Late Holocene droughts and cave ice harvesting by Ancestral Puebloans

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Supplementary Information

S1. Archeological background. Located in the heart of the Western Pueblo world, El Malpais National Monument’s (hereafter ELMA) archeological landscape is typical of the Four Corners region with distinctive Puebolan period sites including the twelfth century Chaco style great house and great kiva site of Las Ventanas. To the east lies the Cebollita Mesa area and the Pueblo of Acoma beyond. To the west are the lava fields of ELMA. This region is part of the ancestral homeland of the Acoma people and is culturally significant for archeological resources and wild and scenic values1. The Las Ventanas community includes the great house and great kiva and a dispersed smaller pueblo sites dating to the Pueblo II period (AD 900-1150) all positioned along the top of Putney Mesa overlooking the lava fields to the west. Cebollita Mesa is the prominent landform and high point for the region. Early research in this area by1 and2,3 included Putney Mesa and laid the foundation for the cultural-chronological sequence of the area. Subsequent cultural resource management studies of the area helped refine the cultural sequence and are relevant to the understanding of subsistence-settlement patterns in ELMA. The mesa tops and canyons bordering the eastern edge of ELMA’s lava flows were at the center of the region’s emergent 9th through 13th century Pre-Contact Puebloan communities whose territory extended far into ELMA’s lava flow landscape. Human occupation of the ELMA - Cebollita Mesa region extends back to the Paleoindian period based on sparse but clear evidence from material culture (likely Folsom) in the Armijo Canyon area4. Subsequent hunter-gather adaptations from the early through late Archaic period (8,000-1,500 B.C.) also are documented by material culture found on the Cretaceous-age sandstone mesas and ridges of Cebollita and Putney mesas along ELMA east side1,5 as well as the older lava fields and remnant Zuni Mountain steptoes and kipukas on ELMA’s west side6,7). Cultural material evidence of these early occupations in the lava fields is rather more circumstantial, however, represented by lithic materials most frequently associated with later Puebloan occupations. Evidence of human activity on the McCartys flow and especially the earlier, tube-bearing lava flows during the Puebloan cultural sequence is extensive5,8.

S2. Geology, present-day climate, and forest fires. Eruptions in the Zuni-Bandera volcanic field began as early as 700,000 years ago, but in ELMA, the basalt flows are younger than 100,000 years9,10. Both aa (jagged and very broken) and pahoehoe (smooth and ropy) lava type flows exist, but only the latter one supports the formation of lava tubes11; Cave 29 is in Bandera Flow (~11,000 years)12. El Malpais’ youngest lava flow is from the McCartys cinder
cone and was active 3,900 years ago, effectively covering probable evidence of earlier human
use of older lava8,13 (Supplementary Fig. S1). From a geomorphological point of view, ELMA is
a high elevation (2100 to 2600 m) desert environment. The mean annual temperature in ELMA
is 10.3°C (-36º to +41ºC), typical for a continental climate. Precipitation averages 218 mm, with
35-40% occurring as monsoonal rainfall between July and August and 37% falls in winter
(October through March) when low-pressure systems moving from west to east across the
Southwest, coalesce with moisture from the Pacific Ocean or the Gulf of Mexico13,14. Unless
localized thunderstorms deliver higher than normal rainfall, the summer precipitations are
hydrologically less important because much of the rain evaporates before it percolates into the
subsurface. Winter precipitation falls primarily as snow that melts in early spring and infiltrates
into the ground. The vegetation in the area comprises ponderosa and piñon-juniper woodland
and savanna, whereas the understory is dominated by native short prairie grasses interspersed
with cacti14 (Supplementary Fig. S5). Depending on their size and age, which among others
control soil development, each lava flow within ELMA supports characteristic vegetation
assemblages. Chances for natural fire ignition (drought, lightning, etc.) and spread are specific
to each individual plant habitats (e.g., ancient or young basal flow, cinder cones, kipukas), thus,
frequency, proportion, and intensity of wildfires are not all the same throughout the park15. The
cold season is not the wildfire season that typically begins during mid-summer monsoons and
sometimes persists through the end of September. The collapsed lava tube that forms the
trench in front of the cave is virtually free of vegetation (other than wet moss garden). There is
little fuel to carry fire to the cave entrance. Though heavy fuels could fall in the trench during
wildfire, there is no evidence around the cave entrance.
Reconstructions of wildfires events using tree-ring data collected in ELMA cover only the period
since AD 1350 and indicate that prior to 1880 the majority of fires occurred approximately once
every five to eight years16,17. In terms of seasonality, the data available between 1600 and 1991
suggest that most wildfires occurred in the early part of the growing season (April to June),
except for the 1740–1840 interval, which was characterized by late-season fires15. The records
compiled for the American Southwest suggest century-long climate forcing of wildfire events,
especially during dry years that are often associated with La Niña18,19.

S3. Lava tubes and ice accumulation in ELMA. Lava tubes are found mainly on ELMA’s
west side in the El Calderon, Hoya de Cibola, Twin Craters, and Bandera lava fields10. Master
tubes and distributary tubes were primary conduits for lava along the length and breadth of the
flows creating numerous passages11. Lava tubes range from small and constricted surface
tubes to long, deep caverns. Sections of deeper tubes are cold traps where temperature and
relative humidity conditions remain constant year round and percolating water (from rain or
snowmelt) is preserved in accumulations of perennial ice in the freezing zone20-22. Seasonal ice
in ELMA occurs near the cave entrances as frozen pools or sheets on cave floors, ice walls, ice
stalagmites and stalactites, and as ribbons of ice clinging to walls or breakdown. This ice
represents a source of water that lasts until early summer when sunlight shines through the
cave entrance and promotes ice melting. Instead perennial ice deposits, which accumulate
further inside the lava tubes provide a year-round water source. Such lava tubes are thought to
have been an important source of domestic water for the Puebloans in the ELMA area5,23.
Worth noting is that like the seasonal ice formations and the ebb and flow of the perennial ice is
linked with the availability of percolation water entering caves. For example, in 1988, the
perennial ice in Cave 23 (in the vicinity of Cave 29) grew large enough to block the main
passage of the cave, receding to a small deposit and ice ponds 20 years later23,24.

S4. Cave ice volume estimation. Generally, lava tubes in ELMA have a rather classic internal
morphology (hollow passages with circular, elliptic, or oval cross-sections and localized
breakdown piles), which allow three-dimensional (3D) volume calculation based on spatial
partitioning, e.g., using voxel (volume elements like cylinders, oval, or rectangles). The result is
a discrete image of the volume model. To calculate the volume of Cave 29 beyond the
constriction (Fig. 1b), we divided this part of the cave into three oval tubes for which the length (L), width (W), and height (H) were obtained from the cave map generated by using a high-resolution terrestrial laser scanning technology (Supplementary Table S1). The volume of each tube is calculated by multiplying the area (A) of the discoretangle (i.e., a geometric shape similar to a stadium, which in fact is a rectangle with equal semicircles on both ends) by the length (L) (Equation 1 in Supplementary Fig. S6). Using the data from cave mapping in Equation 1, a conservative total volume (Vtot) of 1975 m$^3$ was computed by summing up the volume of each oval tube. Next, we estimated how much ice would fit into this cavern. From monitoring studies conducted in other ice caves around the world\textsuperscript{25-28}, it is known that regardless of ventilation type, caves can only host a limited amount of ice and cannot be filled completely, unless they are vertical shafts. As ice volume progressively increases, the available space for surface-sourced cold air accumulation decreases, and the conditions in which new ice layers form become less and less favorable. Considering the morphology of cave passage beyond the constriction zone, which controls the flow of cold air towards the inner part of the cave and using the calcite bathtub line present on the walls as a marker for the highest level of ice (see Results), we inferred that the ice block had a maximum thickness of 3.02 m (i in Supplementary Fig. S6a). The volume occupied by ice (V_{ice}) in each discoretangle was calculated using Equation 2 (see Supplementary Fig. S6). To do this, we first computed the volume of ice fill in the rectangle (V_{ice-rectangle}) and in the cylinder (V_{ice-cylinder}) assuming they were filled with 3 m of ice. The ice filled volume of a rectangle is length (L) times width (a) times ice thickness (i). To calculate the volume of ice that partly fills a horizontal cylinder, we used Equation 3 (Supplementary Fig. S6) in which we subtract from the total volume of the cylinder ($V_{cylinder} = \pi r^2 L$) the area of a circular segment (gray shaded part of the circle in Supplementary Fig. S6) that represents the air-filled portion of the tube. Adding the three values (Supplementary Table S1), a maximum V_{ice} of 1377 m$^3$ was obtained. However, because passages are not perfect geometric shapes and few areas are covered by collapses, which could not be accounted for, we consider these calculations as estimates. Thus, a more conservative and realistic volume of ice would be ~1000 m$^3$ that represents ~1,000,000 liters of water.

Supplementary References

8 Zedeño, M. N., Schrag-James, J. & Basaldu, R. C. Overview and Inventory of ethnographic resources for Petrified Forest National Park, El Malpais National


Supplementary Fig. S1. Map of the El Malpais National Monument showing boundaries of the major lava flows and part of the Ancestral Puebloans trail network. The numbers refer to Candelaria Ice Cave (1) and Cerritos de Jaspe/Pack (2) and Acoma–Zuni (3) trails. The figure was produced with ArcGIS Desktop v. 10.6 by ESRI (https://desktop.arcgis.com/en/) using the geodatabase on file at ELMA.
Supplementary Fig. S2. View of charred material at the edge of the ice block in Cave 29 (Photo by B.P. Onac).
Supplementary Fig. S3. (a) Microphotograph of charcoal fragments from the ice core horizon dated to AD 829, taken with a Nikon SMZ 1500 binocular. (b) Secondary electron microphotograph of soot particles (bright white) in sample NIC 34 (AD 368) collected with a JEOL JSM 6490 scanning electron microscope. Photos by B.P. Onac.
Supplementary Fig. S4. Overview of the ice deposit (maximum height ~2.5 m) and the charcoal blanket covering the cave floor (foreground) (Photo by B.P. Onac).
Supplementary Fig. S5. Landscape photography showing ponderosa pines growing on pahoehoe basalt flow and the collapsed section of a lava tube (Photo by B.P. Onac).
Supplementary Fig. S6. Elements of the discorectangle and a circular segment and the equations used to estimate the total volume and the volume of ice fill. The drawing was produced with Adobe Illustrator CC 2020 v. 24.2.3 (https://www.adobe.com/creativecloud.html).

\[ A = \pi r^2 + 2ra \quad r = H+2; \quad a = W - H \]

\[ V_{\text{tot}} = (\pi r^2 + 2ra) \cdot L \quad (\text{Eq. 1}) \]

\[ V_{\text{ice}} = V_{\text{ice-cylinder}} + V_{\text{ice-rectangle}} \quad (\text{Eq. 2}) \]

\[ V_{\text{ice-cylinder}} = \pi r^2L - (0.5)r^2(\theta - \sin \theta) \quad (\text{Eq. 3}) \]
Supplementary Table S1. Measurements used to estimate the ice volume in Cave 29.

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<th>Voxel</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Height (m)</th>
<th>Volume (m$^3$)</th>
<th>Ice thickness (m)</th>
<th>Ice volume (m$^3$)</th>
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