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Characterization and imaging of lead distribution in bones of lead-exposed birds by
ICP-MS and LA-ICP-MS

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Abstract

Lead (Pb) poisoning in raptors and water birds is a serious problem in many countries. However, only a small fraction of Pb poisoning has been detected in birds. Bone specimens may be useful indices of Pb exposure because bones contain ~90% of the total Pb body burden. The original purpose of this study was to comprehensively analyze Pb accumulation in various bone types using inductively coupled plasma-mass spectrometry (ICP-MS). Since our results showed that Pb accumulation differed greatly depending on bone type, a secondary objective was defined, aiming to investigate the fine Pb distribution and its relation to bone structure and bone marrow by using laser ablation (LA)-ICP-MS. Our findings suggested that bone samples (1) consisting of trabecular tissue and (2) those that contain bone marrow could accumulate high levels of Pb following acute exposure. The shorter turnover time of trabecular bone can cause a rapid accumulation of Pb, and bone marrow may have an important role for internal exposure of Pb to bone tissue. Pb is accumulated in bones via blood flow, and bone marrow receives blood from outside the bones. In conclusion, bone samples provide valuable information on Pb exposure and could be useful to investigate and understand mortalities related to suspected Pb poisoning.

Key words

Pb accumulation, trabecular bone, bone marrow, tissue correlation, eagles, swans

1. Introduction

Many terrestrial and water birds die worldwide due to lead (Pb) poisoning (Andreotti and Borghesi, 2013; Berny et al., 2015; Fisher et al., 2006; Ishii et al., 2017; Kendall et al., 1996; Mateo, 2009; Scheuhammer and Norris, 1996; Whitehead and Tschirner, 1991). Pb is introduced to their habitats in the form of shotgun pellets, rifle bullets (that shatter into fragments on impact), or fishing tackles (i.e., sinkers). Raptors ingest Pb from prey that have been shot with Pb ammunition (Saito, 2009), and water birds ingest Pb fragments from shot pellets or fishing sinkers when they feed or take small stones from the sediment to act as gastroliths (Martinez-Haro et al., 2011).

Pb exposure can cause a variety of sub-lethal toxic effects and direct mortality (Kendall et al., 1996). Sub-lethal effects of Pb are exerted on the nervous system, kidney, liver, intestines and circulatory system, resulting in physiological, biological and behavioral changes (Cade, 2007; Fisher et al., 2006; Scheuhammer, 1987). Pb exposure also decrease the activity of δ -aminolevulinic acid dehydratase (ALA-d) - an enzyme of the heme biosynthesis pathway (Binkowski and Sawicka-Kapusta, 2015). As a result of these changes, birds may become increasingly susceptible to predation, starvation and infection by various diseases, increasing the probability of death from secondary causes (Fisher et al., 2006; Scheuhammer and Norris, 1996). For these reasons it is important to understand the adverse effect of Pb accumulation from the aspect of their conservation. Species with international statuses as endangered, vulnerable or threatened have been reported as ingesting and consequently being poisoned by Pb ammunition fragments, as for instance, Californian condor (*Gymnogyps californianus*), white-rumped vulture (*Gyps bengalensis*), Spanish imperial eagle (*Aquila adalberti*), whooping crane (*Grus americana*), Steller's sea eagle (*Haliaeetus pelagicus*) and white-tailed sea eagle (*Haliaeetus albicilla*) (Fisher et al., 2006). In Hokkaido, the northernmost island of Japan, many endangered Steller's sea eagles and white-tailed sea eagles are dying due to Pb toxicity despite regulations aiming to minimize the

introduction of this element to their habitats (Saito, 2009). Many water birds, including swans, are also exposed to Pb in Japan (Honda et al., 1990) and around the world (Haig et al., 2014; Mateo, 2009; Rattner, 2009; Whitehead and Tschirner, 1991). However, only a fraction of Pb exposure has been identified because weak wild birds tend to hide from humans. Moreover, it is reported that the most important factor precluding the observation of Pb poisoned waterfowl is probably the rapid removal of sick and dead birds by predators and scavengers (Pain, 1991). Therefore, a greater understanding of Pb exposure in birds is necessary to improve the regulation and conservation of avian species.

Concentrations of Pb are generally highest in the blood immediately after absorption, followed by liver and kidneys within days to months, with Pb deposited in bone being able to remain for years (Fisher et al., 2006; Pain, 1996). Although liver or blood samples being traditionally used as indicators of Pb exposure, it might be difficult to obtain these specimens from the natural environment because other animals frequently consume the internal organs of carcasses. Bone specimens, on the other hand, remain in the environment, and many bones are kept in museums or universities, being available for analysis.

Bones contain 84%–90% of the total Pb body burden in raptors (García-Fernández et al., 1997), and Pb can substitute Ca in hydroxyapatite of bones (Ellis et al., 2006). Previous studies investigating Pb exposure in birds using bones have focused on the humerus or femur (Mateo et al., 2003; Pain et al., 2005), and ulna (Ethier et al., 2007). The accumulation patterns of Pb differ depending on the structure and function of the bone. Therefore, an understanding of Pb distribution in various types of bones becomes fundamental for monitoring Pb exposure in birds.

The original purpose of this study was to comprehensively analyze Pb accumulation in various bone types of birds using ICP-MS. Bone types that could potentially be used as indicators for Pb exposure were discussed. The second purpose

was to analyze more detailed accumulation features of Pb in according to bone type, by element imaging using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). By revealing the detailed distribution of Pb, a conjecture upon the route of Pb accumulation in bones can be attained. For this purpose, the femur and tibiotarsus were specifically selected to understand the differences between swans and eagles based on the presence or absence of bone marrow (tibiotarsus possesses bone marrow in both species, but only swans have bone marrow in the femur). LA-ICP-MS plays a key role as a microanalytical technique, and enables multi-element analysis, and has been used to produce images of detailed, regionally-specific element distribution in thin sections of tissues (Becker et al., 2007; Limbeck et al., 2015). Other elements, such as cadmium (Cd), were also measured to compare with Pb accumulation. To our knowledge, this is the first study to perform LA-ICP-MS analysis in avian bones to investigate Pb exposure. Detailed imaging of Pb distribution and the comparison of Pb localization with other elements in bones should help us understand the accumulation mechanisms of Pb, and more accurately assess Pb exposure and mortality in birds.

2. Materials and Methods

2.1. Sampling

This study analyzed carcasses of Steller's sea eagle (n=3), white-tailed sea eagle (n=2), whooper swan (*Cygnus cygnus*, n=2) and an unknown species of swan (n=2) all of which except for one swan (swan D) likely died due to Pb poisoning, according to the hepatic Pb levels. The categories used in Japan are as follows; hepatic Pb concentration in wet weight: < 0.2 mg/kg, normal range; 0.2 – 2 mg/kg, abnormal level of Pb exposure; and > 2 mg/kg, Pb poisoning (Saito, 2009). Swan (D) also accumulated abnormal level of Pb, but not up to the lethality level. Swan (D) was

included in the analysis to elucidate the effects of different levels of Pb accumulation. A mountain hawk-eagle (*Spizaetus nipalensis*, n=1) that died due to other causes in a Pb free environment was used as a control. The Kushiro Nature Conservation Office, Ministry of the Environment, and Institute for Raptor Biomedicine Japan provided all the Steller's sea eagles, one of the white-tailed sea eagles, one of the swans and the mountain hawk-eagle. The Hokkaido Institute of Public Health provided another white-tailed sea eagle. The Ibaraki Prefectural Government, Environmental Policy Division, provided three of the swans. Bones (cranial bone, hyoid bone, atlas, axis, 3rd and 4th cervical vertebrae, notarium, scapula, sternum, keel, coracoideum, costa vertebralis, costa sternalis, ilium, pygostyle, humerus, radius, ulna, phalanx distalis digiti majoris, femur, patella, tibiotarsus, fibula, tarsometatarsus, and os digiti pedis), spinal cord specimens, and bone marrow (axis, radius, ulna, tibiotarsus, and tarsometatarsus) were collected from the birds (Fig. S1). Bone marrow from the femur was collected in all the swans. For the spinal cord, the spinous process was collected. For the long bones, diaphysis was selected. For the femur and tibiotarsus, diaphysis (proximal, medial, and distal) and epiphysis (surface and core in proximal and distal) were collected (Fig. S2). Two samples were collected from the same parts of all the bone types and the average concentration of the two samples was used. The femur and tibiotarsus were specifically selected for this study to understand the differences between swans and eagles based on the presence or absence of bone marrow. Femur bones in swans contain bone marrow, whereas in eagles they do not. Bone marrow is present in the tibiotarsus of both birds. For the duplication of measurements, replicate sub-samples were taken from the same region of the same bone. The average concentration from each region was used for the analysis. Several bone parts could not be collected for the analysis, because they had been used for taxidermy or had already been removed. Bone samples were kept at -20°C. All the samples used during this study were obtained either from animals involved in road-kill incidents or unsuccessful

treatment of poisoning cases, being only analyzed following official approval from the Ministry of the Environment.

2.2. Analysis of element concentrations using ICP-MS

Periosteum (a specialized connective tissue covering all bones of the body) was removed from bone samples. After that, samples were washed with distilled water (Maruyama Manufacturing, Tokyo, Japan) and ultrasonicated to remove other remaining tissue before drying. The analysis of element concentrations followed the method in Yabe et al (Yabe et al., 2015). Samples were dried for 24 hours at 50°C and digested with nitric acid (Kanto Chemical Corporation, Tokyo, Japan) and hydrogen peroxide (Kanto Chemical Corporation) in a microwave digestion system (Speedwave Two, Berghof, Germany). Concentrations of elements were measured with an inductively coupled plasma-mass spectrometer (ICP-MS; 7700 series, Agilent Technology, Tokyo, Japan). Analytical quality control was performed using Bone Ash (National Institute of Standards and Technology, Gaithersburg, MD), DOLT-4 (dogfish liver) and DORM-3 (fish protein) (National Research Council of Canada, Ottawa, Canada) certified reference materials. Replicate analyses of these reference materials showed good recoveries (80%–102%). The detection limits for Pb, iron (Fe), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd) were 0.001, 0.154, 0.007, 0.226, 0.002, and 0.001 µg/kg. RSD values were lower than 10%. More details regarding pretreatment and mass spectrometry procedures are presented in Text S2 and Table S1.

2.3. Analysis of element distribution using LA-ICP-MS

The bones were briefly washed and embedded in epoxy resin, sliced to ~40 µm sections along the transversal axis, and polished. The bone sections were systematically scanned by a focused laser beam using LA (NWR213; ESI, Portland, OR, USA)-ICP-QQQ-MS (8800 series; Agilent Technologies, Tokyo, Japan). LA-ICP-MS

operating conditions were optimized using NIST 610 glass (National Institute of Standards and Technology, Gaithersburg, MD, USA). Images of LA-ICP-MS were reconstructed by iQuant2 (Suzuki et al., submitted to Journal of Mass Spectrometry Society of Japan). More details regarding pretreatment and mass spectrometry procedures are presented in Text S2 and Table S2.

2.4. Statistics

Spearman's rank correlation coefficient (ρ) was used to analyze the relationships among the bones, livers, and kidneys of eagles and swans with a significance level of $p < 0.05$. Statistical analyses were performed in JMP Pro 14 (SAS Institute, Cary, NC).

3. Results

3.1. Differences in Pb concentration depend on bone type

All data, including the concentrations of elements and replicate samples collected from each bone, is shown in Table S4 and S5. There were large differences in Pb concentration depending on bone type. In eagles, the axis, hyoid (around the greater horn), keel, pygostyle and patella accumulated higher Pb concentrations (generally exceeded 50 mg/kg and sometimes 100 mg/kg in several birds) than cortical bones (Fig. 1). In swans, the hyoid bone, scapula, keel, costa vertebralis and pygostyle had higher Pb concentrations (also over 100 mg/kg in several birds) than cortical bones (Fig. 2). Although the Pb concentration in one swan (D) was lower (< 5 mg/kg) than in the other three swans, it exhibited similar Pb distribution patterns (Fig. S3). The levels of Pb in bone marrow were not high when compared to trabecular bones (highly porous or

cellular form of bone). The mountain hawk-eagle used as control had low Pb concentrations in all bones (Table S4).

Steller's sea eagle (C) had higher Pb concentrations (dry weight) in the axis (127.9 mg/kg), hyoid (110.2 mg/kg), and keel (28.9 mg/kg) than the humerus (diaphysis, 3.6 mg/kg) and femur (diaphysis, 4.9 mg/kg). Hepatic Pb concentration in this eagle was very high (58.4 mg/kg, dry weight), indicating severe Pb poisoning.

Within the femur and the tibiotarsus, Pb concentrations in the epiphysis (which mainly consisted of trabecular bone) were substantially higher than the diaphysis (which mainly consisted of cortical bone) for both eagles and swans (Fig. 3-a and -b). Furthermore, in the tibiotarsus, the proximal epiphysis that included bone marrow had the highest concentration. In swans, femur that included bone marrow showed higher Pb concentration than humerus devoid of bone marrow. In eagles, the femur and humerus both lacked bone marrow and showed similar Pb levels. The level of Pb in bone marrow itself sometimes differed depending on whether it was obtained from the proximal or distal part of the same bone (the average is shown in Fig. 1 and 2; data of each level is not shown).

There were significant correlations in Pb concentrations between bones and the liver or kidney in both eagles and swans (Table S3 and Fig. S4). Correlations between humerus and kidney or liver were especially high (humerus-kidney: $\rho = 1.00$ and humerus-liver: $\rho = 0.90$, $p < 0.05$, respectively).

3.2. Detailed distribution pattern of Pb determination using LA-ICP-MS

Photomicrographs of the femur and tibiotarsus of Steller's sea eagle are shown in Fig. S5, and Pb distribution in the femur and tibiotarsus of Steller's sea eagle and whooper swan obtained by element imaging are shown in Fig. 4. The epiphysis in all four bone types had higher signal intensity - counts per second (cps) - of Pb than the

diaphysis. The inner parts of the diaphysis of the bones showed high signal intensity. In the epiphysis of femur from whooper swan or tibiotarsus from Steller's sea eagle and whooper swan, the surface of the trabecular bone had high signal intensity. However, the femur of adult Steller's sea eagle differed from the other bones; Pb accumulation in the surface of the hollow epiphysis was slightly high, but the signal intensity did not differ greatly.

When compared to the accumulation of other elements, areas which revealed high Pb signal intensity showed low signal intensity for Ca (Fig. 5). Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in the femur and tibiotarsus of Steller's sea eagle and whooper swan are shown in Fig. S6-S9.

4. Discussion

4.1. Importance of trabecular bone and bone marrow in Pb accumulation

Our findings suggest that, in avian species, trabecular bone and bones with active marrow can play an important role in understanding Pb toxicity, as they tend to accumulate Pb rapidly.

The hyoid, keel and pygostyle, bones that mainly consist of trabecular bone type, had remarkably high Pb concentration in both eagles and swans (Fig. 1 and 2). In the femur and tibiotarsus, the epiphysis had a higher Pb level than the diaphysis (Fig. 3-a and -b). These levels of Pb concentration differ because the diaphysis is mainly composed of cortical bone, whereas the epiphysis is mainly composed of trabecular bone. This trend is supported by a previous study, which found that, in humans, Pb in trabecular bones is more biologically active than Pb in cortical bones (Barbosa Jr et al., 2005). The authors of the study also reported that trabecular bone had a larger surface area and received a greater volume of blood compared to cortical bone. Moreover, the

shorter turnover time of trabecular bone causes a rapid accumulation of Pb. The half-life of Pb in trabecular bone may vary from a few to 16 years in vertebrae, whereas the half-life in cortical bone often ranges from 5-15 years, but may exceed 25 years (Gerhardsson et al., 2005). Additionally, other trabecular bone, such as the axis, scapula, costa and patella, were found to have higher concentrations of Pb than cortical bone, such as the diaphysis of the humerus, radius, ulna and tarsometatarsus (Fig. 1 and 2).

Bones containing bone marrow are another factor determining Pb accumulation, because Pb is delivered to bone marrow by blood vessels. Avian bone marrow consists of cell rich and highly vascularized tissues (Higgins, 1999; Tavassoli and Yoffey, 1983), which may result in significant Pb accumulation. The Pb level in bone marrow was not particularly high, which may be caused by the differences of half-life of Pb in blood (about 1 month (Hu et al., 1998)) and bones (many years). The Pb level in the femur was higher in swans than that in eagles. Eagle femurs do not contain bone marrow, whereas swan femurs do. In the tibiotarsus, the proximal epiphysis that contained bone marrow had the highest concentration of Pb. The peripheral portion of the marrow cylinder is hyperplastic (a tissue or organ prone to an abnormal increase in the number of cells) in adult birds, whereas the axial portion is hypoplastic (tissue or organ that undergoes incomplete or sub development) and contains a large amount of fat (Higgins, 1999; Jordan and Robeson, 1942). These characteristics may explain the differences in Pb concentrations in bone marrow within the same bone.

Age related differences in Pb accumulation may also exist, because young and adult birds have different bone structure and functions of bone marrow. During postnatal development, a large portion of the skeleton becomes pneumatized, displacing hemopoietic bone marrow (Schepelmann, 1990). In this study, age differences were not evaluated as a factor because the sample size was limited. Further research may clarify the relationship between Pb distribution in bones and age differences.

4.2. Assessment of Pb exposure

In raptors, Pb concentrations >10 mg/kg in the humerus or femur have been considered abnormal levels of accumulation (Mateo et al., 2003). In water birds Pb concentrations of 20 mg/kg in the femur have been considered a high level of exposure (Pain et al., 2005).

This study showed that, although Pb levels in the bones of Steller's sea eagle (C) and swan (C) were lower than the reference levels described above, the concentrations in the liver and kidney were remarkably high (Fig. 1 and 2). Pb levels in the humerus were significantly correlated with liver ($\rho = 0.90$) and kidney ($\rho = 1.00$). Liver and kidney samples are widely used for the assessment of Pb exposure (Beyer et al., 1988; Guitart et al., 1994). Therefore, these results suggest that the humerus may be a good indicator of Pb exposure. However, from our results it would seem that in absolute value, Pb accumulation is lower in humerus. For the same bird, while liver concentrations would indicate high levels of exposure, the humerus concentration would be below the reference level. If humerus (or femur) are to be used for the assessment of Pb exposure, the fact that birds with abnormal levels of Pb accumulation in these bones that are below reference levels should be taken into consideration. On the other hand, trabecular bones, such as the hyoid, keel or pygostyle, may be potential indicators for acute Pb exposure in birds because they could accumulate Pb faster and at higher levels than other bones.

In avian species, acute Pb poisoning and mortality can follow the ingestion of a single Pb pellet (Fisher et al., 2006; Pain and Rattner, 1988). Based on Pb half-life in cortical bone (e.g. diaphysis of the humerus) this may be a better dosimeter of chronic Pb exposure than trabecular bone (e.g. axis) (Hu et al., 1998). In rats and humans, trabecular bone is reported to be a better indicator for acute or intermediate Pb exposure (Brito et al., 2014; Gerhardsson et al., 1993). The Pb distribution patterns in bone would

be different depending on the circumstances surrounding Pb exposure. In cases of acute exposure, Pb levels in trabecular bone could be significantly higher than in cortical bone, whereas in cases of chronic exposure, the differences of concentration between trabecular and cortical bone may be lower (Hu et al., 1998).

4.3. Detailed Pb distribution patterns in femur and tibiotarsus bones using element imaging

The comparison of Pb concentrations in various bone types using ICP-MS indicated that trabecular bone and bones that contain bone marrow accumulate Pb rapidly. Therefore, further and more detailed analyses of Pb distribution using LA-ICP-MS were performed to verify this finding.

The comparison of Ca and Pb distributions also indicated that Pb accumulation may be faster in trabecular bones than in cortical bones. The regions with high Pb signal intensity showed low Ca signal intensity (Fig. 5), suggesting that the Pb accumulation may have started from bone parts with lower density. In humans, the bone density of trabecular bone is lower than that of cortical bone (Lang et al., 2004). A previous study on vultures suggested that the mineralization degree of bones decreases as Pb accumulation increases (Gangoso et al., 2009). Pb and Ca may interact when in a scenario of Pb exposure.

Bone marrow could be an important driver of the differences in Pb distribution among bones. The main difference between the femur of Steller's sea eagle and tibiotarsus of Steller's sea eagle, whooper swan, and the femur of whooper swan, was the absence or presence of bone marrow. The detailed analysis of these bones showed that bone parts in contact with bone marrow had high Pb accumulations. Conversely, the femur of adult Steller's sea eagle had slightly high Pb accumulation in the surface of the hollow epiphysis, but the level did not differ greatly from its inner side. Therefore, bone

marrow plays an important role in carrying Pb into bones. Pb is accumulated into bones via blood flow, and bone marrow due to its strong vascularization, receives large amounts of blood from the systemic circulation.

Pb concentrations in bone marrow showed that bone marrow itself did not have higher Pb concentration than trabecular bone (Fig. 1, 2). The half-life of Pb in blood is around one month (Hu et al., 1998), which is significantly shorter than in bones, resulting in lower Pb signal intensity in bone marrow.

In conclusion, Pb accumulation depends on bone type, and, as such, bones can be effectively used to understand Pb exposure in birds. In Japan, many raptors and water birds die due to Pb toxicity, despite regulations against indiscriminately introducing Pb into the environment. The results obtained in this work added by further research on Pb accumulation in bones will allow this matrix to be used as an indicator for Pb toxicity levels in avian species. The increased knowledge on birds' Pb exposure will, in turn, allow us to develop more appropriate regulations for the protection of this endangered natural resource.

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Fig. 1. Pb distribution in bone and organ tissues from Steller's sea eagle (n=3) and white-tailed sea eagle (n=2). The position of each bone is shown in Fig. S1.

Fig. 2. Pb distribution in bone and organ tissues from swans (n=4). Data for swan (D) was shown in Fig. S3, an expanded version of this figure. The position of each bone is shown in Fig. S1.

Fig. 3. Pb concentrations in the diaphysis and the epiphysis in femur (F) and tibiotarsus (T) in eagles (a) and swans (b). (1): epiphysis (proximal, surface); (2): epiphysis (proximal, core); (3): diaphysis (proximal, internal struts); (4): diaphysis (proximal); (5): diaphysis (medial); (6): diaphysis (distal); (7): diaphysis (distal, internal struts); (8): epiphysis (distal, core); and (9): epiphysis (distal, surface). The position of each part is shown in Fig. S2.

Fig. 4. Pb distribution in femur (distal) and tibiotarsus (proximal) of Steller's sea eagle and whooper swan using LA-ICP-MS. 1) femur of Steller's sea eagle, 2) tibiotarsu of Steller's sea eagle, 3) femur of whooper swan, 4) tibiotarsus of whooper swan. The figures on the bottom row are an expanded version of a, b and c in 1), and 2). Scale bars and ranges of counts per second (cps) of Pb differ between images.

Fig. 5. Ca distribution in femur (distal) and tibiotarsus (proximal) of Steller's sea eagle and whooper swan using LA-ICP-MS. 1) Femur of Steller's sea eagle, 2) tibiotarsus of Steller's sea eagle, 3) femur of whooper swan, 4) tibiotarsus of whooper swan. Scale bars and ranges of counts per second (cps) of Ca differ between images.

1 Graphic abstract

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Scale bars and ranges of counts per second (cps) of Pb differ **between images**.

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Text S1. Analysis of element concentrations using ICP-MS.

Text S2. Analysis of element distribution using LA-ICP-MS.

Table S1. Detailed analytical conditions of ICP-MS.

Table S2. Detailed analytical conditions of LA-ICP-MS.

Table S3. Spearman's rank correlation coefficient (ρ) for Pb levels between bones and livers or kidneys (Sample size > 5 for each tissue). Corresponds to Fig. S4.

Table S4. Concentration of elements in eagles (mg/kg, dry weight).

Table S5. Concentration of elements in swans (mg/kg, dry weight).

Fig. S1. The position of bone and bone marrow samples collected from birds. The diagram of a bird skeleton was modified from "Squelette_oiseau.JPG: BIODIDAC derivative work: mario modesto (Squelette_oiseau.JPG)". The bone marrow in the femur (*¹) exists only in swans, and patella was collected only from the eagles (*²) in this study.

Fig. S2. The position of bone and bone marrow samples collected from birds. (1): epiphysis (proximal, surface); (2): epiphysis (proximal, core); (3): diaphysis (proximal, internal struts); (4): diaphysis (proximal); (5): diaphysis (medial); (6): diaphysis (distal); (7): diaphysis (distal, internal struts); (8): epiphysis (distal, core); and (9): epiphysis (distal, surface). The internal struts (3) were only collected from the femur in Steller's sea eagle (*¹).

Fig. S3. Pb distribution in bone and organ tissues in swan (D). (An expanded version of Fig. 2). Markers indicate the average of two specimens collected from the same bone.

Fig. S4. Correlation coefficients between bones and liver or kidney (Sample size > 5 for each tissue). Spearman's rank correlation coefficient (ρ) for Pb levels are shown in

Table S3. Pink color (triangle) corresponds to eagles and blue color (circle) indicates swans. Red lines indicate the 95% tolerance ellipse.

Fig. S5. Photomicrographs of femur (1) and tibiotarsus (2) of Steller's sea eagle. Due to the large size of the samples, three photomicrographs were combined to make the figure.

Fig. S6. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in femur of Steller's sea eagle. The scale bar is 30 mm. The ranges of elements' counts per second (cps) vary between images.

Fig. S7. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in tibiotarsus of Steller's sea eagle. The scale bar is 20 mm. The ranges of elements' counts per second (cps) vary between images.

Fig. S8. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in femur of whooper swan. The scale bar is 30 mm. The ranges of elements' counts per second (cps) vary between images.

Fig. S9. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in tibiotarsus of whooper swan. The scale bar is 30 mm. The ranges of elements' counts per second (cps) vary between images.

Text S1. Analysis of element concentrations using ICP-MS.

For the metal analysis, 10–30 mg of bones and 100–300 mg of livers or kidneys were dried for 24 hours at 50°C. Preliminary experiments showed that 24 hours was sufficient time to dry the samples. Bones were washed with distilled water (Maruyama Manufacturing, Tokyo, Japan) and ultrasonicated to remove other tissues before drying. All samples were digested with 5 mL of 30% nitric acid (Kanto Chemical Corporation, Tokyo, Japan) and 1 mL of 30% hydrogen peroxide (Kanto Chemical Corporation) in a microwave digestion system (Speedwave Two, Berghof, Germany). The volume was brought to 10 mL with 2% nitric acid. Digestion was performed under the following conditions: 180°C for 15 min, 200°C for 20 min, and 100°C for 20 min. Pb concentration was measured with an inductively coupled plasma-mass spectrometer (ICP-MS; 7700 series, Agilent Technology, Tokyo, Japan). The instrument was calibrated using standard Pb solutions to establish standard curves before analysis. All chemicals and standard stock solutions were pure analytical reagent grade (Wako Pure Chemicals Industries). For sample and reagent dilutions, ultrapure water (Milli-Q, Merck Millipore, Billerica, Massachusetts) was used.

Text S2. Analysis of element distribution using LA-ICP-MS.

Bones were washed with distilled water (Maruyama Manufacturing, Tokyo, Japan) and ultrasonicated to remove other tissues from the outside and inside of the diaphysis and embedded in epoxy resin. Samples were sliced into ~40 µm sections along the transversal axis with a diamond blade and polished. The bone sections were systematically scanned by a focused laser beam with the following parameters; spot diameter: 100 µm (20 µm in zoomed cases), scan speed: 500 µm/sec (20 µm/sec) using LA (NWR213; ESI, Portland, OR, USA)-ICP-QQQ-MS (8800 series; Agilent Technologies, Tokyo, Japan). Detailed analytical conditions are presented in Table S2. We reconstructed two-dimensional images from time resolved analysis data of LA-ICP-MS by iQuant2 (Suzuki et al., submitted to Journal of Mass Spectrometry Society of Japan); an in-house developed software. This software shows the localization of elements. The ranges of the element concentrations in the images differ depending on the type of bone samples.

Table S1. Detailed analytical conditions of ICP-MS.

Parameter	Value
RF Power	1500 W
Argon gas pressure	600 kPa
Cell gas (Helium)	100 kPa
Peak pattern	1
Replicates	3
Sweeps/replicate	100
Stabilization time	30 s

Table S2. Detailed analytical conditions of LA-ICP-MS.

LA system (NWR213, ESI, Portland, OR, USA)	
Wavelength, nm	213
Pulse duration, ns	4
Fluence	2.7 J/cm ²
Repetition rate	10 Hz
Spot diameter	100 μm (zoomed version: 20 μm)
Scan speed	500 μm/ sec (zoomed version: 20 μm/sec)
Ablation mode	line scan
Carrier He gas flow rate	0.8 L/min
Make up Ar gas flow rate	0.8 L/min
ICP-QQQ-MS (8800 series, Agilent Technologies, Tokyo, Japan)	
RF power	1550 W
Plasma Ar gas flow rate	15 L/min
Auxiliary Ar gas	not used
Collision	not used
MS/MS	not used
Integration time	0.01 sec for ²⁰⁶ Pb, ²⁰⁷ Pb, ²⁰⁸ Pb, and 0.005 sec for other isotopes
Measured Isotopes	¹³ C, ²⁵ Mg, ³¹ P, ⁴³ Ca, ⁵⁵ Mn, ⁵⁷ Fe, ⁶⁵ Cu, ⁶⁶ Zn, ²⁰⁶ Pb, ²⁰⁷ Pb, ²⁰⁸ Pb

Table S3. Spearman’s rank correlation coefficient (ρ) for Pb levels between bones and livers or kidneys (Sample size > 5 for each tissue). Corresponds to Fig. S4.

		ρ	p - value
Liver	Humerus	0.90	0.04
Kidney	Humerus	1.00	< 0.001
Kidney	Radius	0.90	0.04
Kidney	Pygostyle	0.90	0.04
Kidney	Os digiti pedis	0.90	0.04
Kidney	Tarsometatarsus	0.90	0.04

Table S4. Concentration of elements in eagles.

(1) Steller's sea eagle (A)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Cranial bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_1	47.6	0.26	144.2	0.04	0.01	32.6
Hyoid bone_2	98.9	0.81	122.7	0.06	0.01	82.8
Atlas_1	60.6	0.42	156.2	0.03	0.01	56.8
Atlas_2	40.1	0.51	170.4	0.04	0.01	30.7
Axis_1	129.2	0.54	261.9	0.06	0.02	167.3
Axis_2	117.5	0.63	230.5	0.03	0.01	133.2
3rd Cervical vertebrae_1	53.4	0.50	184.8	0.03	0.01	37.8
3rd Cervical vertebrae_1	76.3	0.90	184.3	0.04	0.01	37.7
4th Cervical vertebrae_1	65.8	0.71	183.1	0.03	0.01	36.2
4th Cervical vertebrae_1	52.7	0.46	166.5	0.03	0.01	21.7
Spinal cord_1	103.7	5.71	35.4	0.04	0.04	2.2
Spinal cord_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Notarium_1	87.5	0.91	158.6	0.04	0.01	24.6
Notarium_2	66.8	0.72	145.2	0.05	0.01	30.3
Scapula_1	21.3	0.02	107.3	0.01	0.00	25.9
Scapula_2	24.1	0.02	102.2	0.01	0.00	25.3
Sternum_1	28.4	0.09	129.8	0.06	0.01	29.5

Sternum_2	28.5	0.08	129.4	0.05	0.01	33.7
Keel_1	57.0	0.39	128.9	0.14	0.01	32.8
Keel_2	59.6	0.32	134.6	0.04	0.01	35.0
Coracoideum_1	23.9	0.35	141.9	0.05	0.00	16.3
Coracoideum_2	11.9	0.41	140.1	0.03	0.00	19.1
Costa vertebralis_1	18.2	0.19	126.3	0.05	0.01	24.3
Costa vertebralis_2	27.7	0.36	135.7	0.06	0.01	24.1
Costa sternalis_1	31.2	0.16	133.4	0.05	0.01	38.2
Costa sternalis_2	34.9	1.04	125.7	0.12	0.01	30.8
Ilium_1	34.9	0.29	133.7	0.30	0.01	27.2
Ilium_2	24.3	0.36	125.9	0.09	0.01	13.1
Pygostyle_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Pygostyle_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Radius_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Radius_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Ulna_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Ulna_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Phalanx distalis digiti majoris_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Phalanx distalis digiti majoris_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (proximal, surface)_1	15.1	0.00	100.3	0.02	0.01	66.3
Femur_epiphysis (proximal, surface)_2	14.0	0.00	93.6	0.02	0.01	57.9
Femur_epiphysis (proximal, core)_1	6.5	0.00	92.4	0.02	0.00	20.6
Femur_epiphysis (proximal, core)_2	5.6	0.00	87.9	0.01	0.00	17.9
Femur_diaphysis (proximal, internal struts)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal, internal struts)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal)_1	6.3	0.00	108.7	0.01	0.00	15.6
Femur_diaphysis (proximal)_2	5.1	0.00	102.1	0.01	0.00	9.5
Femur_diaphysis (medial)_1	5.8	0.00	101.3	0.01	0.00	8.8
Femur_diaphysis (medial)_2	5.0	0.00	101.1	0.01	0.00	8.6
Femur_diaphysis (distal)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (distal)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (distal, internal struts)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Femur_diaphysis (distal, internal struts) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Liver	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

	Kidney	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
103	N. A.: Not available (Samples were not collected.)						
104							
105	(2) Steller's sea eagle (B)						
	Sample name	Fe	Cu	Zn	As	Cd	Pb
	Cranial bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
	Cranial bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
	Hyoid bone_1	125.9	1.05	161.1	0.06	0.01	113.1
	Hyoid bone_2	143.8	1.26	141.7	0.06	0.01	81.2
	Atlas_1	21.4	0.16	174.9	0.02	0.00	74.0
	Atlas_2	33.2	0.14	163.8	0.02	0.00	61.3
	Axis_1	91.0	0.97	198.9	0.02	0.01	119.3
	Axis_2	73.1	0.34	212.2	0.02	0.01	134.1
	3rd Cervical vertebrae_1	50.2	0.23	173.0	0.03	0.01	38.2
	3rd Cervical vertebrae_1	62.6	0.57	183.1	0.02	0.01	58.6
	4th Cervical vertebrae_1	99.0	0.92	185.4	0.02	0.01	41.3
	4th Cervical vertebrae_1	67.5	0.58	172.8	0.02	0.01	36.2
	Spinal cord_1	158.1	6.87	25.1	0.17	0.01	0.4
	Spinal cord_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
	Notarium_1	68.9	0.40	154.1	0.02	0.01	74.7
	Notarium_2	85.6	0.62	140.3	0.03	0.01	45.2
	Scapula_1	15.8	0.03	102.4	0.00	0.00	33.9
	Scapula_2	17.7	0.24	102.0	0.01	0.00	31.8

Sternum_1	60.4	0.43	157.7	0.03	0.01	48.3
Sternum_2	54.3	0.19	141.2	0.03	0.00	56.0
Keel_1	67.7	0.19	131.8	0.02	0.00	55.0
Keel_2	61.2	0.38	168.3	0.02	0.00	111.5
Coracoideum_1	10.0	0.13	143.9	0.02	0.00	28.9
Coracoideum_2	12.7	0.08	153.5	0.02	0.00	29.5
Costa vertebralis_1	11.4	0.09	136.1	0.02	0.00	42.7
Costa vertebralis_2	18.2	0.09	134.1	0.03	0.00	44.3
Costa sternalis_1	24.9	0.15	148.1	0.03	0.00	58.6
Costa sternalis_2	21.8	0.10	110.1	0.03	0.00	31.0
Ilium_1	37.5	0.31	126.4	0.02	0.01	36.6
Ilium_2	35.2	0.26	120.4	0.02	0.01	37.7
Pygostyle_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Pygostyle_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Radius_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Radius_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Ulna_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Ulna_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Phalanx distalis digiti majoris_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Phalanx distalis digiti majoris_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (proximal, surface) _1	13.9	0.00	84.4	0.00	0.00	34.6
Femur_epiphysis (proximal, surface) _2	15.4	0.00	85.8	0.01	0.00	42.8
Femur_epiphysis (proximal, core) _1	15.5	0.00	86.7	0.00	0.00	37.1
Femur_epiphysis (proximal, core) _2	26.8	0.01	73.5	0.00	0.00	28.7
Femur_diaphysis (proximal, internal struts) _1	4.3	0.00	65.4	0.00	0.00	20.8
Femur_diaphysis (proximal, internal struts) _2	4.5	0.00	64.4	0.00	0.00	18.9
Femur_diaphysis (proximal) _1	7.1	0.00	101.3	0.00	0.00	19.1
Femur_diaphysis (proximal) _2	6.9	0.00	101.1	0.00	0.00	14.4
Femur_diaphysis (medial) _1	5.4	0.00	97.1	0.00	0.00	14.5
Femur_diaphysis (medial) _2	6.8	0.00	101.3	0.00	0.00	15.6
Femur_diaphysis (distal) _1	3.1	0.00	95.3	0.01	0.00	19.3
Femur_diaphysis (distal) _2	2.8	0.00	94.3	0.01	0.00	21.3

Femur_diaphysis (distal, internal struts) _1	2.7	0.00	74.7	0.01	0.00	27.3
Femur_diaphysis (distal, internal struts) _2	2.8	0.00	72.7	0.00	0.00	25.7
Femur_epiphysis (distal, core) _1	10.1	0.00	80.6	0.00	0.00	27.6
Femur_epiphysis (distal, core) _2	10.7	0.00	81.2	0.01	0.00	25.5
Femur_epiphysis (distal, surface) _1	9.3	0.00	87.8	0.00	0.00	45.0
Femur_epiphysis (distal, surface) _2	10.1	0.00	87.2	0.00	0.00	50.8
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Liver	9670.0	39.4	168.0	0.37	0.23	19.6
Kidney	2373.6	65.9	88.6	0.38	1.67	2.7

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107

108 (3) Steller's sea eagle (C)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	17.2	0.58	158.5	0.16	0.01	6.2
Cranial bone_2	12.8	3.12	149.6	0.05	0.00	8.1
Hyoid bone_1	173.4	0.51	165.6	0.02	0.01	101.8
Hyoid bone_2	272.3	0.75	163.4	0.02	0.01	118.6
Atlas_1	10.2	0.21	145.0	0.02	0.00	7.1
Atlas_2	19.1	0.14	142.5	0.02	0.00	7.5
Axis_1	347.9	9.37	222.0	0.15	0.03	131.3
Axis_2	192.9	3.01	208.4	0.04	0.00	113.4
3rd Cervical vertebrae_1	38.3	0.18	166.7	0.02	0.01	22.7
3rd Cervical vertebrae_1	41.0	1.46	168.8	0.02	0.01	16.9
4th Cervical vertebrae_1	33.6	0.12	163.8	0.02	0.01	17.2
4th Cervical vertebrae_1	47.9	0.24	204.5	0.02	0.01	18.7
Spinal cord_1	318.7	9.13	42.8	0.03	0.02	3.6
Spinal cord_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Notarium_1	31.9	0.26	158.3	0.02	0.01	17.6
Notarium_2	16.7	0.10	127.9	0.02	0.00	10.6
Scapula_1	44.8	0.15	170.8	0.04	0.00	20.0

Scapula_2	15.8	0.06	169.5	0.02	0.00	10.8
Sternum_1	17.3	0.60	164.7	0.07	0.01	40.1
Sternum_2	24.4	2.20	135.5	0.04	0.01	40.9
Keel_1	37.2	0.83	177.1	0.08	0.01	15.1
Keel_2	26.2	0.87	149.7	0.04	0.01	42.6
Coracoideum_1	20.2	21.19	173.3	0.09	0.01	13.6
Coracoideum_2	19.9	2.60	149.3	0.04	0.00	12.1
Costa vertebralis_1	10.9	0.16	185.2	0.07	0.01	26.1
Costa vertebralis_2	15.9	0.38	153.8	0.04	0.01	30.5
Costa sternalis_1	11.3	0.31	173.7	0.05	0.00	24.2
Costa sternalis_2	20.9	3.66	157.2	0.04	0.01	40.7
Ilium_1	17.3	0.47	172.4	0.06	0.01	11.9
Ilium_2	16.4	0.45	136.8	0.03	0.01	28.1
Pygostyle_1	57.3	0.14	208.2	0.04	0.00	74.7
Pygostyle_2	44.8	0.13	193.4	0.03	0.00	63.2
Humerus_1	11.3	0.20	196.4	0.03	0.00	3.7
Humerus_2	11.4	0.08	196.2	0.02	0.00	3.6
Radius_1	13.4	1.22	195.6	0.08	0.01	6.4
Radius_2	10.1	0.43	179.0	0.05	0.01	9.4
Bone marrow (Radius)_1	248.6	1.61	24.7	0.04	0.00	2.7
Bone marrow (Radius)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Ulna_1	22.6	0.20	218.0	0.07	0.00	8.0
Ulna_2	10.6	0.84	223.8	0.06	0.01	6.0
Bone marrow (Ulna)_1	228.6	1.26	22.6	0.03	0.00	2.5

Bone marrow (Ulna)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Phalanx distalis digiti majoris_1	6.6	0.00	149.7	0.01	0.00	8.7
Phalanx distalis digiti majoris_2	5.6	0.01	158.1	0.01	0.00	10.6
Patella_1	144.9	0.35	247.4	0.01	0.00	182.0
Patella_2	189.5	0.59	258.5	0.01	0.00	194.2
Fibula_1	30.6	0.22	175.3	0.06	0.01	31.3
Fibula_2	19.3	1.22	145.1	0.04	0.01	12.5
Tarsometatarsus_1	6.3	0.15	181.8	0.06	0.00	4.3
Tarsometatarsus_2	4.8	0.59	147.5	0.04	0.01	4.7
Bone marrow (Tarsometatarsus)_1	210.2	0.87	28.3	0.04	0.00	2.1
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_1	3.4	0.03	188.3	0.01	0.00	3.9
Os digiti pedis II_2	4.0	0.00	198.7	0.02	0.00	3.7
Femur_epiphysis (proximal, surface) _1	7.3	0.05	153.9	0.01	0.00	22.8
Femur_epiphysis (proximal, surface) _2	8.2	0.02	163.7	0.01	0.00	22.0
Femur_epiphysis (proximal, core) _1	5.1	0.00	173.2	0.01	0.00	18.8
Femur_epiphysis (proximal, core) _2	99.2	0.17	156.3	0.01	0.00	12.5
Femur_diaphysis (proximal, internal struts) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal, internal struts) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal) _1	4.9	0.04	202.0	0.01	0.00	5.3
Femur_diaphysis (proximal) _2	6.8	0.00	199.2	0.01	0.00	5.5
Femur_diaphysis (medial) _1	9.1	0.00	201.8	0.01	0.00	4.9
Femur_diaphysis (medial) _2	4.9	0.00	203.0	0.01	0.00	4.9
Femur_diaphysis (distal) _1	7.0	0.02	177.5	0.01	0.00	5.6

Femur_diaphysis (distal) _2	6.3	0.00	182.0	0.01	0.00	5.2
Femur_diaphysis (distal, internal struts) _1	10.2	0.00	161.5	0.01	0.00	7.2
Femur_diaphysis (distal, internal struts) _2	5.7	0.00	159.4	0.01	0.00	6.5
Femur_epiphysis (distal, core) _1	6.2	0.65	173.1	0.01	0.00	11.3
Femur_epiphysis (distal, core) _2	5.9	0.08	170.0	0.01	0.00	13.1
Femur_epiphysis (distal, surface) _1	8.1	0.01	167.1	0.01	0.00	26.0
Femur_epiphysis (distal, surface) _2	6.7	0.07	169.7	0.01	0.00	14.9
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _1	165.2	0.50	243.9	0.01	0.00	164.4
Tibiotarsus_epiphysis (proximal, surface) _2	183.3	0.93	233.9	0.01	0.00	160.7
Tibiotarsus_epiphysis (proximal, core) _1	159.7	0.19	240.7	0.01	0.00	172.1
Tibiotarsus_epiphysis (proximal, core) _2	181.4	0.58	238.2	0.01	0.00	154.7
Tibiotarsus_diaphysis (proximal) _1	14.6	0.06	198.3	0.01	0.00	11.6
Tibiotarsus_diaphysis (proximal) _2	14.2	0.10	193.5	0.01	0.00	10.4
Tibiotarsus_diaphysis (medial) _1	9.5	0.06	183.4	0.01	0.00	4.6
Tibiotarsus_diaphysis (medial) _2	9.9	0.06	196.3	0.01	0.00	4.4
Tibiotarsus_diaphysis (distal) _1	5.7	0.00	188.1	0.01	0.00	4.3
Tibiotarsus_diaphysis (distal) _2	6.6	0.00	178.9	0.01	0.00	4.2
Tibiotarsus_epiphysis (distal, core) _1	24.9	0.06	188.5	0.01	0.00	32.6
Tibiotarsus_epiphysis (distal, core) _2	19.9	0.00	172.6	0.01	0.00	13.0
Tibiotarsus_epiphysis (distal, surface) _1	13.1	0.13	164.3	0.01	0.00	8.6
Tibiotarsus_epiphysis (distal, surface) _2	16.1	0.05	158.4	0.01	0.00	16.5
Bone marrow (Tibiotarsus)_1	1833.9	5.25	71.1	0.04	0.01	6.7

Bone marrow (Tibiotarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Liver	13185.0	50.5	594.0	0.09	0.45	58.4
Kidney	1589.3	79.6	228.4	0.06	4.05	18.3

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111 (4) White-tailed sea eagle (A)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	12.6	0.18	117.6	0.02	0.01	42.8
Cranial bone_2	12.2	0.18	122.5	0.02	0.00	62.6
Hyoid bone_1	58.1	0.86	149.6	0.02	0.01	86.8
Hyoid bone_2	115.6	1.13	154.5	0.03	0.01	113.0
Atlas_1	34.6	0.54	177.0	0.03	0.01	26.8
Atlas_2	38.7	0.43	177.9	0.03	0.01	28.8
Axis_1	85.0	0.80	179.8	0.03	0.01	74.1
Axis_2	84.1	0.54	187.1	0.03	0.01	86.3
3rd Cervical vertebrae_1	64.0	0.52	209.8	0.02	0.01	54.0
3rd Cervical vertebrae_1	40.7	0.41	190.2	0.02	0.01	34.5
4th Cervical vertebrae_1	39.7	0.36	196.3	0.02	0.01	30.3
4th Cervical vertebrae_1	42.5	0.45	218.1	0.03	0.01	24.4
Spinal cord_1	108.5	8.45	54.7	0.08	0.06	6.9
Spinal cord_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Notarium_1	28.8	0.29	141.0	0.02	0.01	29.3
Notarium_2	35.9	0.18	143.3	0.02	0.01	29.5

Scapula_1	30.6	0.16	154.6	0.01	0.00	45.0
Scapula_2	22.1	0.04	149.8	0.01	0.00	45.4
Sternum_1	18.8	0.29	129.3	0.02	0.01	41.4
Sternum_2	22.3	0.46	119.9	0.02	0.02	37.9
Keel_1	43.6	0.81	141.2	0.03	0.01	63.3
Keel_2	259.2	0.70	138.9	0.03	0.01	94.3
Coracoideum_1	5.5	0.20	123.8	0.02	0.00	10.4
Coracoideum_2	6.1	0.18	122.5	0.02	0.00	12.4
Costa vertebralis_1	15.3	0.21	132.7	0.02	0.01	27.5
Costa vertebralis_2	12.9	0.20	131.3	0.02	0.01	29.1
Costa sternalis_1	15.8	0.23	121.2	0.02	0.01	34.7
Costa sternalis_2	11.7	0.19	131.6	0.02	0.01	43.1
Ilium_1	9.9	0.18	92.7	0.02	0.02	17.9
Ilium_2	13.8	0.15	116.2	0.02	0.01	30.5
Pygostyle_1	41.0	0.03	154.4	0.01	0.01	75.4
Pygostyle_2	50.8	0.10	161.0	0.01	0.02	66.5
Humerus_1	4.4	0.05	117.8	0.02	0.00	12.1
Humerus_2	4.4	0.05	117.4	0.01	0.00	8.7
Radius_1	7.3	0.02	125.0	0.02	0.00	15.7
Radius_2	5.0	0.04	122.6	0.01	0.00	14.2
Bone marrow (Radius)_1	201.2	3.68	60.1	0.09	0.06	6.7
Bone marrow (Radius)_2	181.4	3.25	58.6	0.12	0.06	9.6
Ulna_1	5.4	0.02	107.2	0.01	0.00	7.1
Ulna_2	4.0	0.00	96.5	0.01	0.00	5.7

Bone marrow (Ulna)_1	202.6	5.04	85.6	0.14	0.07	15.6
Bone marrow (Ulna)_2	197.3	4.76	94.9	0.13	0.07	20.0
Phalanx distalis digiti majoris_1	7.6	0.04	147.5	0.01	0.00	7.5
Phalanx distalis digiti majoris_2	8.8	0.04	147.4	0.01	0.00	7.6
Patella_1	83.0	0.19	162.3	0.01	0.00	110.1
Patella_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_1	18.0	0.11	110.7	0.01	0.00	56.2
Fibula_2	18.4	0.34	106.2	0.01	0.00	51.4
Tarsometatarsus_1	5.4	0.06	98.1	0.01	0.00	13.2
Tarsometatarsus_2	7.0	0.01	86.3	0.01	0.00	6.7
Bone marrow (Tarsometatarsus)_1	161.6	2.60	76.9	0.19	0.08	27.3
Bone marrow (Tarsometatarsus)_2	111.7	1.23	103.5	0.12	0.05	26.5
Os digiti pedis II_1	6.6	0.00	149.7	0.01	0.00	8.7
Os digiti pedis II_2	5.6	0.01	158.1	0.01	0.00	10.6
Femur_epiphysis (proximal, surface) _1	14.4	0.00	132.0	0.01	0.00	52.9
Femur_epiphysis (proximal, surface) _2	11.9	0.00	128.4	0.01	0.01	56.6
Femur_epiphysis (proximal, core) _1	13.4	0.00	160.6	0.01	0.01	61.9
Femur_epiphysis (proximal, core) _2	16.8	0.00	159.6	0.01	0.01	70.6
Femur_diaphysis (proximal, internal struts) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal, internal struts) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal) _1	5.6	0.02	135.3	0.01	0.00	8.9
Femur_diaphysis (proximal) _2	5.4	0.00	143.1	0.01	0.01	12.4
Femur_diaphysis (medial) _1	5.3	0.00	146.7	0.01	0.00	10.0
Femur_diaphysis (medial) _2	5.2	0.00	135.8	0.01	0.00	9.7

Femur_diaphysis (distal) _1	5.3	0.00	130.1	0.01	0.00	9.1
Femur_diaphysis (distal) _2	5.9	0.01	123.7	0.01	0.00	15.0
Femur_diaphysis (distal, internal struts) _1	19.7	0.14	122.6	0.01	0.01	36.6
Femur_diaphysis (distal, internal struts) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, core) _1	15.1	0.20	154.0	0.01	0.01	60.4
Femur_epiphysis (distal, core) _2	14.3	0.00	154.1	0.01	0.01	64.7
Femur_epiphysis (distal, surface) _1	15.3	0.01	139.5	0.01	0.01	58.7
Femur_epiphysis (distal, surface) _2	12.3	0.00	127.9	0.01	0.00	33.2
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _1	19.8	0.00	112.7	0.00	0.00	41.8
Tibiotarsus_epiphysis (proximal, surface) _2	27.1	0.02	117.5	0.01	0.00	59.8
Tibiotarsus_epiphysis (proximal, core) _1	106.0	0.14	163.6	0.01	0.00	131.2
Tibiotarsus_epiphysis (proximal, core) _2	137.4	0.07	180.3	0.01	0.01	177.0
Tibiotarsus_diaphysis (proximal) _1	13.6	1.05	150.6	0.01	0.00	29.5
Tibiotarsus_diaphysis (proximal) _2	20.0	0.07	153.6	0.01	0.00	46.7
Tibiotarsus_diaphysis (medial) _1	9.8	0.01	162.9	0.01	0.00	8.0
Tibiotarsus_diaphysis (medial) _2	8.3	0.00	143.1	0.01	0.00	8.7
Tibiotarsus_diaphysis (distal) _1	8.7	0.00	136.7	0.01	0.00	9.6
Tibiotarsus_diaphysis (distal) _2	7.8	0.00	141.7	0.01	0.00	10.0
Tibiotarsus_epiphysis (distal, core) _1	11.9	0.00	164.1	0.01	0.00	36.3
Tibiotarsus_epiphysis (distal, core) _2	10.5	0.02	144.7	0.01	0.00	30.5
Tibiotarsus_epiphysis (distal, surface) _1	10.8	0.00	168.4	0.01	0.00	37.4
Tibiotarsus_epiphysis (distal, surface) _2	11.3	0.00	156.6	0.01	0.00	35.4

Bone marrow (Tibiotarsus)_1	507.2	2.17	80.6	0.06	0.05	9.8
Bone marrow (Tibiotarsus)_2	524.4	2.25	76.9	0.06	0.05	9.5
Liver	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Kidney	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

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114 (5) White-tailed sea eagle (B)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Cranial bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_2	131.3	1.24	253.0	0.03	0.02	94.8
Atlas_1	31.8	1.24	184.7	0.02	0.01	27.2
Atlas_2	62.4	1.05	207.1	0.02	0.01	59.4
Axis_1	105.4	7.82	247.7	0.11	0.02	83.3
Axis_2	107.9	5.71	223.7	0.06	0.02	73.6
3rd Cervical vertebrae_1	108.1	13.54	274.6	0.04	0.02	26.0
3rd Cervical vertebrae_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
4th Cervical vertebrae_1	61.0	0.72	261.6	0.05	0.03	18.7
4th Cervical vertebrae_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Spinal cord_1	296.6	17.48	88.1	0.03	0.06	4.8
Spinal cord_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Notarium_1	72.9	0.30	180.8	0.03	0.02	15.4

Notarium_2	57.9	0.29	175.8	0.03	0.02	12.5
Scapula_1	25.6	0.19	162.4	0.04	0.02	24.3
Scapula_2	35.9	1.77	176.5	0.03	0.01	31.0
Sternum_1	27.5	0.18	132.2	0.03	0.01	15.1
Sternum_2	67.5	0.07	135.0	0.03	0.03	13.1
Keel_1	48.2	0.46	184.8	0.03	0.02	36.3
Keel_2	34.2	0.25	153.8	0.02	0.01	24.5
Coracoideum_1	15.3	0.13	158.7	0.04	0.01	9.9
Coracoideum_2	16.4	0.10	153.7	0.04	0.01	8.6
Costa vertebralis_1	21.1	0.11	168.8	0.04	0.02	13.9
Costa vertebralis_2	30.4	0.20	169.6	0.03	0.01	14.0
Costa sternalis_1	66.8	0.12	154.3	0.03	0.02	17.1
Costa sternalis_2	44.5	0.24	165.6	0.03	0.02	18.2
Ilium_1	24.2	0.12	136.5	0.02	0.04	15.6
Ilium_2	39.0	0.45	190.1	0.02	0.02	61.9
Pygostyle_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Pygostyle_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_2	10.9	0.12	178.2	0.03	0.00	7.9
Radius_1	19.1	0.12	169.0	0.03	0.01	8.2
Radius_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Ulna_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Ulna_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Phalanx distalis digiti majoris_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Phalanx distalis digiti majoris_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (proximal, surface) _1	15.5	0.07	146.1	0.01	0.01	23.3
Femur_epiphysis (proximal, surface) _2	18.6	0.77	133.0	0.01	0.01	21.5
Femur_epiphysis (proximal, core) _1	16.0	0.00	118.0	0.01	0.01	19.6
Femur_epiphysis (proximal, core) _2	23.2	0.00	115.7	0.00	0.01	17.9
Femur_diaphysis (proximal, internal struts) _1	16.9	0.00	112.6	0.01	0.00	15.7
Femur_diaphysis (proximal, internal struts) _2	15.8	0.00	113.0	0.01	0.01	17.6
Femur_diaphysis (proximal) _1	7.6	0.04	157.0	0.02	0.00	8.5
Femur_diaphysis (proximal) _2	7.5	0.07	154.8	0.01	0.00	8.7
Femur_diaphysis (medial) _1	14.3	0.07	162.9	0.01	0.00	8.7

Femur_diaphysis (medial) _2	14.7	0.11	163.2	0.01	0.00	9.0
Femur_diaphysis (distal) _1	7.7	0.04	145.5	0.01	0.00	9.6
Femur_diaphysis (distal) _2	9.6	0.07	145.9	0.01	0.00	8.6
Femur_diaphysis (distal, internal struts) _1	6.5	0.00	115.7	0.01	0.01	13.5
Femur_diaphysis (distal, internal struts) _2	8.4	0.00	109.3	0.01	0.01	13.8
Femur_epiphysis (distal, core) _1	11.0	0.15	123.7	0.01	0.01	23.1
Femur_epiphysis (distal, core) _2	11.6	0.00	121.6	0.01	0.01	20.3
Femur_epiphysis (distal, surface) _1	23.0	0.76	133.9	0.01	0.01	23.9
Femur_epiphysis (distal, surface) _2	18.9	0.38	134.7	0.01	0.01	33.9
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Tibiotarsus_epiphysis (distal, surface)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Liver	10804.1	17.3	270.2	0.02	1.29	67.2
Kidney	1223.2	21.9	191.5	0.02	21.8	58.4

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117 (6) Mountain hawk-eagle (Control)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Cranial bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_1	90.6	1.32	165.8	0.03	0.01	0.62
Hyoid bone_2	141.6	2.40	180.0	0.04	0.02	0.79
Atlas_1	42.4	0.77	162.2	0.10	0.01	0.57
Atlas_2	48.9	0.75	153.1	0.05	0.01	0.44
Axis_1	163.1	1.70	203.2	0.09	0.02	0.74
Axis_2	119.9	1.42	197.1	0.07	0.02	0.69
3rd Cervical vertebrae_1	53.2	1.95	260.3	0.04	0.01	0.62
3rd Cervical vertebrae_1	36.2	1.38	193.3	0.04	0.01	0.65
4th Cervical vertebrae_1	44.7	1.74	263.1	0.05	0.02	0.83
4th Cervical vertebrae_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Spinal cord_1	77.3	6.42	44.4	0.02	0.01	0.07
Spinal cord_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Notarium_1	15.6	0.33	183.1	0.04	0.01	0.49
Notarium_2	16.8	0.34	168.7	0.04	0.01	0.48
Scapula_1	9.6	0.00	96.4	0.00	0.00	0.31
Scapula_2	10.3	0.00	95.7	0.01	0.00	0.32
Sternum_1	35.0	0.47	142.6	0.02	0.01	0.42
Sternum_2	45.2	0.70	144.5	0.03	0.02	0.43
Keel_1	51.6	0.42	144.7	0.03	0.01	0.43
Keel_2	36.1	0.67	123.4	0.02	0.01	0.37
Coracoideum_1	15.9	0.13	155.1	0.03	0.00	0.33
Coracoideum_2	13.9	0.18	151.9	0.03	0.00	0.28
Costa vertebralis_1	13.3	0.14	155.9	0.02	0.01	0.41
Costa vertebralis_2	12.1	0.23	155.8	0.02	0.01	0.38
Costa sternalis_1	12.7	0.21	132.9	0.02	0.01	0.36
Costa sternalis_2	13.6	0.26	129.6	0.02	0.01	0.35
Ilium_1	32.8	0.41	131.7	0.02	0.01	0.43
Ilium_2	23.7	0.36	133.7	0.02	0.01	0.43
Pygostyle_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Pygostyle_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Humerus_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Radius_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Radius_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Radius)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Ulna_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Ulna_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Phalanx distalis digiti majoris_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Phalanx distalis digiti majoris_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Patella_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Fibula_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tarsometatarsus_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Os digiti pedis II_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (proximal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (proximal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (proximal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (proximal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal, internal struts) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal, internal struts) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (proximal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Femur_diaphysis (medial) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (medial) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (distal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (distal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (distal, internal struts) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_diaphysis (distal, internal struts) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Femur_epiphysis (distal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (medial) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (distal) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Tibiotarsus_epiphysis (distal, surface) _1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (distal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus)_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Tibiotarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Liver	7122.3	27.38	284.3	0.02	0.52	0.41
Kidney	826.6	17.77	168.5	0.01	1.35	0.21

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Table S5. Concentration of elements in swans (mg/kg, dry weight).

N. A.: Not available (Samples were not collected.)

(1) Swan (A)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Cranial bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Atlas_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Atlas_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Axis_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Axis_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
3rd Cervical vertebrae_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
3rd Cervical vertebrae_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
4th Cervical vertebrae_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
4th Cervical vertebrae_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Notarium_1	288.1	1.22	162.0	0.19	0.01	49.9
Notarium_2	382.3	1.12	161.7	0.13	0.01	57.7
Scapula_1	129.1	1.08	160.0	0.08	0.01	128.2
Scapula_2	129.0	1.12	162.4	0.08	0.01	102.4
Sternum_1	276.2	1.01	162.2	0.08	0.02	88.8
Sternum_2	201.4	0.65	165.5	0.08	0.01	85.2

Keel_1	131.7	1.16	158.2	0.08	0.01	106.4
Keel_2	89.8	0.87	148.9	0.07	0.01	119.8
Coracoideum_1	40.9	0.53	173.1	0.09	0.00	18.3
Coracoideum_2	37.8	0.46	167.3	0.09	0.00	16.7
Costa vertebralis_1	41.6	0.19	167.4	0.05	0.01	182.2
Costa vertebralis_2	58.0	0.37	201.6	0.04	0.00	206.6
Costa sternalis_1	131.0	0.36	191.8	0.06	0.00	93.4
Costa sternalis_2	155.2	0.44	193.3	0.07	0.01	105.0
Ilium_1	82.7	0.41	143.4	0.06	0.01	35.6
Ilium_2	86.9	1.64	141.2	0.06	0.01	33.8
Pygostyle_1	178.9	0.77	131.6	0.07	0.06	179.2
Pygostyle_2	215.3	0.68	129.5	0.09	0.03	158.6
Humerus_1	34.9	0.40	167.2	0.12	0.00	9.2
Humerus_2	17.0	0.32	158.6	0.11	0.00	8.9
Radius_1	24.0	0.53	157.5	0.10	0.00	15.3
Radius_2	30.4	0.49	147.7	0.10	0.00	12.0
Ulna_1	29.0	0.53	155.6	0.11	0.00	15.4
Ulna_2	17.9	0.26	153.5	0.11	0.00	15.7
Phalanx distalis digiti majoris_1	68.0	0.26	116.1	0.08	0.00	26.1
Phalanx distalis digiti majoris_2	74.3	0.30	111.2	0.06	0.01	50.5
Patella_1	66.5	0.96	37.8	0.02	0.01	18.3
Patella_2	66.0	0.98	36.1	0.02	0.01	14.4
Fibula_1	125.2	0.90	148.6	0.05	0.01	129.4
Fibula_2	85.5	0.63	161.1	0.04	0.01	148.0

Tarsometatarsus_1	21.7	0.19	137.5	0.04	0.00	14.6
Tarsometatarsus_2	11.8	0.15	126.6	0.06	0.00	11.5
Os digiti pedis II_1	21.6	0.16	138.1	0.04	0.00	13.0
Os digiti pedis II_2	49.2	0.22	143.4	0.04	0.00	15.0
Femur_epiphysis (proximal, surface) _1	118.4	0.50	117.4	0.04	0.01	143.6
Femur_epiphysis (proximal, surface) _2	123.3	0.47	132.2	0.04	0.01	160.7
Femur_epiphysis (proximal, core) _1	123.4	0.49	127.4	0.04	0.01	188.3
Femur_epiphysis (proximal, core) _2	109.7	0.45	156.5	0.05	0.00	235.6
Femur_diaphysis (proximal) _1	17.9	1.59	153.3	0.07	0.00	49.5
Femur_diaphysis (proximal) _2	24.4	1.24	164.3	0.08	0.00	69.7
Femur_diaphysis (medial) _1	19.0	0.93	157.8	0.10	0.00	28.0
Femur_diaphysis (medial) _2	15.6	1.14	151.2	0.09	0.00	28.0
Femur_diaphysis (distal) _1	12.4	1.36	149.3	0.09	0.00	31.3
Femur_diaphysis (distal) _2	21.4	1.03	156.7	0.09	0.00	32.7
Femur_epiphysis (distal, core) _1	113.0	0.40	137.5	0.04	0.00	151.7
Femur_epiphysis (distal, core) _2	116.4	0.43	140.7	0.04	0.00	146.7
Femur_epiphysis (distal, surface) _1	65.5	0.33	127.0	0.03	0.00	131.4
Femur_epiphysis (distal, surface) _2	72.1	0.33	141.8	0.03	0.00	137.6
Tibiotarsus_epiphysis (proximal, surface) _1	39.5	0.95	144.1	0.05	0.00	80.9
Tibiotarsus_epiphysis (proximal, surface) _2	24.1	0.52	138.9	0.05	0.00	89.4
Tibiotarsus_epiphysis (proximal, core) _1	95.6	0.56	188.4	0.03	0.01	390.2
Tibiotarsus_epiphysis (proximal, core) _2	73.2	0.65	164.3	0.04	0.00	253.5
Tibiotarsus_diaphysis (proximal) _1	10.7	1.01	138.4	0.06	0.00	22.5
Tibiotarsus_diaphysis (proximal) _2	15.3	1.64	145.0	0.07	0.00	27.7

Tibiotarsus_diaphysis (medial) _1	13.6	0.59	132.3	0.08	0.00	22.9
Tibiotarsus_diaphysis (medial) _2	10.2	0.42	126.1	0.08	0.00	16.4
Tibiotarsus_diaphysis (distal) _1	10.1	0.17	116.5	0.07	0.00	8.7
Tibiotarsus_diaphysis (distal) _2	9.6	0.26	117.4	0.07	0.00	8.8
Tibiotarsus_epiphysis (distal, core) _1	20.8	0.16	90.7	0.02	0.00	17.0
Tibiotarsus_epiphysis (distal, core) _2	21.6	0.14	91.8	0.03	0.00	16.4
Tibiotarsus_epiphysis (distal, surface) _1	26.7	0.30	97.9	0.03	0.00	14.2
Tibiotarsus_epiphysis (distal, surface) _2	21.7	0.19	83.0	0.02	0.00	20.5
Spinal cord_1	90.8	3.47	15.5	0.02	0.01	2.4
Bone marrow (Radius)_1	240.9	3.03	37.7	0.03	0.01	15.5
Bone marrow (Radius)_2	32.0	0.39	5.2	0.01	0.00	2.2
Bone marrow (Ulna)_1	39.9	0.62	6.5	0.00	0.00	2.5
Bone marrow (Ulna)_2	117.6	1.38	12.1	0.01	0.01	4.5
Bone marrow (Tarsometatarsus)_1	51.6	0.72	8.9	0.01	0.00	3.2
Bone marrow (Tarsometatarsus)_2	210.8	3.19	32.0	0.02	0.01	11.3
Bone marrow (Femur)	492.3	1.31	26.9	0.01	0.01	10.5
Bone marrow (Femur)	431.8	1.48	24.7	0.01	0.01	7.8
Bone marrow (Tibiotarsus)_1	363.6	1.04	22.6	0.01	0.01	8.4
Bone marrow (Tibiotarsus)_2	107.4	0.38	5.7	0.01	0.00	2.9
Liver	10593.6	1579.5	234.7	0.06	4.1	45.4
Kidney	440.8	16.7	111.0	0.04	11.5	57.0

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126 (2) Swan (B)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	66.2	0.94	189.1	0.10	0.01	121.2
Cranial bone_2	30.5	0.59	188.9	0.06	0.00	67.2
Hyoid bone_1	72.6	0.85	193.5	0.07	0.00	77.9
Hyoid bone_2	70.3	1.19	155.7	0.05	0.00	100.3
Atlas_1	52.2	0.79	215.6	0.05	0.00	87.7
Atlas_2	60.8	0.74	195.4	0.05	0.00	129.8
Axis_1	72.2	1.01	188.2	0.06	0.00	88.0
Axis_2	64.3	0.68	197.5	0.04	0.00	125.4
3rd Cervical vertebrae_1	65.2	0.93	195.9	0.05	0.01	83.0
3rd Cervical vertebrae_2	58.8	0.88	193.1	0.05	0.01	106.0
4th Cervical vertebrae_1	44.4	0.83	197.5	0.05	0.00	68.8
4th Cervical vertebrae_2	42.2	0.49	181.2	0.04	0.00	98.9
Notarium_1	70.8	0.52	177.6	0.05	0.00	87.7
Notarium_2	67.2	0.40	163.3	0.05	0.00	112.7
Scapula_1	38.2	0.37	167.3	0.05	0.00	107.3
Scapula_2	45.5	0.39	157.3	0.05	0.00	104.3
Sternum_1	60.8	0.49	173.6	0.05	0.00	82.9
Sternum_2	54.8	0.41	163.2	0.05	0.00	88.1
Keel_1	52.1	0.72	142.1	0.04	0.00	140.1
Keel_2	54.1	0.59	144.2	0.04	0.00	150.1
Coracoideum_1	24.3	0.53	183.1	0.08	0.00	54.3
Coracoideum_2	25.6	0.66	187.3	0.07	0.00	78.9

Costa vertebralis_1	49.6	0.87	147.4	0.05	0.00	127.5
Costa vertebralis_2	42.4	0.70	150.1	0.05	0.00	126.2
Costa sternalis_1	67.9	0.33	165.1	0.05	0.00	67.8
Costa sternalis_2	48.5	0.25	160.1	0.05	0.00	74.5
Ilium_1	61.7	0.37	145.5	0.03	0.00	86.1
Ilium_2	45.3	0.29	147.2	0.03	0.00	87.7
Pygostyle_1	129.0	0.49	135.0	0.03	0.01	175.9
Pygostyle_2	135.7	0.59	139.5	0.03	0.01	173.9
Humerus_1	7.8	0.25	155.3	0.08	0.00	15.2
Humerus_2	12.2	0.40	141.8	0.08	0.00	21.6
Radius_1	23.0	0.25	132.5	0.08	0.01	17.8
Radius_2	18.2	0.29	138.4	0.08	0.00	17.0
Ulna_1	9.0	0.30	140.6	0.09	0.00	15.1
Ulna_2	9.4	0.22	133.2	0.08	0.00	15.1
Phalanx distalis digiti majoris_1	21.1	0.18	82.0	0.03	0.01	45.9
Phalanx distalis digiti majoris_2	16.4	0.10	100.0	0.04	0.00	28.9
Patella_1	30.3	0.55	71.2	0.02	0.00	53.7
Patella_2	36.0	0.70	22.1	0.00	0.01	12.4
Fibula_1	87.0	0.55	121.2	0.03	0.01	73.5
Fibula_2	82.6	0.51	109.2	0.03	0.00	71.6
Tarsometatarsus_1	18.0	0.12	117.0	0.04	0.00	18.4
Tarsometatarsus_2	21.7	0.12	107.9	0.03	0.00	16.9
Os digiti pedis II_1	39.2	0.13	117.5	0.03	0.00	30.7
Os digiti pedis II_2	26.0	0.12	106.2	0.02	0.00	27.5

Femur_epiphysis (proximal, surface) _1	90.8	0.58	113.7	0.03	0.00	108.5
Femur_epiphysis (proximal, surface) _2	83.9	0.33	102.7	0.03	0.00	144.6
Femur_epiphysis (proximal, core) _1	34.7	0.47	122.1	0.03	0.00	97.6
Femur_epiphysis (proximal, core) _2	33.0	0.45	123.1	0.03	0.00	112.1
Femur_diaphysis (proximal) _1	12.2	0.59	138.5	0.05	0.00	30.3
Femur_diaphysis (proximal) _2	17.0	0.55	115.8	0.05	0.00	24.2
Femur_diaphysis (medial) _1	15.9	0.52	131.5	0.05	0.00	42.8
Femur_diaphysis (medial) _2	14.5	0.51	115.2	0.05	0.00	30.4
Femur_diaphysis (distal) _1	12.5	0.49	116.1	0.05	0.00	29.5
Femur_diaphysis (distal) _2	12.8	0.52	118.4	0.05	0.00	30.7
Femur_epiphysis (distal, core) _1	45.8	0.18	87.2	0.02	0.00	95.2
Femur_epiphysis (distal, core) _2	40.9	0.47	98.4	0.02	0.00	106.2
Femur_epiphysis (distal, surface) _1	45.0	0.23	77.7	0.02	0.00	100.3
Femur_epiphysis (distal, surface) _2	38.9	0.18	67.6	0.01	0.00	91.2
Tibiotarsus_epiphysis (proximal, surface) _1	42.3	0.21	88.4	0.02	0.00	90.5
Tibiotarsus_epiphysis (proximal, surface) _2	28.2	0.21	85.4	0.02	0.00	84.2
Tibiotarsus_epiphysis (proximal, core) _1	45.0	0.26	84.2	0.02	0.00	129.7
Tibiotarsus_epiphysis (proximal, core) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_diaphysis (proximal) _1	14.9	0.79	99.3	0.04	0.00	26.6
Tibiotarsus_diaphysis (proximal) _2	6.5	0.61	95.2	0.03	0.00	22.3
Tibiotarsus_diaphysis (medial) _1	9.9	0.40	84.2	0.04	0.00	14.9
Tibiotarsus_diaphysis (medial) _2	10.6	0.48	85.2	0.04	0.00	18.2
Tibiotarsus_diaphysis (distal) _1	8.4	0.12	68.9	0.04	0.00	11.0
Tibiotarsus_diaphysis (distal) _2	10.6	0.22	69.5	0.04	0.00	10.2

Tibiotarsus_epiphysis (distal, core) _1	9.2	0.04	51.4	0.02	0.00	22.0
Tibiotarsus_epiphysis (distal, core) _2	9.2	0.03	52.5	0.01	0.00	22.6
Tibiotarsus_epiphysis (distal, surface) _1	9.5	0.03	52.4	0.02	0.00	27.4
Tibiotarsus_epiphysis (distal, surface) _2	7.5	0.03	51.3	0.02	0.00	23.6
Spinal cord_1	35.0	2.89	9.0	0.00	0.00	1.9
Bone marrow (Radius)_1	62.5	1.13	17.0	0.01	0.00	6.7
Bone marrow (Radius)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_1	65.1	0.83	10.9	0.01	0.01	8.2
Bone marrow (Ulna)_2	65.5	0.61	8.5	0.01	0.00	4.3
Bone marrow (Tarsometatarsus)_1	74.2	0.27	20.4	0.01	0.00	4.7
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	94.9	0.28	8.7	0.00	0.00	11.1
Bone marrow (Femur)	125.2	0.44	14.6	0.01	0.00	7.5
Bone marrow (Tibiotarsus)_1	101.5	0.22	6.9	0.01	0.00	8.3
Bone marrow (Tibiotarsus)_2	87.7	0.21	6.6	0.01	0.00	5.7
Liver	28180	1003	167.9	0.08	0.75	113.7
Kidney	898	19	159.8	0.02	8.41	146.5

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129 (3) Swan (C)

	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	35.9	0.48	168.1	0.12	0.01	10.1
Cranial bone_2	29.3	0.43	172.5	0.10	0.00	10.3

Hyoid bone_1	209.7	1.40	160.6	0.14	0.01	136.0
Hyoid bone_2	178.6	1.60	169.4	0.13	0.02	157.8
Atlas_1	52.9	0.64	193.4	0.10	0.01	49.6
Atlas_2	102.9	0.76	194.4	0.09	0.01	109.2
Axis_1	65.6	0.78	329.8	0.12	0.01	49.0
Axis_2	58.1	0.34	2.1	0.03	0.00	0.4
3rd Cervical vertebrae_1	50.4	0.50	168.7	0.07	0.01	31.2
3rd Cervical vertebrae_2	65.1	0.54	171.1	0.07	0.00	27.1
4th Cervical vertebrae_1	111.8	1.06	178.3	0.10	0.01	16.3
4th Cervical vertebrae_2	98.4	0.88	177.9	0.11	0.01	21.8
Notarium_1	44.4	0.41	172.0	0.06	0.01	52.5
Notarium_2	44.6	0.46	172.3	0.06	0.01	49.6
Scapula_1	77.5	0.74	188.9	0.10	0.01	137.3
Scapula_2	80.7	0.71	175.3	0.09	0.01	94.5
Sternum_1	81.5	0.61	159.4	0.08	0.01	85.4
Sternum_2	82.2	0.65	164.1	0.08	0.01	109.9
Keel_1	109.3	1.50	132.2	0.07	0.01	77.0
Keel_2	79.3	0.33	90.3	0.05	0.01	42.8
Coracoideum_1	31.2	0.87	181.2	0.17	0.00	24.9
Coracoideum_2	41.0	0.79	182.9	0.16	0.00	20.3
Costa vertebralis_1	61.1	0.41	174.3	0.06	0.00	74.1
Costa vertebralis_2	82.2	0.50	173.5	0.07	0.01	63.1
Costa sternalis_1	66.1	0.43	165.8	0.08	0.01	20.5
Costa sternalis_2	60.0	0.42	167.8	0.07	0.01	24.0

Ilium_1	85.5	0.54	160.2	0.05	0.01	37.1
Ilium_2	75.0	0.48	163.0	0.05	0.01	22.9
Pygostyle_1	77.2	0.36	101.8	0.07	0.01	64.5
Pygostyle_2	62.0	0.32	108.8	0.07	0.01	82.7
Humerus_1	52.2	0.56	166.8	0.21	0.00	12.0
Humerus_2	46.0	0.54	177.2	0.20	0.00	14.2
Radius_1	55.4	0.46	147.5	0.19	0.00	19.5
Radius_2	22.0	0.28	143.9	0.18	0.00	18.3
Ulna_1	25.8	0.36	156.3	0.19	0.00	20.2
Ulna_2	27.4	0.36	153.8	0.19	0.00	15.9
Phalanx distalis digiti majoris_1	37.3	0.25	132.6	0.09	0.00	27.2
Phalanx distalis digiti majoris_2	66.0	0.32	138.1	0.10	0.00	32.4
Patella_1	47.8	1.11	20.3	0.02	0.01	10.5
Patella_2	74.1	1.37	20.3	0.03	0.01	8.4
Fibula_1	66.8	0.75	173.1	0.08	0.00	45.2
Fibula_2	59.8	0.71	166.4	0.08	0.00	34.7
Tarsometatarsus_1	25.6	0.16	124.1	0.07	0.00	8.0
Tarsometatarsus_2	34.0	0.20	124.0	0.08	0.00	8.2
Os digiti pedis II_1	34.2	0.19	131.3	0.08	0.00	10.7
Os digiti pedis II_2	48.0	0.24	124.8	0.09	0.00	10.5
Femur_epiphysis (proximal, surface) _1	72.46	0.44	136.69	0.05	0.00	139.34
Femur_epiphysis (proximal, surface) _2	81.04	0.54	134.41	0.05	0.01	129.00
Femur_epiphysis (proximal, core) _1	63.25	0.29	128.06	0.05	0.00	123.44
Femur_epiphysis (proximal, core) _2	79.93	0.36	129.54	0.04	0.00	140.61

Femur_diaphysis (proximal) _1	16.27	0.85	144.86	0.14	0.00	14.92
Femur_diaphysis (proximal) _2	17.44	0.75	156.72	0.12	0.00	26.49
Femur_diaphysis (medial) _1	17.68	0.80	138.02	0.14	0.00	9.18
Femur_diaphysis (medial) _2	26.16	0.85	138.80	0.14	0.00	14.75
Femur_diaphysis (distal) _1	24.62	0.71	140.47	0.14	0.00	14.59
Femur_diaphysis (distal) _2	25.43	0.75	141.54	0.12	0.01	16.17
Femur_epiphysis (distal, core) _1	83.31	0.21	147.54	0.04	0.00	189.62
Femur_epiphysis (distal, core) _2	72.99	0.59	125.06	0.04	0.00	166.17
Femur_epiphysis (distal, surface) _1	71.79	0.33	101.01	0.04	0.01	83.04
Femur_epiphysis (distal, surface) _2	59.39	0.33	104.57	0.03	0.00	108.80
Tibiotarsus_epiphysis (proximal, surface) _1	24.80	0.48	136.22	0.05	0.00	40.62
Tibiotarsus_epiphysis (proximal, surface) _2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Tibiotarsus_epiphysis (proximal, core) _1	74.0	0.26	145.8	0.05	0.00	143.8
Tibiotarsus_epiphysis (proximal, core) _2	67.1	0.27	148.7	0.05	0.00	145.9
Tibiotarsus_diaphysis (proximal) _1	26.3	1.08	138.1	0.08	0.00	22.6
Tibiotarsus_diaphysis (proximal) _2	21.7	1.07	129.9	0.08	0.00	16.3
Tibiotarsus_diaphysis (medial) _1	16.4	0.88	133.6	0.08	0.00	11.6
Tibiotarsus_diaphysis (medial) _2	22.5	0.98	125.2	0.09	0.00	11.8
Tibiotarsus_diaphysis (distal) _1	14.1	0.14	101.4	0.11	0.00	5.0
Tibiotarsus_diaphysis (distal) _2	8.9	0.09	99.3	0.11	0.00	5.2
Tibiotarsus_epiphysis (distal, core) _1	17.3	0.08	81.5	0.04	0.00	18.5
Tibiotarsus_epiphysis (distal, core) _2	17.0	0.07	79.0	0.04	0.00	17.4
Tibiotarsus_epiphysis (distal, surface) _1	15.5	0.08	78.5	0.04	0.00	11.2
Tibiotarsus_epiphysis (distal, surface) _2	30.9	0.17	76.1	0.04	0.00	19.8

Spinal cord_1	65.3	2.23	11.7	0.01	0.01	2.4
Bone marrow (Radius)_1	103.4	0.51	11.7	0.02	0.01	11.2
Bone marrow (Radius)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Ulna)_1	104.1	0.42	8.8	0.03	0.01	10.4
Bone marrow (Ulna)_2	99.5	0.43	8.5	0.02	0.01	6.9
Bone marrow (Tarsometatarsus)_1	164.9	0.62	17.9	0.02	0.01	12.0
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	266.6	0.80	19.0	0.02	0.01	8.7
Bone marrow (Femur)	291.4	0.79	21.3	0.03	0.01	7.7
Bone marrow (Tibiotarsus)_1	240.7	0.71	16.9	0.03	0.01	12.3
Bone marrow (Tibiotarsus)_2	264.4	0.71	18.2	0.03	0.01	11.6
Liver	14286.3	664.3	199.4	0.14	2.9	69.7
Kidney	892.9	13.2	113.4	0.04	10.4	98.8

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132 (4) Swan (D)

Sample name	Fe	Cu	Zn	As	Cd	Pb
Cranial bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Cranial bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Hyoid bone_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Atlas_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Atlas_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.

Axis_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Axis_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
3rd Cervical vertebrae_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
3rd Cervical vertebrae_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
4th Cervical vertebrae_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
4th Cervical vertebrae_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Notarium_1	40.7	0.37	145.8	0.07	0.01	3.82
Notarium_2	54.0	0.41	159.8	0.08	0.01	5.29
Scapula_1	102.0	0.76	184.9	0.06	0.01	5.06
Scapula_2	79.6	0.58	172.7	0.06	0.01	3.93
Sternum_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Sternum_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Keel_1	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Keel_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Coracoideum_1	34.8	0.40	184.5	0.13	0.00	2.67
Coracoideum_2	30.2	0.33	195.1	0.13	0.00	3.13
Costa vertebralis_1	76.1	0.67	218.9	0.06	0.01	3.80
Costa vertebralis_2	62.7	0.67	214.8	0.06	0.01	4.28
Costa sternalis_1	63.6	0.44	210.9	0.08	0.01	4.79
Costa sternalis_2	45.6	0.39	214.8	0.07	0.02	4.49
Ilium_1	87.1	0.64	152.4	0.06	0.01	3.80
Ilium_2	99.4	0.38	159.9	0.07	0.01	3.98
Pygostyle_1	37.5	0.27	128.1	0.06	0.00	1.77
Pygostyle_2	37.7	0.30	127.4	0.05	0.00	2.52

Humerus_1	16.0	0.28	167.5	0.13	0.00	1.77
Humerus_2	18.1	0.28	165.6	0.13	0.00	1.81
Radius_1	18.2	0.33	158.5	0.12	0.00	1.73
Radius_2	25.0	0.37	167.0	0.12	0.00	2.00
Ulna_1	22.5	0.31	171.0	0.12	0.00	1.87
Ulna_2	15.3	0.29	168.9	0.12	0.00	1.85
Phalanx distalis digiti majoris_1	33.1	0.19	142.6	0.07	0.00	2.60
Phalanx distalis digiti majoris_2	25.7	0.17	130.4	0.06	0.00	2.61
Patella_1	31.8	0.46	120.7	0.04	0.00	4.10
Patella_2	49.8	0.41	155.1	0.05	0.01	5.52
Fibula_1	67.0	0.53	163.6	0.07	0.00	2.69
Fibula_2	31.0	0.66	161.5	0.06	0.00	2.53
Tarsometatarsus_1	18.9	0.17	147.0	0.06	0.00	2.93
Tarsometatarsus_2	9.9	0.15	175.5	0.06	0.00	2.76
Os digiti pedis II_1	21.5	0.17	156.3	0.05	0.00	3.16
Os digiti pedis II_2	29.2	0.70	159.3	0.06	0.00	3.30
Femur_epiphysis (proximal, surface) _1	93.5	0.75	178.0	0.06	0.01	4.95
Femur_epiphysis (proximal, surface) _2	77.9	0.62	180.6	0.06	0.01	5.35
Femur_epiphysis (proximal, core) _1	65.8	0.72	184.2	0.05	0.01	3.79
Femur_epiphysis (proximal, core) _2	87.4	0.68	157.5	0.04	0.01	2.75
Femur_diaphysis (proximal) _1	14.8	1.06	179.2	0.09	0.00	2.90
Femur_diaphysis (proximal) _2	21.6	0.91	166.1	0.10	0.00	2.99
Femur_diaphysis (medial) _1	22.6	0.80	162.6	0.11	0.00	2.45
Femur_diaphysis (medial) _2	18.4	0.69	166.1	0.13	0.00	2.67

Femur_diaphysis (distal) _1	19.8	0.98	172.1	0.11	0.00	2.46
Femur_diaphysis (distal) _2	14.0	0.92	170.2	0.10	0.00	2.77
Femur_epiphysis (distal, core) _1	48.7	0.42	168.1	0.04	0.01	3.76
Femur_epiphysis (distal, core) _2	63.0	0.48	182.7	0.05	0.01	3.91
Femur_epiphysis (distal, surface) _1	61.3	0.39	146.7	0.04	0.01	4.57
Femur_epiphysis (distal, surface) _2	77.2	0.43	134.1	0.04	0.01	4.80
Tibiotarsus_epiphysis (proximal, surface) _1	42.3	4.60	153.3	0.04	0.01	3.95
Tibiotarsus_epiphysis (proximal, surface) _2	60.6	0.58	134.6	0.05	0.01	3.85
Tibiotarsus_epiphysis (proximal, core) _1	63.8	0.53	169.9	0.04	0.01	4.41
Tibiotarsus_epiphysis (proximal, core) _2	83.3	0.63	154.9	0.03	0.01	3.79
Tibiotarsus_diaphysis (proximal) _1	14.9	1.31	140.4	0.07	0.00	3.14
Tibiotarsus_diaphysis (proximal) _2	13.1	1.21	145.6	0.08	0.00	2.81
Tibiotarsus_diaphysis (medial) _1	12.7	0.51	136.9	0.09	0.00	2.14
Tibiotarsus_diaphysis (medial) _2	9.1	0.40	128.9	0.10	0.00	1.72
Tibiotarsus_diaphysis (distal) _1	13.0	0.14	122.6	0.08	0.00	1.53
Tibiotarsus_diaphysis (distal) _2	9.7	0.16	108.2	0.07	0.00	1.57
Tibiotarsus_epiphysis (distal, core) _1	13.0	0.09	110.3	0.03	0.00	2.20
Tibiotarsus_epiphysis (distal, core) _2	11.7	0.09	111.8	0.03	0.00	2.04
Tibiotarsus_epiphysis (distal, surface) _1	29.2	0.25	101.8	0.03	0.00	3.80
Tibiotarsus_epiphysis (distal, surface) _2	22.1	0.20	94.1	0.03	0.00	3.51
Spinal cord_1	178.4	2.74	18.3	0.01	0.01	0.26
Bone marrow (Radius)_1	118.7	0.52	11.0	0.01	0.01	0.11
Bone marrow (Radius)_2	111.0	0.41	10.0	0.01	0.01	0.11
Bone marrow (Ulna)_1	160.5	0.55	11.4	0.01	0.01	0.12

Bone marrow (Ulna)_2	124.9	0.39	16.8	0.01	0.00	0.28
Bone marrow (Tarsometatarsus)_1	174.7	0.57	11.4	0.01	0.01	0.09
Bone marrow (Tarsometatarsus)_2	N. A.	N. A.	N. A.	N. A.	N. A.	N. A.
Bone marrow (Femur)	214.4	0.66	19.8	0.01	0.01	0.21
Bone marrow (Femur)	200.7	0.64	17.1	0.01	0.01	0.15
Bone marrow (Tibiotarsus)_1	209.6	0.60	15.9	0.02	0.01	0.23
Bone marrow (Tibiotarsus)_2	201.9	0.57	15.5	0.02	0.01	0.24
Liver	2445.6	120.4	118.8	0.03	0.54	0.46
Kidney	784.0	14.4	78.8	0.04	5.18	1.86

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Fig. S1. The position of bone and bone marrow samples collected from birds. The diagram of a bird skeleton was modified from “Squelette_oiseau.JPG: BIODIDAC derivative work: mario modesto (Squelette_oiseau.JPG)”. The bone marrow in the femur (*¹) exists only in swans, and patella was collected only from the eagles (*²) in this study.

Fig. S2. The position of bone and bone marrow samples collected from birds. (1):

epiphysis (proximal, surface); (2): epiphysis (proximal, core); (3): diaphysis (proximal, internal struts); (4): diaphysis (proximal); (5): diaphysis (medial); (6): diaphysis (distal); (7): diaphysis (distal, internal struts); (8): epiphysis (distal, core); and (9): epiphysis (distal, surface). The internal struts (3) were only collected from the femur in Steller's sea eagle (*¹).

Fig. S3. Pb distribution in bone and organ tissues in swan (D). (An expanded version of Fig. 2). Markers indicate the average of two specimens collected from the same bone.

Fig. S4. Correlation coefficients between bones and liver or kidney (Sample size > 5 for each tissue). Spearman's rank correlation coefficient (ρ) for Pb levels are shown in Table S3. Pink color (triangle) corresponds to eagles and blue color (circle) indicates swans. Red lines indicate the 95% tolerance ellipse.

Fig. S5. Photomicrographs of femur (1) and tibiotarsus (2) of Steller's sea eagle.

Due to the large size of the samples, three photomicrographs were combined to make the figure.

(1)

(2)

Fig. S6. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in femur of Steller's sea eagle. The scale bar is 30 mm. The ranges of elements' counts per second (cps) vary between images.

Fig. S7. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in tibiotarsus of Steller's sea eagle. The scale bar is 20 mm. The ranges of elements' counts per second (cps) vary between images.

Fig. S8. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in femur of whooper swan. The scale bar is 30 mm. The ranges of elements' counts per second (cps) vary between images.

Fig. S9. Local distributions of ^{13}C , ^{25}Mg , ^{31}P , ^{55}Mn , ^{57}Fe , ^{65}Cu , ^{66}Zn , ^{206}Pb and ^{207}Pb in tibia of whooper swan. The scale bar is 30 mm. The ranges of elements' counts per second (cps) vary between images.