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Abstract

Meteorites, silicious vesicular melt glass, Fe and Si-rich magnetic spherules, positive Ir and Pt anomalies, and burned charcoal-rich Hopewell habitation surfaces demonstrate that a cosmic airburst event occurred over the Ohio River valley during the late Holocene. A comet-shaped earthwork was constructed near the airburst epicenter. Twenty-nine radiocarbon ages demonstrate that the event occurred between 252 and 383 CE, a time when 69 near-Earth comets were documented. While Hopewell people survived the catastrophic event, it likely contributed to their cultural decline. The Hopewell comet airburst expands our understanding of the frequency and impact of cataclysmic cosmic events on complex human societies.

Introduction

Direct positive evidence of catastrophic cosmic airburst and impact events have been found in the Western Hemisphere at the Cretaceous and Tertiary (KT) boundary ~65 million years ago and at the Younger Dryas (YD) boundary ~12,800 years ago.[1,2] Both of these events are associated with global mass extinctions and they occurred before humans culturally evolved into complex, sedentary, agricultural-based societies. The recent discovery of two Holocene cosmic impact events in Argentina (~6,000 B.P. and ~3,000 B.P.), and one in Jordan (~3,700 B.P.), suggests that these natural catastrophes are far more common than previously suspected.[3,4] Between 1,800 and 1,431 years ago (220 and 589 CE), Chinese astronomers documented 69 comets, including Haley's, which came within 0.09 au of earth in 374 CE (1646 B.P.).[5] At this time, human communities and the resources they needed for survival were at a heightened risk of being destroyed by a comet airburst event.

Comets are dirty fractured snowballs composed of cosmic dust, frozen gases, and meteoroids.[6] In some cases, comets such as SL9 break apart and impact planets.[7] If a comet fragment fell into the high-pressure air of earth's thermosphere, an explosion, known as an airburst, would release a devastating high-energy shockwave over a large area resulting in burned agricultural fields, buildings, and forests as evidenced by the Tunguska event of 1908.[8] Comet airburst events produce meteorites, vesicular melt glass from the melting and vaporizing soil, iron (Fe) and silicon (Si) rich magnetic spherules, and positive anomalies of iridium (Ir) and platinum (Pt).[9]

Archaeological evidence of ancient cosmic impact events, such as meteorites, tektites, and vesicular melt glass, has been recovered from archaeological sites of various ages in Europe, the Near East, and China.[10,11] In the western Hemisphere, Hopewell archaeological sites in the Ohio River valley contain an anomalously high concentration and diversity of meteorites when compared to all other cultural periods. They include iron meteorites (e.g., ataxites, hexahedrites, octahedrites), stony iron meteorites (e.g., mesosiderites, pallasites), and stony meteorites (e.g., olivine hypersthene chondrites).[12]

The spatial distribution, contexts, and diverse composition of Hopewell meteorites has been explained as acquisition through long-distance exchange systems and trade networks.[13,14,15,16,17] It is possible, however, that many of the Hopewell meteorites resulted from a single cosmic airburst event. Comets contain a variety of meteoroids with different elemental and mineralogical composition. Here, we present the results of an interdisciplinary examination of multi-proxy evidence for a Hopewell comet airburst event from the systematic investigations of eleven archaeological sites in the Ohio River valley. We use radiocarbon and typological dating to determine the timing of the event and we suggest that it may have contributed to the social decline of the Hopewell.

Hopewell

Genetic analyses demonstrate that modern Native Americans are the direct descendants of the Hopewell.[18,19] The archaeological hallmarks of the Hopewell include monumental landscape architecture—the largest geometric earthen enclosures in the world, intricate water management systems, massive burial mounds, and extensive ceremonial centers.[20,21] Distinctive symbols, artwork, and exotic goods, which have been traced from unprecedented continental distances of more than 2,400 km indicate that the Hopewell had a widespread social network between ~100 BCE and 400 CE, which spanned the Atlantic Ocean to the Rocky Mountains and from Canada to the Gulf of Mexico.[22] The spatial and temporal distribution of Hopewell archaeological sites are associated with a stable and sedentary society with a political hierarchy. The greatest concentration of Hopewell archaeological sites occurs in the Ohio River valley with the largest ceremonial centers (hundreds of hectares) located along the tributaries of the Scioto and the Little and Great Miami rivers.[23,24]

The earliest investigations of Hopewell archaeological sites began in the 18th century and accelerated during the late 19th and 20th century, resulting in detailed site maps, chronometric ages, and artifact provenances.[23,24] While past investigations have focused on Hopewell economies, mortuary practices, sociopolitical interaction, social stratification, and symbolism, the reason for the rapid cultural decline of the Hopewell ~1,600 B.P. remains unresolved.[25] Theoretically, a comet airburst event is a possible explanation for the cultural downturn given that the period of near-Earth comets occurred immediately prior to the terminal age of Hopewell archaeological sites. In order to address this possibility, we examined the contextual and temporal evidence of comet airburst-related proxies at eleven Hopewell sites in the Ohio River valley (Fig. 1).

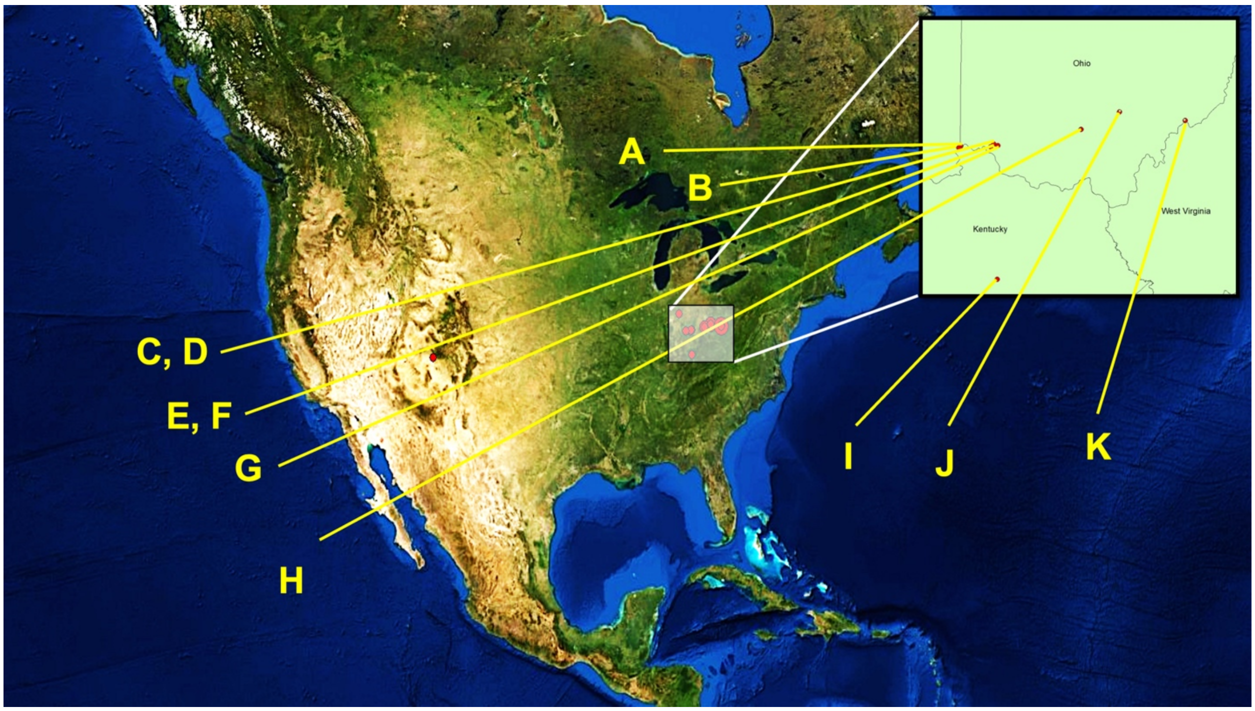

Fig. 1. Geographic setting of Hopewell archaeological study sites for airburst-related proxies: (A) Jennison-Guard village site, Indiana; (B) Miami Fort hilltop earthworks, Ohio; (C) Turner earthworks and village, Ohio; (D) Moundview village and mound, Ohio; (E) Milford earthworks, Ohio; (F) Beech Tree village, Ohio; (G) Foster’s Crossing earthwork, Ohio; (H) Krasnosky earthworks, Ohio; (I) Indian Fort Mountain earthworks, Kentucky; (J) Junction earthworks, Ohio; and (K) Marietta earthworks and mounds.

Results

Comet airburst-related proxies

Our interdisciplinary research focused on six comet airburst-related proxies including meteorites, silicious vesicular melt glass, Fe and Si-rich magnetic spherules, positive Ir and Pt anomalies, and burned carbon-rich strata on Hopewell archaeological sites in the Ohio River valley (Section S1). Of the eleven archaeological sites, which we investigated, meteorites were found at the Turner earthworks and village in Hamilton County, Ohio and the Marietta earthworks and mounds in Washington County, Ohio. The Marietta meteorite was collected in 1819.[13,16,26] Approximately 1,604 g of pallasites have been recovered from the Turner site (Fig. 2).[27,28,29] Some of the meteorites appeared burned and hammered into thinly pounded sheets used in the production of jewelry and musical instruments.[30] Recent pallasites recovered from the Turner site are fine gravel or coarse sand size ($\leq$ 2.5 mm). They were likely missed in previous archaeological investigations because the sediments were not screened (Fig. 2).

It long has been assumed that meteorites from the Turner site were pieces of the Brenham pallasite obtained from Kiowa County, Kansas through trade.[13,14] However, the concentrations of Ga and Ge in the Turner specimens are 10% lower than the Brenham pallasite.[12] While the Ir concentration of the Turner meteorites is well within the range found in the Brenham pallasite the level of Pt is five times lower (Section S2).

In order to determine if the meteorites from the Turner site resulted from a cosmic impact event, sediment from the village habitation stratum was petrographically examined for melt glass. Siliceous melt glass is one of the most prominent cosmic airburst and impact materials because it forms at temperatures $\geq$ 1,700 ^{o}C.[31] Scoria-like vesicular melt glass, up to 0.4 mm in diameter, was identified from the burned carbon-rich habitation stratum of the Turner site (Fig

2). The melt glass is comparable in size to specimens identified in YD boundary strata where it co-occurred with Fe and Si-rich micro-spherules.[31]

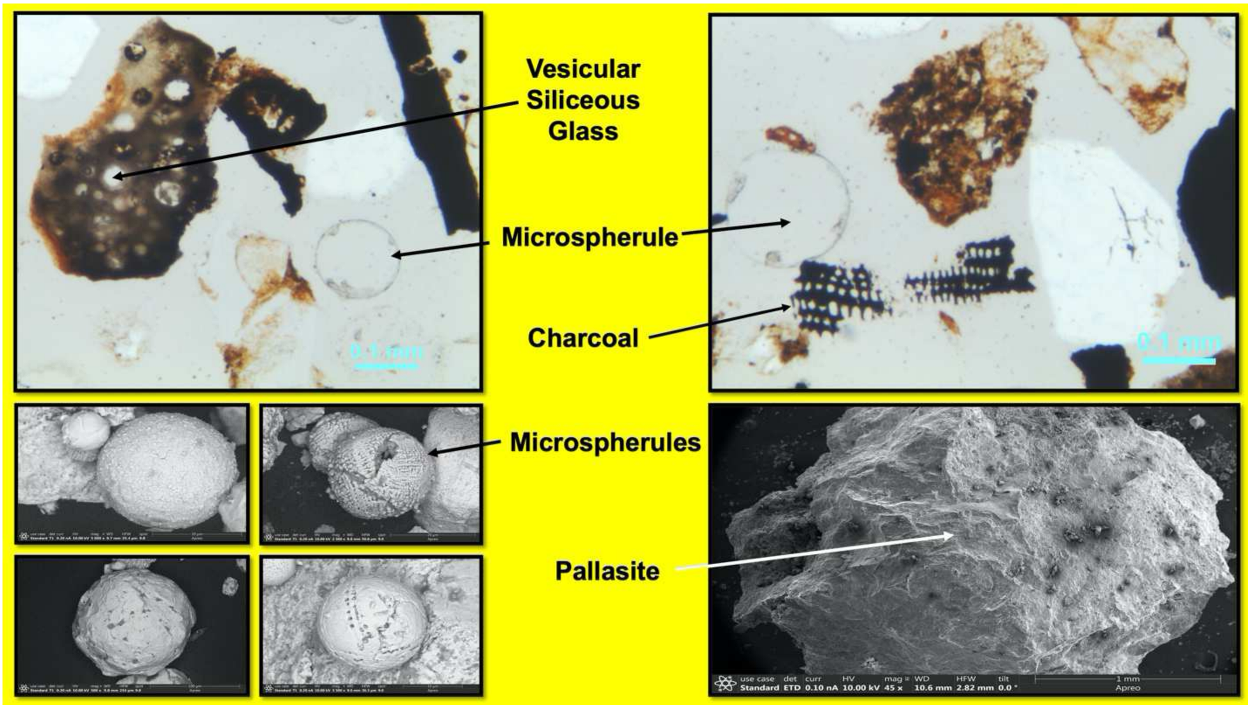

Fig. 2. Airburst-related proxies from the burned, carbon-rich habitation stratum of the Turner village site including silicious vesicular melt glass, Fe and Si-rich magnetic spherules, and a pallasite meteorite.

At the Turner site, Fe and Si-rich magnetic spherules are present as black-to-clear micro-spheroids up to 0.4 mm in diameter (Fig 2). Fe and Si-rich magnetic spherules were also found in the habitation strata of all of the Hopewell archaeological sites sampled, ranging in size from 28.2 to 395.8 µm (Section S1, S3). SEM microscopy shows that the morphology and outer surface textures are distinctive of spherules of Fe and Si-rich magnetic spherules that resulted from rapid quenching. They are well within the size range, morphology, and texture as those recovered from the KT boundary strata (300 µm to 1.4 mm), the YD boundary strata (10 µm to 5.5 mm) and the 1908 Tunguska airburst event site (20 to 100 µm).[1,31,32,33] Like the siliceous melt glass, the Fe and Si-rich micro-spherules do not occur above or below the burned carbon-rich habitation strata.

A positive Ir anomaly (1.08 ppb) was found in the burned carbon-rich Hopewell habitation stratum of the Turner site (Section S3). Ir in the Turner site sediments is 50x as high as the natural crustal abundance (0.02 ppb).[34] Of the eleven Hopewell archaeological sites sampled, Ir levels from burned carbon-rich habitation strata ranged from 0.10 to 1.08 ppb. The level of Ir (1.08 ppb) in the habitation strata of the Turner and the nearby (5 km) Moundview site is approximately twice that commonly found in meteorites (0.5 ppb) (Fig 3.).[34,35] Although the level of Ir in the habitation strata of the Turner and Moundview sites is not as elevated as that found in the KT boundary strata (3.9 ppb), it is well within the range reported from YD boundary strata (< 0.5 to 3.8 ppb).[1,34]

Positive Pt anomalies (0.53 to 6.23 ppb) were found in ten of the eleven Hopewell archaeological sites sampled (Fig. 3). The Pt level of the Turner site (6.23 ppb) is 12x the natural crustal abundance (0.5 ppb) and well within the range reported for the KT (4.0 to 8.0 ppb) and YD (0.3 to 65.6 ppb) boundary strata.[36,37] The Pt abundance in the burned charcoal-rich habitation level of the Krasnosky earthwork (0.53 ppb) fell within the level of the crustal abundance of 0.5 ppb.[37] Positive Pt and Ir anomalies were only found in the burned carbon-rich habitation strata of the Hopewell sites sampled (Section S3). Pt and Ir levels were below detection limits above and below the habitation strata.

The habitation surface of all eleven of the Hopewell sites sampled were fire-hardened, carbon-rich, and contained masses of wood charcoal (Section S3). The burned, carbon-rich nature of Hopewell habitation strata in the Ohio River valley was first described during the late 19th century.[28,39,40] At the Turner site, the remains of Hopewell habitation structures were found on fire-hardened, ash covered surfaces with post-molds filled with wood charcoal.[30] At Foster's Crossing in Warren County, Ohio, the habitation surface was described as having been exposed to extreme heat. The stratum was labeled as "vitreous" with "great masses of slag" resembling "that from a blast furnace," and limestone that had been thermally reduced to lime.[39,41]

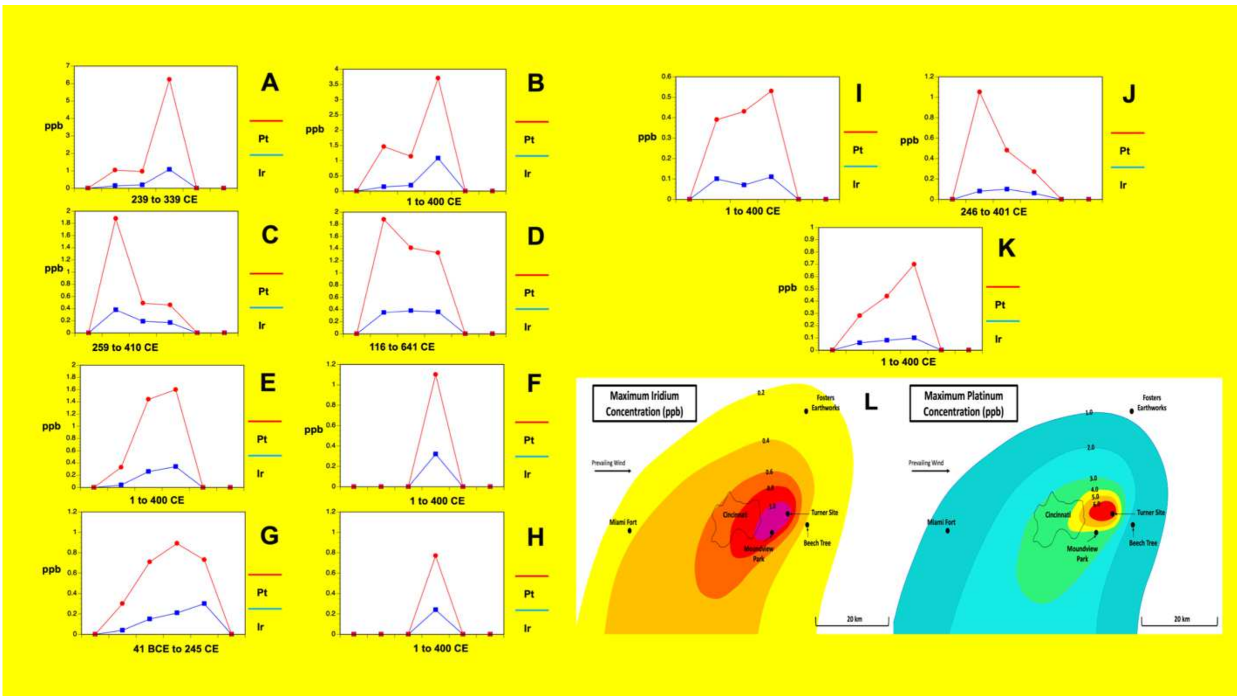

Fig. 3. Positive Ir and Pt anomalies from the burned carbon-rich strata on Hopewell archaeological sites in the Ohio River valley: (A) Turner earthworks and village, Ohio; (B) Moundview village and mound, Ohio; (C) Miami Fort hilltop earthworks, Ohio; (D) Jennison-Guard village site, Indiana; (E) Beech Tree village, Ohio; (F) Milford earthworks, Ohio; (G) Indian Fort Mountain earthworks, Kentucky; (H) Foster's Crossing earthwork, Ohio; (I) Krasnosky earthworks, Ohio; (J) Junction earthworks, Ohio; (K) Marietta earthworks and mounds; and (L) isoline maps of positive Ir and Pt anomalies.

We found similar burned features at the Miami Fort site in Hamilton County, Ohio and the Jennison-Guard site in Dearborn County, Indiana (Section S3). The remains of burned Hopewell structures had been swept into piles of carbonized timbers and thatch, fire-hardened daub, and thermally damaged artifacts. Limestone from the burned structures was reduced to calcium oxide, which indicates a temperature of $\geq$ 765°C. The widespread occurrence of burned wooden structures and carbon-rich, heat-altered habitation surfaces at all eleven of the Hopewell sites examined suggests widespread synchronous fires resulting from a catastrophic cosmic airburst event.

In order to evaluate the impact of the airburst event on vegetation, stable carbon isotope values were obtained on bulk organic matter obtained from Hopewell reservoir sediments at the Miami Fort site (Section S3).[42] The reservoir strata ranged in age from the beginning of the Middle Woodland cultural period, ~100 BCE, to modern. The $\delta^{13}C$ values of bulk organic matter show that the vegetation composition varied through time. The $\delta^{13}C$ isotope values from the Hopewell sediments ranged -23.76 to -24.77 (N = 3) with an average of -24.24 $\pm$ 0.5‰. The $\delta^{13}C$ values of bulk organic matter from the post-Hopewell sediments ranged from to -24.38 to -26.45 (N =17) with an average of -25.33 $\pm$ 0.5‰. Stable carbon isotope values indicate a landscape dominated by C3 vegetation throughout the late Holocene with a significant change in C3 vegetation indicated by a $\delta^{13}C$ value of -23.76, which was obtained from a stratum dating to the time of the Hopewell airburst (Fig. 4).

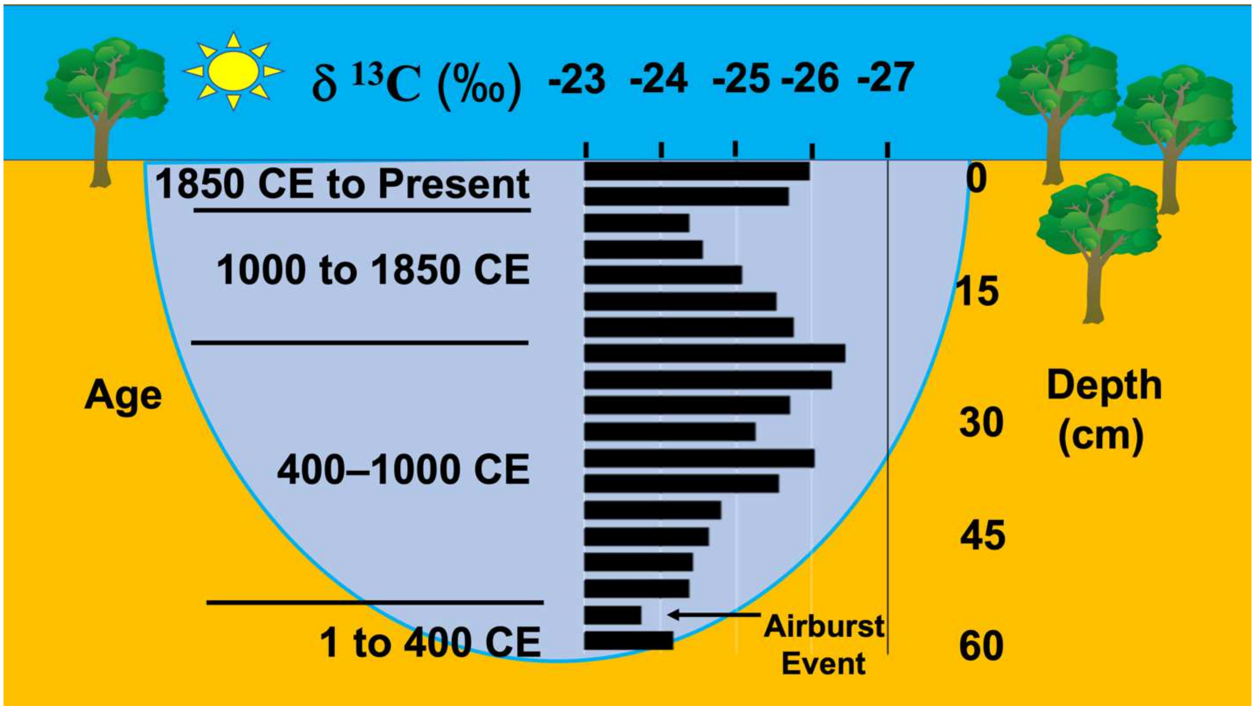

Fig. 4. Chronostratigraphy of a Hopewell reservoir at the Miami Fort earthworks and village site showing the d ^{13}C values and ages by depth.

Chronological context

Radiocarbon and typological dating were used to provide a chronological context for the Hopewell comet airburst related proxies and evaluate their synchroneity. Typologically, distinctive Hopewell artifacts were defined on the basis of similarities in their form, method of manufacture, raw material, style, and use. Temporally diagnostic artifacts, which date between 100 BCE and 400 CE, were found in the Hopewell habitation strata of all eleven of the archaeological sites examined (Section S3). They include Hopewell earthenware pottery and figurines, microblades and microblade cores, mica effigies, and Lowe-flared and Snyders bifaces.[23]

Radiocarbon ages were obtained for the Turner, Jennison-Guard, Miami Fort, Marietta, and Indian Fort Mountain sites (Fig. 5). Radiocarbon ages were calibrated to produce probability density functions using Bayesian statistics with credible intervals assigned to each date (Section S3). We used the IntCal20 calibration curve in the OxCal 4.4 computer program for Bayesian statistical analysis. Radiocarbon ages from the Turner (N = 7) and Jennison-Guard (N = 8) sites are considered high-quality because they were obtained directly from the burned carbon-rich habitation strata, they have the highest number of ages per stratum, the smallest degrees of uncertainties, and they are associated with a plethora of temporally distinctive artifacts.[43] The age of the airburst-proxy stratum at the Turner site is 1712-1612 B.P. (239-339 CE) with a probability of 95%. The age of the airburst-proxy stratum at the Jennison-Guard site is 1691-1541 B.P. (259-410 CE) with a probability of 95%. The Turner and Jennison-Guard site radiocarbon ages overlap at one standard deviation.

The radiocarbon ages from the Marietta (N = 4), Miami Fort (N = 7), and Indian Fort Mountain (N = 2) sites are well-dated, but they have greater degrees of uncertainties. The age of the airburst-proxy stratum at the Marietta site is 1704-1539 B.P. (246-401 CE) with a probability of 95%. The age of the airburst-proxy stratum at the Miami Fort site is 1867-1310 B.P. (116-641 CE) with a probability of 95%. The age of the airburst-proxy stratum at the Indian Fort Mountain site post-dates 1990-1706 B.P. (post-dates 41 BCE-245 CE) with a probability of 95%. Although the Marietta, Miami Fort, and Indian Fort Mountain radiocarbon ages are not considered high-quality, they do overlap at one standard deviation with the Turner and Jennison-Guard site radiocarbon ages. Twenty-eight radiocarbon ages place the Hopewell airburst proxies at 1699-1567 B.P. (252-383 CE).

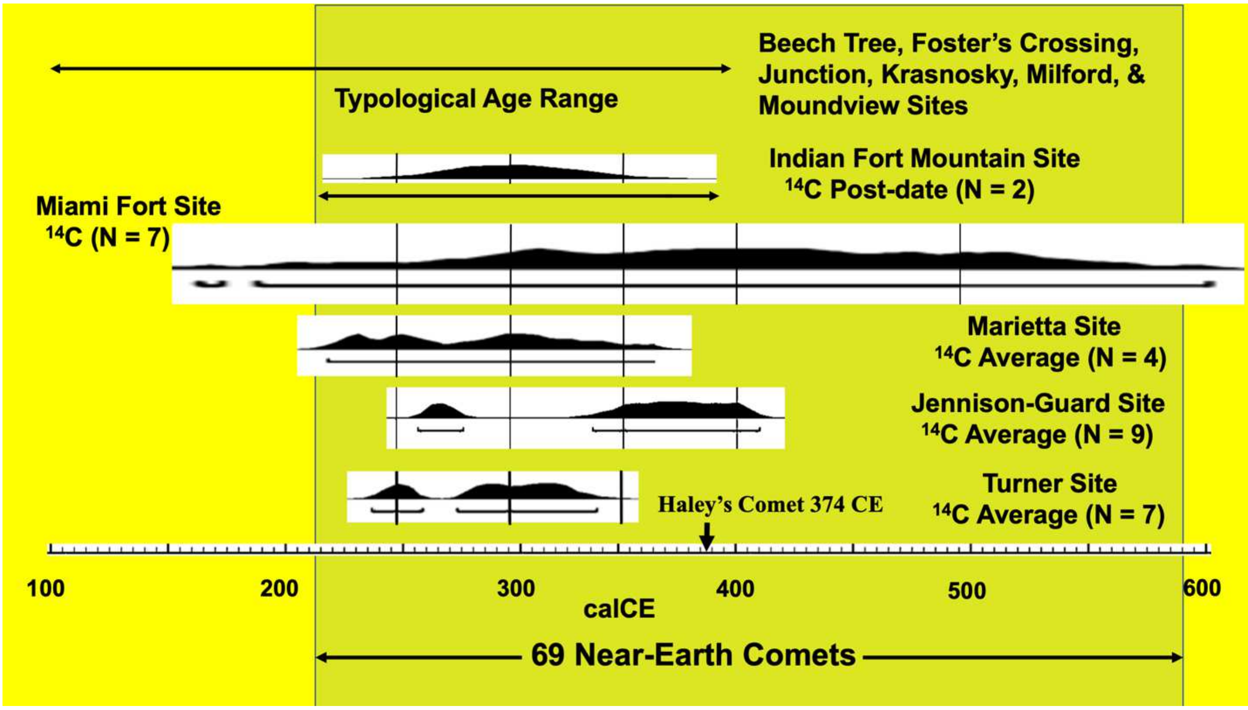

Fig. 5. Typological age range and Bayesian adjustments of the radiocarbon ages averages for the Hopewell archaeological study sites using the IntCal20 calibration curve in the OxCal 4.4 computer program relative to the timing of 69 near-Earth comets.

Discussion

Meteorites, vesicular melt glass, the highest levels of Ir and Pt, and the largest Fe and Si-rich magnetic spherules occur in a burned, charcoal-rich Hopewell stratum of the Turner site, which suggests it was at or near the epicenter of the airburst (Figs. 2 & 3). The spatial distribution of six independent proxies shows that the trajectory of the comet airburst was from the northeast to the southwest and the deposition of the ejecta was influenced by the prevailing westerly winds. The levels of Ir and Pt and the diameter of Fe and Si-rich magnetic spherules decrease with increasing distance from the epicenter. The high positive Pt anomaly at the Marieta earthwork suggests that multiple comet fragments likely impacted the Ohio River valley.

It is unknown whether or not there were human casualties from the airburst. Following the airburst event, Hopewell people collected meteorites, which they used in the production of objects that were interred with human remains. A Hopewell earthwork was constructed in the shape of a comet in the immediate vicinity of the airburst epicenter (Fig 6). Hopewell symbolic systems continue to be used ritually by descendant tribes as well as told in their oral histories, which refer to an ancient cosmic event.[44,45]

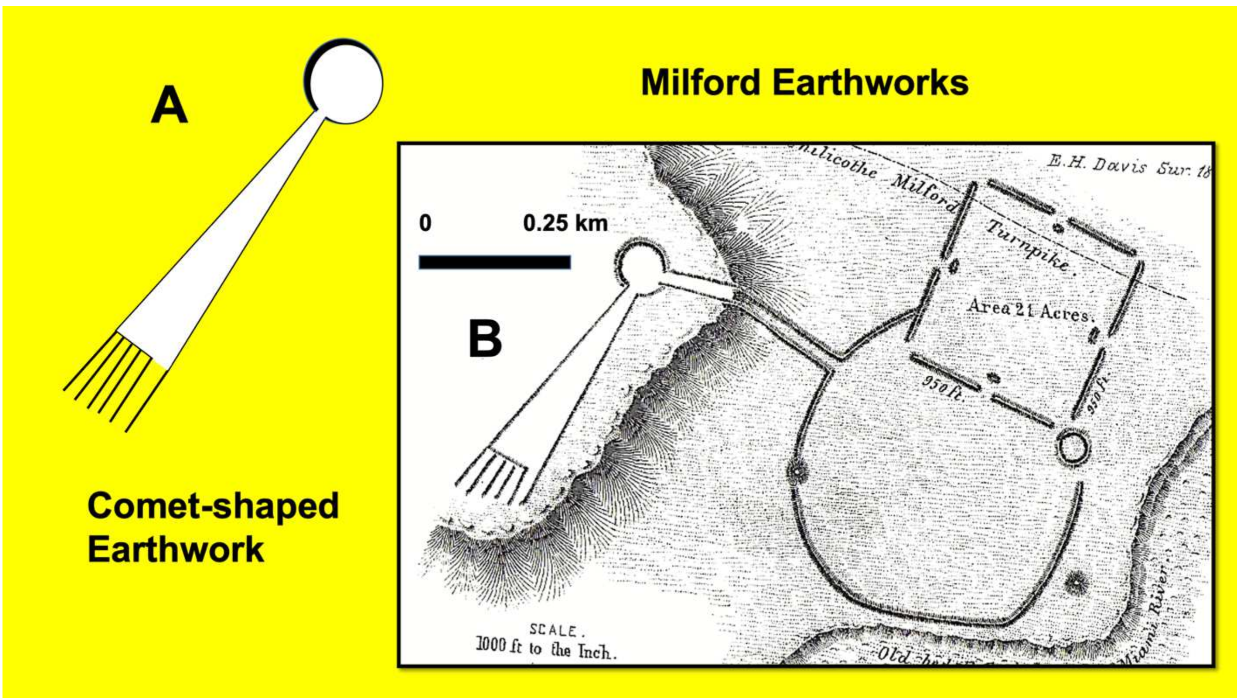

Fig. 6. Comet-shaped Milford earthwork based on E. G. Squier and E. H. Davis' 1848 *Ancient Monuments of the Mississippi Valley Comprising the Results of Extensive Original Surveys and Explorations* (Smithsonian Institution, Washington D.C.).

The Myaamia observed an ancient comet, which they call *Lenipinšia*, a horned serpent that crossed the sky and dropped rocks on the land before plummeting into the river.[46] The Shawnee word *Tekoomsē* refers to a comet known as the Sky Panther.[47] The Haudenosaunee say that the Sky Panther, *Dajoji*, has the power to tear down forests.[48] Ottawa oral histories describe a day when the sun fell from the sky, and the Huron and Wyandot recount a time when a black cloud rolled across the sky and was destroyed with a fiery dart by *Hehnoh*.[49] These millennial generational oral histories are deeply rooted in eye-witnessed events.[50]

Conclusion

The Hopewell comet airburst event adds to our growing body of knowledge of catastrophic cosmic events, which led to cultural downturns in ancient complex, sedentary, and agricultural-based societies. Multiple comet airburst event proxies have been found on eleven Hopewell archaeological sites in the Ohio River valley, which have typological and calibrated radiocarbon age ranges of 1699-1567 B.P. (252-383 CE). This time period coincides with historically documented near-Earth comets and occurs prior to the cultural downturn of the Hopewell. The discovery of meteorites, silicious vesicular melt glass, Fe and Si-rich magnetic spherules, vitrified clay, and thermally decomposed limestone on burned, charcoal-rich Hopewell habitation surfaces suggests that surface temperatures reached $\geq$ 1,700 ^{o}C, which would have burned wooden structures and altered the composition of C3 vegetation.

The cultural impact and geographic extent of cosmic airbust events can only be evaluated and interpreted through interdisciplinary investigations that include chronostratigraphy, petrography, and geochemical analyses. These methods, if carried out rigorously, will provide a greater understanding of ancient catastrophic cosmic airburst events, their impact on complex human societies, and their frequency not only in the Western Hemisphere, but elsewhere in the world.

Methods

Sediment samples were obtained from archaeological units and trenches, which were hand excavated by the authors (Section S3). Stable carbon isotope samples were extracted using a split-spoon, 5-cm diameter solid sediment core and a hand-operated drop-hammer. Soil horizons and stratigraphic boundaries were defined in the field on the basis of color, texture, structure, and pedogenic features and confirmed in the lab with particle size analysis and Munsell soil color charts (Section 3). The location of all archaeological features, sediment cores, excavation units, and trenches were recorded in the field using a hand-held GPS (Section S1). AMS radiocarbon samples and XRD samples were collected from excavation units, trenches, and solid sediment cores (Section S3). AMS radiocarbon ages were determined at Beta Analytic and the Center for Applied Isotope Studies at the University of Georgia (Section S3). Radiocarbon ages were calibrated and Bayesian statistical analysis was done using the IntCal20 calibration curve in the OxCal 4.4 computer program (https://c14.arch.ox.ac.uk/oxcal.html). Scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS/EDAX) was accomplished in the Advanced Materials Characterization Center at the University of Cincinnati (Sections S1 and S3). ICP-MS analyses were conducted at the Center for Applied Isotope Studies at the University of Georgia and are discussed completely in the Supplementary Materials (Sections S1, S2 and S4). Stable carbon isotope analyses were conducted at the Center for Applied Isotope Studies at the Reston Stable Isotope Laboratory, United States Geological Survey and are discussed in the Supplementary Materials (Section S5). Extraction of the Fe and Si-rich magnetic spherules from Hopewell archaeological contexts was accomplished in the Ohio Valley Archaeology Labortatory at the University of Cincinnati and are discussed in the Supplementary Materials (Section S6).

Data availability

All data generated or analyzed during this study are included in this published article (and its Supplementary Information files).

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Author contributions

K.B.T. conceived of the project and wrote most of the manuscript. K.B.T. and S.D.M. directed the fieldwork. S.D.M. conducted the soil and stratigraphic analyses. K.B.T., J.A.J., and L.H. directed the laboratory work. D.L.L. and S.A.M. conducted the archaeobotanical analyses.

Competing interests

The authors declare no competing interests.

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