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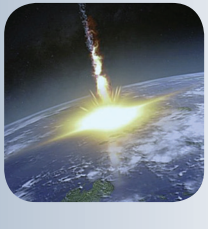

Research Article

Evidence for a large late-Holocene Strewn Field in Kiowa County, Kansas, USA

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ABSTRACT

The Brenham/Haviland meteor crater is just one of a plethora of impact features comprising a large (~800 ha) late-Holocene-age strewn field in Kiowa County, Kansas. More than 10,000 kg of pallasites, a rare class of stony meteorites, have been recovered from impact features and the surface of the strewn field. Six AMS radiocarbon ages demonstrate there is a 95.4% probability that the impact event occurred within a range of 1497 BCE to 419 BCE and most likely between 754 BCE and 419 BCE. The impact event is well described in Pawnee oral histories and illustrated in petroglyphs near the strewn field. The age and geographic extent of the Kiowa County, Kansas, strewn field increases our understanding of the frequency of cosmic impact events on Earth and their influence on people and culture change.

KEYWORDS

cosmic impact event, meteorites, pallasites, Great Plains, Native Americans, ethnoastronomy

Introduction

There is evidence that Native Americans have transgenerational knowledge of past cosmic impact events that have been passed down through their oral histories and cultural traditions [1]. The homeland of one Native American tribe, the Pawnee, is in the Great Plains of North America, including Kansas. The Pawnee are known for the accuracy of their astronomical knowledge [2, 3]. Pawnee oral histories tell of a time when the stars flew and fell upon the Earth [2–6].

The Pawnee recorded this cosmic event as images engraved on sandstone cliff faces and ledges (Figure 1). Archaeologists refer to this site as the Star Shelter (14Kw301). Petroglyphs in that shelter (Figure 2B) are interpreted as depicting stars falling from the sky and landing among the people and animals. The Pawnee used distinctive crosses (+) to illustrate stars in the petroglyphs as well as on their star charts (Figure 2A) [5]. Archaeologically, they date to the Plains Village cultural period (~900 to 1850 CE).

Pawnee oral histories describe how they discovered the strewn field and collected the brightly colored meteorites for their sacred bundles [2, 3]. The Pawnee described finding a barren place where there were colorful turtle-shaped stones, some of which were so heavy that the people could not carry them [5–7]. Today, pallasites, a rare class of stony-iron meteorite, are found near the Star Shelter, appearing turtle-shaped with brightly colored translucent green

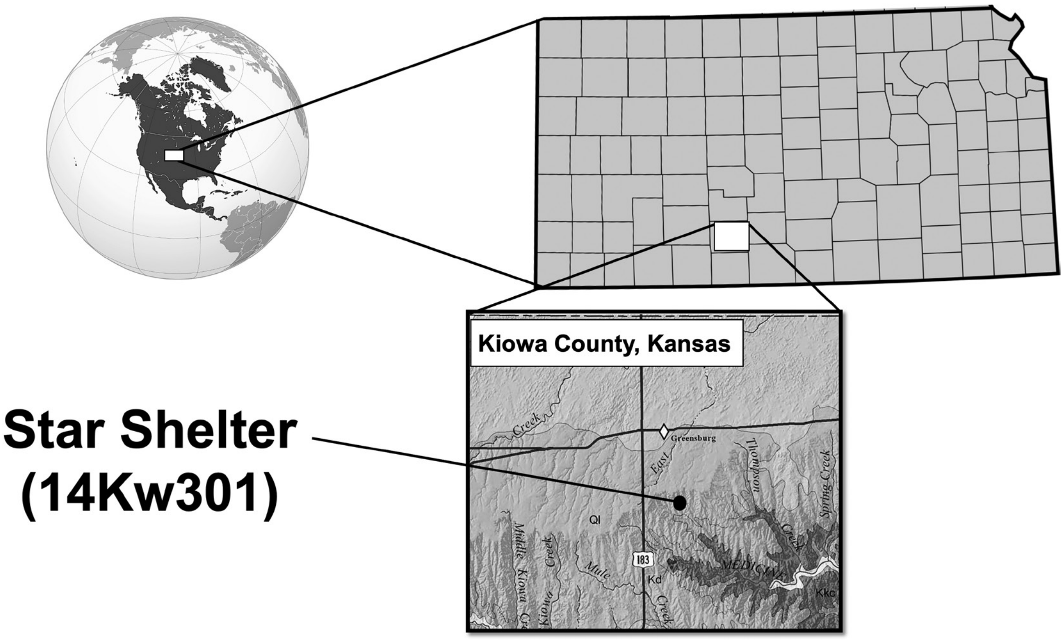

Figure 1: **The geographic location of the Star Shelter petroglyphs.**

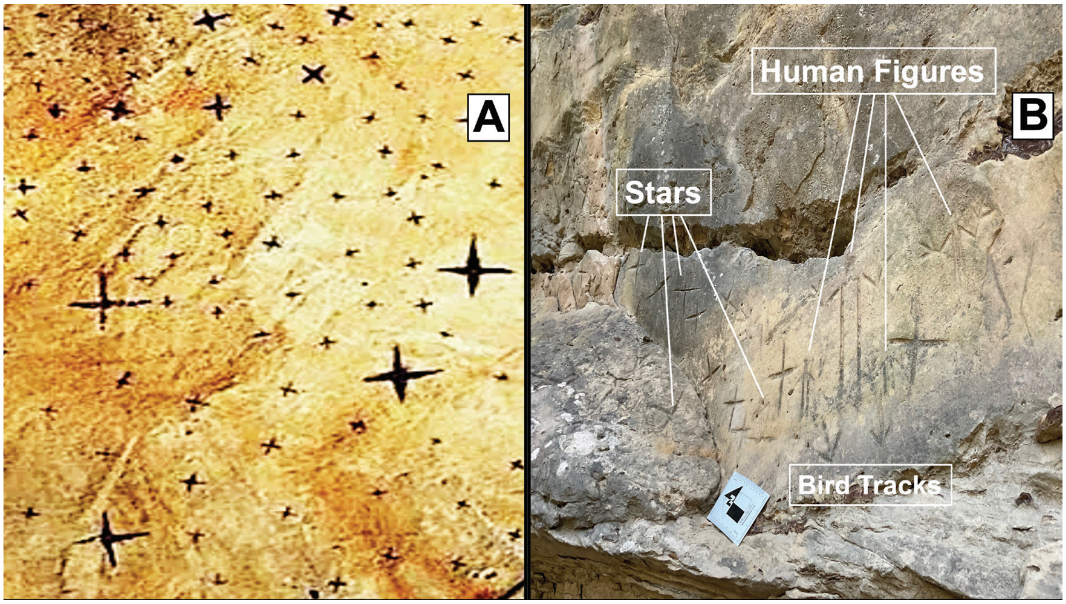

Figure 2: **Pawnee star symbols. (A)** Historic Pawnee star chart. **(B)** Pawnee petroglyphs at the Star Shelter. Note that the stars are in the sky as well as on the ground with the human and animal figures.

and yellow olivine crystals. An ancestral Pawnee lodge site located near Grandview, Kansas, contained a pallasite effigy painted as a box turtle carapace. It has been radiocarbon dated to between 1325 and 1450 CE, the same cultural period as the Star Shelter petroglyphs [7]. The radiocarbon age for the Pawnee lodge and the Star Shelter petroglyphs suggest that a cosmic impact event occurred in the Pawnee homeland of what is today Kiowa County, Kansas, during the late-Holocene.

Background information

The area surrounding the Star Shelter was once an extensive plain consisting of a near level to gently sloping (0–3%)

upland with loamy eolian soils. Today, it is known as Kiowa County, Kansas, and the Plains Border section of the Central Great Plains physiographic province of North America [8]. The county's northern portion includes the upper Arkansas River drainage basin and its tributaries Rattlesnake Creek, Medicine Lodge River, and Mule Creek. The southwestern portion of the county is in the Cimarron drainage basin and its tributary Sand Creek. Surficial deposits include Holocene and Pleistocene age alluvium (unconsolidated clay, silt, sand, gravel), loess (eolian silts), and dune sand.

Sand hills and sand-dune topography occur in the northern part of the county with flat, gentle, and moderate slopes in the central portion of the county and deeply dissected topography in the south with about 90 m of relief [8]. Surficial sediments are underlain by the Late Permian age Nippewalla Group, which includes the Whitehorse sandstone, Dog Creek shale, and the Medicine Lodge gypsum members of the Blaine Formation [8]. These strata are underlain by the Early Cretaceous age Dakota Formation (claystone, lignite, mudstone, sandstone, shale siltstone) and Kiowa Shale and Cheyenne Sandstone Formation (conglomerate, limestone, sandstone, shale).

This landscape was once covered by climax prairie grasses such as big bluestem, Indiangrass, little bluestem, and switchgrass [8]. Since the second half of the 19th century, this region has been used for cattle rangeland and plowed cropland. Ranch hands collected meteorites from a small depression they thought was a buffalo wallow approximately 20 km north of the Star Shelter petroglyphs. The ranch owners, Eliza and Frank Kimberly made a subsequent collection of meteorites from the area (~900 kg).

On March 13, 1890, Francis Whitmore Cragin identified the specimens in the Kimberly collection as a rare form of stony-iron meteorite known as a pallasite [9]. Details of their discovery and the pallasite's chemical and mineralogical composition were published in the journal *Science* later that year [9–11]. In 1925, Harvey Harlow Nininger, a self-taught American meteoriticist, visited the Kimberly ranch. He believed the buffalo wallow was the discernable rim of a cosmic impact feature. Nininger collected "small oxidized meteoric fragments" along the rounded rim of the 11 × 17-meter depression [12].

In 1926, the Kimberly's dug a hole in the depression and exposed a layer of pallasites at a depth of ~1 m. In 1933, Nininger and Jesse Dade Figgins were permitted to conduct a more formal excavation of the depression under the auspices of the Colorado Museum of Natural History [12]. They found a layer of pallasites above a highly oxidized horizon 1–2 cm thick (Figure 3). The oxidized horizon was created by the decomposition of the pallasites during seasonal water ponding in the impact feature. While chronometric data were not obtained from the excavation, it was determined that a large amount of time was not required to create the underlying iron-stained stratum.

Since the Nininger and Figgins' excavation, the depression on the Kimberly ranch has become known as the Brenham or Haviland meteorite crater or astrobleme [13]. Most meteoriticists assume that there was only one impact site. They also minimize the impact event by listing the Brenham/Haviland crater as one of the smallest impact craters in the world [13]. However, Pawnee oral histories suggest that the geographic

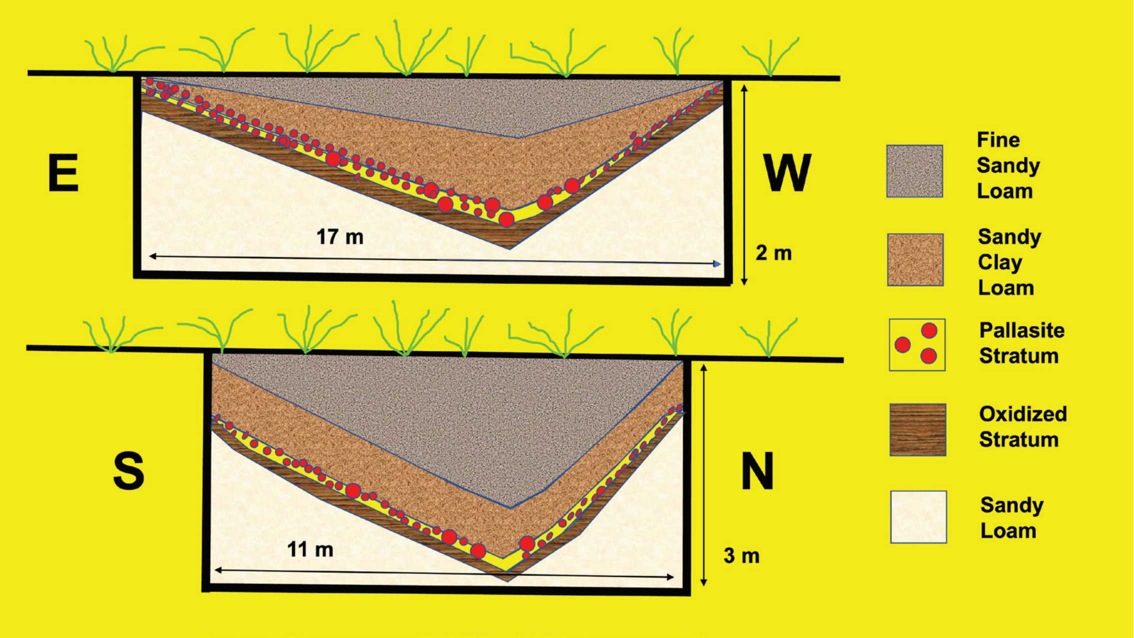

Figure 3: **This stratigraphy was exposed in the 1933 Nininger and Figgins' excavation.**

extent of the impact event covered a much larger geographic area. If the Pawnee oral histories are correct, then many buffalo wallows on the prairie land north of Star Shelter are impact features comparable to the Benham/Haviland crater and part of a much larger strewn field.

Meteorite masses greater than 9,000 kg can penetrate the atmosphere and create a large strewn field with multiple meteorite impact features posing a hazard to human populations [14]. Documenting a large, geologically recent (≤4,200 years ago) strewn field is a scientifically significant topic and severely understudied. Currently, direct evidence of Holocene cosmic impact events is significantly underrepresented [15]. Here, we present the results of a field and laboratory examination, which documents a large late-Holocene-age strewn field in the Pawnee homeland of Kansas.

Methods

Our investigation is based on archival research, geophysical survey, excavation, accelerator mass spectrometry (AMS) radiocarbon dating, scanning electron microscopy (SEM), and elemental analyses. Archival research included pallasite findspot data collected between 1890 and 1979 by George F. Kunz and Ellis L. Peck [10, 16]. A geophysical survey of the subsurface of ~10 km^2 surrounding the Brenham/Haviland impact feature was conducted using a Pulse Star II magnetometer (tb electronic GmbH • Hall-Str. 5 • 58638 Iserlohn) with an elliptically shaped coil, 3 m major and 0.9 m minor axes (Figure 4). The magnetometer provided audible localization signals associated with the pallasites' iron-nickel alloy fraction at depths >90 cm. The magnetometer was used in a gridded search pattern with a raster scan and a 30 cm overlap of a survey area. A distinctive slow rise and fall in the magnetometer's audible signal was an indication that an impact feature had been located.

Because the strewn field has been heavily plowed for more than 100 years, the surfaces of impact features have been totally obscured. Subsurface impact features detected with the magnetometer were hand excavated to expose the pallasite-bearing stratum, underlying oxidized horizon, and overlying strata (Figures 5–8). A backhoe was used to excavate the larger and deeper impact features. Stratigraphic units were characterized using Munsell soil color, sedimentary structures, and particle size. AMS radiocarbon samples were collected for chronometric dating. Pallasites were collected for SEM microscopy and elemental analyses. Pallasites were initially identified in the field using J.T. Baker Ni2+ ion-specific test strips impregnated with a colorimetric reagent for semi-quantitative field analysis. Specimens that tested positive for Ni were subsequently cut with a diamond saw to expose olivine crystals and the characteristic Widmanstätten NiFe crystal structure.

Accelerator Mass Spectrometry (AMS) radiocarbon dating of the sediments that were penetrated and contained meteorites is the most effective chronometric method to date geologically recent impact events [14, 15, 17]. AMS radiocarbon samples collected from the pallasite-bearing stratum and underlying stratum were submitted to the Center for Applied Isotope Studies at the University of Georgia. All rootlets were removed

Figure 4: Magnetometer survey conducted in a gridded search pattern with a raster scan and a 30 cm overlap of a survey area. Note the complete absence of impact surface features.

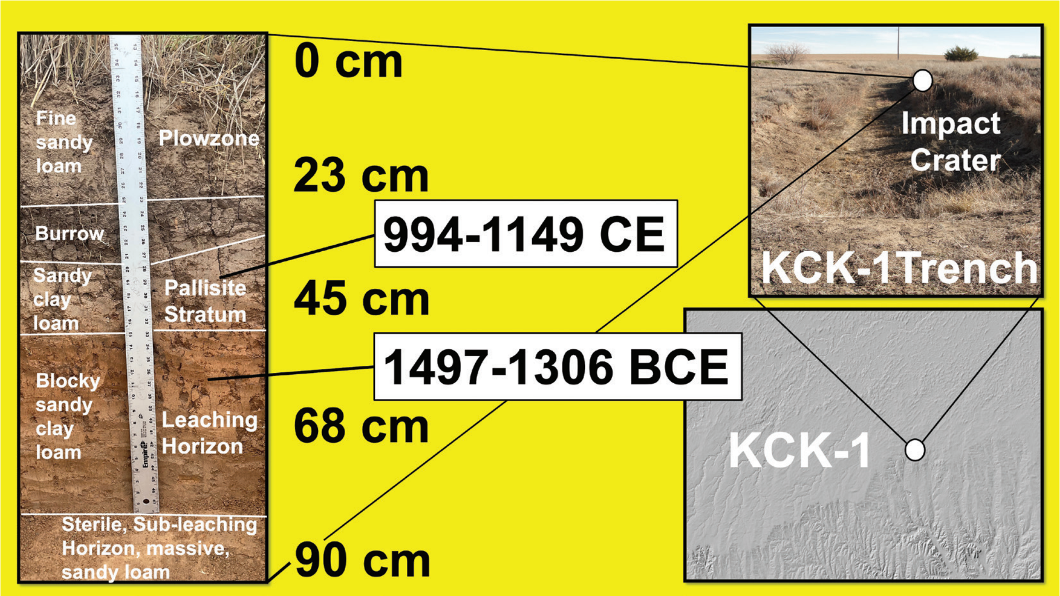

Figure 5: Chronostratigraphy of the Brenham/Haviland impact crater.

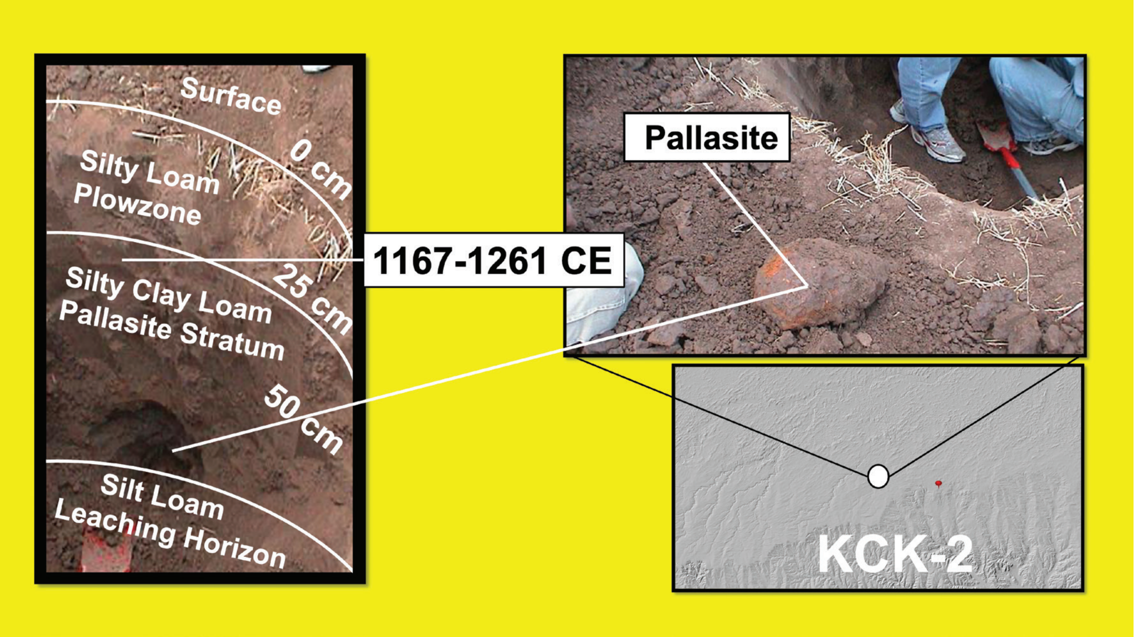

Figure 6: Chronostratigraphy of the KCK-2 impact feature.

from the sample using an ultrasonic bath and a wet nylon filter. The samples were then chemically pre-treated with 1 M HCl to remove carbonates, washed in pure water, and dried at 105 °C. Stable $^{13}C/^{12}C$ ratios were measured separately using a stable isotope ratio mass spectrometer and expressed as $\delta\ ^{13}C$ with respect to PDB with an error of less than 0.1‰.

Pallasites and sediment samples were analyzed using SEM and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) analyses. SEM was conducted at the Advanced Materials Characterization Center at the University of Cincinnati. SEM was used to identify olivine crystal structures in the pallasites and the surface morphology of the NiFe. Specimens were mounted on an SEM stub with a double-sided carbon adhesive. A SCIOS dual-beam SEM with a focused ion beam was used for high-resolution imaging.

ICP-MS was conducted at the Center for Applied Isotope Studies at the University of Georgia. ICP-MS instrumentation included a Thermo X-Series II (Thermo Fisher

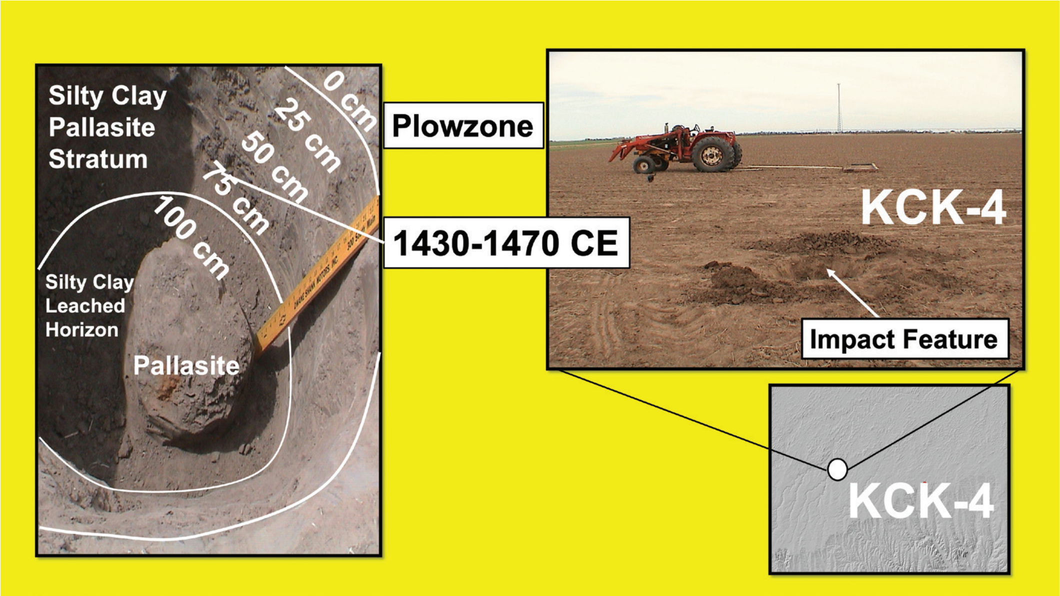

Figure 7: Chronostratigraphy of the KCK-4 impact feature.

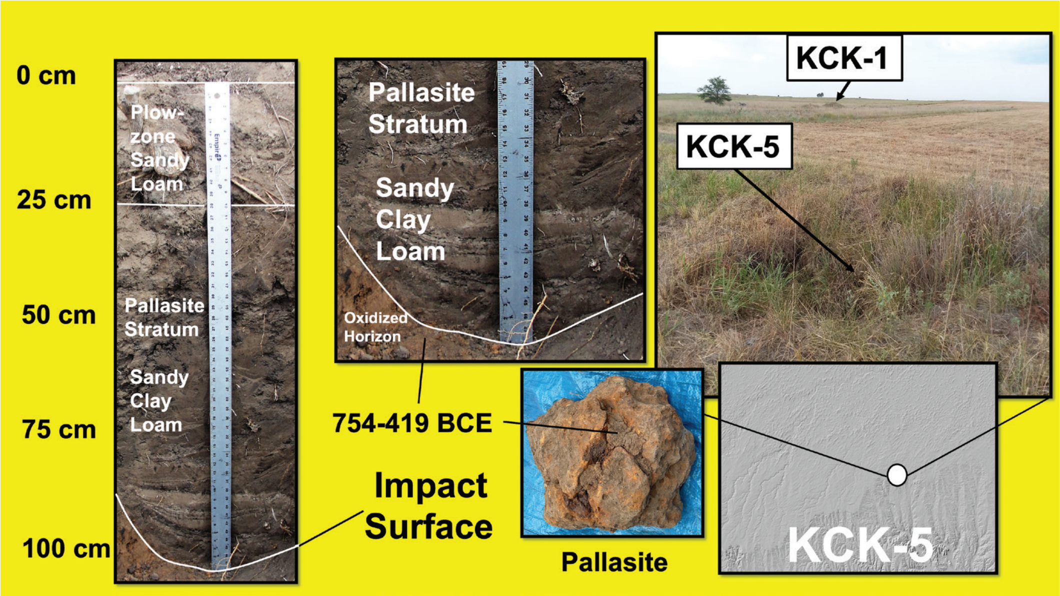

Figure 8: Chronostratigraphy of the KCK-5 impact feature.

Scientific, Germany) with peristaltic pumps and Cetac ASX 520 auto-sampler (USA). The leachate concentrations of 26 elements including Li, Be, Na, Mg, Al, K, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Ag, Cd, Cs, Ba, Ti, Pb, and U were measured at the ppm and the leachate concentrations of Ir and Pt were measured at the ppb. The purpose of these analyses was twofold: (1) to determine trace elemental variation within the pallasites and (2) to determine the quantity of Ir and Pt leaching into the pallasite-bearing stratum.

Results

Spatial distribution

More than 10,000 kg of pallasites and micrometeorites (<4 mm) were discovered across the late-Holocene-age surface of Kiowa County, Kansas [8]. Individual pallasites weighing between 0.5 and 680.4 kg were found within a ~800 ha strewn field in a west-north-west to east-south-east line of fall (Figure 4). A low correlation was found between pallasite depth (cm) and mass (kg) ($R^2 = 0.4$, $F(1,46) = 30.83$,

$p < 0.001$, $\beta = .037$, $p < 0.001$) (Table 1). Pallasites ≤450 kg are common in the upper 40 cm of late-Holocene loam, and many of them occur on the surface. Pallasites weighing between 450 and 680 kg occur at a depth between 1.2 m and 3.05 m (Figures 9–11).

Table 1: Provenience of pallasites in the strewn field.

Latitude	Longitude	Weight (kg)	Depth (cm)
W 99.1972°	N 37.5884°	18.64	86.36
W 99.1972°	N 37.5874°	31.82	58.42
W 99.2013°	N 37.5884°	45.45	114.3
W 99.2021°	N 37.5883°	10.00	91.44
W 99.2038°	N 37.5875°	4.39	86.36
W 99.2017°	N 37.5900°	17.27	134.62
W 99.2031°	N 37.5902°	3.95	81.28
W 99.1976°	N 37.5901°	9.09	101.6
W 99.1952°	N 37.5886°	40.00	147.32
W 99.1955°	N 37.5914°	5.00	50.80
W 99.1954°	N 37.5919°	35.45	121.92
W 99.1852°	N 37.5857°	44.55	86.36
W 99.2483°	N 37.5997°	11.82	66.04
W 99.1778°	N 37.5849°	63.64	60.96
W 99.1746°	N 37.5860°	70.45	60.96
W 99.1746°	N 37.5864°	39.09	60.96
W 99.1709°	N 37.5862°	46.82	53.34
W 99.1691°	N 37.5838°	31.82	0.00
W 99.1697°	N 37.5848°	77.27	71.12
W 99.1725°	N 37.5827°	31.82	81.28
W 99.1794°	N 37.5849°	34.55	86.36
W 99.1795°	N 37.5846°	27.27	91.44
W 99.1741°	N 37.5833°	147.73	58.42
W 99.1738°	N 37.5830°	135.45	71.12
W 99.1852°	N 37.5857°	44.55	86.36
W 99.1633°	N 37.5792°	3.64	2.54
W 99.1537°	N 37.5874°	1.82	22.86
W 99.2023°	N 37.5960°	17.73	60.96
W 99.1689°	N 37.5836°	334.09	162.56
W 99.1644°	N 37.5814°	125.00	162.00
W 99.1644°	N 37.5814°	140.00	162.00
W 99.1792°	N 37.5847°	55.00	91.44
W 99.2005°	N 37.5897°	31.82	0.00
W 99.1974°	N 37.5885°	11.36	0.00
W 99.2578°	N 37.5874°	3.64	15.24
W 99.1929°	N 37.5922°	645.45	243.84
W 99.1724°	N 37.5894°	36.36	91.44
W 99.1774°	N 37.5882°	136.36	91.44
W 99.2213°	N 37.5950°	150,00	0.00
W 99.2160°	N 37.5863°	11.82	0.00
W 99.1725°	N 37.5827°	454.55	152.4
W 99.1589°	N 37.5879°	681.82	38.00–152.00
W 99.1925°	N 37.5862°	136.36	0.00
W 99.1630°	N 37.5833°	19.09	91.44
W 99.1638°	N 37.5830°	545.45	304.8
W 99.2037°	N 37.5863°	27.27	86.36
W 99.1905°	N 37.5861°	150.00	152.4
W 99.1662°	N 37.5867°	235.45	162.56
W 99.1537°	N 37.5913°	7.27	30.48
W 99.1545°	N 37.5778°	494.09	127.00
W 99.2153°	N 37.5930°	11.82	162.56
W 99.2250°	N 37.5922°	3.64	12.70
W 99.2023°	N 37.5960°	17.36	60.96
W 99.1503°	N 37.5844°	6.16	15.24
W 99.2095°	N 37.5920°	3.00	93.98

Stratigraphy and AMS radiocarbon dating

The stratigraphy and age of the Brenham/Haviland crater (KCK-1) and four additional impact features (KCK-2, KCK-3, KCK-4, KCK-5) were examined (Figures 10 and 12). All the impact features occur in permeable, loamy, late-Holocene age sediments (Table 2). The strata of the impact features have been depressed and compressed forming asymmetrical troughs of loamy strata, which dip toward each other. All the strata dip toward the center of the impact features where the youngest stratum is located.

Four AMS radiocarbon samples were collected from the pallasite-bearing strata and two samples were collected from the underlying oxidized horizon. The IntCal20 calibration curve in the OxCal 4.4 computer program calibrated the AMS radiocarbon ages obtained from stratigraphic contexts at the impact features sampled. OxCal uses calibration curves created by the IntCal group. Because the atmospheric radiocarbon concentration has varied through time, multiple age ranges are possible for a single radiocarbon age determination. This probability method provides an adjusted estimate of the calendar age range. Table 3 lists calibrated radiocarbon with a 95.4% confidence interval based on the IntCal20 calibration curve.

All the samples dated to the late-Holocene. AMS radiocarbon ages of 1000 ± 20 yr. BP, 994–1195 cal. CE (95.4%) (KCK-1), 840 ± 20 yr. B.P., 1167–1261 cal. CE (95.4%) (KCK-2), 530 ± 20 yr. B.P., 1329–1435 cal. CE (95.4%) (KCK-3), and 440 ± 20 yr. BP, 1430–1470 cal. CE (95.4%) (KCK-4) were obtained from the pallasite-bearing strata of impact features. Two AMS radiocarbon ages of 3140 ± 30 yr. B.P., 1306–1497 cal. BCE (95.4%) (KCK-1) and 2460 ± 20 yr. B.P., 754–419 cal. BCE (95.4%) (KCK-5) were obtained from the oxidized horizon, which underlies the pallasite-bearing stratum.

The AMS radiocarbon sample from impact feature KCK-5 was collected from fissures in a 19.1 kg pallasite excavated from the impact surface (Figure 13). The fissures were on the impact surface side of the pallasite and filled with compressed carbon-rich sediment (Figure 8). Thus, the 754–419 BCE age is considered high-quality because it was obtained directly from a pallasite, it was collected from a pallasite that was in direct contact with the meteor impact surface, and it has a small degree of uncertainty.

SEM microscopy

Olivine crystals occur as prolate ellipsoids with dimensions of 1 cm × 0.8 cm and as spheres 0.4 cm in diameter. The rounded olivine crystals are cracked with fissures ≤50 μm in width (Figure 14). The fractures likely resulted from one or more of three processes: (1) the parent pallasite body underwent frequent collisions in space; (2) after experiencing intense temperatures, thermal expansion between the NiFe

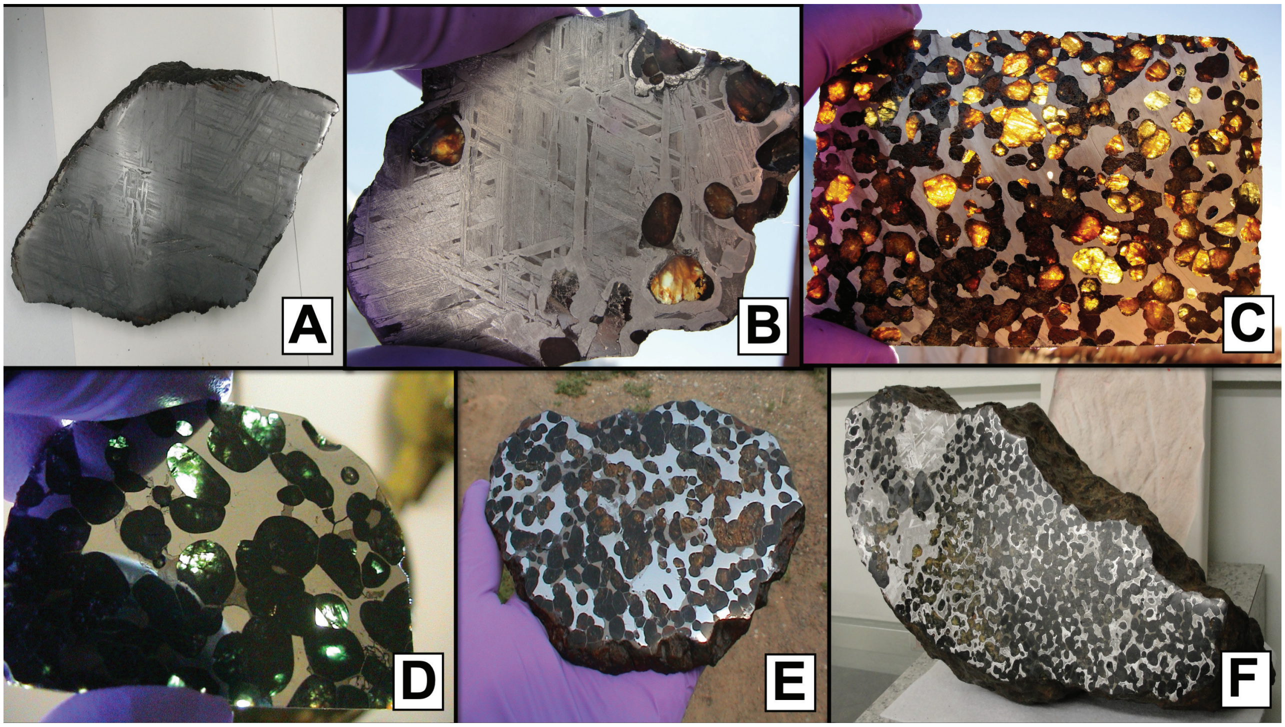

Figure 9: **Cut, polished, and acid-etched pallasites collected from impact feature sample sites located at 37°35.98′ N 99°14.897′ W, 37°35.48′ N, 99°9.22′ W, 37°35.246′ N, 99°15.467′ W, 37°34.67′ N 99° 9.27′ W.** Pallasite dimensions: **(A)** 12 cm × 19 cm, **(B)** 7 cm × 5.5 cm, **(C)** 8.5 cm × 6 cm, **(D)** 7 cm × 4 cm, **(E)** 12 cm × 12 cm, **(F)** 27 cm × 16 cm.

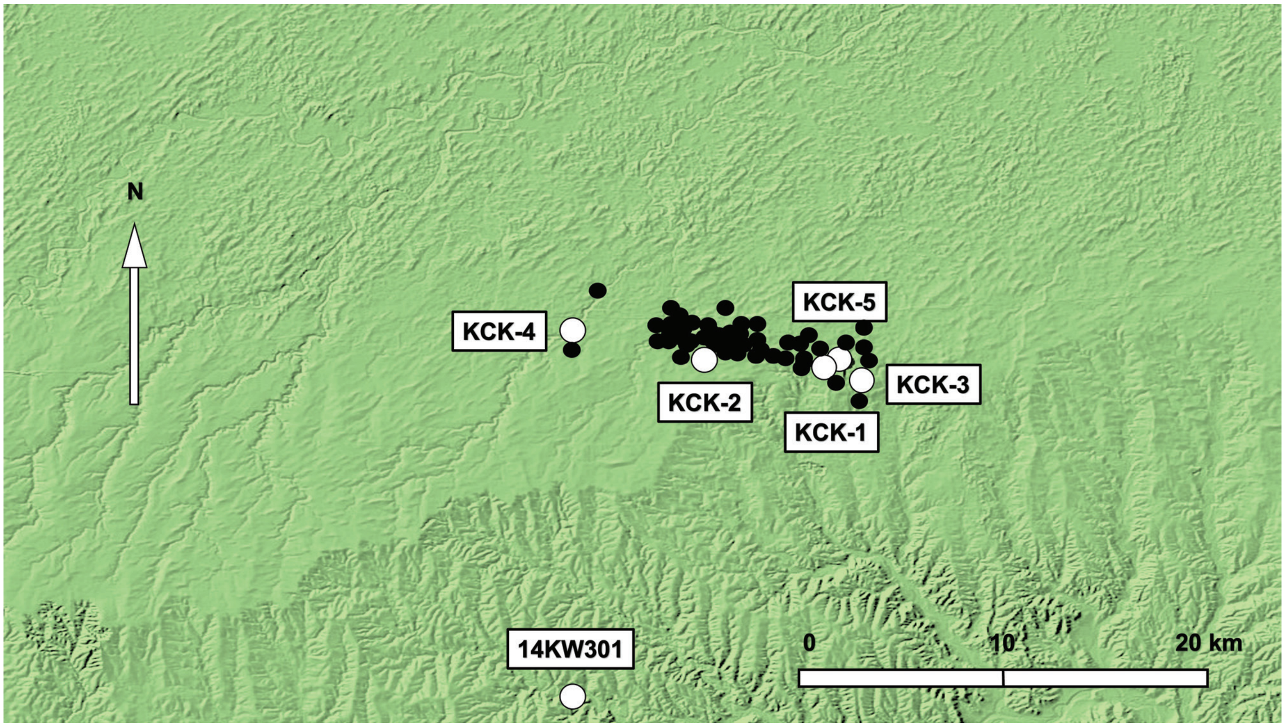

Figure 10: **Spatial distribution of the impact features excavated (KCK-1, KCK-2, KCK-3, KCK-4, KCK-5), Star Shelter (14KW301), and the pallasite strewn field plotted on a LiDAR image of Kiowa County, Kansas.**

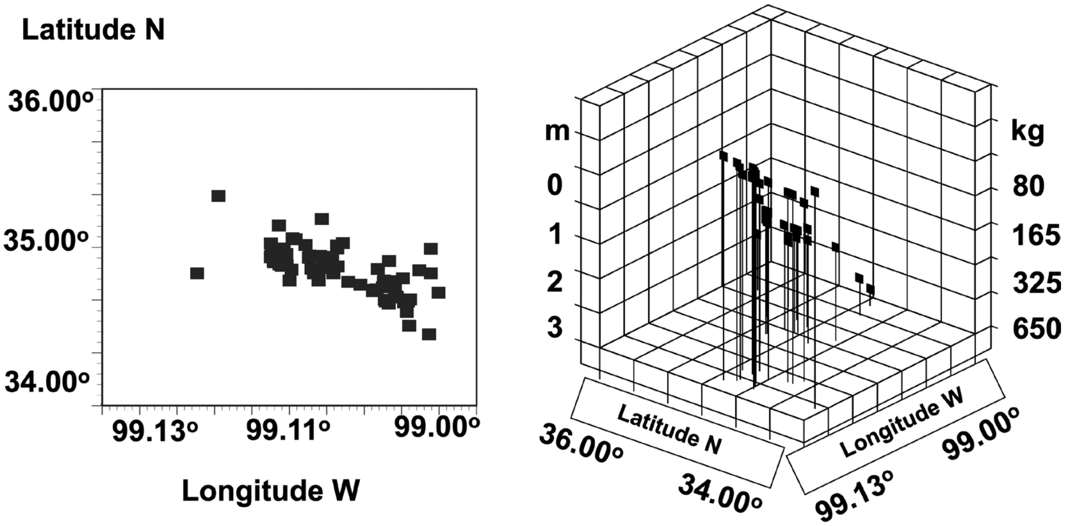

Figure 11: Two- and three-dimensional spatial data for pallasites recovered from the strewn field.

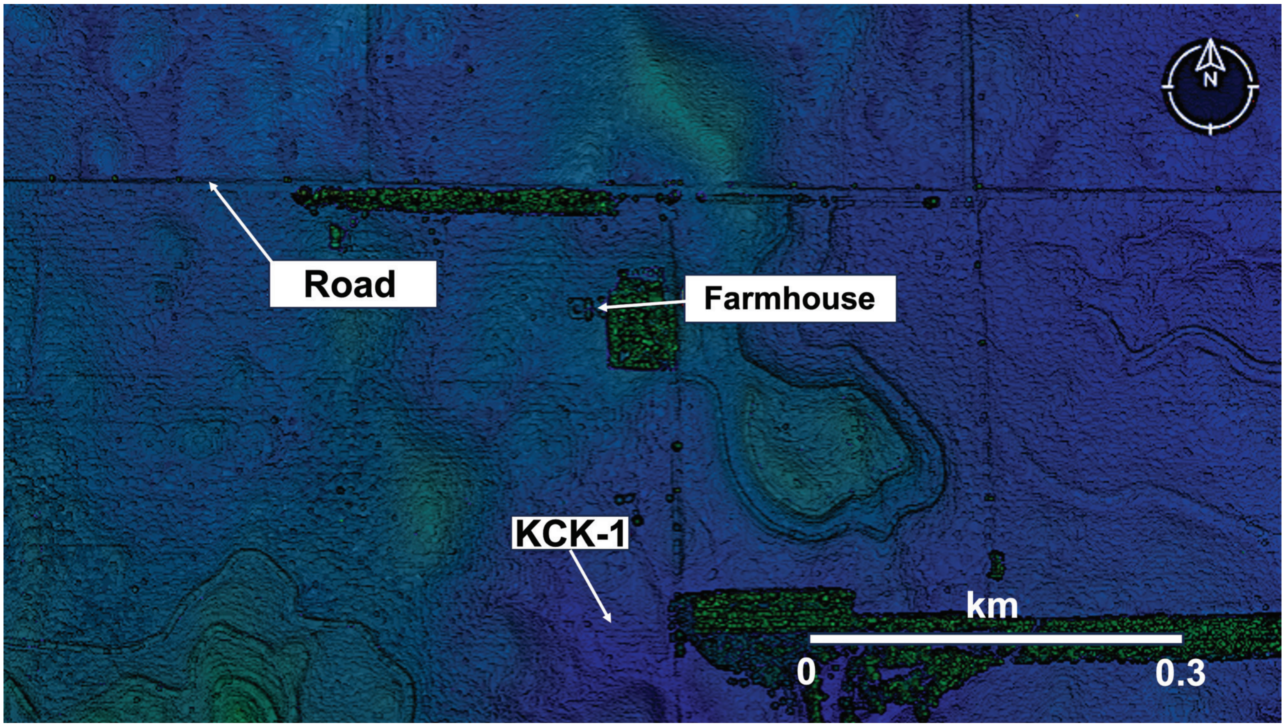

Figure 12: LiDAR image of the Brenham/Haviland impact crater (KCK-1) and the immediate vicinity.

and the olivine caused fracturing during cooling because of different thermal coefficients; and/or, (3) the pallasite impact with the Earth produced fracturing.

Weathered olivine crystal faces have distinctive acicular surfaces (Figure 15). A bright green nickel magnesium oxide occurs in pockets of the pallasites as botryoidal crystal aggregates with individual crystal faces exposed at the crest of the aggregates (Figure 16). Micrometeorites found on the surface at apparent impact craters have a high degree of sphericity, a well-rounded morphology, and protruding olivine crystals (Figure 17).

ICP-MS analysis

Positive anomalies of the leachate concentrations (ppm) of the elements As, Co, Cr, Cu, Fe, Ga, Mg, Ni, Se, and V were found in the ICP-MS analyses of pallasites (NiFe

Table 2: Stratigraphic descriptions of five exemplary impact features.

Sample Site Location	Depth (cm)	Munsell Color	Texture
	0–25	Brown (10YR 5/3)	Friable fine sandy loam
KCK-1	25–118	Brown (10YR 4/3 to 10YR 5/3)	Hard, blocky, sandy clay loam
37°34′59″ N, 99°9′50″ W	≥118	Yellowish brown (10YR 4/4)	Massive, alkaline, sandy loam
	0–36	Grayish brown to dark grayish brown (10YR 4/2 to 10YR 5/2))	Granular, silty loam
KCK-2	36–127	Brown to yellowish brown (10YR 5/2 to 10YR 5/4)	Granular, blocky, alkaline silty clay loam
37°35′35″ N 99°12′41″ W	≥127	Yellowish brown (10YR 5/4)	Massive, hard, alkaline, silt loam
	0–28	Brown to very dark grayish brown (10YR 4/2 to 10YR 3/2)	Granular, loam
KCK-3	28–130	Brown to light brown (7.5YR 5/2 to 7.5YR 6/4)	Hard, blocky, clay loam
37°35′35″ N 99°12′41″ W	≥130	Light brown (7.5YR 6/4)	Massive, hard, alkaline clay loam
	0–28	Gray (10YR 5/1)	Thick, hard, blocky, silty clay
KCK-4	28–127	Light brownish gray (10YR 6/2)	Hard, blocky, neutral silty clay
37°35′59″ N 99°14′56″ W	≥127	Pale brown (10YR 6/3)	Massive, hard, alkaline, silt clay loam
	0–25	Brown (10YR 5/3)	Friable fine sandy loam
KCK-5	25–118	Brown (10YR 4/3 to 10YR 5/3)	Hard, blocky, sandy clay loam
37°35′0″ N 99°9′47″ W	≥118	Yellowish brown (10YR 4/4)	Massive, alkaline, sandy loam

Table 3: AMS radiocarbon samples were obtained from the pallasite-bearing strata and the underlying leached horizon.

Sample	Site	Depth (cm)	Location	^{14}C Age B.P.	Calibrated Age 95.4% Probability Distribution[1]	
				1 Sigma	CE/BCE	2 Sigma
Pallasite-Bearing Strata						
UGa-60250	KCK-4	75	37°35′59″ N	440 ± 20	1430–1470 CE	1.000
			99°14′56″ W			
UGa-60249	KCK-3	28	37°34′56″ N	530 ± 20	1329–1334 CE	0.020
			99°9′30″ W		1396–1435 CE	0.980
UGa-60248	KCK-2	35	37°35′35″ N	840 ± 20	1167–1171 CE	0.016
			99°12′41″ W		1174–1234 CE	0.781
					1237–1261 CE	0.203
UGa-60247	KCK-1	40	37°34′59″ N	1000 ± 20	994–1048 CE	0.778
			99°9′50″ W		1083–1096 CE	0.060
					1101–1126 CE	0.134
					1140–1149 CE	0.028
Oxidized Leached Horizon						
UGa-60251	KCK-5	100	37°35′0″ N	2460 ± 20	754–681 BCE	0.372
			99°9′47″ W		669–608 BCE	0.192
					595–460 BCE	0.405
					439–419 BCE	0.031
UGa-61041	KCK-1	68	37°34′59″ N	3140 ± 30	1497–1470 BCE	0.105
			99°9′50″ W		1465–1378 BCE	0.725
					1345–1306 BCE	0.170

[1] Reimer, P.J.; Austin, W.E.N.; Bard, E.; Bayliss, A.; Blackwell, P.G.; Ramsey, C.B.; Butzin, M.; Cheng, H.; Edwards, R.L.; Friedrich, M.; et al. IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve. *Radiocarbon* 2020, **62**. doi:10.1017/RDC.2020.41.

+ Olivine) and isolated olivine crystals. Leachate concentrations of these elements exceed their crustal abundance (Table 4). Positive anomalies of the leachate concentrations (ppb) of Ir and Pt in the pallasites and isolated olivine crystals also greatly exceed their crustal abundance (Table 5). The leachate concentrations (ppb) of Ir and Pt for pallasites from sample sites KCK-1 and KCK-2 are likely higher than reported given that the specimens were not completely digested.

Positive anomalies of the leachate concentrations (ppb) of Pt were found in samples from the pallasite-bearing strata at impact sites KCK-1, KCK-2, KCK-3, and KCK-5. The leachate concentrations (ppb) of Ir were slightly above the crustal abundance in samples from the pallasite-bearing strata at impact sites KCK-3 and KCK-5. The leachate concentrations (ppb) of Ir and Pt for the pallasite-bearing strata of sample sites KCK-1, KCK-2, KCK-3, KCK-4, and KCK-5 (Table 6) are likely higher than reported given that they were

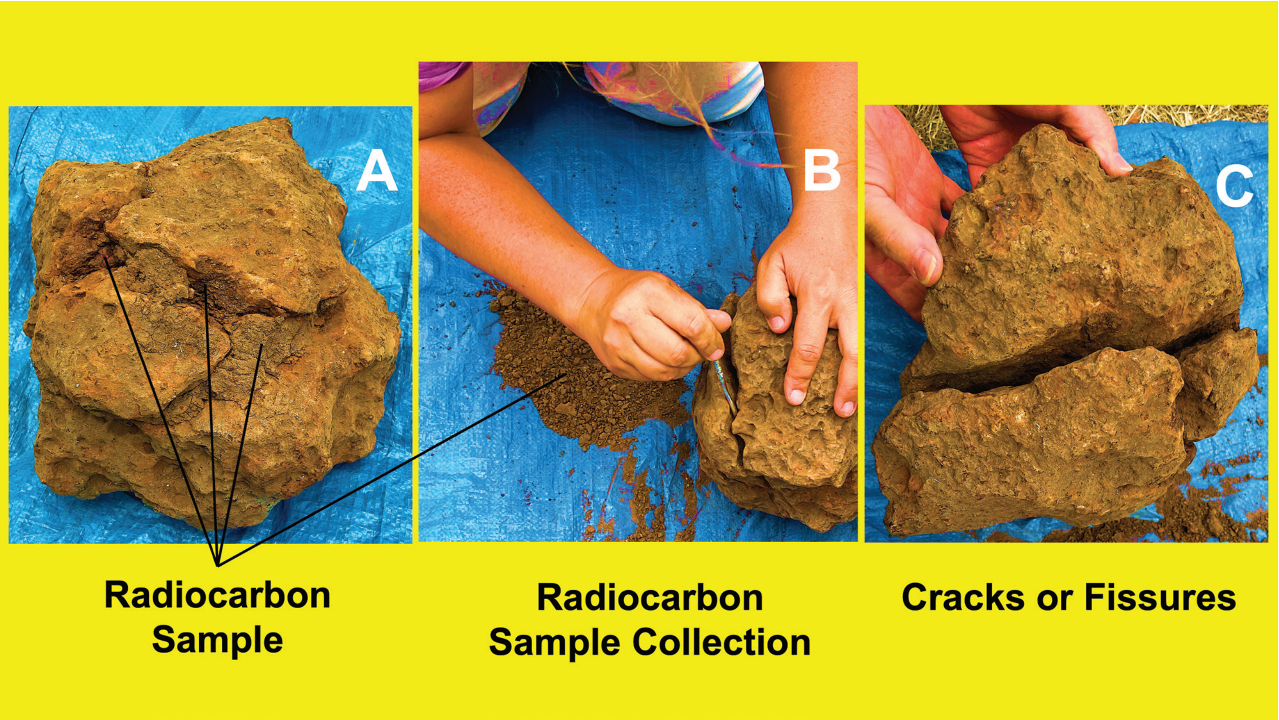

Figure 13: **Collecting an AMS radiocarbon sample from a 19.1 kg pallasite excavated from the impact surface of impact feature KCK-5. (A–C).** These panels illustrate the sequential process of extracting carbon-rich sediments from cracks or fissures in the pallasite.

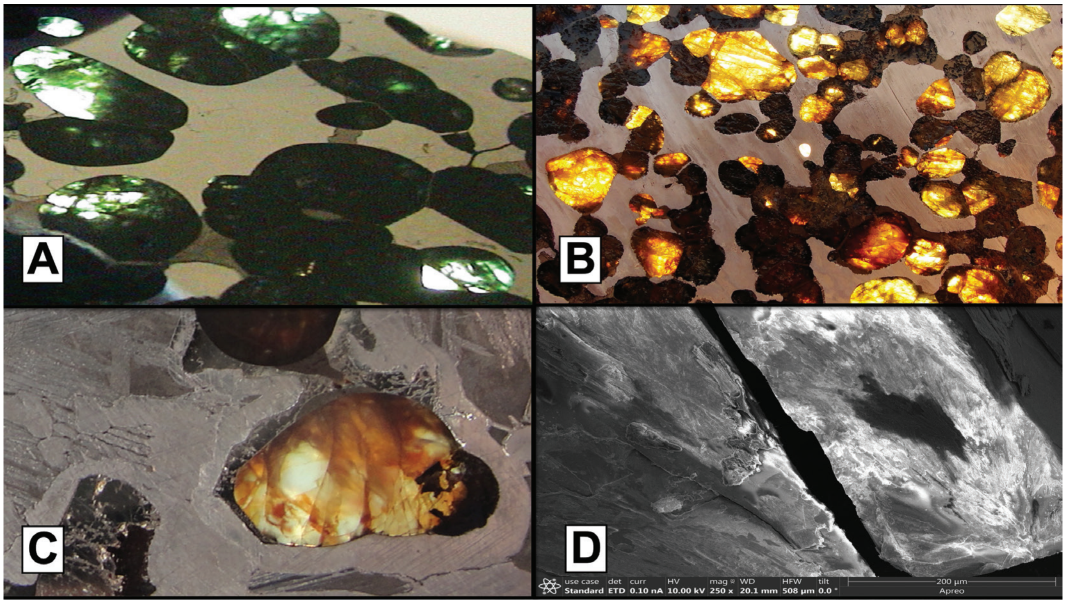

Figure 14: **Unweathered, polished, and acid-etched pallasites from penetration funnel sample site KCK-4 (37°35′59″ N, 99°14′56″ W). (A–C)** NiFe and rounded olivine crystals with fractures. **(D)** SEM micrograph of an olivine crystal cracked with ≤50 µm fissures.

not completely digested. Indeed, less than 20% of the samples were digested. The low quantities of Ir and Pt in the pallasite-bearing deposit may also result from a geologically brief leaching time (i.e., ≤1,000 years ago).

Discussion

Rather than a single small meteor impact crater, an archival and geophysical survey of Kiowa County, Kansas, identified a large (~800 ha) strewn field of impact features. More than

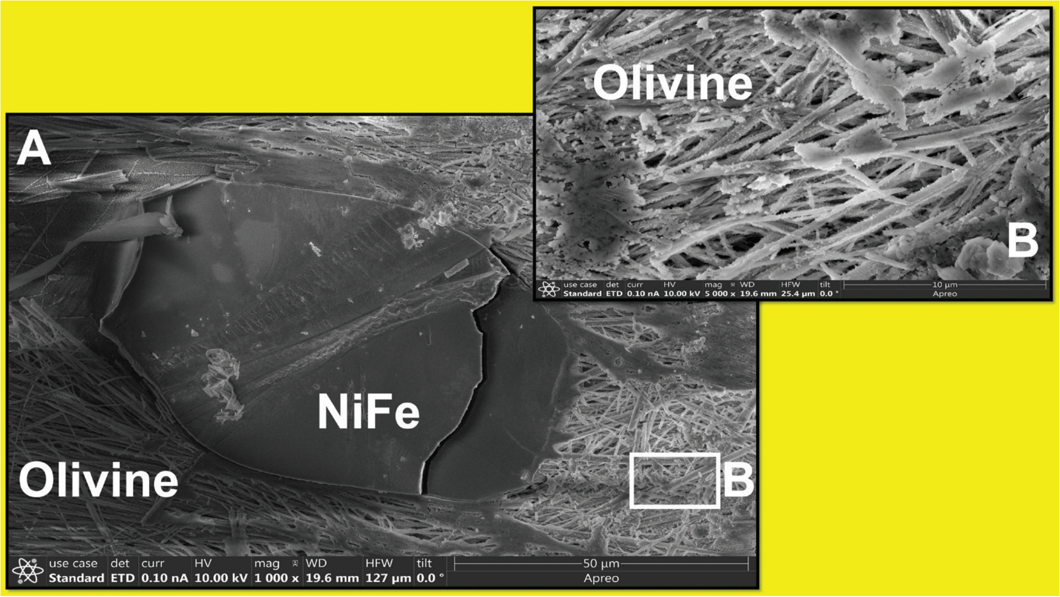

Figure 15: **SEM micrograph of a pallasite from impact feature sample site KCK-5 (37°35′0″ N, 99°9′47″ W). (A)** Comparison **(B)** SEM micrograph the olivine surface.

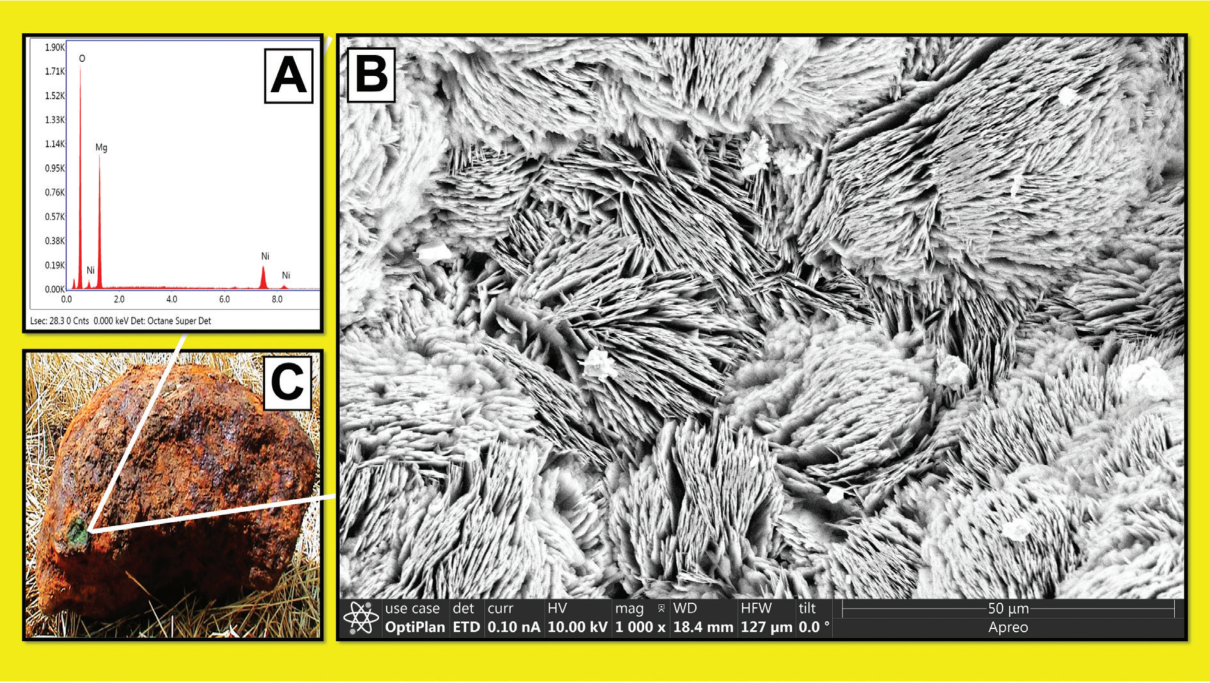

Figure 16: **A 235 kg pallasite from the impact feature sample site KCK-5 (37°35′0″ N, 99°9′47″ W). (A)** EDS spectrum shows the relative abundance of magnesium, nickel, and oxygen. **(B)** SEM micrograph of aggregates of nickel and magnesium oxide crystals. **(C)** A pocket of bright green aggregates of nickel and magnesium oxide crystals.

10,000 kg of pallasites have been collected from impact features in late-Holocene-age sediments. According to the law of superposition, the age of the impact event cannot be older than the stratum that underlies the pallasite-bearing strata. The chronometric age of strata containing pallasites and the underlying heavily oxidized horizon was determined using AMS radiocarbon dating.

All the AMS radiocarbon ages for the pallasite-bearing stratum and the underlying oxidized stratum date to the late-Holocene, consistent with their geologic contexts. Four

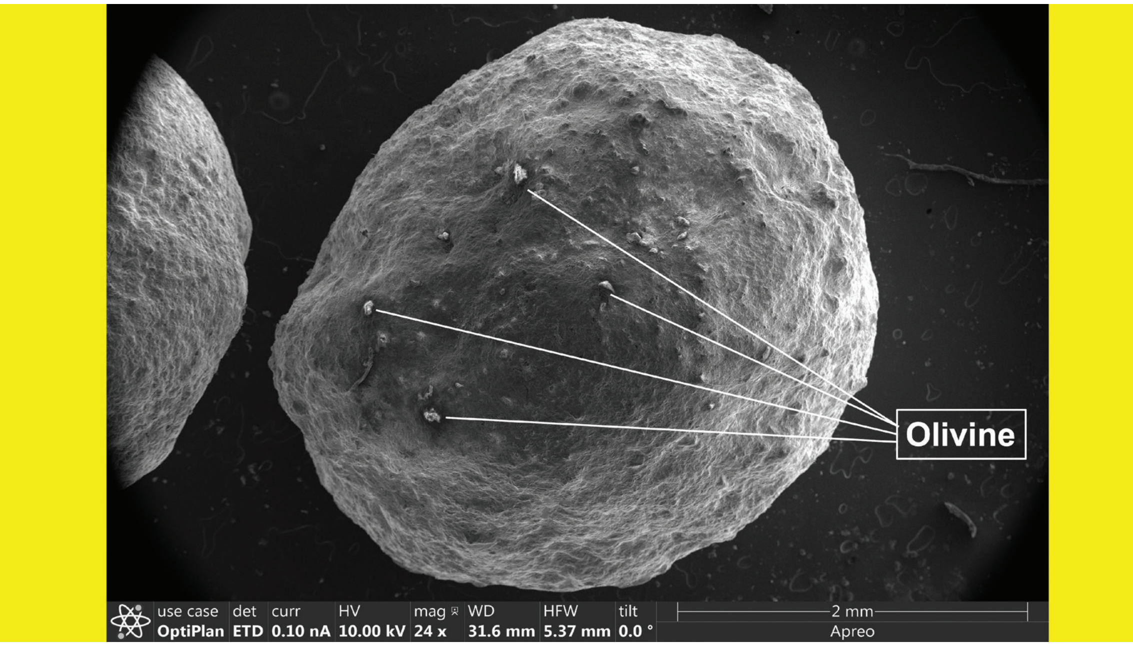

Figure 17: **SEM micrograph of a micrometeorite from impact feature sample site KCK-3 (37°34′56″ N, 99°9′30″ W) with olivine crystals exposed on the surface.**

Table 4: ICP-MS analyses of trace elements in pallasite (NiFe + olivine) and olivine leachate concentrations.

Element	NiFe + Olivine (ppm)	Olivine (ppm)	Crustal Abundance (ppm)	SARM-7 (ppm)	NIST SRM 2706 (ppm)
Li	<0.14–2.00	0.718	21	1.84	10.1
Be	<0.05–1.54	<0.075	2.1	<0.064	0.45
Na	4.79–60.3	5.82	32,700	4057	194
Mg	8,647–107,213	202,715	24,800	13,582	2,218
Al	7–374	538	15,400	32,217	11,127
K	<3–697	5.57	28,000	803	1,834
V	4–336	7.62	97	14.7	37.4
Cr	15–101	172	92	220	23.6
Mn	100–694	1,122	24,800	176	199
Fe	212,416–396,905	223,913	50,400	17,763	22,203
Co	408–1,852	577	17.3	47.2	5.92
Ni	7,419–51,022	9,633	47	1,985	19.2
Cu	19.9–80.6	39.7	28	1,129	95.9
Zn	1.2–27.5	3.37	67	10.5	137
Ga	8.0–20.5	3.86	17.5	4.61	4.24
As	4.4–63.2	2.34	4.8	1.16	30.4
Se	<0.30–4.93	2.75	1.6	1.59	0.66
Rb	0.01–9.57	0.886	84	5.19	12.9
Sr	0.2–15.0	5.46	320	96.5	29.5
Ag	0.02–0.09	0.135	53	0.58	0.12
Cd	<1.00	0.046	0.09	0.08	0.34
Cs	<0.740	0.085	4.9	0.25	0.72
Ba	0.1–98.3	14.4	624	40.3	84.9
Ti	<0.001–0.096	0.017	6,400	0.06	0.12
Pb	0.01–4.56	0.504	17	17.7	783
U	<2.44	0.295	2.7	0.14	0.87

AMS radiocarbon ages from the pallasite-bearing stratum have calibrated age ranges from 994 CE to 1470 CE with a 95.4% probability distribution. Two AMS radiocarbon ages from the heavily oxidized underlying stratum have calibrated age ranges from 1497 BCE to 419 BCE with a 95.4% probability distribution. Based on the law of superposition,

Table 5: ICP-MS analyses of Ir and Pt for pallasite (NiFe + olivine) and olivine leachate concentrations.

Sample	Impact Feature	Ir (ppb)	SARM-7 Ir (Control)	Pt (ppb)	SARM-7 Pt (Control)	% Digested
NiFe + Olivine	KCK 1	17.2–18.3	33.0–33.5	977–1313	1217–1423	14.5
Olivine	KCK 1	4.5	33.0	317	1217	100
NiFe + Olivine	KCK 2	4.1	33.0	268	1217	39
NiFe + Olivine	KCK 3	9.8–17.9	33.0	632–701	1217	100
NiFe + Olivine	KCK 4	9.3	33.5	677	1423	100
	Ir Range 4.1–18.3 ppb				**Pt Range 268–1313**	
	Ir Crustal Abundance 0.2 ppb				**Pt Crustal Abundance 0.5**	

Table 6: ICP-MS analyses of Ir and Pt leachate concentrations for pallasite-bearing sediment.

Sample	Depth/Context (cm)	Ir (ppb)	Pt (ppb)	% Digested
KCK-1	0–40	0.2	0.8	6.2
KCK-2	0–40	0.2	0.6	12.0
KCK-3	0–40	0.3	1.0	19.0
KCK-4	0–40	0.1	0.3	17.0
KCK-5	100	0.3	1.0	9.2
	SARM-7	33.7	1718.0	
	Crustal Abundance	0.2	0.5	

there is a 95.4% probability that the impact event occurred at or sometime after 1497 BCE to 419 BCE. A 419 BCE to 754 BCE age range may be more accurate because the AMS radiocarbon sample was obtained directly from carbon-rich sediments inside the fissures of a 19.1 kg pallasite excavated from a meteor impact surface.

Calibrated AMS radiocarbon ages of the pallasite-bearing strata of sample sites KCK-3 and KCK-4 overlap at one standard deviation (Table 3). Their ages range between 1329 and 1470 CE and occur on the eastern and western ends of the strewn field (Figure 10). The calibrated AMS radiocarbon ages of the pallasite-bearing strata of sample sites KCK-1 and KCK-2 date between 994 CE and 1261 CE (Table 3). They are from the central portion of the strewn field, which was subjected to differential deposition, weathering, and erosional processes related to changes in surface water, groundwater, and vegetation prior to the impact event.

Calibrated AMS radiocarbon ages from the pallasite-bearing deposits (994–1470 CE) overlap at one standard deviation with the Pawnee Plains Village cultural period (~900 to 1850 CE), the age of the Star Shelter petroglyphs, and the calibrated radiocarbon age (1325 CE–1450 CE) obtained on the Pawnee lodge near Grandview Kansas, which contained a pallasite effigy painted as a box turtle carapace. It is impossible to know how long after the impact event that the Pawnee petroglyphs and pallasite effigy were made. However, Pawnee oral histories state specifically that the strewn field was discovered two or three years after the impact event when they were on a buffalo hunt [3–5].

Apart from the Brenham/Haviland crater, more than 100 years of intensive cultivation have completely obscured surface features associated with meteor impact craters in the strewn field. They are undetectable in LiDAR images or in the conventional magnetometers used by archaeologists and geologists. Meteor impact features can be found with a Pulse Star II magnetometer, which produces a distinctive audible localization signal for iron-nickel alloys at depths >90 cm.

SEM micrographs of the pallasite surfaces exhibit distinctive surface morphologies that have not been previously documented from the strewn field including fractured olivine with acicular crystal surfaces and aggregates of nickel and magnesium oxide crystals. These characteristic mineralogical crystalline features should be considered when comparing meteorites obtained from archaeological sites that are greatly distant from the strewn field.

Conclusion

The possibility that Native American populations recorded the fall of cosmic bodies (e.g., meteorites) has been made in the past but evidence that connects such records to actual events is generally regarded as thin. The example discussed herein may be among the first cases of an actual Holocene impact site and event correlated with Pawnee oral histories and material culture (e.g., petroglyphs and artifacts). This study provides future investigators with the tools needed to follow up on similar Native American oral histories. They could provide an especially rich fount of information that opens the many cosmic impact features suspected of being Holocene cosmic impact events but have not drawn attention due to their small and poorly defined impact features, rendering them unknown and uninvestigated.

Although meteoriticists consider Brenham/Haviland the world's smallest meteor crater, it is just one of many impact features spread across a large (~800 ha) late-Holocene-age strewn field in Kiowa County, Kansas. Six calibrated AMS radiocarbon ages demonstrate a 95.4% probability that the impact event occurred between 1497 BCE to 419 BCE. However, a 419 BCE to 754 BCE is more likely to be accurate for the impact. The age of the pallasite-bearing deposits is ~994 CE and 1470 CE, which is consistent with the age of transgenerational Pawnee oral histories and nearby petroglyphs.

At the time of the cosmic impact event, the Great Plains was sparsely populated compared to the densely populated metropolises of the 21st century. The 10,000 kg of pallasites collected from the strewn field to date may represent a small fraction of the total meteorite mass, which impacted the late-Holocene surface. This prehistoric impact event on the Great Plains was likely powerful enough that, if such an impact occurred today, it could destroy significant portions of nearby modern metropolitan areas and cause a significant loss of human life.

Knowing the frequency of cosmic impact events involving impactors >15 m is vital to disaster managers who develop plans to reduce the loss of human life during catastrophic events [18–21]. Currently, there is a dearth of chronostratigraphic data for late-Holocene-age impact events, but more examples in the archaeological and geologic records are expected to be found [22]. To be useful, these data must be obtained and interpreted through interdisciplinary investigations that include AMS radiocarbon dating of strata with cosmic impact event proxies. They will provide a greater understanding of the occurrence and frequency of past cosmic impact events and their influence on human societies in the Western Hemisphere and elsewhere in the world.

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Data availability

All the data generated or analyzed during this study are included in this published article.

Author contributions

K.B.T. conceived of the project and wrote most of the manuscript. K.B.T. and D.I.S. directed the fieldwork. K.B.T. and S.A.M. conducted the hand excavation, soil, and stratigraphic analyses. D.I.S. and S.M.K. conducted the backhoe trench and collected pallasite provenance data. K.B.T. directed the laboratory work.

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Competing interests

The authors declare no competing interests.

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