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Spontaneously arising disease

Dental and temporomandibular joint pathology of the Arctic fox (*Vulpes lagopus*)

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ABSTRACT

Museum skull specimens from 224 Arctic foxes (*Vulpes lagopus*) were examined macroscopically using an established protocol for examination of mammalian skull specimens. Foxes were collected from coastal and island regions of Alaska, USA, except for two individuals. Collection years ranged from 1931 to 2016 with most specimens collected during the 1950s and 1960s. The study population comprised more females (n = 134, 59.8%) than males (n = 83, 37.0%) and individuals of unknown sex (n = 7, 3.1%). There were 108 (48.2%) young adults, 115 (51.3%) adults, and one (0.4%) individual of unknown age. A total of 8,891 teeth (94.5%) were available for examination. The most common types of pathology observed were periodontitis (n = 222, 99.1%), dental fractures (n = 175, 78.1%) and attrition/abrasion (n = 198, 88.4%). Periapical lesions (n = 12, 5.3%), temporomandibular joint (TMJ) osteoarthritis (n = 3, 1.3%) and root number variation (n = 5, 2.2%) were less common. Enamel hypoplasia was noted in eight foxes (3.6%), all of which were discovered on St. Matthew Island, Alaska, in 1963. As in other canid species, periodontitis, attrition/abrasion and tooth fractures are common in the Arctic fox, while TMJ pathology is rare. Loss of tooth crown substance probably reflects the influence of diet, interspecific and conspecific aggression and oral trauma due to trapping and hunting methods. The high prevalence of periodontitis is probably also due to the combined effects of diet, genetics and host immune reaction to oral bacteria.

1. Introduction

The Arctic fox (*Vulpes lagopus*) is one of two canine inhabitants of the north circumpolar region, with the other being the red fox (*Vulpes vulpes*). The Arctic fox was previously named *Alopex lagopus* and is classified by the International Union for the Conservation of Nature (IUCN) as ‘least concern’. The general population has remained stable in recent decades but more recent monitoring is required to determine its current status [1,2]. The species is spread across a wide territory from the northernmost Arctic tundra, marine and costal habitats, to subarctic deciduous forest. Humans have also introduced the Arctic fox to some northern island habitats such as the Aleutian islands [3,4]. There are currently eight known subspecies of *V. lagopus* [3].

The Arctic fox is a small mammal that is well adapted to the harsh climate of the northernmost regions of the planet. Adults weigh 3–5 kg with males usually heavier. The lifespan is typically 3–5 years in the wild and can reach 9–12 years in captivity [3]. This fox is a carnivorous predator and scavenger, consuming lemmings (subfamily Arvicolinae) and other small mammals, sea birds, eggs and reindeer and moose carrion, with its diet highly dependent on the microhabitats in which each individual lives. Populations and subspecies have been divided into specialists, which prey primarily on lemmings, and coastal generalists [5–7]. Arctic foxes have also been documented to take advantage of anthropogenic food sources as human presence in the Arctic increases [7]. Food availability greatly impacts individual fitness as fox numbers and population stability have been shown to vary with the abundance of lemmings [6,8,9].

Like other canid species, the Arctic fox normally has a heterodont dentition with 42 permanent teeth. The dental formula includes incisor (I), canine (C), premolar (P) and molar (M) teeth (I 3/3, C 1/1, P 4/4, M2/3) (Fig. 1) [4]. Dental anomalies and pathology in this species have been documented to a limited extent. Supernumerary roots, supernumerary teeth, abnormal tooth crowns, periodontal disease and missing teeth have been reported [10,11].

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Dental pathology in other canid and fox species has been studied systematically, revealing that phylogenetically similar species are subject to tooth abnormalities such as tooth fractures, attrition/abrasion and periodontal disease [12–14]. Assessing dental pathology can inform and reflect ecology, behaviour and genetics of a species and influence survivability and fitness [15,16].

The Arctic fox is an iconic species that is of important economic value to humans, can act as a vector for zoonotic and interspecies diseases and serves as a keystone indicator of overall health of the northern polar regions. In some regions, roughly 100,000 individuals are harvested every year for the fur trade [4]. Additionally, as human presence in the northern polar regions increases, exposure of humans to zoonotic diseases such as rabies from the Arctic fox has been documented [17]. Similarly, Arctic foxes are subject to the same diseases as other canids, including canine distemper virus (CDV), intestinal parasites and sarcoptic mange (*Sarcoptes scabiei*), which can influence their population stability and transmission of disease to other species [4,17–19]. Arctic fox populations are also subject to the effects of climate change as they have been shown to use sea ice to travel long distances for food [1]. Additionally, as global temperature continues to increase, the Arctic fox is subject to increased interspecific competition from the red fox as the latter expands its territory northwards [4,7].

Museum skull specimens offer a non-invasive means of assessing abnormalities and pathology of the hard tissues and have proven to be successful in characterizing dental and oral disease in many mammalian species [12–14,20–31]. The aim of the current study was to utilize museum specimens to systematically survey the dental pathology of the Arctic fox using a previously tested methodology. We hypothesized that the Arctic fox is subject to similar dental pathology as other fox and canid species, including tooth fractures, attrition/abrasion and periodontal disease, and has a lower prevalence of temporomandibular joint (TMJ) disease.

2. Materials and methods

2.1. Skull specimens

Macroscopic examination of 265 Arctic fox skull specimens from the Museum of the North of the University of Alaska at Fairbanks, Alaska, was performed with 224 skull specimens included in this study. The skull specimens were labelled with a unique numerical identification number, collection date, sex and subspecies. Age estimation of the individuals at time of death was determined by the presence or absence of deciduous dentition and closure of the basospheno-basooccipital suture and intersphenoidal suture [32]. Skull specimens with fractures extending through the skull such that the sutures were obliterated were marked as of unknown age. The specimens were placed into various age categories on the basis of these characteristics: juvenile (deciduous or mixed dentition); young adult (open sutures present); and adult (closed sutures). Juveniles and skulls with severe damage obscuring overall anatomy or with missing tooth-bearing regions were excluded from further study.

2.2. Dental and bone examination

All teeth, surrounding bony tissue and TMJs were examined for abnormalities and wear using previously determined criteria (Table 1) [22–24,27,28,33]. Tooth number comparison with a normal dental quadrant for this species was recorded. Missing teeth were not pooled into calculations for prevalence of abnormally formed teeth, attrition/abrasion, fractures and enamel hypoplasia because their status could not be confirmed. A full dental quadrant was assumed when calculating the prevalence of supernumerary teeth, periapical lesions and bony changes consistent with periodontitis.

The teeth were assessed for any congenital or developmental abnormalities. Tooth form and root number were determined by examining the crown as well as any visible portion of the root. Supernumerary and persistent deciduous teeth and enamel changes consistent with enamel hypoplasia were also recorded.

Additionally, the teeth were examined for acquired pathological abnormalities. Assessment of fractures followed criteria outlined by the World Health Organization for use in human dentistry, as modified for use in carnivores [34]. Artefactual fractures, denoted by sharp edges and occurring along non-physiological angles, were detected and omitted. Periapical lesions, defined as macroscopically visible bone loss and/or periosteal reaction overlying a tooth root apex, were also recorded. Periodontal status was determined based on a staging system adapted for use on skulls (Table 1) [16]. Stage 1 periodontitis was omitted as it refers to gingivitis, which could not be judged from viewing only hard tissue specimens. The teeth were also assessed for attrition and abrasion characterized by rounding of the cuspal tip and exposure of dentine with or without pulp cavity exposure. The TMJ and other skull bones were also evaluated for proliferative lesions, fractures, osteophytosis/enthesophytes or osteolysis.

2.3. Statistical analysis

The data were analysed by separating each tooth type and comparing the prevalence of lesions within the different age and sex groups. Significant differences in the prevalence of dental pathology and abnormalities between young adults and adults, as well as between males and females, were detected using Fisher's exact test and the chi-square test. Differences in the prevalence of pathology and abnormalities were compared among tooth types by pooling data from incisors, canines, premolars and molars, and performing a chi-square test. Logistic regression was used to quantify the joint effects of age and sex on the prevalence of attrition and abrasion, and to identify potentially significant interactions between these variables. Ordinal data were assessed for normality using the Shapiro–Wilk test and then analysed for trends using the Mann–Whitney *U* test or Kruskal–Wallis test, depending on the number of testable groups. Results were considered significant at $P < 0.05$.

3. Results

3.1. Study population

Of the 265 skull specimens examined, 224 were of adequate quality for examination and had complete adult dentition. Specimen collection dates ranged from 1931 to 2016. Five (2.2%) skull specimens were collected in 1931, 199 (88.8%) from 1953 to 1967, two (0.9%) in 1978 and 16 (7.1%) from 2012 to 2016. Two specimens did not have recorded collection dates. The study population consisted of 134 (59.8%) females, 83 (37.0%) males and seven (3.1%) individuals of unknown sex. There were 108 (48.2%) young adults, 115 (51.3%) adults and one (0.4%) individual of unknown age. Specimen collection locations included St. Lawrence Island, Western Alaska (SLI) (168, 75.0%), the northern Alaska coast (NAC) (25, 11.2%), St. Matthew Island, western Alaska (SMI) (14, 6.3%), Saint George Island, western Alaska (SGI) (eight, 3.6%), the Trinity Islands, southern Alaska (two, 0.9%), Saint Paul Island, western Alaska (two, 0.9%), Teller Quad, western Alaska (two, 0.9%), Kolskii Peninsula, northeastern Russia (one, 0.4%), western Greenland (one, 0.4%) and Hooper Bay, western Alaska (one, 0.4%).

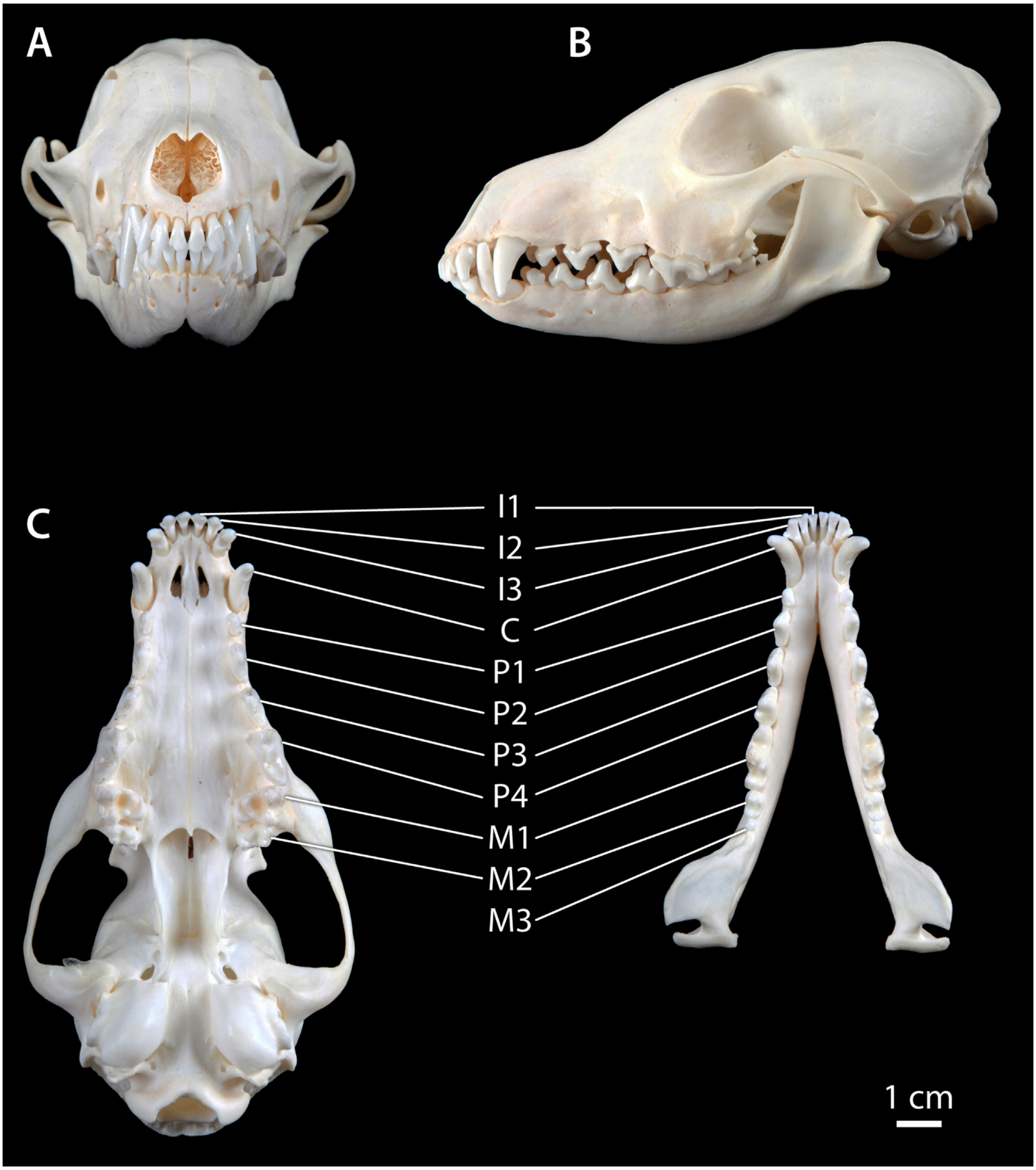

Fig. 1. **(A–C)** Representative dentition in an adult Arctic fox. (Specimen from University of California Davis collection and not included in data analysis.)

3.2. Presence of teeth

The total number of teeth available for examination was 8,891 (94.5%) out of a possible 9,408 teeth. A total of 366 (3.9%) teeth were absent artefactually *post mortem*. A total of 34 teeth (0.4%) from 25 individual skulls were considered congenitally absent and 117 (1.2%) teeth from 38 skulls were deemed absent due to acquired tooth loss (Table 2). The most common sites for congenital tooth absence were the left and right mandibular third molar tooth (n = 12 and n = 10, respectively). The most common sites for acquired tooth loss were the right and left mandibular first incisor teeth (n = 10 and n = 9, respectively). The right maxillary canine tooth was the most common site for artefactual tooth loss as some of the specimens were utilized for a previous study and had been extracted (n = 153) [35]. Premolar and molar teeth were significantly more likely to be congenitally absent (n = 9, 0.2% and n = 25, 1.1%, respectively) compared with other tooth types (*P* <0.0001). Incisor teeth were significantly more likely to be subject to acquired tooth loss (n = 58, 2.2%) compared with other tooth types (*P* <0.0001). Adults had a significantly higher frequency of acquired tooth loss

Table 1
Inclusion criteria of congenital, developmental and acquired abnormalities

Observation	Criteria
Tooth artefactually absent	Jaw fragment missing or tooth absent but a well-defined, sharp-edged, normally shaped, empty alveolus present; no lesions visible in the alveolar bone; tooth presumed lost during preparation or post-mortem manipulation of the skull.
Tooth absent—presumably acquired	Tooth absent; alveolus or remnant of alveolus visible; alveolar bone has lesions (rounding of the alveolar margin, shallow alveolus, periosteal reaction on alveolar bone, increased vascular foramina).
Tooth absent—presumably congenital	Tooth and alveolus absent; smooth, morphologically normal bone present at the site; no evidence of acquired tooth loss of adjacent teeth.
Malformed tooth	Presence of an abnormally shaped crown.
Supernumerary tooth	Presence of a supernumerary tooth adjacent to the normal tooth.
Number of roots	One, two or three roots.
Persistent deciduous tooth	A persistent deciduous tooth adjacent to a fully erupted tooth.
Attrition/abrasion	Rounding or flattening of the cusp tip; exposure of dentine, with or without tertiary dentine formation.
Enamel fracture	A chip fracture or crack of the enamel only.
Uncomplicated crown fracture	A fracture affecting enamel and dentine, but not exposing the pulp.
Complicated crown fracture	A fracture affecting enamel and dentine, and exposing the pulp.
Uncomplicated crown-root fracture	A fracture affecting enamel, dentine and cementum, but not exposing the pulp.
Complicated crown-root fracture	A fracture affecting enamel, dentine and cementum, and exposing the pulp.
Root fracture	A fracture affecting dentine, cementum and the pulp.
Periapical lesions	Macroscopically visible periapical bone loss, root tip resorption, sinus tract formation originating periapically, or obvious focal periosteal reaction overlying the apex.
Periodontitis stage 2	Evidence of increased vascularity at the alveolar margin (more prominent vascular foramina in, and slightly rougher texture of, the bone of the alveolar margin).
Periodontitis stage 3	Rounding of the alveolar margin; moderate horizontal or vertical bone loss.
Periodontitis stage 4	Widening of the periodontal space; severe horizontal or vertical bone loss; tooth unstable in the alveolus.
Enamel hypoplasia	Irregular pitting, or a band-shaped absence or thinning of the enamel, consistent with the clinical signs of enamel hypoplasia.
Mild TMJ osteoarthritis	Early periarticular new bone formation/osteophytes and/or minimal subchondral bone change; mandibular head or fossa affected, but not both.
Moderate TMJ osteoarthritis	Periarticular new bone formation and/or subchondral bone changes; mandibular head and/or fossa affected.
Severe TMJ osteoarthritis	All previously described signs are present and more pronounced; subchondral bone lysis present; both mandibular head and fossa affected.

TMJ, temporomandibular joint.

than young adults (n = 30, 26.1% and n = 8, 7.4%, respectively; $P = 0.0003$). There was no significant difference in acquired tooth loss between males and females ($P = 0.0940$). Males had a significantly higher frequency of congenital tooth absence than females (n = 15, 18.1% and n = 9, 6.7%, respectively; $P = 0.0135$), There was no significant difference in congenital tooth absence between young adults and adults ($P = 0.2084$). There was no statistically significant difference in the frequency of acquired or congenital tooth loss for different specimen collection time periods ($P = 0.8783$ and $P = 0.1332$, respectively). There was no statistically significant difference in the frequency of acquired or congenital tooth loss for different collection locations ($P = 0.4079$ and $P = 0.4033$, respectively).

3.3. Persistent deciduous teeth

None of the specimens had persistent deciduous teeth (Table 2).

3.4. Supernumerary teeth

Two specimens (0.9%) had one supernumerary tooth (Table 2). One of these foxes had a supernumerary left maxillary second molar tooth while the other fox had a supernumerary left mandibular third molar tooth.

3.5. Tooth form

None of the specimens had any variations in tooth form.

3.6. Root number variation

Five skull specimens (2.2%) had at least one tooth with a supernumerary root with a total of eight affected teeth (Table 2). Teeth with a supernumerary root included right and left maxillary first premolar teeth, a left maxillary third premolar tooth, a right maxillary fourth premolar tooth, left and right mandibular first premolar teeth and a right mandibular third molar tooth. One specimen had three teeth with supernumerary roots while another had two with supernumerary roots.

3.7. Enamel hypoplasia

Eight skull specimens (3.6%) had teeth with variable degrees of enamel hypoplasia, affecting 83 (0.9%) teeth in total (Fig. 2; Table 2). The number of affected teeth ranged from three in one specimen to 20 in another specimen. All specimens with enamel hypoplasia originated from SMI and had been collected in 1963.

3.8. Alveolar bone changes consistent with periodontitis

Almost all (n = 222, 99.1%) skull specimens had bone change consistent with periodontitis (Fig. 3). A total of 220 (98.2%) skull specimens had evidence of at least one tooth with stage 2 periodontitis, 118 (52.7%) had evidence of at least one tooth with stage 3 periodontitis and 38 (17.0%) had evidence of at least one tooth with stage 4 periodontitis (Table 2). A total of 3,181 (33.8%) teeth had evidence of stage 2 periodontitis, 670 (7.1%) had evidence of stage 3 periodontitis and 155 (1.6%) had evidence of stage 4 periodontitis (Table 2). The most common sites for stage 2 periodontitis were the left maxillary first molar (n = 141), left maxillary second molar (n = 132) and right maxillary first molar (n = 122) teeth. The most common sites for stage 3 periodontitis were the right and left mandibular third incisor (n = 44 and n = 43, respectively) teeth. The most common sites for stage 4 periodontitis were the right and left mandibular first incisor (n = 9 and n = 8, respectively) and the right mandibular second incisor (n = 8) teeth. Overall, incisor teeth were more frequently affected by periodontitis than any other tooth type (n = 1,386, 51.6% of incisor teeth; $P < 0.0001$). Incisor and molar teeth were more frequently affected by stage 2 periodontitis (n = 1,022, 38.0% of incisor teeth and n = 43, 3% of molar teeth,

Table 2
Summary of foxes affected and teeth affected by different pathology and developmental anomalies

Abnormality	Number of foxes affected	Number of teeth affected
Absent teeth		
Congenital	25 (11.1%)	34 (0.4%)
Acquired	38 (17.0%)	117 (1.2%)
Persistent deciduous teeth	0 (0%)	0 (0%)
Supernumerary teeth	2 (0.9%)	2 (0.02%)
Root number variation	5 (2.2%)	8 (0.09%)
Enamel hypoplasia	8 (3.6%)	83 (0.9%)
Periodontitis		
Stage 2	220 (98.2%)	3,181 (33.8%)
Stage 3	118 (52.7%)	670 (7.12%)
Stage 4	38 (17.0%)	155 (1.6%)
Tooth fractures		
EF	31 (13.8%)	61 (0.6%)
UCF	128 (57.1%)	408 (4.3%)
CCF	85 (37.9%)	170 (1.8%)
UCRF	4 (1.8%)	5 (0.05%)
CCRF	65 (29.0%)	144 (1.5%)
RF	61 (27.2%)	199 (2.1%)
Periapical lesions	12 (5.3%)	29 (0.3%)
Attrition/abrasion	198 (88.4%)	3772 (40.1%)
TMJ pathology	3 (1.3%)	NA

EF, enamel fractures; UCF, uncomplicated crown fractures; CCF, complicated crown fractures; UCRF, uncomplicated crown-root fractures; CCRF, complicated crown-root fractures; RF, root fractures; TMJ, temporomandibular joint; NA, not applicable.

respectively; P <0.0001). Incisor teeth were more commonly subject to stage 3 (n = 298, 11.0% of incisor teeth; P <0.0001) and stage 4 (n = 66, 2.5% of incisor teeth; P <0.0001) periodontitis than other tooth types. There was no significant difference between the frequency of stage 2 periodontitis in young adults and adults (P = 0.9999). However, the number of teeth with stage 2 periodontitis was higher in adults (median = 11) than in young adults (median = 11) (P = 0.0147). A higher percentage of adults was affected by stage 3 periodontitis than young adults (67.0% and 38.0% respectively; P <0.0001) and the number of teeth affected by stage 3 periodontitis was higher in adults (median = 2) than young adults (median = 0) (P <0.0001). A higher percentage of adults had stage 4 periodontitis than young adults (26.0% and 7.4% respectively; P = 0.0003) and the number of teeth with stage 4 periodontitis was higher in adults (median = 0) than in young adults (median = 0; P = 0.0002). There was no significant relationship between sex and frequency of stage 2, 3 or 4 periodontitis (P = 0.3004, P = 0.4885 and P = 0.1338, respectively) and no significant sex differences in the number of teeth affected by stage 2, 3, or 4 periodontitis (P = 0.8306, P = 0.2523 and P = 0.1012, respectively). There were no statistically significant differences in the prevalences of stage 2, stage 3 or stage 4 periodontitis when comparing time periods in which specimens had been collected (P = 0.8066, P = 0.1497 and P = 0.1497, respectively) or in stage 2 or stage 4 periodontitis when comparing locations at which specimens had been collected (P = 0.7674 and P = 0.1325, respectively). However, foxes collected from NAC and SLI had a higher prevalence of stage 3 periodontitis than foxes from SMI or SGI (68.0%, 54.0%, 7.1% and 37.5%, respectively) (P = 0.0020).

3.9. Tooth fractures

Dental fractures were identified in 175 (78.1%) skull specimens and 987 (10.5%) teeth examined (Fig. 4, Table 2). All tooth fracture types were found in the study population. In total, 31(13.8%) foxes had enamel fractures, 128 (51.1%) had uncomplicated crown fractures, 85 (37.9%) had complicated crown fractures, four (1.8%) had uncomplicated crown-root fractures, 65 (29.0%) had complicated crown-root fractures and 61 (27.2%) had root fractures. A total of 61 (0.6%) teeth had enamel fractures, 408 (4.3%) had uncomplicated crown fractures, 170 (1.8%) had complicated crown fractures, five (0.05%) had uncomplicated crown-root fractures, 144 (1.5%) had complicated crown-root fractures and 199 (2.1%) had root fractures. A total of 115 (51.3%) individuals had 1–5 fractured teeth, 35 (15.6%) had 6–10 fractured teeth, 11 (4.9%) had 11–15 fractured teeth, nine (4.0%) had 16–20 fractured teeth and five (2.2%) had 21–25 fractured teeth. Canine teeth and premolar teeth had significantly higher proportions of fractures than other tooth types (n = 123, 13.7% of canine teeth and n = 549, 15.3% of premolar teeth, respectively; P <0.0001). There was no significant relationship between the presence of fractured teeth in general and sex or age (P = 0.1785 and P = 0.052, respectively) nor between age groups with respect to the presence of complicated crown fractures (odds ratio [OR] = 0.87, 95% confidence interval [CI] = 0.18–4.29; P = 0.8691), complicated crown-root fractures (OR = 4.87, 95% CI 0.74–36.38; P = 0.1101), and root fractures (OR = 1.28, 95% CI = 0.19–9.52; P = 0.7993) when corrected for sex. There was no significant relationship between sex and presence of complicated crown fractures (OR = 0.53, 95% CI = 0.08–3.2; P = 0.4890), complicated crown-root fractures (OR = 2.27, 95% CI = 0.24–22.15; P = 0.4697) and root fractures (OR = 0.28, 95% CI = 0.02–3.27; P = 0.3204) when corrected for age. There were no statistically significant differences in the number of complicated crown fractures, complicated crown-root fractures or root fractures with respect to location at which the foxes had been collected (P = 0.3864, P = 0.8157 and P = 0.3626, respectively), in total number of tooth fractures with respect to location at which the specimens had been collected (P = 0.4178) or in the number of complicated crown fractures or complicated crown-root fractures with respect to the time period in which the foxes had been collected (P = 0.1644 and P = 0.0545, respectively). Although there was no statistically significant difference in total number of tooth fractures with respect to the time period in which the specimens had been collected (P = 0.1051), the number of teeth with root fractures was higher for foxes collected from 2012 to 2016 (median = 1) compared with foxes collected in the 1930s (median = 0) or from 1953 to 1967 (median = 0; P = 0.0244).

3.10. Periapical lesions

Twelve (5.3%) skull specimens had evidence of periapical lesions affecting a total of 29 (0.3%) teeth (Fig. 5, Table 2). The number of affected teeth per fox ranged from one to 11. Canine teeth were more commonly associated with periapical lesions when compared with other tooth types (n = 7, 0.8%; P = 0.0471). Adults were more commonly affected by periapical lesions than young adults (n = 11, 9.6% and n = 1, 0.9%, respectively; P = 0.0054). There was no significant relationship between sex and the presence of periapical lesions (P = 0.7707) or between time periods in which a specimen had been collected and the presence of periapical disease (P = 0.3241). Skull specimens collected from SMI had a higher prevalence of periapical disease (21.4%) compared with specimens collected from NAC (12.0%), SLI (1.7%) and SGI (12.5%) (P = 0.0011).

3.11. Attrition/abrasion

Attrition and/or abrasion was found in 198 (88.4%) skull specimens, affecting 40.1% of the teeth (Table 2). Canine teeth more commonly had attrition/abrasion compared with other tooth types (n = 346, 50.9%; P <0.0001). There was no significant relationship between age or sex with the presence of attrition/abrasion (P = 0.2101 and P = 0.6618, respectively) or in the prevalence of attrition/abrasion when comparing time periods in which a specimen

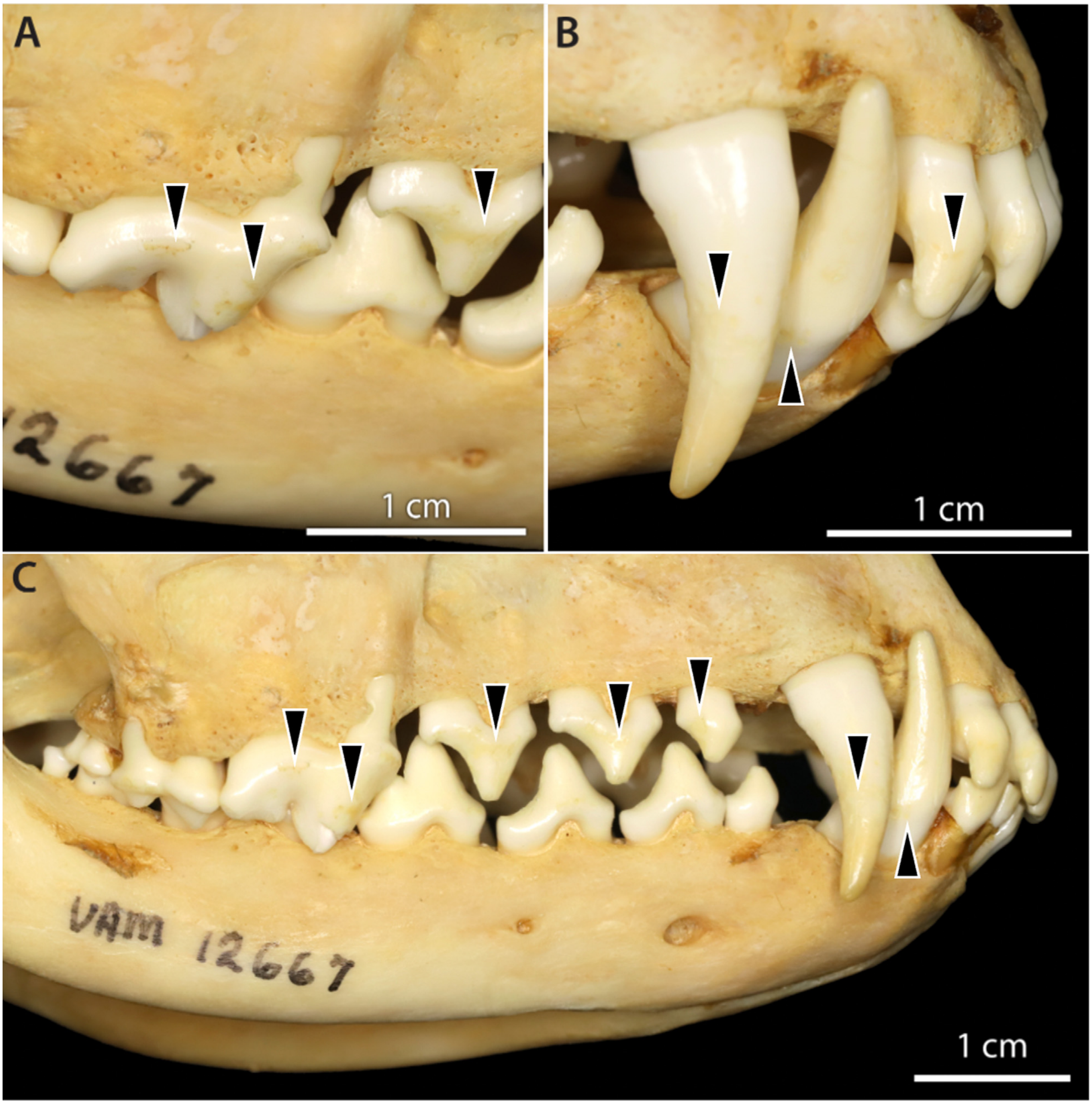

Fig. 2. Semigeneralized enamel hypoplasia. **(A)** Right maxillary third and fourth premolar teeth with enamel defects (arrowheads). **(B)** Enamel defects (arrowheads) in right maxillary third incisor and canine teeth and right mandibular canine tooth. **(C)** Right maxillary and mandibular quadrants with enamel defects (arrowheads) involving teeth from right maxillary third incisor tooth to right maxillary fourth premolar tooth and right mandibular canine tooth (UAM 12667).

had been collected ($P = 0.4662$) or between location of collection of specimens and the prevalence of attrition/abrasion ($P = 0.6091$).

3.12. *Fenestration*

Eight (3.6%) skull specimens had at least one tooth with fenestration of the maxillary alveolar bone. Fenestration was associated with 17 (0.19%) teeth and the most affected site was the right maxillary fourth premolar tooth (n = 6, 35.3%). Other affected sites included the right and left maxillary first molar teeth (n = 4, 23.5% and n = 4, 23.5%, respectively) and the left maxillary fourth premolar tooth (n = 3, 17.6%). There were no significant differences in fenestration between age and sex groups ($P = 0.3773$ and $P = 0.3410$, respectively).

3.13. *Temporomandibular joint pathology*

Three skull specimens had TMJ pathology (Table 2). One had evidence of severe osteoarthritis of the mandibular head and temporomandibular fossa of the left TMJ (Fig. 6), one had evidence of mild osteoarthritis of the right mandibular head while the third had evidence of mild osteoarthritis of the left mandibular head.

3.14. *Other findings*

Two skull specimens had dental or maxillofacial abnormalities that did not fall into any of the categories described. One skull had a partially erupted right mandibular fourth premolar tooth while another had unilateral thickening of the left mandible in the region

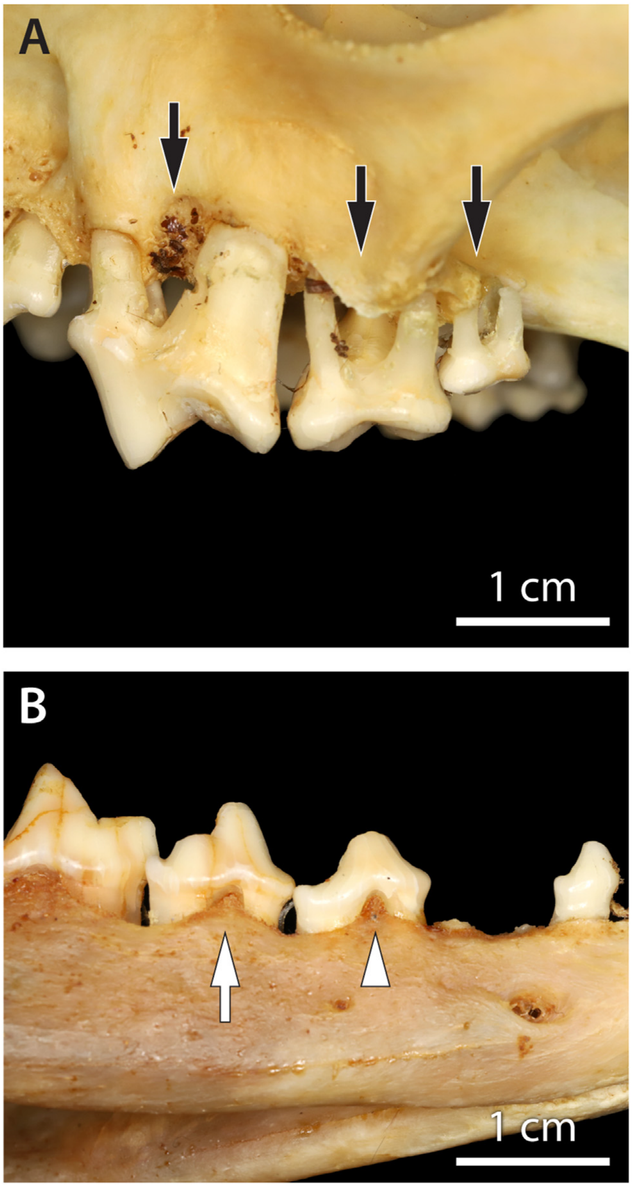

Fig. 3. Varying degrees of periodontitis in an adult Arctic fox (UAM 18703). **(A)** Severe periodontitis of left maxillary third premolar tooth and left maxillary first and second molar teeth with furcation exposure (arrows). **(B)** Stage 2 periodontitis of right mandibular third premolar tooth (arrowhead) and stage 3 periodontitis of right mandibular fourth premolar tooth without furcation exposure (arrow).

of the left mandibular fourth premolar tooth to second molar tooth. Another specimen had generalized periosteal reaction of the rostral mandibles consistent with osteomyelitis or neoplasia. Bilateral diastemata between the left and right mandibular third and fourth premolar teeth was present in one specimen, one had a chronic, non-union fracture of the left mandible (Fig. 7) while another had evidence of bite wound injuries to the frontal bone and left maxillary bones.

4. Discussion

This study characterized dental and TMJ pathology in Arctic foxes mainly originating from coastal and island regions in Alaska and collected non-uniformly during the 20th and early 21st centuries. Like other canid species, the Arctic fox displays a high prevalence of bony changes consistent with periodontitis, tooth fractures and attrition/abrasion [12–14]. However, TMJ osteoarthritis, variations in tooth form, enamel hypoplasia and supernumerary teeth appeared to be rare in this species. Acquired tooth loss was more common than congenital tooth loss in the Arctic fox. Compared with the grey fox (*Urocyon cinereoargenteus*) and the grey wolf (*Canis lupus*), the Arctic fox had considerably less acquired tooth loss but a similar frequency of acquired tooth loss compared with the kit fox (*Vulpes macrotis*) [12–14]. Another study on museum skulls from a red fox population originating in Lithuania reported a much lower prevalence of tooth loss [36]. Differences in acquired tooth loss when compared with other canid species could be a result of variations in diet, behaviour or genetics. Furthermore, the grey fox and grey wolf have a longer life span on average than the kit fox and Arctic fox [37,38]. Therefore, the frequency of tooth loss could be a function of longevity and progressive dental disease. The study population had a high degree of artefactual tooth loss of the maxillary canine teeth as these teeth had been extracted *post mortem* for a previous study [35].

Almost all the skull specimens examined had some degree of bone change consistent with periodontitis and this was predominated by evidence of early periodontitis. There was no significant difference between the prevalence of stage 2 periodontitis in adults when compared with young adults, suggesting that the onset of periodontitis occurs early in life and can progress to more severe stages. The Arctic fox population examined had a higher prevalence of periodontitis compared with other canid species studied with the same protocol and also had a higher frequency of more severe periodontitis than other canid species [12–14]. A study that discussed stage 3 and stage 4 periodontitis in Lithuanian red foxes reported a much lower frequency of bone change consistent with periodontitis [36]. The difference observed is difficult to explain from variations in diet or natural history alone as other fox species are also omnivorous mesopredators. Proteomic and genomic studies of the oral microbiota of the Arctic fox and other canid species would be required to further characterize the predisposing factors for the development of periodontal disease in the species.

The study population had a high frequency of tooth fractures and many specimens had generalized traumatic injury to the teeth. The prevalence of tooth fractures was similar to other canid species [12–14]. A recent study of red fox specimens from Lithuania reported a very low prevalence of fractures [36]. However, as that study only reported the prevalence of complicated and uncomplicated crown fractures it is possible that the true fracture prevalence in the red fox study population is underreported. The Arctic fox is seasonally harvested using baited trap methods and it is likely that many of the specimens in the current study population had been obtained from commercial trappers. Furthermore, foxes are trapped in baited cages or foothold traps for research purposes and subsequently released [39,40]. It is likely that a trapped fox will cause immense trauma to its teeth on the hard structural components of the trap. Additionally, depending on how the fox is killed by hunters (by concussive force or ballistic trauma), additional tooth fractures may occur. Therefore, the prevalence of tooth fractures in the study population compared with the total wild population is probably an overestimate. The Arctic fox feeds on carrion and sometimes hard-shelled marine species, which may also explain the high prevalence of tooth fractures. Almost all foxes in the present study were collected from coastal or island regions of Alaska and it is possible that differences in food sources could result in an altered prevalence of tooth fractures compared with inland fox populations. When considering tooth fractures, sex and age differences were identified in the study population with more adults and males having complicated fractures. However, multiple logistic regression analysis demonstrated that this difference was not significant when each variable was considered individually.

Fig. 4. Root fractures of left and right mandibular first, second and third premolar teeth. Fracture of right mandibular third incisor tooth suspected to be artefactual, characterized by sharp edges and a portion of coronal segment at base of crown (arrowhead) (UAM 12488).

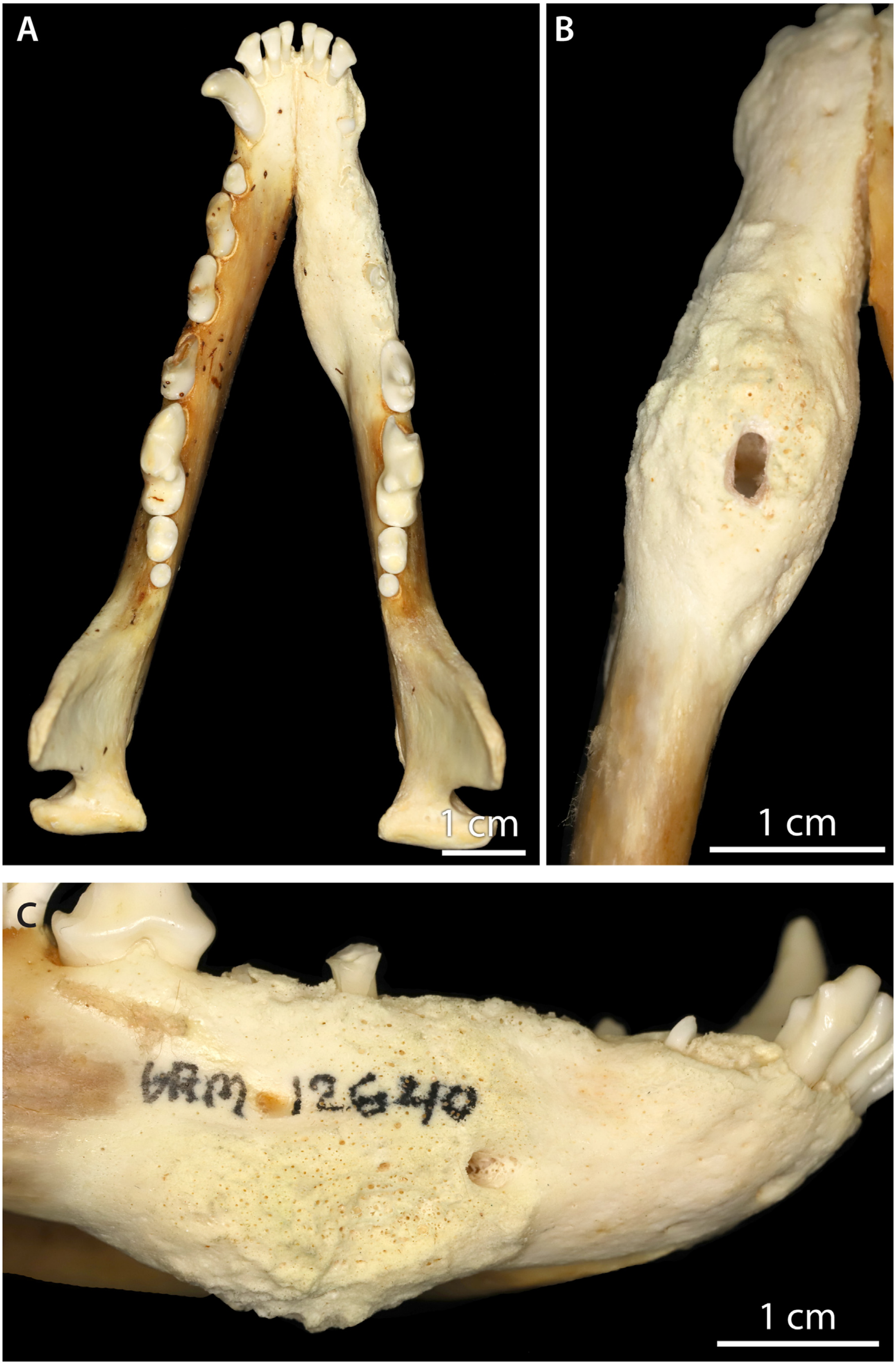

Fig. 5. **(A)** Dorsal view of periapical lesion associated with right mandibular canine tooth and right mandibular first, second and third premolar teeth. **(B)** Ventral view of lesion showing fenestration on ventral portion of right mandible indicating a draining tract. **(C)** Right lateral view of lesion (UAM 12640).

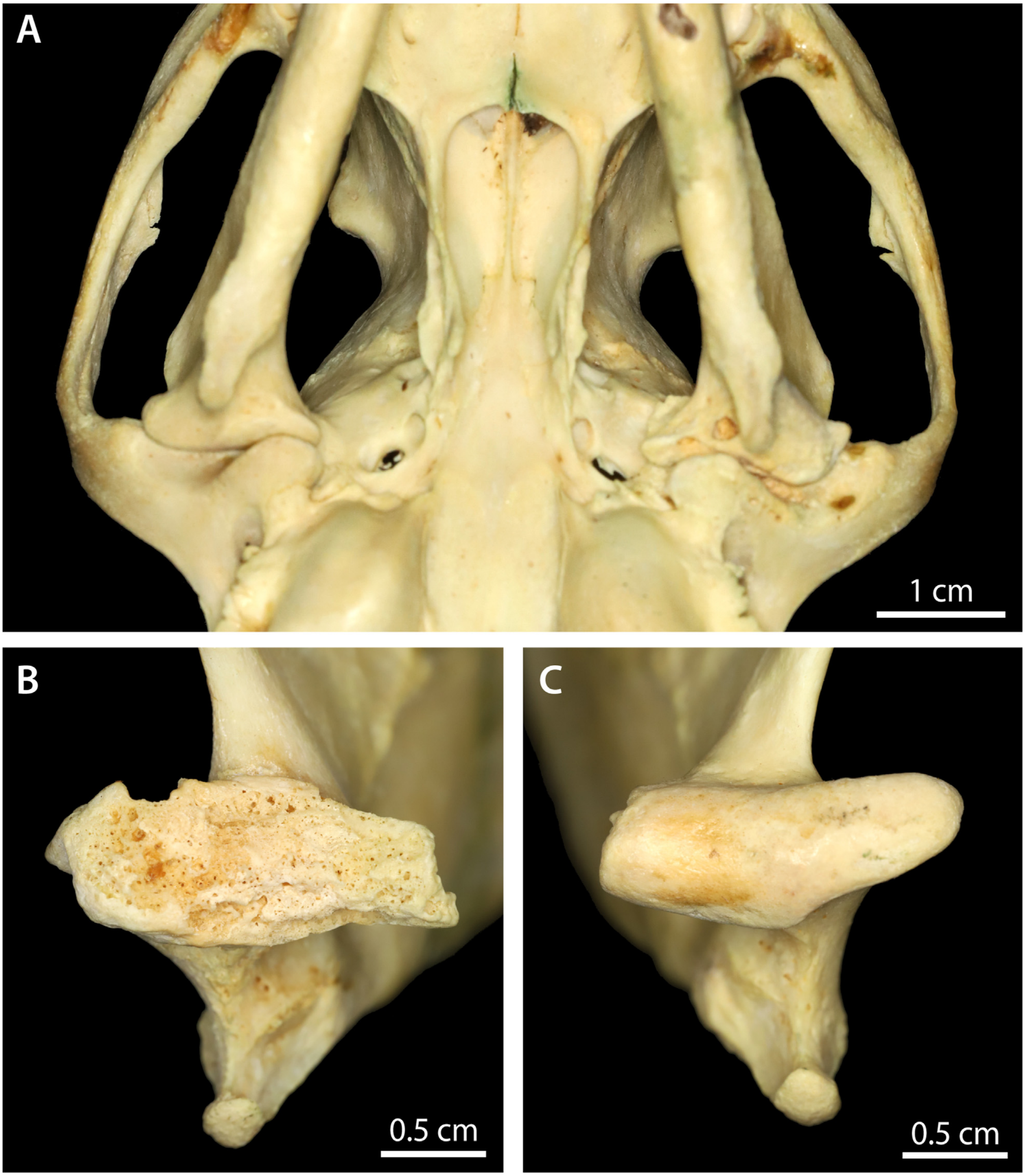

Fig. 6. **(A)** Ventral view of skull base and mandible with osteoarthritis associated with left mandibular head and temporomandibular fossa. **(B)** Caudocranial view of left mandibular head with severely roughened joint surface. **(C)** Normal right mandibular head of same specimen (UAM 12631).

Although the study population did not support a difference in prevalence of tooth fractures among the sexes, it is possible that there could be a higher prevalence of complicated fractures in male foxes in the general population because of the complex social structures that exist in this species. While monogamous pairs are the dominant social structure with both parents contributing to rearing the young, extra-pair mating is common depending on population density [41]. Males generally exhibit territorial aggression during the breeding season [41]. Although the effects of dentoalveolar trauma are difficult to confirm, fractured teeth probably cause pain, impact survival and fitness and can lead to periapical inflammation and infection [42]. Therefore, it would be prudent for future research in which live capture is performed to utilize capture methods that are less likely to result in damage to the oral cavity. Periapical lesions were a relatively uncommon finding in the current study, affecting only 5.3% of specimens,

Fig. 7. Chronic left mandibular fracture in region of left mandibular fourth premolar tooth with evidence of osseous remodelling and bone callous formation (UAM 12420).

which is similar to other canids [12–14]. However, this number is unlikely to represent the true prevalence in the study population as there are likely to be periapical lesions that are only visible with diagnostic imaging.

TMJ disease was a rare finding in the study population, affecting only three individuals. A very low prevalence of TMJ disease in the Arctic fox contrasts with other canids, such as the kit fox and grey wolf, in which evidence of TMJ disease was found in 6.3% and 11.6% of specimens, respectively. TMJ disease has been shown to affect more significant proportions of large predators such as the California mountain lion (*Puma concolor cougar*), North American brown bear (*Ursus arctos*) and American black bear (*Ursus americanus*) but not the California bobcat (*Lynx rufus californicus*) [25,26,29–31,43]. The reason for the difference between species is uncertain; however, differences in feeding behaviours probably contribute to the divergence in the prevalence of TMJ disease. Large predators commonly hunt larger prey that require more force to capture and consume. It is possible that repeated exposure of the TMJ to such forces over time may result in additive traumatic injury leading to chronic TMJ osteoarthritis. Small mesopredators such as the Arctic fox consume much smaller prey or scavenge for food items, incurring less TMJ damage over time. In addition, a low prevalence of joint incongruity and differences in life span also may contribute to the low prevalence of TMJ disease in the Arctic fox when compared with similar North American species [12,14].

Enamel hypoplasia was found in eight specimens, which is similar to the frequency reported in the kit fox and grey wolf [12,14]. However, the Arctic fox is unique from other species in that most specimens with enamel hypoplasia had semi-generalized or generalized enamel hypoplasia resulting in horizontal bands across the teeth at approximately the same height on each crown. All specimens with enamel hypoplasia had been collected from SMI in 1963. While enamel hypoplasia can result from traumatic injury to the tooth during amelogenesis, the distribution and morphology found suggests an infectious, nutritional or genetic aetiology [44]. In the early to middle 20th century, SMI was used as a harvesting location for Arctic fox fur and subsequently as an American military base during the second world war [45]. Domestic reindeer were released onto the island in the 1940s but a population crash in the 1960s is suspected to have been due to limited food resources and the harsh winter [46]. It is possible that changes in food availability, as with the reindeer population, affected multiple levels of the ecosystem and could have driven nutritional deficiency severe enough to cause enamel defects. Additionally, it is possible that the enamel hypoplasia identified in these specimens was caused by a febrile illness such as canine distemper. The Arctic fox population could have experienced increased exposure to pathogens such as CDV due to the increased presence of humans and domestic dogs. Finally, the Arctic fox population on SMI could have been subject to founder effect and an ancestor of these foxes could have passed on a gene responsible for precipitating enamel defects, as has been described in some breeds of domestic dog [47,48]. The degree of gene flow between the SMI and mainland Arctic fox populations is unknown. Without further research, including histology of affected teeth, genomic investigation and serial population monitoring, the confirmed aetiology of the observed enamel defects will remain undiscovered.

5. Conclusions

While the current study characterized dental and TMJ pathology in Arctic foxes mostly from coastal regions of Alaska, the use of museum specimens to investigate disease and abnormalities in wild populations has several caveats. First, the frequency of pathology such as tooth fractures and trauma in the study population is probably inflated compared to observations in wild populations, as many specimens were probably collected from trappers and/or from areas that can be easily accessed by humans. Additionally, data collection was inconsistent over time with most specimens collected during the 1950s and 1960s. Although the frequency of most abnormalities did not differ significantly between modern day foxes and mid-20th century foxes, the frequency of the abnormalities identified may be different from what is seen in current live populations. Finally, museum storage techniques and specimen maintenance affect the quality of specimens and ultimately the accuracy and precision of the data collected. Artefactual changes from processing and storage can be mistaken for ante-mortem pathology.

The specimens were of good quality and may be representative of disease and abnormalities likely to be seen in living Arctic foxes.

However, wildlife monitoring studies over time in living specimens, distributed over a large geographical range, are required to determine the true prevalence and cause of abnormalities. Periodontitis, attrition/abrasion and tooth fractures were extremely common in the Arctic fox population of this study. Supernumerary teeth and variations in tooth form and TMJ disease are uncommon in the Arctic fox. The current study offers a non-invasive means of characterizing the type and frequency of dental and TMJ pathology in the Arctic fox, which probably impacts survival and fitness.

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Declaration of competing interest

The authors declared no conflict of interest in relation to the research, authorship or publication of this article, and do not have a conflict of interest with any of the materials or companies described in the manuscript.

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Appendix A. Supplementary data

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