activity and drought in the same or following year

	Major Eruption		No Major Eruption		Total
Drought	**81**		**120**		201
		58.29		*142.71*	
No drought	**35**		**164**		199
		57.71		*141.29*	
Total	116		284		400

Bold = empirically observed numbers; italics = expected numbers.

Table 10. Test statistics and *p* values for comparing volcanic activity with drought *k* years later

Lag *k*	χ^2	*p* [a]
0	14.8	.0001
1	20.3	.000006
2	4.87	.0273
3	1.09	.2973
4	4.65	.0310
5	.98	.3211
6	.02	.8873
7	.64	.4225
8	1.01	.3147
9	1.63	.2015
10	.18	.6714
11	1.34	.2478
12	.31	.5781
13	.76	.3838
14	1.31	.2519
15	.33	.5627
16	.31	.5773
17	1.51	.2191
18	3.61	.0574
19	.68	.4081
20	2.41	.1209

[a] *P* values lower than .05 indicate a correlation at or above the 95% confidence level.

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context, we say that the data are auto-correlated (correlated with themselves) by observing patterns that repeat over time. The auto-correlation function (ACF) computes the correlation between the current time-ordered record of activity and the same displaced by *k* years, where *k* is known as the lag. For example, if we examine sunspot data, we will find a period of 11 years. That is, we observe solar maxima about every 11 years. We use the same time-ordered record technique to examine the binary data in this study (Bloomfield 2000).

When we examined the time series individually, we observed that the period of major volcanic activity appears to follow that of times series having periods (or cycles) of 4 years and 22 years. It is the four-year period in these data that accounts for the finding of significance in the 2×2 table for major volcanic activity and Mesoamerican drought four years later. In fact, it is not the recurrence of drought but, rather, the recurrence of major volcanic activity (or inactivity) that produces this anomaly. We can conclude, then, that there is no direct correlation between volcanic eruptions and drought four years later. Rather, there is a tendency for another eruption to occur, producing another drought in the same year.

The time series of Mesoamerican drought has cycles (or periods) of 1, 2, 7, and 25 years. Notice that this finding is consistent with other findings that Mesoamerican droughts tend to last for one or two years, which accounts for the one-year period and the two-year period. Further, these data corroborate the recurrence of Mesoamerican drought in periods of approximately 25 years.

Famine and Drought

The chi-square test used in the context of 2×2 contingency tables is based on asymptotic properties. When the samples are smaller, its use can produce falsely optimistic findings or findings of significance where none are present. If the expected values in the contingency table are lower than 5, one is cautioned not to use the chi-square approximation. Rather, one should use the exact distribution, which is hypergeometric. The subsequent test is known as Fisher's exact test in honor of the father of modern statistical thought, Sir Ronald Fisher. We mention this result to analyze the famine data reported in the Yucatan Peninsula between A.D. 1440 and 1840. Of the 24 recorded Yucatecan famines, 13 can be attributed to drought and 11 to other causes. Of the 13 drought-induced famines, 11 were preceded by a major volcanic eruption. However, none of the famines were preceded by a major volcanic eruption. These data are summarized in the 2×2 contingency table in Table 11.

We used Fisher's exact test rather than the chi-square approximation on these data because the sample sizes are small and lead us to expect numbers near 5 (see Conover 1999). By using the exact (hypergeometric) distribution, we find that a major volcanic eruption preceded a drought-induced famine more frequently than famines induced by other causes with a *p* value of .001776 (1.7 in 1,000). If one used the chi-square approximation in this case, the subsequent *p* value would have been overly optimistic at .000034 (3.4 in 100,000). These data strongly support the connection between major tropical volcanic eruptions and drought seen through the eyes of famine in Yucatan.

Table 11. Major tropical volcanic activity and Yucatecan drought/famines

	Major Eruption	No Major Eruption	Total
Drought/famine	**11**	**2**	13
Other famines	**0**	**11**	11
Total	11	13	24

Bold = empirically observed numbers.

Multiple Volcanic Eruptions

The occurrence of multiple volcanoes in a given year provides more evidence to support the hypotheses put forth in this article. Multiple eruptions in the same year increase the chance that enough sulfur will be injected into the stratosphere to change global circulation patterns. There are 13 years between 1440 and 1840 in which multiple volcanoes ejected enough material to be classified as major eruptions—that is, VEI magnitude 4 or higher. Let *p* be the probability that a Mesoamerican drought follows in a year that has two major volcanic eruptions. In this case, we can estimate the probability based on the data. However, a more important finding would be to place a 95% lower confidence bound on the probability, *p*. Let γ be the level of confidence, and let n be the number of years in which drought follows multiple major volcanic eruptions. Since there are no occurrences in which drought does not follow multiple major volcanic eruptions, a lower $100\gamma\%$ confidence-bound on *p* can be found by solving the following inequality for *p* (Conover 1999):

$$p^{n} < 1 - \gamma.$$

If we set $\gamma = .95$ to obtain a 95% lower confidence bound and $n = 13$, the number of years in which Mesoamerican drought followed multiple major volcanic eruptions in the same year without fail, the lower confidence bound is 79.42%. That is, we are 95% confident that the probability that a Mesoamerican drought will follow multiple major volcanic eruptions exceeds 79.42%. This goes far beyond attributing the incidence to chance and indeed says that we are 95% confident that Mesoamerican drought will follow in 80% of the years with multiple major volcanic eruptions. This is another stunning statistical confirmation of the hypothesis that volcanic eruptions were correlated with Mesoamerican drought during the years 1440 to 1840.

Further, historical meteorological records confirm that 1902, a year in which three tropical volcanoes erupted, was followed by severe drought in Yucatan between 1902 and 1904.

VOLCANISM AND MESOAMERICAN ARCHAEOLOGY

We have looked at evidence from Colonial historical records of drought in Mesoamerica and at the record of known volcanic eruptions between 1440 and 1840, and we have analyzed them statistically to show a definite and strong correlation between volcanic eruptions and Mesoamerican drought. But what can we say about volcanoes and their relationship to demographic disasters known from the archaeological record in Mesoamerica?

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Of course, the farther back in time we go, the fuzzier the record becomes, and it is not possible to state with certainty the exact years in which eruptions occurred or archaeological events took place. That should not prevent us, however, from taking a look at the evidence that is available to see whether any patterns can be determined.

In terms of ancient volcanic activity, it will not be possible to tie a particular volcano to a particular year. Because of the vagaries of radiocarbon dating, we cannot know the exact years of volcanic eruptions or the exact years in which droughts of interest may have occurred. Thus, it is impossible to tie them together definitively.

However, we do know the magnitudes of eruptions that occurred more or less at the right time to be associated with drought. Given the ties we have already seen between volcanoes and drought, we can speculate that a major volcanic eruption occurring at more or less the right time may be connected to drought and demographic disaster occurring in Mesoamerica. It is certainly not proof positive, but let us look and see what we find.

Preclassic Abandonment

The first serious demographic disaster that befell the Maya on a large scale—at least, the first that has been identified to date—was the Preclassic Abandonment around A.D. 150–200. Cities from the northern Lowlands to the southern coast of Guatemala were abandoned or seriously depopulated. The most important city of the time, El Mirador, was abandoned during a period of severe drought. Unfortunately, as we will find for most archaeological contexts, the drought cannot be tied to an exact year. El Mirador never regained its former importance (Hansen 1990:216–221).

The most powerful eruption of the past 12,000 years, at Taupo in New Zealand, occurred sometime between A.D. 150 and 200. It was a truly phenomenal eruption that sent its column 50 km into the sky. Although it was not the largest in terms of total erupted magma, it was the most explosively powerful eruption and undoubtedly ejected its eruption column higher than any other in the past 12,000 years. There is no question that volcanic debris and sulfur were injected into the stratosphere. In fact, more than 80% of Taupo's eruption products were deposited at distances greater than 226 km from the volcano. Although it cannot be proved with certainty, there is a very strong probability that a colossal eruption such as Taupo would have caused worldwide climatic aberrations that could have resulted in the serious droughts that drove the Preclassic Abandonment. The available evidence, although not probative, is at least consistent with this possibility (Walker 1980).

Hiatus

The next demographic disaster to devastate the Maya Lowlands was the Hiatus, which began around A.D. 536 and lasted at least until the end of the century. The Hiatus seems to have affected some areas more severely than others. The areas around Caracol and the Caribbean littoral may have been less affected than, say, Río Azul, which was totally abandoned at the time. Rural populations plunged by more than 70% in the Three Rivers area where Guatemala, Belize, and Mexico meet, which includes Río Azul. Tikal was devastated, as were the cities along the Río de la Pasión and the Usumacinta. There is no question that the Hiatus was a serious demographic disaster for the Maya. Elsewhere in Mesoamerica, Teotihuacan was battered and lost its position as the Mesoamerican world power. It survived into the eighth century as just another city, albeit a large one. A serious drought at this time has been determined from a lake core taken from Punta Laguna in the Yucatan Peninsula. Once again, we see the pattern of drought and demographic disaster (Adams 1991:196–197; Willey 1977:72–73).

But the Hiatus was different because it was not just a Mesoamerican phenomenon. It was a time of worldwide climatic aberrations and atmospheric disturbances. From the available historical accounts, it seems that a dry fog was seen in most of the world beginning in A.D. 536 and lasting up to 18 months. It was the densest and most persistent dry fog in recorded history. According to Cassiodorus Senator, the praetorian prefect (prime minister) of the Visigothic kingdom of Italy, the sun in the Italian peninsula during this time shone for only four hours a day in the summer, and a person standing in the noonday sun would not cast a shadow. The sun was blue-colored; frosts occurred during the summer, killing the crops; and there was serious drought. The people were terrified (Gunn 2000:5–20; Rampino et al. 1988; Stothers 1984).

Procopius, a Byzantine historian traveling with Byzantine General Belisarius in North Africa and Sicily, reported that the "sun gave forth its light without brightness, like the moon, during this whole year [A.D. 536] and it seemed exceedingly like the sun in eclipse, for the beams it shed were not clear nor such as it is accustomed to shed. And from the time when this thing happened men were free neither from war nor pestilence nor any other thing leading to death" (Procopius 1914:39–42).

Similar reports can be found from all around the world. Clearly, something catastrophic happened—but what was it? The answer is not clear. One would first suspect a volcano, but the ice-core record is ambiguous. The most recent ice core from Greenland, the GISP2 core, does not contain an acid peak at the time of the Hiatus. However, the core has a gap that starts around or shortly after the time of the Hiatus. It may be that the peak is missing because of the gap in the core rather than because there is no peak (Zielinski 1995:20, 939).

If a volcano was in fact responsible for the dry fog, then El Chichón in the southern Mexican state of Chiapas is a likely candidate. Radiocarbon dating shows a probable sixth-century eruption at the volcano. To date, however, no studies have been carried out to determine the magnitude of the eruption or to refine the date further.

However, archaeologist Mike Baillie questions whether a volcano was the cause. As he puts it:

> We now know that if we define the period of downturn as A.D. 536–545, in that period European oaks register their 3rd worst conditions in 1,500 years; Fennoscandian temperatures reconstruct their second coldest summer in 1,500 years; Foxtail pines from the Sierra Nevada reconstruct their 2nd, 3rd and 4th coldest years in 2,000 years; Fitzroya from Chile show their coldest year in 1,500 years, etc. (none of the other extreme years match up). Put bluntly, the episode around A.D. 540 is totally anomalous; no volcano in the last 1,500 years has shown anything equivalent, so, what caused the event? [Baillie 1999b]

Baillie has argued that the event in A.D. 536 was the result not of a volcanic eruption but, rather, of an extraterrestrial impact—a comet or an asteroid striking one of the world's oceans, throwing

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a cloud of water and debris into the stratosphere. He points out that a lot of mythology, located traditionally at the time of the 536–545 event, suggests that things were going on in the sky, including dragons, fireballs, and fiery lances. Cassiodorus, for example, says "something mysterious and unusual seems to be coming on us from the stars" (Stothers 1984). Thus, Baillie believes the possible working hypothesis that the Earth suffered a bombardment event in the window from A.D. 536 to 545 in the style of one of Victor Clube and Bill Napier's "cosmic swarms," in which the Earth is struck by a large number of Tunguska-class objects in a short space of time (days to years). Now that the question of an impact has been raised, it clearly deserves further research (Michael Baillie, personal communication, 1998; Baillie 1994:216, 1995, 1999a; Clube and Napier 1990; Stothers 1984; Zielinski 1995:20, 939).

For our purposes, however, we do not need to identify the exact cause. Let us look at the relationship between a past dry fog and Mesoamerica. A serious dry fog was recorded in Europe and North America in 1783, the year of the famous Laki eruption in Iceland and of two others—one also in Iceland and the other at Asama in Japan. The first American physicist, Benjamin Franklin, delivered a paper at the Manchester Philosophical Society on December 22, 1784, in which he tied the dry fog to the Laki eruption. (He was evidently unaware of the other two.) He was the first scientist to link volcanic eruptions to global climatic effects (Goodman 1984:1, 12).

The dry fog in Europe was followed by severe drought and famine in Mesoamerica—although this was not reported in Yucatan. The years 1784–1785 were called the *años de hambre*, the years of hunger, in the Valley of Mexico and central Mexico, probably the most widespread and severe famine in this region during the Colonial period (Castorena et al. 1980).

Thus, we have a historical record of a dry fog culminating in demographic disaster in Mesoamerica. It happened in 1783–1785. Because the dry fog in A.D. 536 was so much worse, it is likely that it happened during the Hiatus, as well, whether the source of the dry fog was El Chichón, another volcano, or an extraterrestrial impact or series of impacts. After all, it is unreasonable to believe that the coincident worldwide climatic aberrations seriously affected regions throughout the world but that the Hiatus was just a localized Maya phenomenon that coincidentally occurred at the same time as the other events in the rest of the world.

The effects of the dry fog of 536 were felt not only in the Maya Lowlands but also in the Highlands. Teotihuacan, the Early Classic superpower of Mesoamerica, was seriously wounded. It lost its primary position at this time and was never again the dominant city in Mesoamerica. Once again, its collapse at the time that cities and peoples around the world, much less Mesoamerica, were suffering from the effects of the dry fog suggest that it, too, should be counted among the dry fog's victims.

Classic Collapse

From a Maya perspective, of course, the great demographic disaster of the past 2,000 years was the Classic Collapse, a time in which millions of people disappeared from the Maya Lowlands in what was clearly a demographic disaster with few parallels in the history of the world.

We propose, based on last dates at large Maya cities, that the Collapse was characterized by three distinct phases of collapse: the first in 810, which affected the western Maya Lowlands; the next in 860, which affected the eastern Lowlands; and the final phase in 910, which wiped out the cities in the central core that had hung on through the other two phases and the cities in the north that had actually flourished for a brief period after the collapse in the south (Gill 2000:323–329).

Palaeoclimatic data from lake-sediment cores recovered by David Hodell, Mark Brenner, and Jason Curtis of the University of Florida show that the Lowlands were in the grip of a devastating drought during this time period—the driest in the past 7,000 years. In an otherwise very dry century, therefore, there were three periods of particularly brutal drought (Hodell, Curtis, and Brenner 1995; Hodell, Brenner, Curtis, and Guilderson 2001).

What is the possibility that these devastating droughts were driven by volcanic eruptions? Once again, we cannot tie specific volcanic eruptions to specific years, and frankly, our dating of the phases of collapse and the presumably associated brutal droughts is not accurate to the year, either. But let us look at what we know about the volcanic activity of the ninth and early tenth centuries:

- The GISP2 ice-core record from Greenland shows an acid peak at A.D. 822 and 823, indicating either one or two large unknown volcanic eruptions somewhere in the world (Zielinski 1995);
- *Volcanoes of the World* lists an unknown eruption in 860, determined from a sharp drop in tree-ring widths. In addition, an ice-core acid peak is listed at 853, which may or may not be the same eruption (Simkin and Siebert 1994);
- There are additional acid peaks at 875, 900, 902, and 915 (Simkin and Siebert 1994);
- Swedish tree rings show that periods of particularly cold summers occurred around 800, 860, and 910 (Karlén 1982, 1984); and
- Scandinavian glaciers show evidence of strong advances around 800, 860, and 910 (Karlén 1982, 1984).

Popocatepetl, located in the Mexican Highlands near Mexico City, is a huge volcano. Not only is it very high, at nearly 19,000 feet, but it has an enormous internal plumbing system. When it explodes, it is capable of emitting enormous quantities of material. Its last major eruption occurred in the early ninth century—perhaps in A.D. 822 if it is the volcano responsible for the acid peak in the GISP2 ice core in that year that is technically listed as unknown.

Remember that for a volcano to be climatically effective, it must inject sulfurous compounds into the stratosphere. It must therefore be a very sulfurous volcano. Popocatepetl starts out some 18,000 feet or so closer to the stratosphere because of its altitude. In addition, it is the single most sulfurous volcano measured to date. Finally, Claus Siebe believes that Popocatepetl's was one of the 10 most explosive eruptions anywhere during the past 2,000 years. These factors taken together, Popocatepetl's huge internal plumbing system, altitude, and sulfurousness along with the size of the explosion, suggest that it would have had a tremendous impact on the global climate. Because of the vagaries of radiocarbon dating, however, we cannot pin the eruption date down any more precisely than to say that it occurred during the ninth century, and most likely during the early ninth century. In fact, it may be the volcano responsible for the unknown peak in the ice-core record in A.D. 822–823 (Siebe et al. 1996; Claus Siebe, personal communication, 2000).

In addition, El Chichón, located in the southern Mexican state of Chiapas, may well have erupted early in the ninth century. A

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mathematical combination of the two youngest carbon samples recovered from one of the eruption deposits show a calibrated one-sigma split range of dates of A.D. 680 to 820 and 840 to 860. El Chichón is also very sulfurous—almost as sulfurous as Popocatepetl. Although no studies have been done yet to determine the size of its previous eruptions, eyeball estimates of the deposits suggest that the eighth- to ninth-century eruption would have been large and therefore climatically effective (Macías et al. 1997).

Is it possible that one of these volcanoes erupted in 810–820 and the other around 860? Yes, certainly, but we cannot say which, and we cannot say definitively that either erupted exactly at those times. What we can say is that radiocarbon evidence is consistent with eruptions of both volcanoes at those times. We have acid peaks in the GISP2 ice core in 822 and 823 and an unknown eruption listed in *Volcanoes of the World* in 860, determined by its drastic effect on northern tree rings. Thus, it is pretty clear that there was a volcanic eruption around the time of the first phase of collapse and one at the time of the second phase.

Of course, other eruptions occurred at other volcanoes around the world during this time period, as well. Magnitude 4 eruptions are reported in *Volcanoes of the World* at Mono Craters in California in 810 ± 20; at Mt. Fuji in Japan around 800, the dating determined magnetically; at Mt. Furnas in the Azores between 800 and 1020; at Bardarbunga, Iceland, in 900; and at Tolbachik in Kamchatka in 900; and a magnitude 5 eruption is reported at Ksudach in Kamchatka between 890–920 and 950–1030. Numerous other eruptions are also reported for the relevant time periods whose magnitudes have not been determined. There is, therefore, no lack of candidate volcanoes. When and how they erupted—singly or multiply—and their sulfur content have not been determined (Simkin and Siebert 1994).

What we do know is that Scandinavia had particularly cold summers around 800, 860, and 910; ice-core acid peaks suggest eruptions in 822, 823, 853, 875, 900, 902, and 915; and tree rings suggest an eruption in 860. The supply of candidate volcanoes that may have erupted at these times is large and include, in particular, two of the world's most sulfurous, Popocatepetl and El Chichón. Given the ties we have seen between volcanism and famine in Mesoamerica, we might well speculate that volcanoes, in conjunction with the global climatic conditions of the ninth and tenth centuries, could have driven the droughts and famines of the Collapse that resulted in the disappearance of Classic Maya civilization. But there is no undisputable proof at this time.

Tula

By the twelfth century, the Toltecs had consolidated the Highlands of Mexico into a state, with Tula as their capital. Colonization movements had established new frontiers of agriculture in the north-central Highlands of Mexico and in a band of the northern Highlands along the western Sierra Madre to the extreme north of the state of Durango. The northward surge of civilization occurred during a time of warm, humid weather in the region—known as the Medieval Optimum in the rest of the world—that made the area suitable for farming. The rise of Tula as an imperial capital, located far north of the normal seats of power in central Mexico and halfway between the Valley of Mexico and the new agricultural lands of the north, is evidence that the population center had shifted to the north. The northern advance of this civilization, however, ended in complete collapse. Beginning in the twelfth century, a mass exodus of sedentary people, instigated by a southward shift of the northern zone of aridity, produced a permanent retreat of the agricultural frontier; at the same time, there was an apparent exodus of Toltecs to the south, perhaps to Culhuacan. By 1179, it was all over: Tula fell during the last part of the twelfth century (Armillas 1964:76; Diehl 1983).

Pedro Armillas believed that a cooling process that began in the twelfth century culminated in the Little Ice Age between the fifteenth and nineteenth centuries. The cooling resulted in increased aridity in northern Mexico. The Mexican steppes were displaced southward, forcing the sedentary people of the region to migrate south, toward more humid conditions. The advance and retreat of the frontier of Mesoamerican civilization in northern Mexico, then, can be explained by the environmental changes produced by changes in the general circulation of the atmosphere, and particularly in rainfall in northern Mesoamerica, similar to the advance and retreat of ecotones in Western Europe and the Sahel. The result was a southward retreat of the northern border of Mesoamerica and the northern zone of aridity, an ecotonal shift of at least 250 km. The Fennoscandian tree rings in Arctic Sweden suggest a period of cold in Arctic Europe at the same time. Drought, cold, famine, and war appear to have played important roles in the fall of the Toltec Empire (Armillas 1964:78–79).

Was there a role for volcanoes? Ice cores from the Antarctic show an acid peak around the year A.D. 1168. The increased acidity lasted for 7.6 years, the longest period of acidity in the Antarctic ice record in the past 16,000 years. Clearly, the eruption responsible for such an acid peak was huge, and it coincides with the fall of Tula (Hammer et al. 1997:6).

To date, the guilty volcano remains unidentified. This enormous eruption does not show up in the Greenland cores, however, which suggests that it was located in the Southern Hemisphere.

Postclassic Abandonment, Mayapan, and the Famine of 1 Rabbit

Although drought and cold weather began as early as 1447, a devastating drought followed that culminated in the famine of 1 Rabbit, the Mexica name for the year 1454. The following historical reports are drawn from those compiled by Anton Kovar from chronicles written shortly after the Conquest (Kovar 1970:28–31):

1447 There was so much snow that many people died. (*Codex Telleriano-Remensis*)

1449 Also in this year so much snow fell that it covered everything. (*Relations of Chalco Amaquemecan, seventh relation*)

1450 [T]he snow that fell over the entire land was so high that it reached in most parts a stadium and a half, which caused the destruction and collapse of many houses as well as the destruction of all trees and plants, and the country was so cold that many people died and especially older people; and during the three following years all plantings and products of the Earth were lost so that most people died. (*Alva Ixtlilxóchitl*)

This year there were heavy frosts which froze everything. There was hunger and need. Thus began the five years during which there was nothing to eat. (*Relations of Chalco Amaquemecan, Third Relation)*

1451 Third year of hunger. All the way to Chalco came the ferocious beasts and buzzards and birds of prey, the same as to all other villages. Everywhere, in the forest and grasslands, died even young men and women. Their flesh was wrinkled and dry as if they were old persons. Hunger was very great. (*Relations of Chalco Amaquemecan, Seventh Relation*)

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1452 Second year of hunger, need, and suffering for lack of food in Chalco. The buzzards were searching everywhere for corpses to eat in the hills, lowlands, and forests. The young men looked like old people because their flesh was so full of folds and wrinkles. The boys and girls became so because of hunger. (*Relations of Chalco Amaquemecan, Third Relation*)

1453 [A]nother frost fell during the Tecuilhuitl [the Feast of the Lords, June 12–July 1]. Then the ears froze. In this year there was also an earthquake and fissures appeared in the ground and chinampas collapsed; and people were selling themselves to others because of hunger. (*Anales de Tlatelolco and Códice de Tlatelolco*)

In the year 128 [after the foundation of Tenochtitlan], hail fell in Mexico to such a degree that houses collapsed and the lake froze over. (*Historia de los Mexicanos por sus pinturas*)

1454 This is the year in which it was said that people "became scared" (*gente se aconejó*) for reason of a great mortality, pestilences, and hunger. Coyotes, ferocious beasts, and birds of prey came all the way to Chalco in search of people to attack. Such was the hunger that the ancient Mexicans sold themselves as slaves to obtain something to eat. Others went into the hills trying to escape the aridity and dryness which affected the vegetation and there they tried to plant something with their hoes. Certainly, there was nothing to eat, and because of this the old Mexicans sold themselves as slaves in exchange for food. Thus another kind of people arose with those who "became Totonacs" (*atotonocados*) because a great number of said Totonacs bought Mexicans in exchange of dry maize, shelled, both in Cuextlan where the Mexicans went to sell themselves and in Tenochtitlan where dry shelled maize was brought to buy them, but even with tortillas folded and dipped into something, there was not enough to go around and for this reason some people simply made holes in the ground and crawled into them to await death and when it came they were devoured by buzzards because there was no one to bury them. There was some relief only in those parts of the country where some rain fell. (*Relations of Chalco Amaquemecan, Seventh Relation*)

It is said that this year, 1 Rabbit, was an extremely unfortunate one; there were many deaths. The people died of thirst. From Chalco came foxes, ferocious beasts, lizards, etc., and they devoured the people. The famine was so great that the old Mexicans sold themselves; they took refuge in the woods, where they lived unhappy and feeble. For four years there was nothing to eat in the country, so the older Mexicans sold themselves and two divisions, it is said, delivered themselves into servitude. (*Annals of Chimalpahin*)

At the beginning there was a very large eclipse of the sun, and then illness grew, and so many people were dying that it appeared as if nobody was going to survive, such was the calamity that afflicted this land and hunger was so great that many sold their children in exchange for maize in the province of Totonicapan where no such calamity occurred. (*Alva Ixtlilxóchitl*)

People sold themselves into slavery for food while buzzards and lizards ate the corpses of the dead. It was a terrible time. These pictures of drought-ravaged Mexica are awful scenes of suffering, pain, and death.

The drought of 1 Rabbit also devastated Yucatan. A written record of drought in Yucatan is found in *The Book of Chilam Balam of Maní* and can be dated, by its reference to the fall of Mayapan around 1451, which falls in katun 8 Ahau.

> The city of Mayapán was destroyed on a day of a Katún 8 Ahau. Lahun Chablé will establish, to the south, a Katún 8 Ahau. With his eyes on the heavens, the ruler will implore food and drink. The warrior will thank him who will give him food and drink. The fields, having been impoverished, shall be searched for food and water which will not be found anywhere in the Petén or in the entire land, wherever there are Bacabs. [Craine and Reindorp 1979:83]

> The destruction of Mayapán, which is in the south, took place in the Katún 8 Ahau. Lahun Chan established the Katún 8 Ahau and directed his powerful gaze toward heaven, imploring hard bread and water. No one entertained the soldier with bread or water. The people, on the plain and in the forest, were chilled. Everything was searched, but nothing [neither food nor water] could be found on the plains, or in the forest, or in the whole world, or in all of Petén [Craine and Reindorp 1979:156].

The same drought is most likely also described in *The Book of Chilam Balam of Chumayel*. As shown earlier, Alva Ixtlilxochitl reported an eclipse during the famine of 1 Rabbit (1454), which falls in katun 8 Ahau. The following passage describes the eclipse, drought, and famine most likely at the fall of Mayapan, as well.

> Katun 8 Ahau came. 8 Ahau was the name of the katun when their government occurred. There was a change of the katun, then there was a change of rulers [missing fragment] . . . when our rulers increased in numbers, according to the words of their priest to them. Then they introduced the drought. That which came was a drought, according to their words, when the hoofs [of the animals] burned, when the seashore burned, a sea of misery. So it was said on high, so it was said. Then the face of the sun was eaten; then the face of the sun was darkened; then its face was extinguished. They were terrified on high, when it burned at the word of their priest to them, when the word of our ruler was fulfilled at the word of their priest to them. [Roys 1967/1933:77]

The physical destruction of Mayapan resulted from an internal revolt of its vassals during a time of cold and drought. Once again, we see the pattern of drought, cold, famine, and conflict. The drought beginning around 1450 was part of a global pattern of weather changes, including the onset of the first Little Ice Age in Europe in 1450–1500; one of the two severest periods of cold in the Sierra Nevada in the past 2,000 years; and the brutal drought and famine of 1 Rabbit in the Mexican Highlands.

Kuwae volcano in Indonesia exploded in an enormous, very sulfurous magnitude 6 eruption around 1452, which resulted in the greatest atmospheric perturbation of the past 700 years, possibly even greater than Tambora's 1815 eruption. The date is tied to acid peaks in the Arctic and Antarctic ice cores. The effect was global, with, for example, unusually severe weather in China in the early 1450s and bizarre optical atmospheric phenomena reported during the siege of Constantinople in 1453. It was also the time of the Postclassic Abandonment and the fall of Mayapan in the Lowlands and the devastating famine of 1 Rabbit in the Mexican Highlands. In addition, El Chichón appears to have erupted in the fifteenth century, although the exact year cannot be as clearly determined as that of Kuwae (Witter 1999:1, 8).

It is possible to speculate, therefore, that Mesoamerica may have received a double punch from volcanoes. Because of the vagaries of radiocarbon dating, however, the double punch must remain for the moment merely intriguing speculation.

SUMMARY AND DISCUSSION

Weather in Mesoamerica, primarily the difference between ample rainfall and drought, is determined by the proximity or distance of the North Atlantic High pressure system. There may be other possible causes of drought, as well, but for Mesoamerica, the North Atlantic High is a major weather-maker in the Atlantic Basin.

The High develops under the descending branch of the Hadley cell circulation, a thermodynamically driven convection cell in the atmosphere. Thus, it is dependent on solar radiation as a prin-

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cipal source of energy. Anything that blocks incoming solar energy therefore will affect the energy available to the Hadley cell.

When the energy is blocked from reaching the Hadley cell, the cell appears to contract in size, and the North Atlantic High shifts to the southwest, closer to Mesoamerica. Changes in arriving solar energy result from two factors: variance in the energy output of the sun and something in the atmosphere that blocks the energy, keeping it from reaching the Hadley cell.

When a powerful, sulfurous volcanic eruption occurs, a layer of sulfur aerosols is deposited in the lower level of the stratosphere, just above the tropopause. This layer, known as the Junge layer, is very effective at absorbing and reflecting solar energy, thus denying some of the incident solar radiation to the Hadley cell and, according to our model, causing a contraction in the areal extent of the cell and a southwestward shift in the position of the North Atlantic High.

We now have identified a mechanism through which volcanoes affect the patterns of global atmospheric circulation that, in turn, bring about drought in Mesoamerica. It is important to emphasize that the volcanic effect we are describing is an indirect one and is not tied to the local effects of volcanoes, which can burn and bury people, kill livestock and crops, and cause much regionalized destruction—as was seen in the famous examples of Pompeii and Herculaneum, victims of Vesuvius in A.D. 79.

The evidence also seems to show that volcanoes are much more destructive to Mesoamerica during periods that are already cold, such as the Little Ice Age that was ongoing during 1440–1840, the period of our study. The North Atlantic High is more likely to be located far to the southwest at the time of the eruption, so that any volcanic kick would be more likely to bring it close to Mesoamerica. If the High started close to Europe, for example, as would be the case during a period of global warmth, the volcanic effects of a shift in the position of the North Atlantic High might not be felt in Mesoamerica.

Now that we know how volcanoes can affect the global climate, is there any evidence to show that volcanoes actually did affect Mesoamerica? In examining the historical record of volcanic eruptions and drought, we determined that the probability that the droughts seen in Mesoamerica during the same year or the two years following large volcanic eruptions has only 56 chances out of 100 million of being attributable to chance. This is a stunning number that should remove all reasonable doubt regarding a connection between volcanoes and drought in Mesoamerica between 1440 and 1840. The effect was most pronounced in the Yucatan Peninsula and the Valley of Mexico and begins to attenuate as one moves away from there.

The statistical methods we used are called non-parametric because we made no assumptions about the true distributions of the number of occurrences of volcanic activity or drought classifications, except that the eruptions and droughts either occurred or did not occur. Our analysis, then, takes the most conservative approach possible. Yet it demonstrates a strong, statistically significant direct correlation between volcanism and drought in Mesoamerica, as can be seen in Figure 1.

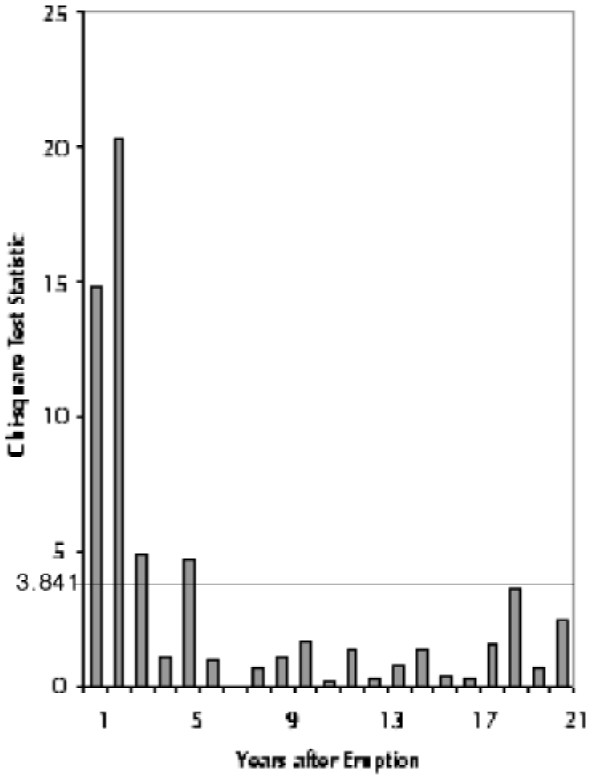


Figure 1. The chi-square test statistic for significance in years 0 to 20 following a volcanic eruption, data from Table 10. Year 0 is the year of the eruption. Any value above the threshold of 3.841 is considered statistically significant. As can be seen, the correlations in years 0 and 1 are far above the significance level, and significance continues into year 2. The variation seen in years 3 through 20 is characteristic of random occurrence. The seemingly significant value in year 4 is a result of recurring volcanism rather than direct correlation to an eruption in year 0.

Our rigorous statistical analysis strongly supports the conclusion that the death and destruction historically reported in Mesoamerica between 1440 and 1840 were related to volcanic eruptions. From our analysis, it seems clear beyond a reasonable doubt that volcanoes around the world were repeatedly the long-distance assassins of Mesoamerican populations between 1440 and 1840. They may therefore have played a critical role in the destruction of ancient Mesoamerican civilizations, as well.

We end, then, where we began: with an idea that at first seems too counterintuitive and fantastic to believe. Although our study does not conclusively prove that volcanoes were involved in any of the great demographic disasters in the Mesoamerican archaeological record, the body of evidence we have presented makes a compelling circumstantial case, and it sets the stage to begin asking the questions and looking for the evidence.

RESUMEN

Parece inverosímil creer que las erupciones volcánicas en cualquier parte del mundo pudieran causar desastres en Mesoamérica. Con todo, la sequía es un fenómeno recurrente en la región y ha devastado poblaciones una y otra vez en toda la historia registrada, así como en el registro arqueológico. La diferencia entre periodos de amplia lluvia y periodos de sequía está frecuentemente unida a la posición de la Alta Atlántico Norte.

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Como una célula de convección termodinámica, la Alta responde a variaciones en la energía disponible proveniente de la radiación solar. Si algo bloquea la entrada de radiación, la célula se contrae, moviendo a la Alta Atlántico Norte cerca de Mesoamérica y llevando condiciones propicias para la sequía. Una gran erupción volcánica que inyecta sulfuro hacia la estratosfera provoca una capa de ácido sulfúrico que se forma justo encima de la tropopausa. Este aerosol sulfuroso absorbe o refleja la entrada de radiación solar, así priva a la convección atmosférica de algo de su energía. El resultado es un cambio hacia el suroeste de la Alta Atlántico Norte hacia Mesoamérica, terminando frecuentemente en sequía. Este efecto es más pronunciado durante periodos de clima frío en el Hemisferio Norte. Examinamos los reportes de sequía y hambruna durante el periodo de 1440 a 1840, durante la Pequeña Edad de Hielo, y las comparamos con grandes erupciones volcánicas conocidas. Entonces usamos técnicas estadísticas no paramétricas para determinar si las coincidencias vistas entre erupciones volcánicas y sequías dentro de los siguientes dos años se debieron al azar o si hubo, de hecho, una correlación. Encontramos una correlación y la posibilidad de que fuera al azar tiene una probabilidad de 56 en cien millones. Podemos concluir, entonces, que debido a su posición geográfica única, la actividad volcánica mundial puede tener efectos desastrosos en Mesoamérica y podemos empezar a preguntar si erupciones volcánicas pasadas estuvieron implicadas en pasados desastres demográficos mesoamericanos. En este punto, no podemos hacer afirmaciones definitivas, pero las posibilidades que examinamos son intrigantes.

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