Determining the Postmortem Timing of Sharp Force Damage and the Pre-Burning Condition of Burnt Bone

Authors

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Abstract

Major complications in the palaeopathological analysis of burnt human remains include distinguishing whether bone was fresh or dry at the time of burning and whether trauma/damage was inflicted "perimortem" or postmortem. Some prehistoric societies are suggested to have defleshed human remains prior to cremation, mostly classified based on the lack of warping and thumbnail fractures. The distinction between perimortem and postmortem sharp force trauma (SFT) features has rarely been investigated on burnt bones. This study investigates whether these features are distinguishable on burnt bone, the rate of cutmark survival, and the presence of heat-induced fractures in relation to the bone's pre-burnt collagen content.

Pig (*Sus scrofa domesticus*) tibiae were left to decay in a field for 14, 34, 91, 180, and 365 days in Wytham Woods, Oxfordshire, UK. Prior to burning, bones were inflicted with SFT by a non-serrated and partially-serrated knife and a flint blade (N=15/bone). Fleshed bones with cutmarks and bones without trauma served as controls. Cutmark survival, features, and heat-induced fractures were recorded on burnt bones and compared with the collagen extracted from unburnt bones at the abovementioned time intervals. Statistical analysis included linear regression and MANOVA.

Heat-induced fractures did not depend on the limited collagen loss during the one-year postmortem inverval (PMI) prior to burning. There was a loss (mean 18.43%) of identifiable cutmarks after the outdoor burning. Major changes in the cutmark features appeared after 6 months of exposure in burnt bones marked by the increase in postmortem features, which can inform on the pre-burning PMI.

Keywords

Sharp-force trauma, burning, taphonomy, perimortem, human remains, cremation

1. Introduction

Differentiation between perimortem injury and postmortem damage on skeletal remains presents a major challenge in archaeological and medicolegal contexts. Perimortem injury refers to trauma inflicted around the time of death in forensic anthropology, and thus it is trauma that was inflicted on fresh or 'wet' bone (Byers, 2007; Wheatley, 2008). An added complication for the differentiation of perimortem and postmortem trauma/damage occurs when dealing with burnt skeletal remains. Although the skeleton cannot be destroyed solely by fire (Bass, 1984), the alterations fire or heat cause to bone compromise methods used by osteologists to identify age and sex, pathology, and possible pre-existing trauma (C. Schmidt & Symes, 2005; T. J. U. Thompson, 2015). Bone goes through a series of chemical and morphological changes until it becomes fully calcined, including differential soft tissue loss, colour changes, fracturing, histological changes, and structural reordering of the bioapatite crystals (Shipman et al., 1984; Fairgrieve, 2008; Thompson, 2015). The two most important factors determining the nature and severity of these changes are the temperature and duration of heat, but other variables play a role as well, such as the location (i.e., outdoors vs indoors), abundance of oxygen, clothing, accelerants (DeHaan, 2012).

In a medicolegal context a variety of events can lead to the recovery of burnt human remains/human remains from fatal fires, such as homicide, suicide, accidental fires, explosions, wildfires, and transportation accidents (Fairgrieve, 2008; Ubelaker, 2009). Fire can be employed on a corpse in an attempt to hide forensic evidence, such as the victim's identity and evidence of violent injury (Fairgrieve, 2008). Two real-life cases of this have been reported in the forensic anthropological literature (Bontrager & Nawrocki, 2008; Garrido-Varas & Intriago-Leiva, 2015), where the postmortem interval (PMI) and time of burning were established based on animal gnawing and patterned thermal destruction. Since human bones are compromised by heat-induced changes, identification of the remains becomes exceptionally complex and, in many cases, impossible; thus, studies on burnt bone are of extreme importance in forensic science (Fairgrieve, 2008; Symes et al., 2008).

Due to the difficulty of analysing such material, assessments of burnt human remains are, with some exceptions, rare in the earlier archaeological scholarship (Gejvall, 1947; Merbs, 1967; McKinley, 2000, 2004). At many prehistoric funerary sites, including examples in Britain, Ireland, Scotland, France, and Luxembourg, archaeologists have proposed that human skeletal remains were burnt dry or after the soft tissue had already decomposed [e.g., (Geber et al., 2017; Lambot et al., 1994)]. The reduction to skeletal remains may have been attained in various ways: from active removal of the flesh using tools; from the exhumation of interred burials after some period of time; or from passive excarnation through subaerial exposure (Booth & Brück, 2020). Although excarnation might have been the dominant funerary rite for much of the Late Bronze Age and Iron Age in southern Britain (Carr & Knüsel, 1997), this type of treatment prior to cremation has so far been invisible for archaeologists. Until recently (Végh et al., 2022), there were no publications to our knowledge on estimating the postmortem interval of sub-aerial exposure (i.e., passive excarnation) prior to burning from a single burnt bone fragment. Nevertheless, indirect evidence from bone deposits has been found suggesting the existence of excarnation as a separate funerary rite from cremation. This includes:

(1) differing radiocarbon dates from unburnt bones in the same deposits (Booth & Brück, 2020);

(2) disarticulated unburnt and burnt bones within the same context on a pyre (Chesterman, 1979; Renfrew, 1979);

(3) bacterial attack on burnt bone (Grévin et al., 1991);

(4) discolouration (oxidation) and fragmentation associated with dry bone at various sites (Piggott, 1962; Wells, 1962; Mckinley, 1999, 2000, 2008; Lee, 2006);

(5) insufficient weight of cremation deposits (Booth & Brück, 2020);

(6) absence of heat-induced fractures characteristic of burnt fresh bone (Wells, 1978; Cooney, 2014)

(7) the presence of cutmarks on cremated remains (Niblett, 1999; Kilpatrick, 2021);

(8) signs of weathering on cremated bone (Chesterman, 1979);

(9) the lack of representation of all major body parts in deposits (McKinley, 2000; Carr, 2007); and

(10) the corrosion and fragmentation of iron fibulae prior to cremation (Metzler-Zens et al., 1999).

Additionally, historic and ethnographic accounts confirm the existence of ritual practices involving the display of the dead prior to cremation in Southeast Asia (Terwiel, 1975; Evans, 1991; Wong, 1998; Falk, 2010; Ward & Tayles, 2015). Moreover, from the same geographical area, archaeological evidence of defleshing has been found on early Holocene human remains (Lara et al., 2013). Here, the skeletal remains of an individual were burnt and exhibited cutmarks, impact scars indicative of disarticulation, scrape marks, as well as defleshing, suggesting an early example of ritualistic treatment of the body prior to cremation (Lara et al., 2013).

Many of these archaeological examples are questionable; for example, points 5 and 9 can be explained by selective/token collection of cremated remains from the pyre for burial [cf. (McKinley, 2000; Booth & Brück, 2020)). Equally debateable is point 8, those interpreting signs of weathering as due to excarnation [cf.(Behrensmeyer, 1978)] since fire hides signs of weathering on bone, or point 1, the differing radiocarbon dates from the disarticulated human remains (Booth & Brück, 2020). The possible issue with the latter is that the dated remains were not sampled from the same stratigraphic context.

The present study uses points 4, 6, and 7 to establish and validate the use of fragmentation, heat-induced fracturing, and signs of active excarnation (cutmarks) on burnt bone through an experimental approach. If perimortem and postmortem sharp-force trauma (SFT) induced prior to burning are distinguishable in bones with ≤ 1-year PMI post-burning, it might be possible to confirm or refute the presence of active excarnation in prehistoric cremated bones together with information on type of cutmark, location and number of marks on the skeleton. This study investigates: (1) the percentage of preserved cutmarks post-burning; (2) whether it is possible to tell if SFT was inflicted subsequently after death or after a certain amount of time within a year on burnt bones; and (3) if retained collagen content affects heat-induced fracture characteristics and warping, and the appearance of SFT on burnt bone. This research aims to contribute to the identification of specific mortuary practices in past populations by analysing burnt skeletal remains. By examining the preservation of pre-burning cutmarks at different stages of the PMI, distinguishing perimortem and postmortem cutmarks, and investigating the role of collagen content, we aim to shed light on the cultural and ritualistic treatment of the deceased in ancient societies.

1.1 Fragmentation and Heat-Induced Fracturing

Characteristics of heat-induced fracturing include: longitudinal, transverse, and/or curved transverse (thumbnail) fracture morphology; patina; delamination; and warping (Baby, 1954; Shipman et al., 1984; Mayne, 1990; Pope and Smith, 2004; Pope, 2007; Symes et al., 2008). These are possible to record because post-burning breakage or fracturing/fragmentation can be distinguished from heat-induced fractures by the colouration and charring of the fractured surfaces (Buikstra & Swegle, 1989; Symes et al., 2008; Dirkmaat et al., 2012). Thumbnail fractures and warping were proposed to be associated with fresh bones burnt with soft tissue (Baby, 1954; Binford, 1963; Buikstra & Swegle, 1989; Spennemann & Colley, 1989; Etxeberria, 1994; Whyte, 2001), but these features were subsequently shown to be problematic, as they may relate to the amount and/or distribution of collagen within the bone (Thompson 2005, Gonçalves et al., 2011). Gonçalves et al. (2011) concluded that warping is present on 'dry' bones if enough collagen is retained to enable bending. This is due to collagen loss in dry bone, which reduces bone elasticity making it weaker to mechanical forces (Zioupos et al., 1999). Similar conclusions have been drawn regarding thumbnail fractures (Gonçalves et al., 2011). However, the latter study did not include measurements of collagen content before experimental burning, which is especially important in the present study because the bone's collagen content can also influence the characteristics of trauma or damage at the time of burning. Bone contains ~20-35 wt% organic material, of which the most abundant biomolecule is type I collagen (Rogers & Zioupos, 1999; Collins et al., 2002; Elliott, 2002; Caruso et al., 2020). Collagen degradation begins even during life but is much more pronounced after death. Since this research investigates a multi-stage funerary rite in which the body is first excarnated and then processed prior to burning, and collagen content affects both the heat-induced fractures and the appearance of trauma/damage, the extent of postmortem collagen loss is investigated in this study.

1.2 Perimortem vs Postmortem Damage

Differentiation between wet ("perimortem") versus dry (postmortem) bone sharp force trauma/damage features (both referred to as SFT below) has so far not been attempted on burnt bones. However, observational studies and reports on archaeological cremated bone with possible pre-burning inflicted SFT exist (Cressey et al., 2003; Kilpatrick 2021). For instance, on a burnt skull fragment, cutmarks inflicted pre-burning were observed from a Bronze Age cemetery in Scotland (Cressey et al., 2003), but it was not possible to determine if the marks were inflicted pre- or post-mortem (*ibid*). Another skull fragment with a linear defect from Dunragit, Galloway, was also interpreted as a cutmark, due to its different appearance (sharp edges) as opposed to the other weathered damages (rounded edges) (Kilpatrick, 2021). It has been assumed that this SFT was inflicted around the time of death and prior to burning (*ibid*). Most scholarship agrees that pre-existing trauma may be distinguished from heat-induced fractures (Pope & Smith, 2004a; Ubelaker, 2009; Poppa et al., 2011; Végh & Rando, 2017; Waltenberger & Schutkowski, 2017; Alunni et al., 2018;). Pre-existing SFT exhibits different characteristics, such as presence of tool marks (e.g., striations), thicker bevelling, and kerf/fracture discolouration, due to the exposed internal bone structure (Ubelaker & Adams, 1995; Mayne Correia, 1997; Herrmann & Bennett, 1999; Pope, 2007; Symes et al., 2008; Dirkmaat et al., 2012; Galloway et al., 2014). SFT is distinguishable from heat-induced fracturing using the presence of fracture lines, striations on kerf walls, and from the chipping of bone (Berryman & Symes, 1998; Bass, 2005; Byers, 2007). However, heat-induced fragmentation can obscure SFT on bones, which can result in overlooked trauma (Emanovsky et al., 2002), while step and transverse heat fractures may be indistinguishable from SFT (Mata Tutor et al., 2021).

Establishing the timing of the injury (antermortem, perimortem, postmortem) is crucial in forensic investigation as it can assist with reconstruction of manner and cause of death (Sauer, 1998; Sauer, 2003; Kemp, 2016). While antemortem trauma is more easily identified using evidence of regeneration (callus), distinguishing perimortem from postmortem trauma/damage is more difficult (Pope, 2007; Galloway et al., 2014; Symes et al., 2014). The perimortem stage can extend months or even years after death depending on the depositional microenvironment (Sauer, 1998; White, 2000; Symes et al., 2002; Galloway et al., 2014; Moraitis & Spiliopoulou, 2006). Bone elasticity can measurably deteriorate only 5 hours after death (Fitzgerald, 1977) and the moisture content in bone can decline rapidly in the first two months postmortem (Wieberg & Wescott, 2008), but fresh bone fracture characteristics may persist for several months to years postmortem (Maples, 1986; Ubelaker & Adams, 1995; Wheatley, 2008). Furthermore, taphonomic agents might produce postmortem damage on bones that may be confused with perimortem trauma (Sauer, 1998). Perimortem and postmortem trauma are usually distinguished using staining/colour differences of the fracture surfaces, the fracture pattern morphology, the angle of fracture margins, and other taphonomic modifications (e.g., carnivore gnawing, weathering, vegetation) (Symes et al., 2002; Haglund and Sorg, 2006; Sorg, 2019). A recent study found that perimortem fracture patterns (from falls, blunt force trauma, traffic accidents, and gunshot wounds) could be identified and reconstructed in 11-29% of the cases after cremation in gas furnaces for 90 minutes at 1280°C (Franceschetti et al., 2021). Discolouration of fracture surfaces was a contributor to the successful determination; perimortem fracture margins exhibited yellow/brownish, spotted or widespread discolouration, as opposed to postmortem cases (*ibid*). Franseschetti et al. (2021) suggest that the colouration in the peri-mortem fractures may be attributed to hemorrhaging and clotting on the fracture margins, which could affect the impact of fire in that area. In contrast, heat-induced fractures in this study exhibited acute and sharp edges with white colouration (*ibid)*, suggesting that staining and colour differences could serve as useful indicators of the timing of trauma infliction even after the skeleton has been burnt.

There is significantly less research on the timing of sharp force trauma (SFT) infliction as opposed to blunt force trauma (Crowder et al., 2013; Galloway et al., 2014). A number of qualitative features have previously been proposed to have potential for differentiating cutmarks inflicted on wet and dry bone (Crowder et al., 2013). SFT on fresh bone tends to exhibit irregular edges, curling or uplifting at edges, splintering and splintered bone connected to existing bone structures (Mayne, 1990; Sauer, 1998; Symes et al., 2008; Ubelaker, 2009; Crowder et al., 2013). Dry bone features of SFT include regularity in morphology, sharp-edged, discoloured kerfs, and complete separation from existing bone structures into numerous pieces (Mayne, 1990; Symes et al., 2008, 2014; Crowder et al., 2013; Wedel, 2014; Devlin & Herrmann, 2015). The present study uses these features to distinguish between “perimortem” and postmortem SFT in burnt bone.

V.2 Materials and Methods

Fleshed *Sus scrofa domesticus* (pig) tibiae (N=25) were left to decay for 14, 34, 91, 180, and 365 days within a cage in a field in Wytham Woods, Oxfordshire, UK (Végh et al., 2021, 2022). Fleshed, fresh tibiae served as a control for the PMI groups. After each postmortem interval (PMI), four[1] tibiae were collected and manually inflicted with sharp force trauma (SFT) by three different instruments. One of the bones from each PMI stage was left without trauma to serve as a control for heat-induced fractures. The 0-day control tibiae were subjected to the same trauma following collection from a local butcher and immediately before burning (Fig. 1). The instruments were chosen based on their analogues and commonality in both modern and archaeological times: a non-serrated knife (NK), a partially serrated knife (SK), and a flint blade (F; Fig. 2, Table 1). This way, changes could be monitored on several type of cutmarks with different morphology. Five cutmarks were produced per instrument on each bone, totalling 15 SFT per bone. Kerfs were produced by a constant force by cutting the bone twenty times with all instruments. All cutmarks were produced manually by one right-handed person in order to limit the variability of the cutmark features as much as possible.

In addition to the experimentally burnt pig bones, a 5.5k ya old unburnt *Bos* (cow) bone from Ireland was included in the study. It was experimentally burnt in a kiln at mean 515°C temperature for 2 h 45 mins. This bone was included as a no- to low-collagen (<0.5% collagen measured from %N) control for the heat-induced fracturing investigations.

[1] Although five tibiae were deposited per PMI, some were removed from the cage by animals. One bone was removed from the 34-day group and four from the 365-day group.

Fig. 1 A: An example of a fleshed tibia subjected to sharp force trauma. The skin was carefully cut through and then each incision was produced on the bone itself; **B**: One of the 14-day PMI tibia cut with the same implements

Fig. 2 The instruments (knife and flint blade) used for the SFT infliction. The combat knife (Gerber, USA) used for all knife-related wounds. The knife is comprised of a single edged, non-serrated upper part and a partially serrated part. Both parts had a single edge bevel on the left side. There is a total of 11 serrations of the knife with four patterned double serrations (4.8 mm each). The non-serrated gaps are 5.5 mm long. The single edged flint blade, which was produced for this study. The blade's cutting surface is wider than that of the knife, while the width from the point of bevelling is larger

Instrument	**Cutting Edge Length (mm)**	**Blade width (from root of bevelling; mm)**	**Blade width (most upper point; mm)**
NK	70	1.09	0.66
SK	35	1.95	0.66
F	78.95	1.69	0.98

Table 1 -- Dimensions of the instruments used in this study. NK=non-serrated knife; SK=partially serrated knife, F=flint blade. All instruments were used in a cutting motion.

Following the SFT, the bones were burnt in an outdoor fire as described in Végh et al. (2021). An outdoor fire was preferred over a furnace due to its more realistic burning process in terms of the loss of SFT due to fragmentation (cf. Pope and Smith, 2004). Bone temperatures were monitored continuously throughout the burning events, with an average of 553 °C and a recorded maximum of 751 °C, for 2.5 – 3.5 hours per fire event, until the bones became calcined (Fig. 3). The bones were left to cool to ambient temperature before collection, since hot bones are extremely fragile [cf. (Alunni et al., 2018)]. After collection, the bones were photographed with a Nikon D2Xs camera fitted with a 60mm Nikon macro lens. The images used for the visualisation of the trauma were taken with light microscopy (Wild Photomacroscope, Wild Heerbrugg, Heerbrugg, Switzerland) fitted with a LMscope, VTC4x2

(LCMOS, Brunel Microscopes, Chippenham, UK) USB camera together with ToupView 3.7 (ToupTek Photonics, Zhejiang, China) software. The lowest magnification used was 6.3x after calibration in order to be able to visualise larger areas of the cut-marks, and for details 16x magnification was used. Images of the cutmarks were stitched together using Image Composite Editor 2.0.3 (Microsoft, Redmond, Washington, USA). For qualitative analysis, only the light microscopy images were used, as they produced more detailed images of the cutmarks than the macroscopic images.

The presence of cutmarks was recorded for each bone to quantify the likelihood of cutmarks survival post-burning with repercussions on the proportion of such marks likely to be recovered after cremation in archaeological and forensic contexts. The kerf features were qualitatively analysed by the first author (EV) based on established features of fresh/wet bone and dry bone trauma features (Table 2). Features assessed were irregular edges (IRR), curling or uplifting (CUR), splintering (SPL), and flaking (FLA) for perimortem and regular shaped kerf (RES), sharp edges (SHA), discolouration (DIS), and crumbling (CRL) for postmortem features.

Fig. 3 A: The bones soon after the fire was lit. While the two bones in the middle started charring, the other bones are yet to be altered to the same level; **B:** 2.5 h after the start of the outdoor fire, most bones turned white

Perimortem vs Postmortem SFT Features			
'Perimortem'/Wet Bone Features		**Postmortem/Dry Bone Features**	
Feature	**Appearance**	**Feature**	**Appearance**
Irregular edges (IRR)	The edges of the cutmark are not straight or follow the shape of the instrument.	Regular shaped kerf (RES)	The edges of the cutmark appear regular, following the shape of the instrument.
Curling or uplifting (CUR)	Elevation at the edge/shoulder of the kerfs.	Sharp edges (SHA)	Kerf edges and walls appear sharp without splinters.
Splintering (SPL)	Splintered pieces on kerf walls and/or edges that tend to be attached to one another (wall projections).	Discolouration (DIS)	The kerf is a different colour to the surrounding bone.
Flaking (FLA)	Layer of bone come or fall away from the surface (edge or wall of the kerf) in flakes.	Crumbling (CRL)	Uneven edged lumps at the start or end of the kerfs or on kerf floors.

Table 2 -- The timing of trauma (perimortem vs postmortem) specific features used for the qualitative analysis of the kerfs.

The presence and severity of heat-induced fractures were recorded on the burnt bones by counting the total number and the type of fractures. Those classed as heat-induced fractures of interest to this study were thumbnail (curved transverse) and warping fractures. Other heat-induced fractures expected in long bones (e.g., longitudinal and transverse) were present in all bones.

It has been shown that the amount of collagen in bone prior to burning can affect heat-induced fracture patterns (Thompson, 2005; Gonçalves et al., 2011). Thus, the retained collagen in the unburnt bone was measured for each PMI group in order to determine its impact on kerf features, fracturing severity, and the presence of thumbnail fractures and warping. Samples for collagen extraction were taken from the smallest diameter of the diaphysis of each tibia. Duplicate samples were taken from two randomly chosen bones to assess differences in collagen distribution in a single bone. The unburnt samples were defatted in a 2:1 chloroform:methanol mixture for 8-20 weeks. Surface contamination of the dried bones was removed by AlO_2 shotblaster. Then, the bones were finely crushed and ~500 mg of the resulting bone powder was decalcified with a modified Longin method (Longin, 1971; Brock et al., 2010), by 0.5 mol/L HCl, with fresh acid replaced three times and left overnight. The decalcified solution was then rinsed with Milli-Q® ultrapure distilled water, followed by 0.1

mol/L NaOH soak for 30 mins to eliminate humic substances and non-collagenous residues. Samples were then rinsed with Milli-Q®, washed with 0.5 mol/L HCl. Gelatinisation was done by a hot acid solution (pH 3, 70 °C) for 20 h. The gelatinised solution was EZEE filtered, frozen at -18°C for 4 h, and freeze dried. Collagen yields were calculated using a high-precision electronic balance. The 5.5k year-old cow rib's collagen content was estimated by %N.

The data from the cutmark features, heat-induced fractures, and collagen measurements were statistically analysed using descriptive statistics, linear regression, MANOVA, and multivariate comparison testing in Jupyter notebook in Python programming language.

3 Results

3.1 Heat-induced Fracturing and Collagen Content

The percentage of original cutmarks preserved per instrument is presented in Fig. 4. Cutmark survival was not associated with PMI ($r=-0.358$, $p<0.485$), but the 180- and 365-day bones had the most cutmarks preserved as opposed to the fresher samples. Fracturing severity, the number of fragments post-burning, did not show a linear decrease with time since deposition or with collagen content (Fig. 5). The presence of introduced SFT did not affect fracture severity or type of heat-induced fracturing. Thumbnail fractures and warping were present in most samples. Thumbnail fractures were absent only on a 14-day (WSF2D2W5) and a 91-day (WSF3D3M4) sample. Warping was absent only on a 14-day (WSF2D2W4) and on two 180-day (WSF5D6M1 and WSF5D6M2) samples. The archaeological cow rib with <0.5% collagen presented no heat-induced fractures.

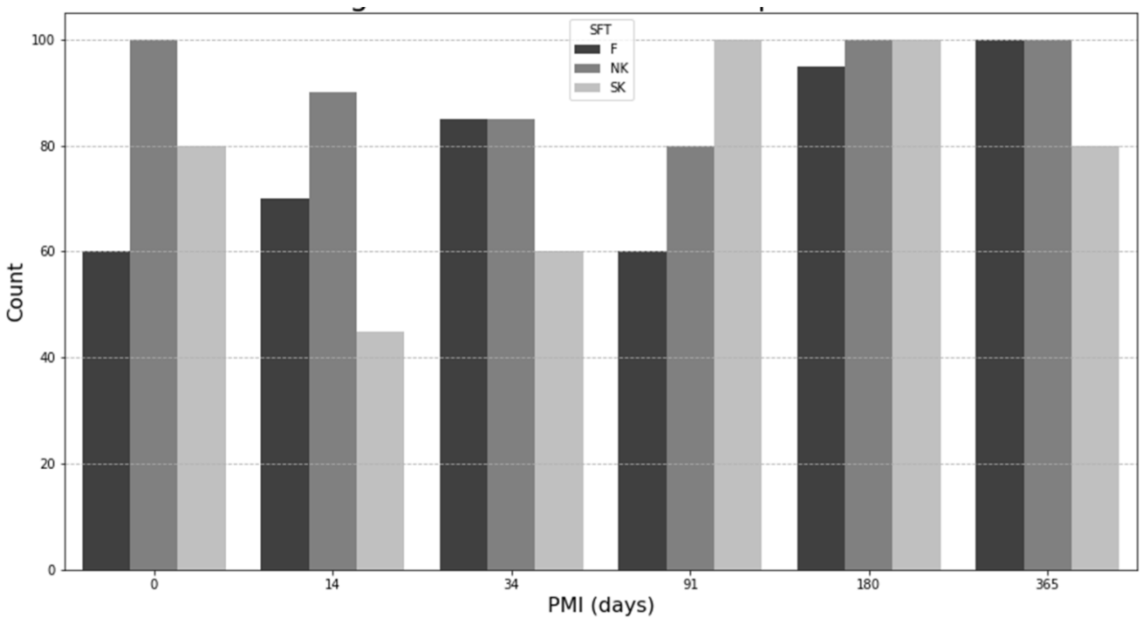

Fig. 4 The percentage of cutmarks preserved post-burning as a function of time. A cutmark was counted as present if any portion of the kerf was present. F = flint blade, NK = non-serrated knife, SK = partially-serrated knife

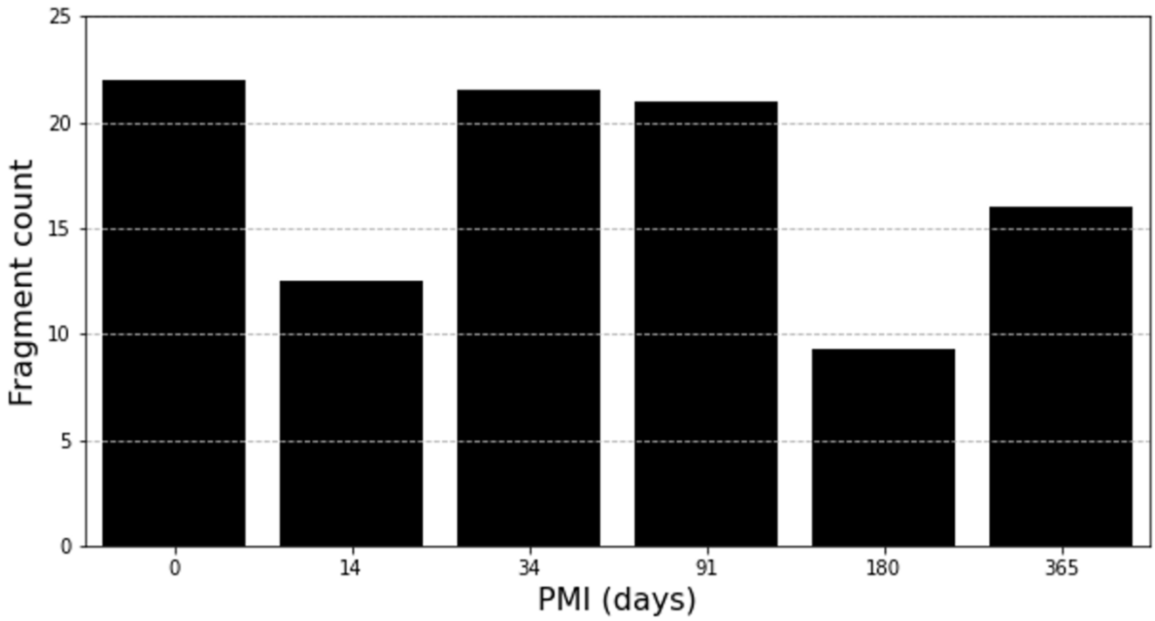

Fig. 5 Fracture severity (number of fragments per bone post-burning) of bones at different postmortem intervals.

Collagen content in fresh bone is between ~20-35 wt % (Rogers and Zioupos, 1999), while here retained collagen in individual samples prior to burning ranged from 23.80% (14-day sample) to 10.25% (365-day sample; Table 3). The 14-day samples presented the highest mean values (20.70% ±2.77%) and the 91-day ones the lowest (14.98% ±2.88%), but no linear decrease was observed in collagen content through time (r=-0.508, p<0.382). However, duplicate measurements from the same bones suggest that the amount of collagen can vary greatly by location in the same bone (e.g., WSF3D3M2 had a 7.34% difference, Table 3). Moreover, the statistical test has low power because of the small sample size per group.

PMI (days)	Sample	Starting Weight (mg)	Collagen yield (mg)	Collagen %	Mean (%)	SD (%)	Coeff. Var.
14	WSF2D2W1	562	98.19	17.47	20.70	2.77	0.13
	WSF2D2W2	515	119.67	23.24			
	WSF2D2W3	513	104.31	20.33			
	WSF2D2W4	554	103.44	18.67			
	WSF2D2W5	588	139.93	23.80			
34	WSF3D1M1	537	103.92	19.35	17.39	3.99	0.23
	WSF3D1M2	518	87.89	16.97			
	WSF3D1M3	230	48.56	21.11			
	WSF3D1M4	526	56.61	10.76			
	WSF3D1M5	484	90.82	18.76			
91	WSF3D3M1	506	81.77	16.16	14.98	2.88	0.19
	WSF3D3M2.1	471	52.34	11.11			
	WSF3D3M2.2	597	110.17	18.45			
	WSF3D3M3	574	75.05	13.07			
	WSF3D3M4	528	84.92	16.08			
180	WSF5D6M1	585	128.74	22.01	16.55	3.38	0.20
	WSF5D6M2	591	103.53	17.52			
	WSF5D6M3	532	72.49	13.63			
	WSF5D6M4	593	85.76	14.46			
	WSF5D6M5	527	79.84	15.15			
365	SWF5D1Y1.1	208	21.31	10.25	16.08	8.25	0.51
	SWF5D1Y1.2	515	112.84	21.91			

Table 3 -- The retained collagen in unburnt bone at different PMIs.

3.2 Perimortem and Postmortem SFT Features

There was a linear decrease in the appearance of three perimortem features (irregular edges, curving or uplifting, and splintering) and an increase in two postmortem SFT features (regular shaped edges, sharp edges) with time (Table 4; Fig. 6). Kerfs inflicted by NK were the only features that were not significantly impacted by time in the appearance of curling or uplifting of the edges. Regular shaped edges and sharp edges were observed in a linearly increasing fashion with time (Fig. 7) regardless of the instrument. However, these two features were sometimes present at earlier PMIs on the flint-inflicted cutmarks (Fig 6C-E). Flaking, discolouration, and crumbling were not associated with time in burnt bones. Flaking was always present, regardless of PMI or instrument.

Timing	Feature	NK		SK		F		All SFT	
		r	**p**	**r**	**p**	**r**	**p**	**r**	**p**
Peri-mortem	IRR	-0.874	**0.023**	-0.906	**0.013**	-0.839	**0.037**	-0.798	**7.19E-05**
	CUR	-0.728	0.101	-0.882	**0.020**	-0.858	**0.029**	-0.729	**0.001**
	SPL	-0.833	**0.040**	-0.870	**0.024**	-0.639	0.172	-0.731	**0.001**
	FLA	0.221	0.674	0.000	1.000	-0.527	0.282	-0.173	0.493
Post-mortem	RES	0.876	**0.022**	0.927	**0.008**	0.896	**0.016**	0.818	**3.41E-05**
	SHA	0.960	**0.002**	0.926	**0.008**	0.964	**0.002**	0.905	**2.54E-07**
	DIS	-0.330	0.523	-0.400	0.432	-0.351	0.495	-0.306	0.218
	CRL	0.502	0.310	0.616	0.193	0.219	0.677	0.352	0.152

Table 4 -- The linear regression results on the perimortem and postmortem SFT features. Significant p-values are bold.

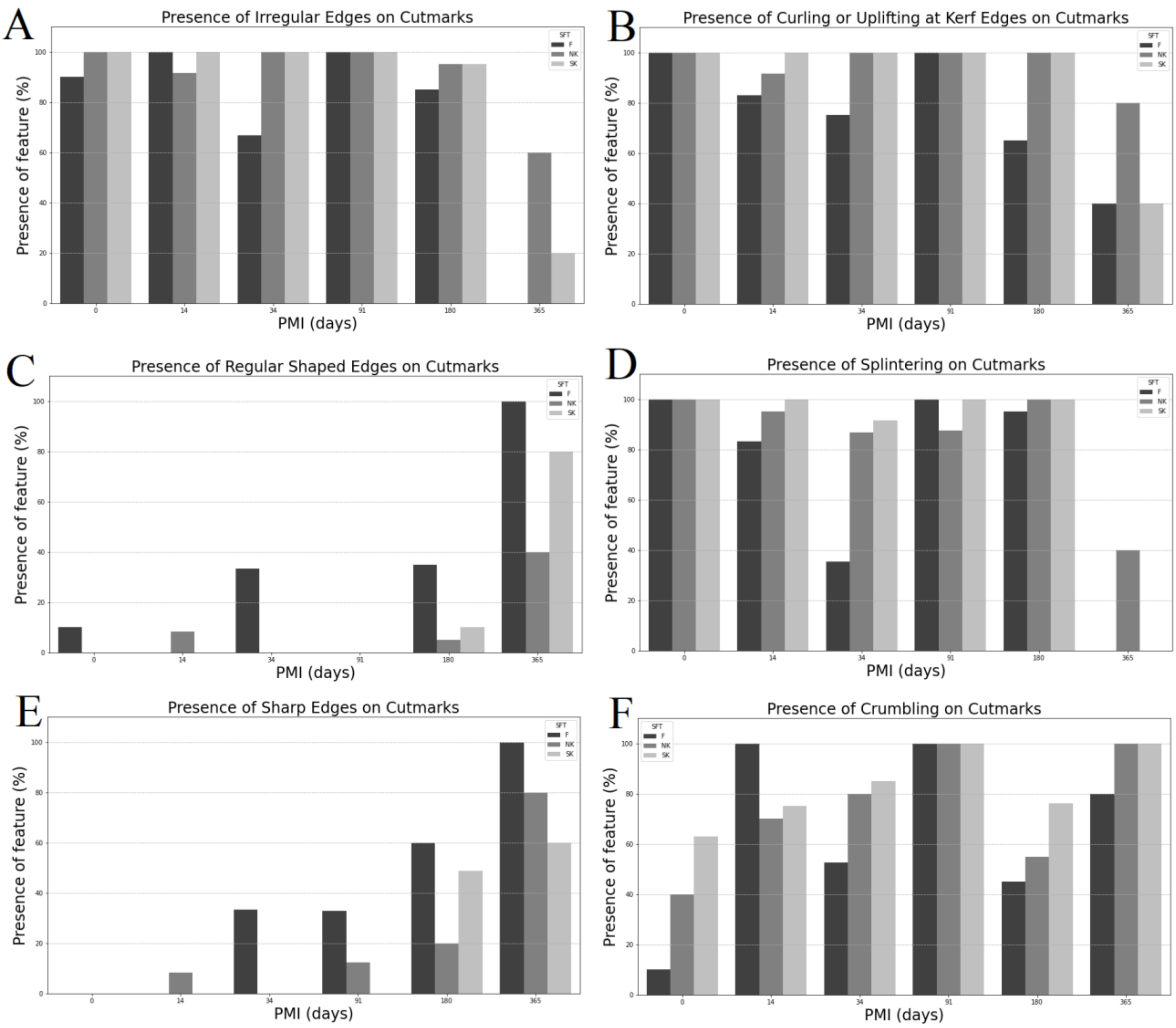

Fig. 6 The percentage of perimortem and postmortem SFT features as a function of time (days) on the kerfs. Hues show the different instruments the trauma was inflicted by – black: flint (F), darker grey: non-serrated knife (NK), lighter grey: partially-serrated knife (SK). **A**: The presence of irregular edges on cutmarks (perimortem feature); **B:** presence of curling or uplifting on the edges of the cutmarks (perimortem feature); **C:** presence of regular shaped edges on cutmarks (postmortem feature); **D:** presence of splintering on cutmarks (perimortem feature); **E:** presence of sharp edges on cutmarks (postmortem feature); **F:** presence of crumbling on cutmarks (postmortem), which did not change significantly with PMI

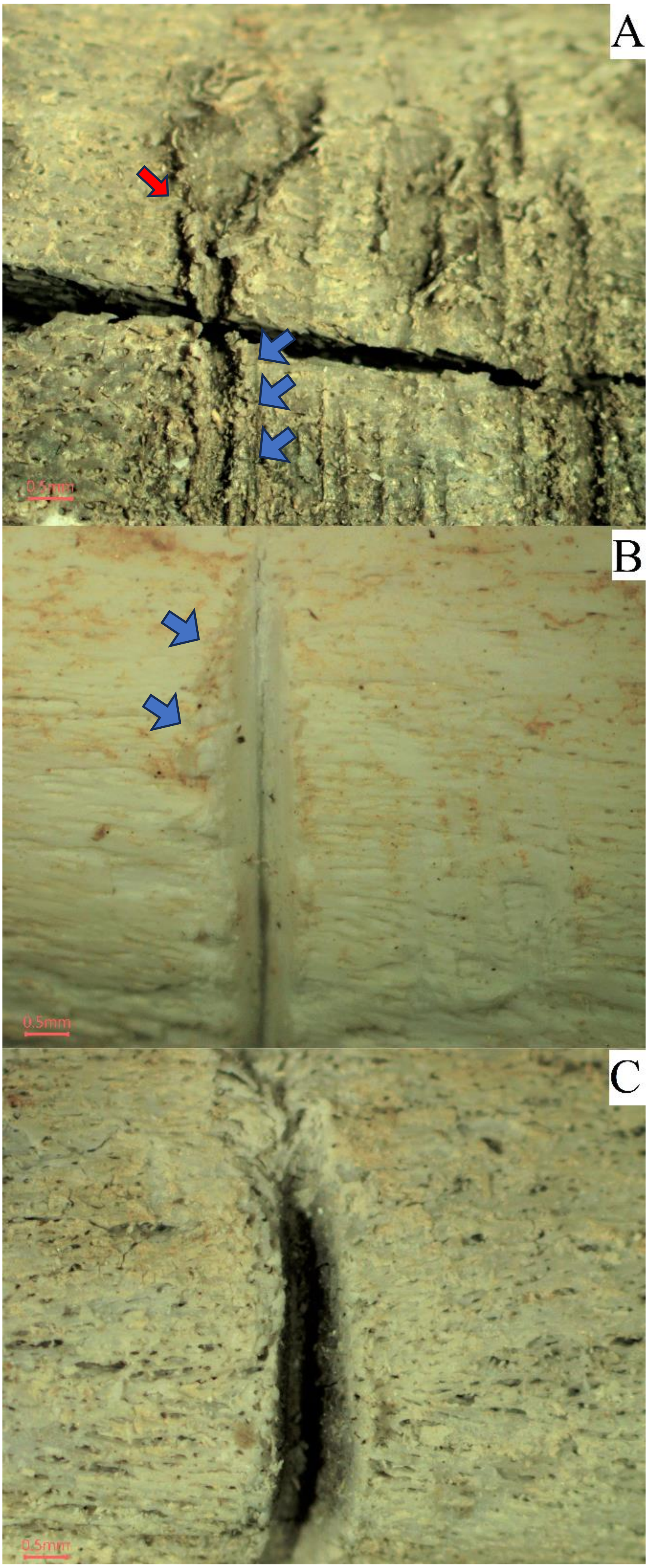
A
0.5mm
B
0.5mm
C
0.5mm

Fig. 7 Examples of changes in kerf outline with a particular attention to the kerf edges. All SFT was inflicted by the same instrument, a partially-serrated knife (SK); **A:** Burnt 14-day cutmark (WSF2D2W3_SK2). Note the irregular edges, curling or uplifting (blue arrows) at the edges, and splintering (red arrow); **B:** Burnt 180-day cutmark (WSF5D6M4_SK3). Note the regular shaped and sharp edges, the loss of the irregularity and the still present curling or uplifting (blue arrows) at the edges. **C:** Burnt 365-day cutmark (SWF5D1Y1_SK4). It exhibits regular shaped and sharp edges, without irregularity or curling and uplifting

A multiple comparison of means shows the differences that were observed between PMI groups (Table 5). When the instrument type was not selected for and all SFT was considered, the 365-day group was significantly different from all other PMI groups across a number of features (IRR, SPL, RES). The perimortem FLA and CUR and the postmortem DIS and CRL were not significantly different in any groups. SHA appeared after 6 months postmortem on all types of cutmarks and were also observed on the 1-year PMI group.

SFT inflicted by NK showed significant differences only in SPL, where the 365-day group was different from the 0-, 14-, and 180-day groups. SK trauma had a significant difference between the 365-day PMI groups and all other groups across a number of features: IRR, CUR, SPL, RES, SHA. Kerfs inflicted by the flint showed no significant difference between any PMI groups for any feature.

Multiple Comparison of Means: Features with significant differences between PMI groups (all instruments)				
Features	**group1**	**group2**	**meandiff**	**p-adj**
Irregular edges (IRR)	0-day	365-day	-2.83	0.001
	14-day	365-day	-2.85	0.001
	180-day	365-day	-2.63	0.001
	34-day	365-day	-2.52	0.001
	365-day	91-day	2.97	0.001
Curling/Uplifting (CUR)	0-day	365-day	-2.09	0.035
	365-day	91-day	2.09	0.035
Splintering (SPL)	0-day	365-day	-3.09	0.001
	14-day	365-day	-2.84	0.001
	180-day	34-day	-0.97	0.031
	180-day	365-day	-3.03	0.001
	34-day	365-day	-2.07	0.001
	365-day	91-day	2.95	0.001
Flaking (FLA)	N/A	N/A	N/A	N/A

Regular shaped edges (RES)	0-day	365-day	2.64	0.001
	14-day	365-day	2.66	0.001
	180-day	365-day	2.13	0.003
	34-day	365-day	2.34	0.001
	365-day	91-day	-2.76	0.001
Sharp edges (SHA)	0-day	180-day	1.28	0.028
	0-day	365-day	2.39	0.002
	14-day	180-day	1.20	0.008
	14-day	365-day	2.31	0.001
	34-day	365-day	2.06	0.005
	365-day	91-day	-1.94	0.016
Discolouration (DIS)	N/A	N/A	N/A	N/A
Crumbling (CRL)	0-day	91-day	1.79	0.0169

Table 5 -- The significant results of the multiple comparison of means when all SFT instruments are considered.

4. Discussion

The results of this study demonstrate that the number of fragments, warping, and thumbnail fractures do not depend on the slight decrease in collagen content of the bone during the first-year postmortem. Although collagen content did not linearly decrease with time, some bones suffered considerable collagen loss within only one-year postmortem [the highest loss (~50-33%) was observed in one of the 365-day samples]. The decrease of perimortem features (irregular edges, splintering, curling or uplifting) and increase of postmortem features (regular shaped and sharp edges) can potentially inform on the timing of SFT infliction in burnt bones as they appear after 6 months PMI and are observable in burnt bones.

Sus scrofa domesticus (pig) was selected as the animal model in this study, due to its extensive use as a substitutes for human bodies research on decomposition, fire effects, and trauma (Bonney et al., 2011; Forbes et al., 2005; Lynn & Fairgrieve, 2009; Symes et al., 2012; Végh & Rando, 2017). Pigs are considered reasonable proxies in various aspects, including bone macro- and microstructure, remodelling, and mineral concentration and density. Furthermore, the porcine model offers unique potential for evaluating tissue engineering, as it exhibits similarity in cortical bone thickness, which is associated with collagen crosslinks (Cone et al., 2017). Additionally, the porcine model has been utilised in imaging collagen fibres to investigate its potential for age-related changes in humans (Ambekar et al., 2012). While the appropriateness of using pigs as human analogues is subject to discussion (Matuszewski et al., 2020), numerous studies have demonstrated their usefulness in drawing meaningful inferences about human decomposition and bone response to fire and trauma in the fields of archaeology and forensic science (*ibid*). Therefore, the findings presented in this study are highly likely to have applicability to human skeletal tissues. Furthermore, although not a focus of this study, quantification of the reduced ability to identify cutmarks on faunal remains is also of relevance in zooarchaeological studies, particularly in contexts wherein unburnt bone does not survive due to soil conditions (Seitsonen et al., 2017; Ukkonen, 2004).

The incorporation of the cow bone in this study served as a comparative element to the burnt pig bones concerning heat-induced fracturing. Specifically, the cow bone was used as a control with a collagen content measuring below 0.5%, signifying a low to no-collagen reference sample. While *Bos* animal models have been employed in previous experimental archaeological and forensic anthropological research, in this particular study, the cow bone was exclusively used as a control to assess the heat-induced fracturing patterns exhibited by both the pig bones, which possessed varying levels of collagen, and the cow bone.

Recently it has been shown that in human remains burnt 10 years postmortem, only 13% of the inflicted SFT and chopping trauma could be identified post-burning (Mata Tutor et al., 2021). This ratio might be even lower in fresh burnt remains, since it is found here that the longer the PMI, the more cutmarks are recorded after burning. Here, this loss was not due to heat damage obscuring the kerfs. When pre-existing SFT was present it was always distinguishable from heat-induced fractures, in agreement with the literature (Pope & Smith, 2004b; Ubelaker, 2009; Poppa et al., 2011; Végh & Rando, 2017; Waltenberger & Schutkowski, 2017; Alunni et al., 2018). It was also not due to the fracturing severity, or how many bone fragments the bones broke into post-burning; rather, it was due to the location of these fractures. The fresher the bone was, the more likely it was for the longitudinal and transverse heat-induced fractures to slice the kerfs perpendicularly, resulting in the loss of small fragments.

Gonçalves et al. (2011) proposed that warping and thumbnail fractures might be due to the collagen content and/or distribution in the bone cortex. Supporting this, the experimentally burnt Neolithic cow rib bone (<0.5% collagen) showed no thumbnail fractures or warping, and in fact it showed no heat-induced fractures whatsoever. However, in the experimental pig bones no connection was found between the presence of thumbnail fractures and warping and collagen content in the ≤ 1-year PMI bones, though this is likely due to the limited length of the PMI. In fact, one of the only bones that did not present thumbnail fracture (14-day PMI; WSF2D2W5) showed the highest collagen content (23.80%) of all bones. Duplicate collagen measurements taken from the same part of bone resulted in variable collagen preservation, which suggests that collagen distribution can vary not only in the same bone, but also in the same bone area. This aligns with previous research on variable intra-skeletal N content in archaeological bone (Jacob et al., 2018). Thus, collagen presence and distribution might determine whether these fractures are present, but if this is highly variable even across the same bone, it might not add to our understanding of when the bone was burnt. Although the cool-temperate climate and the length of PMI did not allow for significant collagen loss in the present study, excarnation and further processing before cremation is unlikely to occur after many years (<1-2 years) which would be a sufficient PMI for significant collagen loss. It is simply suggested here that more research is needed in bone collagen distribution in relation to the PMI. Nevertheless, the overwhelming presence of thumbnail fractures and warping would classify all our samples as bones burnt in a fresh state (Baby, 1954; Binford, 1963; Buikstra and Swegle, 1989; Spennemann and Colley, 1989; Etxeberria, 1994; Whyte, 2001), even when burnt after 6 to 12 months exposure to the elements.

The features used to distinguish perimortem vs postmortem cuts (Mayne, 1990; Sauer, 1998; Symes et al., 2008; Ubelaker, 2009; Crowder et al., 2013) survived burning. Contrary to the findings of Mata Tutor et al. (2021), it was always possible to distinguish SFT from heat-induced fractures due to their shape and the sharper and more jagged edges of the heat-induced fractures (Fig. 8). The presence of two of the perimortem (irregular edges and splintering) and two postmortem (regular shaped edges and sharp edges) features in burnt bone have the potential to be used to discriminate between SFT inflicted <6 months postmortem before burning. If regular shaped kerfs and sharp edges are present on cutmarks on burnt bone, it is likely that the SFT was inflicted over 6 months after death prior to the fire event. The strongest case for this was presented by the SK-inflicted kerfs, in which all cutmarks started to present regular shaped and sharp edges only after 6 months postmortem, while the other kerfs produced by NK and F were only less likely to show these two postmortem features in bone samples with shorter PMIs. In most cases, the 365-day group's kerfs did not display irregular edges and splintering, meaning these features are mostly lost somewhere between 6 months and 1-year postmortem in surface-exposed remains. The perimortem (irregular edges and splintering) and postmortem (regular shaped edges and sharp edges) features might not be associated with retained collagen in the ≤ 1-year exposed bones, since there was no significant difference between the collagen content of the PMI groups. It is proposed here that moisture, other than collagen, might cause the difference in the bone's viscoelastic response to trauma. Rapid moisture loss was previously documented after two months, after which the decrease slowed (Wieberg & Wescott, 2008). Unburied, surface exposed bones should lose moisture faster than those buried.

Fig. 8 The observable difference between SFT inflicted by the non-serrated knife and a heat-induced fracture (middle) on a 91-day PMI burnt bone (WSF3D3M3). From left to right: NK4, heat-induced fracture, NK3. Note the rugged, non-viscoelastic breakage of the fracture surfaces (green arrows) caused by heat-induced fractures (light microscopy image).

There was a linear decrease with PMI in the appearance of curling and uplifting of the kerf edges in cutmarks inflicted by SK and F, but this feature seems to be associated with both PMI and instrument type, since it was not present in cutmarks caused by NK. This is probably because the non-serrated blade did not separate bone fibres in both directions. Although discolouration at cutmark edges has been suggested as an indication of trauma inflicted in unburnt dry bones (Crowder et al., 2013; Galloway et al., 2014; Mayne, 1990), and in burnt modern bones (Franceschetti et al., 2021), here burning completely obscured this colour change. There was a complete lack of a yellowish/brownish matt discolouration in the perimortem cutmarks (cf. Franceschetti et al., 2021). Since crumbling at the bottom of the kerfs was not associated with either PMI or type of instrument (Fig. 6F), it cannot determine the timing of trauma infliction. Flaking was always present in and around the kerfs; thus, it is not a reliable indication of perimortem trauma in burnt bones after only one year of PMI. It is possible that bones might not need to be dry for this feature to disappear post-burning.

One of the limitations of this study is the choice of animal model (pig) instead of human cadavers. Studies in human remains often lack control samples, exhibit high variability, which makes experiments difficult to conduct (Matuszewski et al., 2020). Due to these and other reasons, such as the general unavailability of human cadavers for archaeological research and ethical considerations, pig cadavers are the next best alternative for experimentation. Another limitation of the study is the length of time the bones were exposed as it was insufficient to result in significant collagen loss in a cool-temperate climate. Therefore, further research is needed in collagen distribution in the same and different areas of the same bone at different stages of early diagenesis. There is also need for measurements of moisture loss in bones in the future, as this may be another relevant factor in fracture characteristics.

5 Conclusion

This study attempted to differentiate between freshly burnt and early diagenetic burnt bones up to 1-year postmortem interval by assessing (1) SFT features inflicted by three different sharp force instruments; (2) heat-induced fractures relating to fresh bone (thumbnail fractures and warping); (3) fracture severity; and (4) retained collagen content. To our knowledge this is the first study to inflict SFT at different PMIs after exposure but subsequently before burning as well as attempting to compare heat-induced fracture types to collagen content. Pig tibiae, commonly used as a proxy for humans, was chosen for this study due to its widespread use as an animal model and its resemblance to human bone in terms of macro- and microstructure, collagen composition, and mineral content.

Fracturing severity (measured by the number of pieces the bone broke into) of the bones did not depend on the length of the PMI. However, cutmarks inflicted on the bones were more likely to be preserved if the bones were exposed longer postmortem (180 and 365 days) than with shorter intervals (<180 days), because heat-induced fractures were more abundant in the area where the cutmarks were inflicted on the fresher samples than on the longer-exposed bones.

Thumbnail fractures and warping were present on almost all of the bones and did not depend on retained collagen content, with the exception of the archaeological bone with <0.5% collagen. These fractures might be more closely associated with other (non-collagenous) moisture in the bone or the highly variable collagen distribution in the same bone.

The perimortem vs. postmortem SFT features survived burning in this study, which made it possible to inform on the postmortem interval before burning. It is proposed here that the loss of some of these perimortem features (irregular edges, splintering, and curling or uplifting) with the appearance of some postmortem features (regular shaped and sharp edges) on cutmarks might be useful indications of delay between time of death and the burning event. The loss of these features is steady and continuous, but 6 months of surface exposure of the remains might produce significant and noticeable reductions in the investigated perimortem SFT features. The appearance of regular shaped kerfs and sharp edges might be the best indication of the body being surface exposed for 6 months after death and before burning, especially when the SFT was caused by (partially-) serrated instruments. One year of surface exposure was insufficiently long for flaking to disappear, regardless of the type of cutting implement. Colour differences at trauma surfaces were obscured by burning-induced colour changes and crumbling was not related to PMI or the type of instrument in burnt bones. The results of this study contribute to understanding the effects of heat-induced changes and to the recognition of osteogenic reaction for applications both in osteoarchaeology and forensic anthropology.

Declarations

The authors declare no competing interests or funding.

Authors' contributions

Emese Végh: Conceptualization-Lead, Data Curation-Lead, Formal analysis-Lead, Funding acquisition-Lead, Investigation-Lead, Methodology-Lead, Project administration-Lead, Resources-Lead, Software-Lead, Validation-Lead, Visualization-Lead, Writing – original draft-Lead, Writing – review & editing-Equal

Nicholas Marquez-Grant: Conceptualization-Supporting, Supervision-Supporting, Writing – review & editing-Supporting

Rick Schulting: Conceptualization-Supporting, Funding acquisition-Supporting, Investigation-Equal, Methodology-Supporting, Supervision-Lead, Writing – review & editing-Lead

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Availability of data and materials

Supporting data to this paper is available in the online *supplementary materials* file.

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