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Geometric morphometric analysis of cranium shape differences in sheep from colonial Sydney, Australia

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ABSTRACT

Geometric morphometrics (GMMs) is a valuable tool that can be used to identify variability within species, thereby distinguishing between breeds and closely related animals (e.g. sheep and goats). Identifying fine morphological differences is key to better understanding early herd management practices. Interestingly, GMMs has yet to be used in a colonial Australian context, particularly in the foundational period of colonial Sydney from 1790 to 1850. Given the overall importance of sheep to the development of colonial Australia, this analytical gap provides an opportunity to identify potential morphological variability, and so better understand colonial herd management strategies. Here we use GMMs to analyse an archaeological assemblage of sheep crania ($n = 27$) from the colonial Clarence Street site, in Sydney, Australia. These crania are compared to modern sheep specimens to test GMMs' effectiveness at distinguishing between, as well as potentially allocating individuals to, specific breeds. We found certain morphological variations between the study assemblages, and so discuss our results in the context of a variety of explanatory frameworks such as differences in husbandry practices in colonial Sydney.

1. Introduction

From the founding flock onwards, sheep (*Ovis aries*) have played a key role in the development of colonial Australia, prompting the well-known notion that Australia was built 'on the sheep's back' (Garran and White, 1985). Sheep can be used for multiple purposes, including primary products such as meat, tallow, hide and bone, and for a range of secondary products such as milk and wool (Greenfield, 2002). Initially, livestock imported to Australia were viewed as a meat supply, and by the early 1800 s there were several different sheep breeds in Australia intended for the primary production of mutton (Walsh, 1969; Garran and White, 1985; Pearson and Lennon, 2010). These included the hairy Ronderib Afrikaner or fat-tailed Cape sheep (imported 1788 from Cape of Good Hope), the Bengal (1793 from Bangladesh), as well as British shortwool and longwool breeds; the Southdown and Teeswater (imported 1790 s), respectively (Cottle, 2010b).

Throughout the 1800–1840 s, more British sheep breeds were imported into the initial mutton flocks, however these were known more for their wool quality, including the English Leicester (imported 1838) and the Lincoln (imported to Tasmania 1830 s and mainland 1860 s) (Garran and White, 1985; Pearson and Lennon, 2010; Cottle, 2010b). The most well-known wool breed in Australia however is the Merino, being first imported to Australia in 1797 from South Africa (Garran and White, 1985; Cottle, 2010b). Being a fine woolly sheep that was better suited to the harsh Australian environment than other breeds, it proved most popular and was often cross-bred with British wool breeds as a result (i.e. Leicester and Lincoln) (Garran and White, 1985). From the 1820 s onwards, the increasing importation of Merino sheep to Australia meant the wool industry boomed and the colonial economy thrived (Garran and White, 1985).

Limited archaeological attention has been directed to sheep in colonial contexts, and while Merino sheep have been the wool standard for years in Australia, little is known of the specific early sheep breeds used for secondary products. A preliminary study of a colonial Sydney sheep assemblage (the Clarence Street site), used mandibular tooth eruption to establish age-at-death ranges that were consistent with what is expected for sheep used for secondary products – i.e. 4 to 7 years old (Nussbaumer, 2018). This suggests that the Clarence St. sheep were likely used primarily for wool, and the question then becomes – can we tell what *breed* these early wool sheep were?

We use Geometric morphometrics (GMMs) to test the results of these mandibular profiles (Nussbaumer, 2018) and if secondary function is

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reflected in bone morphology, by comparing the cranial shape of archaeological sheep with both a modern wool (Merino) and meat (Southdown) breed. GMMs has been proven to successfully separate domestic sheep breeds (see section 2.1.1) (Yalcin et al., 2010; Parés-Casanova, 2014; Demircioğlu et al., 2022; Bader et al., 2022; Boz et al., 2023; Demiraslan et al., 2023; Gaastra, 2023; Gündemir et al., 2023; Özkan et al., 2024; Baş-Ekici et al., 2024), therefore if GMMs suggest relative homogeneity of the colonial population, we can imply the individuals are likely of the same breed. Given the focus was on meat breeds during the early sheep economy in New South Wales, there is a more limited variety of potential wool breeds (such as the Merino and English Leicester) (Garran and White, 1985; Pearson and Lennon, 2010). On the other hand, if the results of the Procrustes ANOVAs on shape data are significant, this could suggest the possibility of different breeds within the assemblage, originating from various geographical locations – i.e. Britain, India or Bangladesh, and South Africa.

Similarly to Jeanjean et al. (2023) which compare modern molar samples against ancient specimens for species identification, here we use modern sheep crania (Southdown, Merino and unknown) to compare shape against an archaeological assemblage for possible breed identification. These modern samples provide a good comparison given that Southdown sheep were one of the earliest British sheep in Australia and notable for their high-quality meat but also fine wool, while the Merino was the preference for wool from the 1820 s onwards (Cottle, 2010b).

2. Background

2.1. Gmms and faunal remains

There are few applications of GMMs in Australian zooarchaeology, with the most recent focusing on comparisons of cranial morphology of the modern and ancient Dingo and its close relatives (Koungoulos, 2020; 2021), differentiation between species of marsupials (Mein and Manne, 2021; Mein et al., 2022) and identification of extinct megafauna in rock art (Cobden et al., 2017). To date, there has been no published research applying GMMs to introduced European domesticates in Australian colonial contexts despite their importance in the development of colonial Australia. Sheep are abundant in colonial assemblages and can provide insight into the early economy of Sydney, the beginnings of the wool industry and human responses to new environments. Importantly, analyses of skeletal variability through GMMs can highlight morphological changes resulting from environmental influences such as animal domestication processes and the agrobiodiversity signature (e.g. through processes of colonisation, dispersal, adaptation, diversification and changes in husbandry strategies and livestock economies) (Evin et al., 2022).

To date, published research using Geometric morphometrics on sheep has primarily focused on the differentiation from morphologically closely related taxa, such as goats, using postcranial bones (Haruda, 2017; Salvagno and Albarella, 2017; Lloveras et al., 2022; Gaastra, 2023), as well as cranial bones, mandibles and molars (Mallet et al., 2019; Parès-Casanova and Domènech- Domènech, 2021; Jeanjean et al., 2022; Demircioğlu et al., 2023; Karaavci et al., 2023). Similar methods have been used to differentiate between domesticated and wild sheep using the skull, mandible and petrous bone (Yalcin et al., 2010; Parés-Casanova and Sabaté, 2013; Bader et al., 2022), as well as the astragalus (Pölläth et al., 2019).

2.1.1. Intra and inter breed variability

Geometric morphometrics can provide significant insight into herd management practices, sheep mobility and animal exchange by examining morphological variation, using both cranial and post-cranial bones (Parés-Casanova, 2013; 2014; Parés-Casanova and Bravi, 2014; Vuillien et al., 2018; Colominas et al., 2019; Haruda et al., 2019; Parès-Casanova et al., 2019; Abbasabadi et al., 2020; Demircioğlu et al., 2021; 2022; Vila et al., 2021; ÖZGER, 2021; Bader et al., 2022; Lloveras et al., 2022; Boz et al., 2023; Demiraslan et al., 2023; Gaastra, 2023; Gündemir et al., 2023; Opale et al., 2023a; Özkan et al., 2024; Baş-Ekici et al., 2024). The skull is one of the skeletal regions most suitable for standardization, and often the most characteristic feature between different breeds, therefore cranial bones can be more informative than post-cranial in determining variation due to breed and sex (Abbasabadi et al., 2020; Demircioğlu et al., 2021; Güzel and Işbilir, 2024).

GMMs has been used to determine age at death through allometry in mandible centroid size (Parés-Casanova, 2013), as well as provide an in-depth look at skull asymmetry and its implications (Parés-Casanova and Bravi, 2014; Parés-Casanova, 2019; Parès-Casanova et al., 2019; Manuta et al., 2024). Geometric morphometrics has also been used to examine sexual dimorphism in skulls and mandibles (Parés-Casanova, 2014; Abbasabadi et al., 2020; Demircioğlu et al., 2021; Demiraslan et al., 2023). Most importantly however, recent studies demonstrate that GMMs is an effective tool for breed differentiation in ovines. This includes comparing skull shape (Parés-Casanova, 2014; Demircioğlu et al., 2022; Gündemir et al., 2023; Baş-Ekici et al., 2024), as well as mandible shape (Boz et al., 2023; Demiraslan et al., 2023; Özkan et al., 2024) to successfully differentiate between domestic sheep breeds from different geographical locations.

2.2. The Clarence Street site

This study builds on the life histories of colonial Sydney sheep by examining faunal remains from excavations at 161–165 Clarence Street and 304 Kent Street, Sydney, heretofore referred to as the Clarence St. site (Fig. 1). A large number of artefacts were found alongside the faunal remains dating from as early as the 1780 s through to the 1880 s (Harris, 2016).

This site covers an important early phase in Australian history, with the first major establishment in the area being the Wynyard Military Barracks, housing military troops from 1790 to about 1823 (Fig. 2) (Houison, 1903; Walker, 1911). The Barracks were well-provisioned and self-sufficient with their own yard for rearing stock. Once the regiment left in 1814 the barracks diminished in size and by 1823 most of the soldiers' lots had been sold to private owners (Houison, 1903; Walker, 1911; Higgnbotham, E, 2017a). The next phase of the Clarence St. site saw the construction of houses and shops, occupied by residential dwellings and small commercial enterprises (Fig. 2) such as carpenters, dressmakers and tailors, leatherworkers, shoemakers and a butcher (Walker, 1911; Thorp, 1996; Karskens, 1997; Higgnbotham, E, 2017a; Higgnbotham, E, 2017b). All of these were likely responsible for the majority of artefacts (such as shoe making/repair items, ceramics, glassware, tobacco pipes, buttons etc.) and faunal remains (primarily butchered sheep, cattle and pig) on site (see Fig. S1 for breakdown of artefact materials).

3. Material

3.1. The colonial sheep

The archaeological salvage excavations focused on two back-filled wells, the faunal assemblage for this study being recovered from well 2. The bone deposit has been interpreted as being part of rubbish disposal which occurred during the 1840 s to 1850 s from the establishments on and around Clarence and Kent Street. Sheep remains represented 33.4 % of the total mammal remains (Fig. S1), likely part of the commercial/industrial butchery business (Fillios, 2016; Harris, 2016). This study examined 27 domestic sheep (*Ovis aries*) crania (Table 1), stored in the archaeology lab at the University of New England (UNE), Australia.

The majority of the crania are unusually well preserved, making them ideal for analysis. This preservation is likely due to a stable environment with little to no post-depositional movement within the well (Fillios, 2016). The sex ratio of these sheep is unknown, however the

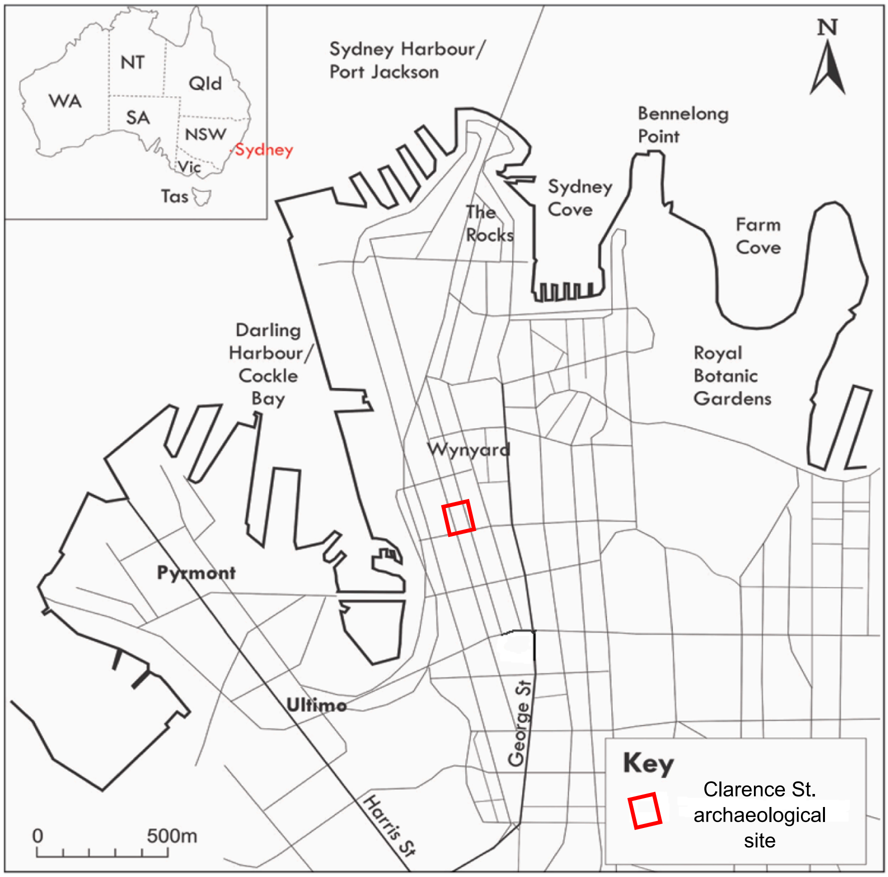

Fig. 1. Location of the Clarence St. site in Sydney, Australia (map adapted from Owen et al., 2017, p.35).

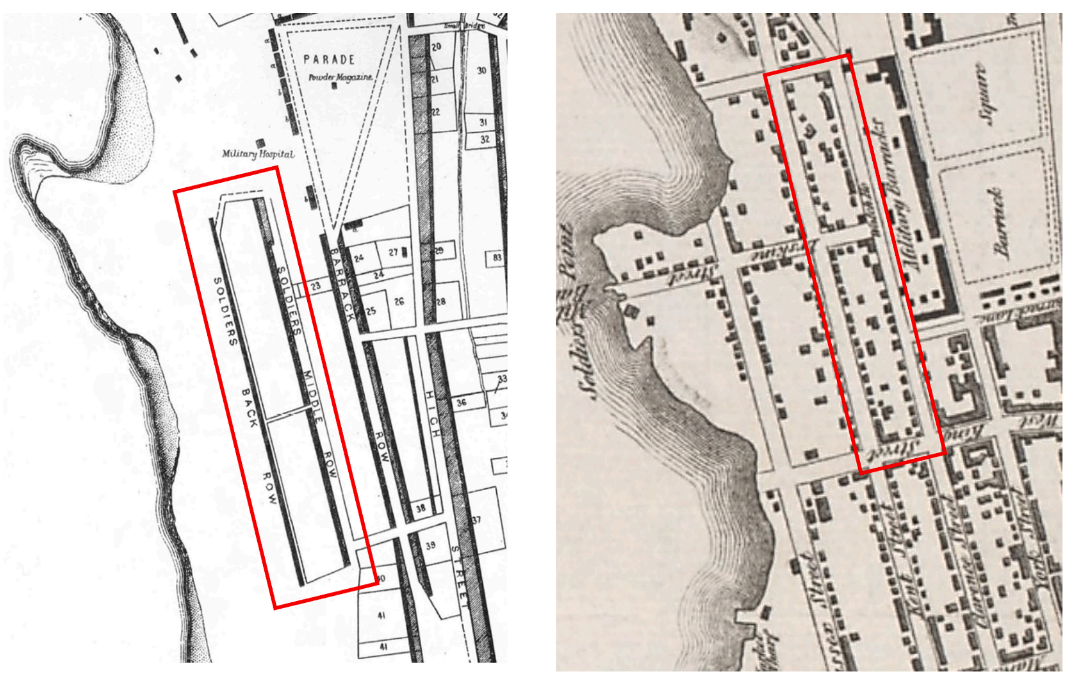

Fig. 2. Left) Location of the Clarence St. site in 1807 (Meehan and Bligh, 1850) and right) in the 1830 s (Carmichael and Tegg, 1837).

presence/absence of horns on the specimens could be an indicator of sex. In some breeds, both sexes are hornless/polled (a large proportion of colonial British breeds including the Southdown) (Cottle, 2010a), while for others such as the Merino, only the males have horns (Ibsen, 1944; Simon et al., 2022). In this study, 18 of the 27 craniums have horns of varying sizes (Fig. S2), which could suggest a mixed flock. All 27 sheep

Table 1
Summary of known information of analysed colonial Sydney crania.

Specimen no.	Specimen label [1]	Age (years) [2]	Date range [3]	Horns[4]	Length of horn core[5]
1	CSS15_B1_b12_TN1	4–7	1840–60	Y	Long
2	CSS15_B3_b1_TN1	4–7	1840–60	Y	Short stub
3	CSS15_B3_b9_TN1	3–4/ 4–7	1840–60	Y	Long
4	CSS15_B11_b16_TN1	3–4	1840–60	N	–
5	CSS15_B13A_b3_TN1	3–4/ 4–7	1840–60	Y	Long
6	CSS15_B13A_b4_TN1	4–7	1840–60	Y	Long
7	CSS15_B13A_b5_TN1	4–7	1840–60	Y	Long
8	CSS15_B13A_b5_TN2	4–7	1840–60	N	–
9	CSS15_B15_b13_TN1	4–7	1840–60	N	–
10	CSS15_B29_b1_TN1	3–4/ 4–7	**1800–30**	Y	Long
11	CSS15_B36_b13_TN1	4–7	1840–60	Y	Short stub
12	CSS15_B40_b10_TN1	3–4	Unknown	N	–
13	CSS15_B43_b4_TN1	4–7	1840–60	Y	Long
14	CSS15_B44_b1_TN1	4–7	1840–60	Y	Long
15	CSS15_B45_b11_TN1	3–4/ 4–7	1840–60	Y	Short stub
16	CSS15_B47_b3_TN1	3–4/ 4–7	1840–60	Y	Short stub
17	CSS15_B48_b4_TN1	3–4/ 4–7	1840–60	N	–
18	CSS15_B48_b4_TN2	3–4/ 4–7	1840–60	N	–
19	CSS15_B49_b3_TN1	4–7	1840–60	N	–
20	CSS15_B49_b4_TN1	3–4/ 4–7	1840–60	Y	Long
21	CSS15_B50_b6_TN1	3–4	1840–60	Y	Long-broken off
22	CSS15_B51_b3_TN1	4–7	1840–60	Y	Long
23	CSS15_B52_b3_TN1	4–7	1840–60	Y	Long
24	CSS15_B52_b3_TN2	4–7	1840–60	Y	Long
25	CSS15_B53_b1_TN1	4–7	1840–60	Y	Long
26	CSS15_B53_b1_TN2	4–7	1840–60	N	–
27	CSS15_B54_b5_TN1	3–4	**1800–30**	N	–

[1] CSS15 (archaeological site), B (box), b (bag number), TN1 or TN2 (according to quantity in bag – distinguished according to size or presence/lack of horns.
[2] ages determined from M_2 (molar 2) and M_3 (molar 3) via Grant's (1982:93) tooth wear stages.
[3] Estimated according to dateable artefacts found alongside in deposit levels (Table S1).
[4] Y = yes, N = no.
[5] For this study, 'Long' refers to the horn core being longer than just a 'stub', or over 2cms.

specimens used for this study are between 3 to 7 years old (Table 1). Twenty-five sheep are from a homogenous deposit with an estimated date range of 1840 to 1860 s, with two from an earlier 19th century occupation date range of 1800 to 1830 s (Table 1) (Harris, 2016).

3.2. Modern reference collection

Five modern domestic sheep crania from the UNE archaeology lab (Table 2) were examined to provide a shape comparison. Modern Sheep 1, 2 and 3 are of unknown breed/sex (no information was logged at the university), while modern Sheep 4 and 5 are both New England Merino, with 5 being a ram with large horns. Additionally, three modern domestic Southdown sheep crania were also used for comparison (from the Granite Belt region, Southeast Queensland). One modern domestic goat cranium (from Southeast Queensland- breed unknown) was also added to test species differentiation.

Table 2
Summary of Modern sheep and goat crania.

Specimen name	Context[1]	Breed	Age (years)[2]	Horns	Sex
Modern Sheep 1	UNE	Unknown	3–4	Y – sawn off	Unknown
Modern Sheep 2	UNE	Unknown	3–4/4–7	Y- long	Unknown
Modern Sheep 3	UNE	Unknown	3–4/4–7	N	Unknown
Modern Sheep 4	UNE	New England Merino	4–7	N	Female
Modern Sheep 5	UNE	New England Merino	4–7	Y	Male
Modern Sheep 6	SE QUEENSLAND	Southdown	10	N	Female
Modern Sheep 7	SE QUEENSLAND	Southdown	1.8	N	Male
Modern Sheep 8	SE QUEENSLAND	Southdown	1.8	N	Male
Modern Goat	SE QUEENSLAND	Unknown	2–3/3–4	Y	Unknown

[1] context here is refers to place cranium was stored/located.
[2] ages determined from M_2 (molar 2) and M_3 (molar 3) via (Grant, 1982) tooth wear stages.

4. Method

As an inexpensive and non-destructive analytical tool, GMMs was used to quantify and visualize shape variation at intraspecific and interspecific levels. Variability was interrogated through effective analysis of scale and shape relationships and differences, utilising specific landmark coordinates instead of traditional measurements (Webster and Sheets, 2010; Okumura and Araujo, 2019).

4.1. 3D scanner Imaging

All crania in this study were visualised through the production of 3D models using an Artec Space Spider 3D hand-held scanner from the Environmental Science Department at UNE (www.artec3D.com). The crania were mounted on a turn table with clear cast acrylic Perspex blocks placed underneath them. The data acquisition was performed using Artec Studio Professional v.13 and v.15. In this set-up, a complete specimen scan was obtained within 6–12 scans, and auto or manually aligned along the scanning process before being fused into a single mesh and exported as an OBJ file.

All 3D images were uploaded to the UNE Pedestal3D database (Pedestal3D - Home), measurements were automatically calibrated and crania were positioned with a scale. The 3D image database allows the reference material to be readily available if needed for future (especially if analyses are destructive to original crania), and as the start of a reference collection. Consistent alignment of the crania was performed using the automatic orthographic view options in Pedestal3D, allowing for uniform screenshots to be taken from the dorsal (top) and lateral (side on) orientation, and saved in.png format. Alignment error was assessed by realigning three crania to dorsal view over a number of days and placing landmarks on each image (Fig.S3).

Due to the potential asymmetry between the left and right sides of the sheep skull, only the left will be used in this study (Parés-Casanova, 2019; Parès-Casanova et al., 2019; Manuta et al., 2024). The right lateral side of sheep crania has been found to be larger and more asymmetric than the left, potentially due to greater use of one side than the other during rumination, similarly to primates who have a definite right-side chewing preference (Parés-Casanova, 2019; Parès-Casanova et al., 2019).

4.2. Digitizing and landmark selection

Images were converted to '.tps' format using the tpsUtil64 (version 1.82) program and the landmarks were then marked using tpsDig232 software. In total, we selected 17 landmarks (LMs) for the dorsal view (Fig. 3, Table 3) and 9 LMs for the lateral view (Fig. 4, Table 4) (Parés-Casanova and Bravi, 2014; Parés-Casanova, 2014; Parés-Casanova, 2019; Demircioğlu et al., 2022).

4.2.1. Repeatability tests

In order to test consistency and reduce LM placement error, crania from four sheep specimens (chosen randomly) were landmarked five times from the dorsal view, over five days (Fig. S4). Repeatability test results were satisfactory in showing consistency between LM placements.

4.3. Statistical analysis

The landmark coordinates were analysed using MorphoJ version 1.07a to conduct comparative analyses. First, all specimens were superimposed using Generalized Procrustes Analysis (GPA) (Rohlf and Slice, 1990; Bookstein, 1991) to remove the effects of position, orientation, and size. The GPA provides 1) a centroid size (i.e. "the square root of the sum of squared distances of all the landmarks of an object from their centroid" (Klingenberg, 2016), and 2) Procrustes coordinates (shape) of each specimen for subsequent analyses. Next, data outliers (average shape vs deviations) were examined, as well as a Covariance matrix and wireframe generated.

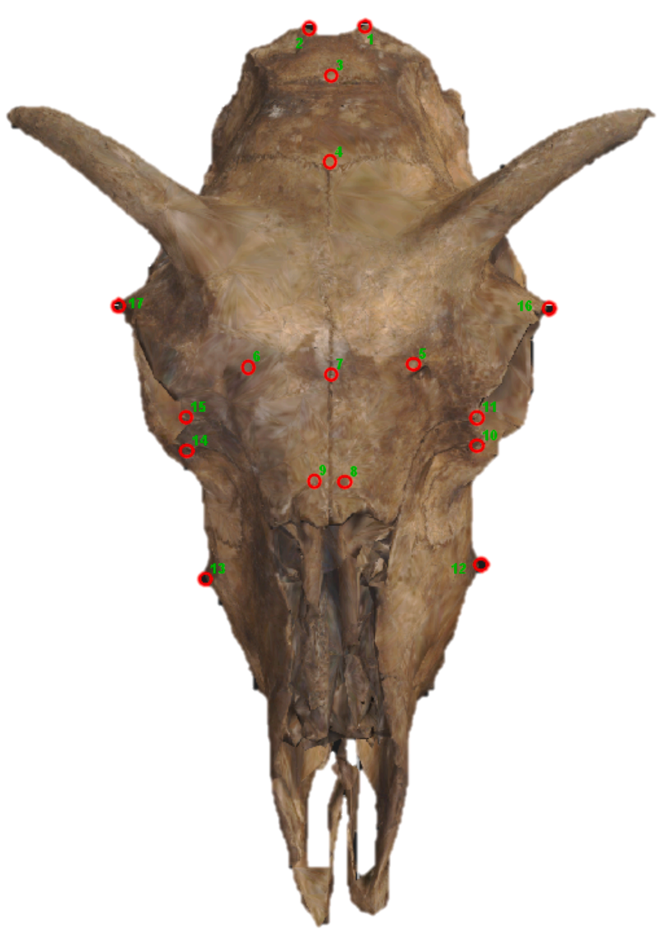

Fig. 3. View of dorsal landmarks (LMs) on Specimen 5 skull.

Table 3
Anatomical description of dorsal landmarks (LMs).

1. Left nuchal tubercle	**10.** Left temporo-zygomatic suture
2. Right nuchal tubercle	**11.** Left zygomatic-lacrimal suture
3. Occipito-temporal suture	**12.** Left facial tubercle
4. Fronto-parietal suture	**13.** Right facial tubercle
5. Left supraorbital foramen	**14.** Right zygomatic-lacrimal suture
6. Right supraorbital foramen	**15.** Right temporo-zygomatic suture
7. Medial point on the line between 5 & 6	**16.** Left ectorbitale
8. Left fronto-nasal suture	**17.** Right ectorbitale
9. Right fronto-nasal suture	

4.3.1. Principal Component analysis (PCA)

PCA was used to investigate the overall morphological variability of the archaeological and modern sheep skulls, to visualise potential patterns (such as clusters or major outliers) (O'Higgins and Jones, 2006; Klingenberg, 2011). Overall, it is expected that specimens will cluster together if they have similar morphological features and likewise present as outliers if they have larger variation in cranium shape. A variety of analyses were created to visualise morphological variation, both within the colonial sheep assemblage as well as between the colonial and modern sheep. Additionally, as the presence or absence of horns on the colonial crania is a visible morphological variation, this trait was also tested for possible morphological distinction. Wireframe diagrams were created to visualize shape differences between the crania for Principal Component 1 (PC1) and 2 (PC2); representing both the average shape as well as maximum variation (the most positive PC score axis).

4.3.2. Procrustes ANOVA

To test the skull shape and centroid size variation between sheep breeds, we performed six Procrustes ANOVAs using dorsal and lateral shape data (i.e. colonial/Merino, colonial/Southdown, colonial/unknown, Merino/Southdown, Merino/unknown, and Southdown/unknown). Additionally, we performed a Procrustes ANOVAs to test skull shape variation between horned and non-horned colonial sheep.

4.3.3. Canonical variate analysis (CVA)

A Canonical variate analysis was performed to determine the grouping characteristics of the data. A CVA finds shape features which maximise the morphological separation between groups, and considers individual specimens as members of groups rather than unrelated individuals as in a PCA (Zelditch et al., 2004; Webster and Sheets, 2010). Importantly, a CVA allows for the classification of unknown individuals (i.e. colonial specimens) into one of the known groups (Manthey and Ousley, 2020). Sample size may be an issue by not sufficiently allowing difference between certain groups to be detected. Here it is expected that groups can be reliably separated according to morphology, however if no groupings occur they are too morphologically similar to statistically differentiate (Cobden et al., 2017). Two CVA runs were made, the first considering the 4 main groups (Colonial, modern Merino, modern Southdown and modern unknown), and the second separating the specimens according to sex (i.e. modern male, modern female, colonial unknown sex). Wireframe diagrams were created for Canonical Variate 1 (CV1) and 2 (CV2) to illustrate shape changes. Similarly, pairwise wireframe comparisons between the colonial and modern sheep were also performed to visualize crania shape differences based on breed.

4.3.4. Goat comparative sample

GMMs has been an effective tool in discriminating between sheep and goats (Mallet et al., 2019; Parès-Casanova and Domènech-Domènech, 2021; Jeanjean et al., 2022; Demircioğlu et al., 2023; Karaavci et al., 2023). Here we include a goat for comparison within the dorsal and lateral view PCAs to ensure there are no goats within the colonial assemblage.

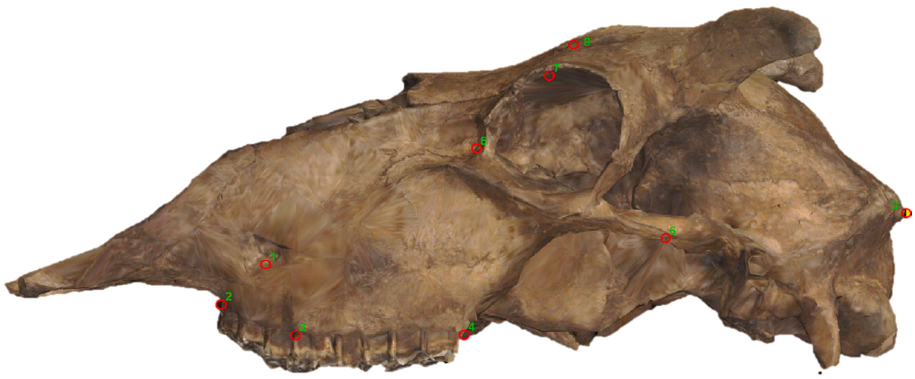

Fig. 4. View of lateral landmarks (LMs) on Specimen 5 skull.

Table 4
Anatomical description of lateral landmarks (LMs).

1. Infraorbital foramen	**6.** Zygomatic arch
2. Anterio-dorsal edge of PM1	**7.** Supraorbital process
3. Caudal edge of PM3	**8.** Supraorbital foramen
4. Caudal edge of M3	**9.** External occipital protuberance
5. External lacrimal fossa	

5. Results

5.1. Colonial sheep variation

Morphological variation between the colonial sheep is shown through dorsal and lateral PCA plots and corresponding wireframes (Fig. 5). There is a relative dispersion of specimens but no clear groupings are visible. Additionally, the specimens remain greatly intermingled with no distinction between the horned vs non-horned sheep. The results of the ANOVA was non-significant for both dorsal ($p = 0.22$) and for lateral ($p = 0.08$).

For the dorsal view, the first axis (PC1) of the PCA shows that the largest shape changes are associated with length, i.e. areas of LMs 1, 2 and 3 (left and right nuchal tubercle and occipito-temporal suture) and 5, 6, 7 (left and right supraorbital foramen) are shorter than the mean shape. While LMs 12 and 13 (left and right facial tubercle) is longer than the mean shape. For the second axis (PC2), the majority of changes are associated with width, i.e. LMs 5 and 6, as well as 10, 11, 14, 15, 16, 17 (left and right temporo-zygomatic suture, zygomatic-lacrimal suture, ectorbitale) are much narrower, while LMs 1, 2, 3 and 8, 9 are longer than the mean shape.

In lateral view, the shape changes are more subtle. For the first axis (PC1), affected LMs are 1 (the infraorbital foramen) and 2, 3 and 4 (the dental region: anterio-dorsal edge of PM1, caudal edge of PM3 and M3) which is slightly shorter and wider than the mean shape. Likewise LM 8 (left fronto-nasal suture) is more slanted. On the second axis (PC2), the shape changes are also associated with width, i.e. LM 4 is wider and LMs 7 and 8 (supraorbital process and foramen) is higher and wider.

5.1.1. Are there Goats?

The goat specimen appears relatively isolated in dorsal and a clear outlier in lateral view, while the pairwise comparison wireframes likewise show shape variations (Fig. S5). This suggests there are no other similar goats in the sample.

5.2. Interbreed variation

5.2.1. Principal components analysis

The PCA on dorsal view shape data resulted in 30 components to explain the overall variation. Principal Component 1 (PC1) and Principal Component 2 (PC2) explained 54.97 % of the total variation (Fig. 6). There is no definite colonial sheep cluster, however the modern unknown intermingle with the colonial specimens. The rest of the modern breeds (Merino and Southdown) scatter around them. The first axis (38.57 % of the total variance) is characterized by the strong divergence of the Merino ram, and one of the colonial sheep (Specimen 8). The second axis (16.40 % of variance) mostly isolates the Southdown specimens. The shape changes involved on the first axis (PC1) include a reduced distance between LMs 1, 2, 3 (the left and right nuchal tubercle and occipito-temporal suture) and 5, 6, 7 (left and right supraorbital foramen), as well as a lengthening and narrowing to LMs 12 and 13 (the left and right facial tubercles). For the second axis (PC2), the crania appears more slender on both the lateral sides from the ectorbitale to the facial tubercle (LMs 10, 11, 12, 13, 14, 15, 16 and 17). This suggests the Southdown sheep have the widest crania. There is no evident pattern for the known male (squares) or female (triangle) specimens, however the ANOVA test conducted between the modern males, modern females and colonial unknown sex showed a significant difference (**$p = 0 < .0001$**) for both dorsal and lateral.

The lateral view shape data analysis resulted in 14 components to explain overall variation. Principal Component 1 (PC1) and Principal Component 2 (PC2) explaining 46.76 % of the total variation (Fig. 6). The colonial specimens appear more scattered, with the modern breeds (Merino, Southdown, unknown) all to one side. The first axis (29.24 % of the total variance) is characterized by the divergence of the Southdown sheep and one modern unknown (Specimen MS1). The second axis (17.52 %) again isolates the modern unknown (Specimen MS1) and two colonial sheep on the other side (Specimens 8 & 14). The shape changes for the first axis (PC1) include a narrower and longer dental region (LMs 2, 3, 4) and a less pointed supraorbital foramen (LM 8). While for the second axis (PC2), the supraorbital foramen is more prominent, and the external occipital protuberance (LM 9) is lower. Again there is no evident pattern for the male or female specimens.

5.2.2. Canonical variate analysis

The CVA plots displayed the main patterns of morphological separation among all groups of sheep. For the dorsal view, CV1 and CV2 represented 75.55 % and 18.89 % respectively, together accounting for 94.44 % of the relative between-group variation (Fig. 7). CV1 clearly discriminated the Merino from the others (colonial, Southdown, unknown) (potentially partly due to the CVA isolating small groups). The unknown sheep are also quite distinct from the colonial and Southdown. CV2 mostly distinguished the Southdown and unknown sheep from the others (colonial and Merino). The main aspects of variation are visualized via the wireframes, with only subtle changes around the left and right fronto-nasal suture and facial tubercles (CV1) and widening of the left and right temporo-zygomatic suture and zygomatic-lacrical suture (CV2).

For the lateral view, CV1 and CV2 represented 63.98 % and 20.39 % respectively, together accounting for 84.37 % of the total between-group

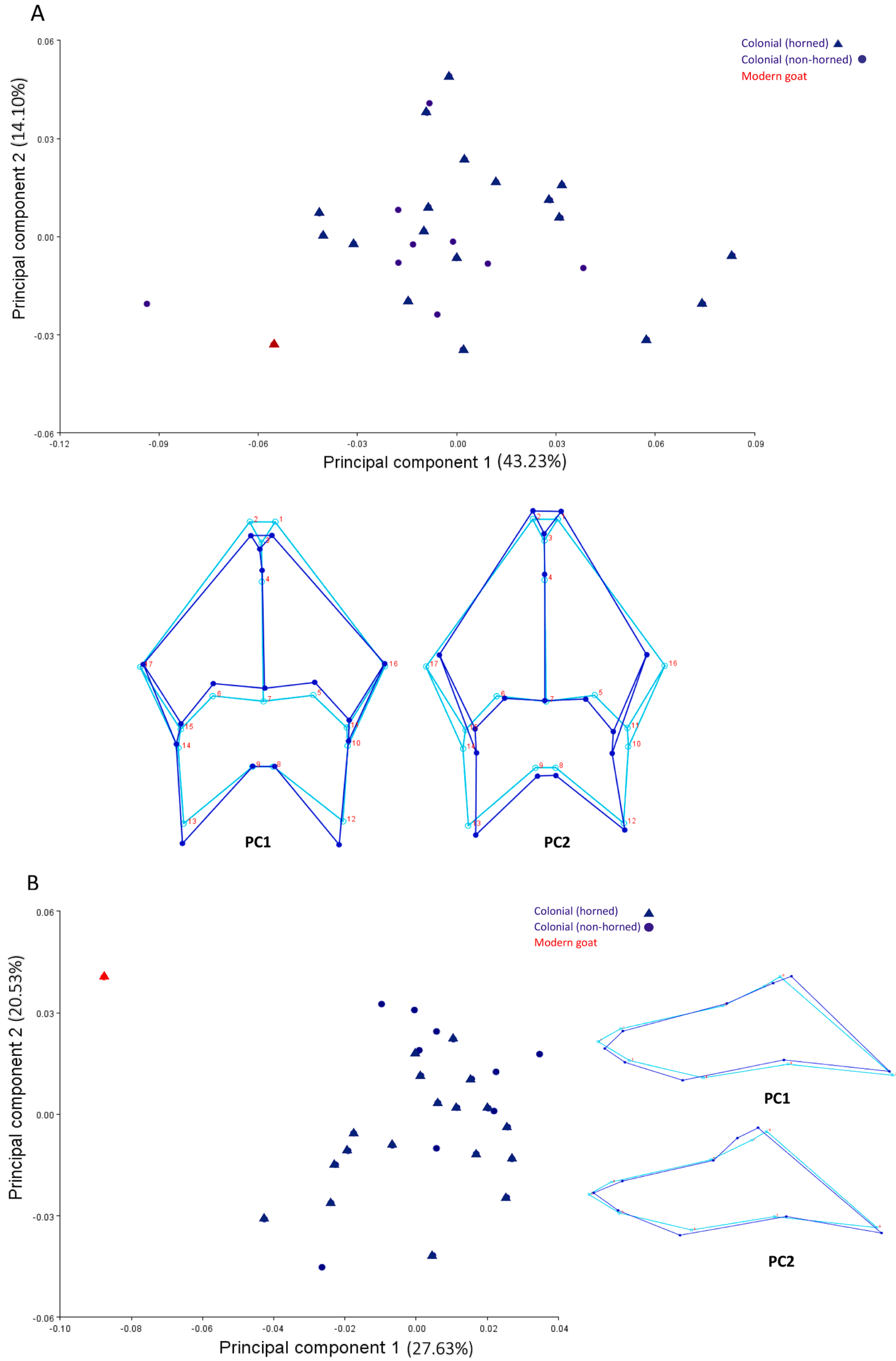

Fig. 5. PCA of all colonial sheep specimens with modern goat for comparison A) Dorsal view B) Lateral view; Wireframes show average crania shape (light blue) with maximum shape variations (blue), Note: wireframe comparisons are only of the colonial sheep and do not include the goat.

variation (Fig. 7). CV1 clearly discriminated the Southdown sheep from the others (colonial, unknown and Merino), while showing the similarity of the colonial and modern unknown sheep due to their close proximity. The main aspects of variation include a slanted anterio-dorsal edge of PM1 and a lower occipital protuberance. CV2 discriminated the Merino sheep from the others (colonial, unknown and Southdown), again showing the proximity of the colonial and modern unknown sheep. Main aspects of variation include a widening of the whole nasal and dental

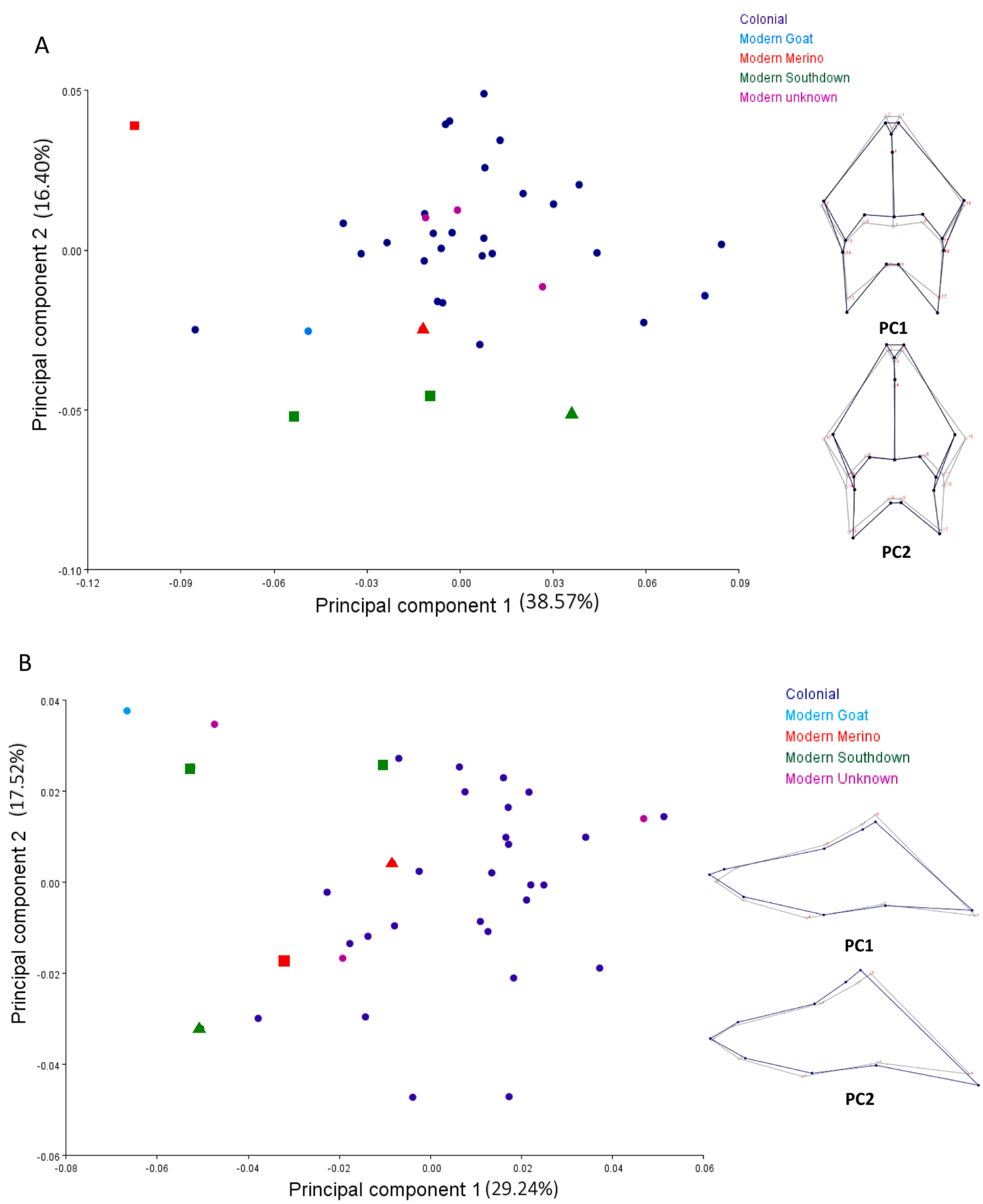

Fig. 6. PCA comparing morphology of all the colonial and modern sheep crania (with goat as comparison), A) Dorsal view B) Lateral view; sex distribution illustrated by triangles (female) and squares (males); wireframes show average crania shape (grey) with maximum shape variations (dark blue). Wireframes do not include the goat specimen.

region of the skull, as well as a lower occipital protuberance.

In addition, a CVA was conducted to examine potential degree of separation associated with sex (modern female, modern male, colonial unknown) (Fig. S6). Groups were largely separate, although due to the small sample size of known sex, as well as the influence of breed, results are inconclusive.

P-values of the Mahalanobis distances (MD) (Table 5, 6) suggest Southdown sheep skulls show significant difference from all others in the dorsal view. For the lateral view, Merino showed a significant difference from the unknown sheep.

5.2.3. *Pairwise comparisons*

Differences among the overall average of each group are shown in Fig. 8. as pairwise comparisons. For the dorsal view, Merino sheep have lower supraorbital foramen and ectorbitale, while the distance to the facial tubercles is also reduced. The Southdown sheep appear much wider than colonial sheep in the orbital region as well as a shorter distance to the facial tubercles. The unknown sheep show the most subtle differences to the colonial sheep, with a higher fronto-nasal suture, but otherwise appears more similar than the others.

5.2.4. *Procrustes ANOVA*

The Procrustes ANOVA results of comparisons between all sheep groups (colonial, modern Merino, modern Southdown and modern unknown) is shown in Tables 7 & 8. The results suggest that Southdown sheep have a significantly different dorsal and lateral crania shape from the colonial specimens. They are also significantly different dorsally from the modern unknown. The pairwise comparisons suggest the

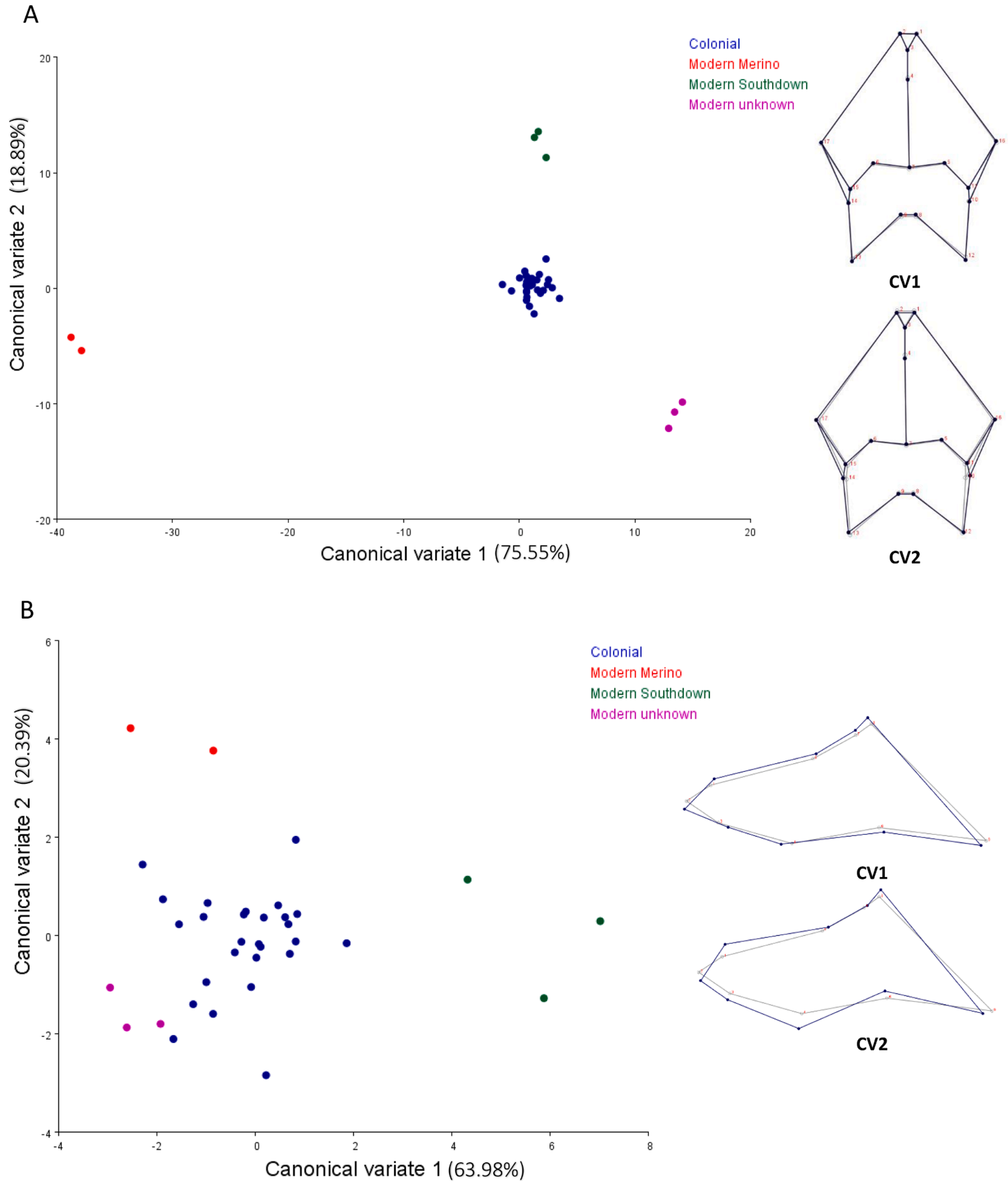

Fig. 7. CVA showing maximum morphological separation between sheep groups A) Dorsal view B) Lateral view; wireframes show average crania shape (grey) with maximum shape variations (dark blue).

Table 5
P-values from permutation tests (10000 permutation rounds) for Mahalanobis distances (MD) and Procrustes distances (PD) among sheep groups (dorsal view).

	Colonial		Merino		Southdown	
	MD	PD	MD	PD	MD	PD
Merino	0.0007	0.0237				
Southdown	**0<.0001**	0.0136	**0<.0001**	0.2013		
Unknown	0.0003	0.1840	0.0677	0.1678	**0<.0001**	0.0815

Southdown sheep have a much wider crania shape on average. The Merino sheep show a significant difference from the colonial sheep for dorsal view (being slightly wider and shorter on average). The difference in centroid size was only significant between the Merino and colonial sheep skulls in dorsal view (the Merino ram having a slightly larger crania than the majority of colonial sheep).

6. Discussion

6.1. *Colonial sheep herd management*

During the early years of colonial New South Wales, there were a variety of sheep breeds present, including the hairy breeds primarily intended for meat such as the Cape and Bengal (imported through trade

Table 6
P-values from permutation tests (10000 permutation rounds) for Mahalanobis distances (MD) and Procrustes distances (PD) among sheep groups (lateral view).

	Colonial		Merino		Southdown	
	MD	PD	MD	PD	MD	PD
Merino	0.0001	0.1554				
Southdown	0.0003	0.0006	0.0676	0.2738		
Unknown	0.0007	0.0846	**0<.0001**	0.3364	0.0905	0.1022

with the East India Company from South Africa and Bangladesh respectively) (Garran and White, 1985; Pearson and Lennon, 2010). However, a previous study examining the Clarence Street sheep mandibles found an age profile of 3 to 9 years old, suggesting they were instead used for wool production first (Nussbaumer, 2018). This follows the British cultural preference at the time for mutton (rather than lamb), as well as a necessity for wool due to clothing shortages, and thus it seems likely that the colonial Clarence St. sheep are a breed that could be used for both meat and wool. Given their likely dual purpose, here we focused analysis on specific early sheep breeds used for secondary production in colonial Sydney.

From the early 1800 s to 1830 s, British wool-producing sheep (Southdown, Teeswater, Leicester and Lincoln) as well as increasing numbers of Merino sheep, were being imported into the colony (Pearson and Lennon, 2010; Cottle, 2010a). A clothing shortage in the colonies and the woolly Merinos' ability to thrive in Australian conditions, slowly shifted focus toward producing larger quantities of wool (Crowley, 1980). The Merino became the most prolific wool breed in Australia from the 1820 s onwards. Although the British Leicester and the Southdown were both wool-producing breeds, they were noted as less common, despite the Southdown's wool being almost as fine as that of the Merinos and it producing quality mutton (Garran and White, 1985).

While this study cannot definitively assign the Clarence St. sheep to a particular breed, we can perhaps use the archaeological record to augment the morphological data. According to the excavation report, there are two possible periods to which the faunal assemblage may have belonged. The first phase during the 1790–1820 s when Clarence Street housed the Military Barracks is more likely to have had flocks of the early meat sheep breeds other than Merino (Houison, 1903; Walker, 1911). This is supported by historical sources that record that during the first 30 years of settlement, there were only about 30 Merinos imported (Garran and White, 1985). The second phase is from the 1820–1880 s when Clarence Street housed a number of commercial businesses (Walker, 1911; Thorp, 1996; Karskens, 1997; Higgnbotham, E, 2017a; Higgnbotham, E, 2017b). Previous research suggests that the skeletal element frequencies and quality of these body parts likely points towards consumers being of low-medium socio-economic status (Nussbaumer, 2018). It was from the 1820 s onwards that the Merino populations soared and the wool economy took off, which also occurred in other British colonies, such as New Zealand, South Africa and North America (Connor, 1921; Bell, 1970; Mcdowell, 2000; Beinart, 2003; Woods, 2017b). Given that all but two crania for this study were found in contexts alongside artefacts dated from the 1840 s onwards (Harris, 2016), it seems very likely that these skulls are from the second phase,

Table 7
Procrustes ANOVA Shape (S) and Centroid size (CS) p-values for dorsal view.

	Colonial		Merino		Southdown	
	S	CS	S	CS	S	CS
Merino	**0<.0001**	**0<.0001**				
Southdown	**0<.0001**	0.060	0.035	0.080		
Unknown	0.062	0.076	0.008	0.100	**0<.0001**	0.968

Table 8
Procrustes ANOVA Shape (S) and Centroid size (CS) p-values for lateral view.

	Colonial		Merino		Southdown	
	S	CS	S	CS	S	CS
Merino	0.084	0.258				
Southdown	**0<.0001**	0.480	0.292	0.115		
Unknown	0.038	0.424	0.479	0.107	0.043	0.676

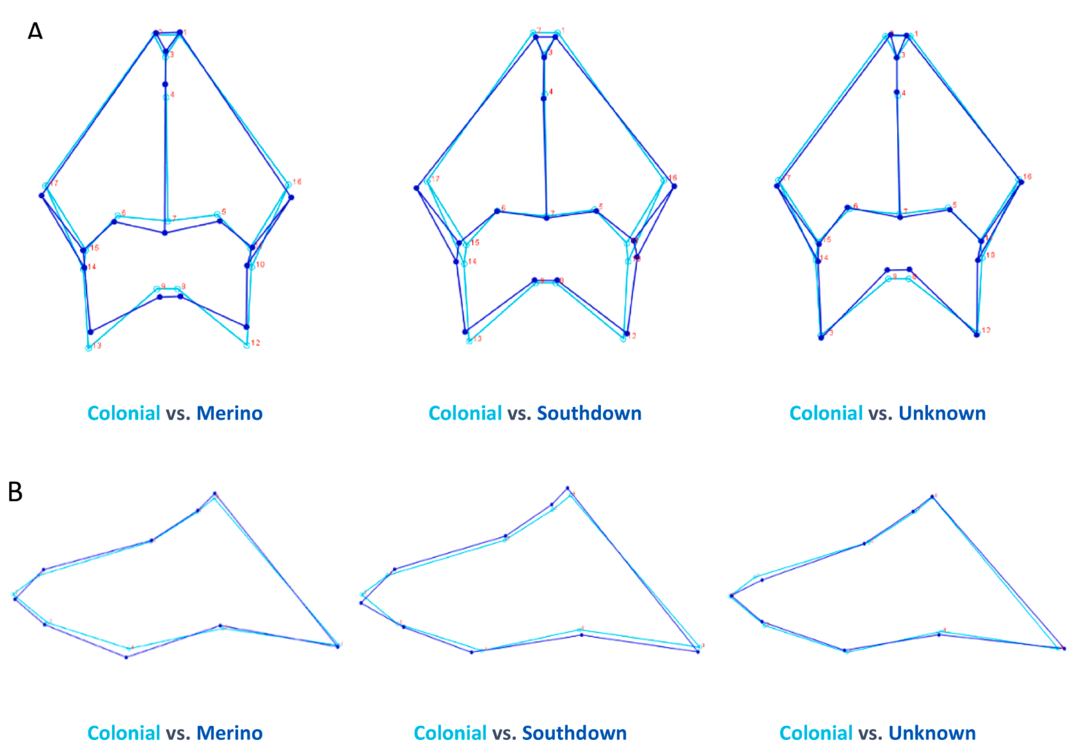

Fig. 8. Wireframe comparisons of differences between the average cranial shape of the colonial and modern sheep, A) Dorsal view B) Lateral view.

increasing the likelihood of them being Merinos.

6.2. Intra breed variability

Before discussing potential crania variation within the Clarence Street sheep, we must consider whether they are the same breed. Overall, there were no obvious crania shape distinctions on the PCAs between the colonial specimens. However, the presence or absence of horns is a clear visible trait that differs between the colonial specimens, and as both horned and polled sheep breeds were present in Australia during 1790 to the 1850 s, this feature was tested to potentially discriminate between different breeds or sex.

6.2.1. Horns: Different breed or sex?

A preliminary study on the Clarence Street sheep skulls (Fillios, 2016) did not undertake sex assignation based on horn cores as the males from several early sheep breeds are polled. However, while horn growth varies depending on the sheep breed and peak horn length, the most rapid horn growth generally occurs within the first few years of life– for example, the wild bighorn sheep will have reached 75 % of their horn length by age four (Festa-Bianchet et al., 2004; Pigeon et al., 2016). In the case of the Merino, the “outgrowth of bone from the frontal region of the skull, which later becomes the bony core of the horn”, can be seen as early as 118 days (or almost 4 months) in fetus rams (Lyne and Hollis, 1973). As the colonial sheep are all between 3 to 7 years old, a lack of horns at this stage suggests the sheep is either polled, or female.

The results of this study suggest the presence of horns on some specimens played no role in variation – and so likely does not indicate different breeds but potentially sex (unfortunately due to small sample numbers, tests on sex in this study were inconclusive). In other words, out of the 27 colonial sheep, 9 could be female and 18 male, which would further support a wool-producing economy (i.e. a mixed sex flock) (Wapnish and Hesse, 1988; Dai et al., 2015). Likewise, sheep flock sex ratios which include high proportions of males, specifically wethers, suggest a wool economy as they are better suited to wool production than females due to their size and fleece quality (Holmes, 2018). Both sexes of the British sheep breeds brought to colonial Australia between 1790 to the 1840 s (the Southdown, Teeswater, Leicester and Lincoln), are polled or hornless (Ibsen, 1944; Cottle, 2010a). The Merino is a breed whereby the males have large curved horns, while the females can sometimes have scurs, but are usually polled (Nordby, 1928; Ibsen, 1944; Simon et al., 2022).

6.2.2. Sexual dimorphism

Sexual dimorphism is another aspect that could lead to variation within the colonial group (if all specimens are the same breed). Generally, post-cranial bones yield better results for distinguishing between males, females and castrates within assemblages (Opale et al., 2023a; Opale et al., 2023b), nonetheless, the sex of sheep can also impact the shape and size of the skull (Gündemir et al., 2023). Sexual dimorphism has been associated with function, for example meat sheep skulls being larger than those of dairy sheep (Gündemir et al., 2023) and can be significant in certain breeds (e.g. Awassi and Romanov sheep) (Demircioğlu et al., 2021; Güzel and Işbilir, 2024), Likewise, there is evident sexual dimorphism in the length and width of Merino skulls, which on average measured longer and wider in males than females (de la Barra et al., 2014; Hernández et al., 2017). This was also the case in this study with the modern Merino ram being larger in size than the ewe.

However, other breeds such as the Zell and Fardasca sheep (Parés-Casanova, 2014; Abbasabadi et al., 2020) were not found to be cranially dimorphic, concluding that determining sex through skull shape and size was likely to be ineffective, depending largely on the sheep breed. The CVA results in this study were inconclusive due to the small sample size. Certainly establishing the sex distribution within this assemblage would further understanding of colonial Australian flock management and husbandry. In the case of the Clarence St. assemblage, there does not appear to be significant variation *within* the colonial group, and so they appear to be of a very similar, or the same, wool-producing breed.

6.3. Inter breed variability

Similar studies that examine sheep inter breed variation suggest that different breeds are generally statistically significant in shape variation (Parés-Casanova, 2014; Demircioğlu et al., 2022; Boz et al., 2023; Demiraslan et al., 2023; Gündemir et al., 2023). Statistical evidence suggests considerable variation between some of the breeds/specimen groups.

6.3.1. The British Southdown breed

We found that the Southdown cranial shape was significantly different from that of the colonial sheep specimens in all results. The Southdown sheep are known for both quality meat and fine but short wool, however it is a hornless breed, which would not explain the horned sheep in the archaeological assemblage. Overall therefore it seems unlikely that the Clarence Street sheep were Southdowns. Another British breed possibility is the Leicester, which inter-bred incredibly well with Merinos to produce fine long wool from the 1830 s onwards (Cottle, 2010b). However, both male and female Leicesters are also polled, making it unlikely (Garran and White, 1985).

6.3.2. The Merino breed

It is interesting to note the difference between the Merino ewe and ram, with the former presenting with a more similar cranial shape to the colonial specimens than the latter (PCA results). It is difficult to draw conclusions with such a small sample size, however modern Australian Merino rams have been selectively bred to be hardier and broader with longer wool since the early sheep in the colonial period (largely helped by the infusion of the Leicester blood) (Garran and White, 1985; Cottle, 2010b). In one newspaper article from 1878, a Merino ram was even referred to as inferior and unequal to the ewe in both frame and wool covering (Woods, 2017a). Overall, during colonial Australia there were a number of Merino varieties, such as the Spanish, Saxon and later Vermont, while several early sheep breeds were also interbred with Merinos (including the Cape, Bengal and Leicester sheep) (Garran and White, 1985; Woods, 2017a). There is the potential that the colonial sheep are some early variety, or cross-breed of Merino.

6.3.3. Modern unknown

Given the results, the modern unknown were highly likely also not of the Southdown breed. Surprisingly, the modern unknown sheep were the most similar in cranial shape to the archaeological specimens (PCA, wireframes, ANOVA). Furthermore, there was no statistically significant difference between them and the modern Merino, therefore they may also be a Merino breed. This is highly likely given they are local to the New England region which is known for Merino sheep grazing. Having a number of specimens of unknown breed further prompts the need for large reference collections to compare against using GMMs to determine breed.

6.4. Modern reference collection and future research

This study highlights the promise of GMMs to address early herd management and breed selection, however its small sample size and incomplete reference collections highlight the need to create a detailed Australian modern reference collection to which to compare colonial sheep. The UK sheep project or ‘Medieval wool project’ (Popkin et al., 2012; Worley et al., 2016) has led the way in this area, focusing on osteological evidence for wool production. As castrated sheep enhance wool quality, identification of wethers in archaeological assemblages can reveal much about past sheep management. The UK sheep project created a research collection by studying modern Shetland sheep skeletons with known life histories (i.e. their age, sex, castration and nutrition status) and collected data on the relationship with skeletal growth, epiphyseal fusion timing, morphometric variation and dental eruption and wear (Popkin et al., 2012; Worley et al., 2016). The Shetland sheep was chosen as it is the smallest British breed and likely to most resemble prehistoric and early historic sheep (Baker, 2024).

Likewise, the EVOSHEEP project (Vila et al., 2021) aims to create a modern reference collection of sheep breeds from the Middle East (Iran, Lebanon) and Africa (Ethiopia), combining GMMs and genetics to address changes in physical appearance and phenotypic characteristics of sheep in the ancient Near East. Similar research with a large quantity of modern Australian sheep all of known breed, age and sex would be invaluable for future studies of colonial sheep.

The ability to analyse morphometric shape variation between known and unknown breeds would provide further insight into colonial Australian flock management, such as breeds exploited and potential morphometric changes over time arising from changes in flock management. Future research could be strengthened by using additional analytical methods. For example, recently Jeanjean et al. (2023) combined the use of GMMs with ZooMS (Zooarchaeology by Mass Spectrometry), to reliably distinguish between, and identify, sheep and goat. Furthermore, combining GMMs with aDNA, as has been done with pigs and dogs (Ottoni et al., 2012; Rowley-Conwy and Zeder, 2014; Evin et al., 2015; Ameen et al., 2019) or with isotopes (Cucchi et al., 2016; Frémondeau et al., 2012; Fisher, 2019) or even all three approaches (Balasse et al., 2016; Pilaar Birch et al., 2019), could provide unparalleled understanding of historical sheep management, which can benefit modern herd management.

7. Conclusions

The application of geometric morphometrics to European domesticated animal species in Australia has been overlooked despite the importance of sheep to the colonial economy. This study is a first step in redressing this gap. While a larger reference collection is needed, this study has also created a 3D image database of readily accessible reference material beneficial for the future. Our results demonstrate the potential of geometric morphometrics as a tool to distinguish between fine morphological differences within sheep crania to address larger questions around early breed. These results contribute significantly to our understanding of sheep management practices and early breeds exploited for wool, highlighting the further potential of GMMs in colonial Australian domestic assemblages to address wider questions of herd management in the early historical economy.

CRediT authorship contribution statement

Tanja Nussbaumer: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Melanie Fillios:** Writing – review & editing, Supervision.

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Declaration of competing interest

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104876.

Data availability

Data will be made available on request.

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