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Laser ablation strontium isotope analysis of human remains from Harlaa and Sofi, eastern Ethiopia, and the implications for Islamisation and mobility

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ABSTRACT
The ancient city of Harlaa in eastern Ethiopia was occupied between the mid-6th and early 15th centuries AD and played a significant role as a trading centre with links internationally. Besides goods, these trade links also served in spreading cultural and religious ideas between continents, including Islamic traditions which became prevalent in Ethiopia during this time. Here, we present the first strontium isotope analysis of human remains from an Islamic site in Ethiopia. Results show that individuals buried following Islamic traditions include people born and raised both in Harlaa itself and also in rural communities from the surrounding hinterland, revealing a resident local Muslim community and potential co-existence of Muslim and non-Muslim individuals across economic sectors. The repeatability of results produced by laser ablation in human teeth sampled multiple times around the tooth cusp is also confirmed, although small differences between simultaneously-forming molar elements from a single individual were observed.

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Introduction

The aim of the *Becoming Muslim* project (694254 ERC-2015-Adg) is to investigate how and when conversion to Islam in eastern Ethiopia occurred. In Ethiopia, Islamic archaeology has been under-explored in comparison to, for example, the archaeology of the late Classical Kingdom of Aksum (e.g. Munro-Hay 1989; Phillipson 2000, 2004; Finneran 2007), or the architecture and archaeology of Ethiopian Orthodox Christianity (e.g. Finneran 2009, 2012; Phillipson 2009; Bosc-Tiessé et al. 2014). This is a significant omission, for historical records indicate that contacts by Muslims with Ethiopia were maintained from the very beginning of Islam. This is indicated, for example, by a group of the Prophet Muhammad's followers who, in fleeing persecution in Mecca in AD 615, found asylum in the kingdom of Aksum (Lapidus 1988, 25; Kapteijns 2000, 228), providing, perhaps, the most famous example of these early Islamic contacts. Subsequently, parts of the Horn of Africa, including areas of Ethiopia, were incorporated in the Islamicate world through trade and other contacts. These were maintained via Red Sea ports such as Zeila and Berbera, with trade routes stretching into the African interior. Slaves, ivory, timber, and other commodities were exchanged for textiles, glass vessels and beads, glazed ceramics, marine shell, and silver coinage. Entangled commercial networks extended beyond the ports to the Arabian Peninsula, Egypt, the Arabian/Persian Gulf, and South Asia (Insoll et al. in press). Various Islamic states and sultanates also developed in Ethiopia, commencing with Shawā or Shoa in the late 9th century AD (all dates are AD unless otherwise specified), which was absorbed by Ifat in the late 13th century (Hiskett 1994, 139). Ifat, in turn, weakened by internal political rivalries and conflict with the Ethiopian Christian state, declined in the early 15th century, and was succeeded by the sultanate of Adal. This was centred in eastern Ethiopia and was the powerbase of Imam Ahmad Gragn in his *jihads* against Christian Ethiopia, until his death in 1543 (Kapteijns 2000, 229).

The limited historical sources only sketch out a basic framework. Archaeological research offers the means for exploring the chronology of contacts with the Islamicate world, conversion to Islam, and Islamisation in Ethiopia. *Becoming Muslim* has focused on eastern Ethiopia, as the most Islamised area, and has examined a wide range of material and archaeological indicators of Islamisation including, for example, changes in diet (Gaastra and Insoll 2020), the construction of mosques (Insoll and Zekaria 2019), the appearance of Qur'anic and related Arabic epigraphy (Insoll in preparation; Insoll et al. in press), and the adoption of Muslim burial traditions which, as further discussed below, include orientation, absence of grave

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goods, type of grave, and position of the body (Insoll 1999, 170–173).

A central research question is the composition of the first Muslim communities in Ethiopia, whether local, foreign, or more mixed. This is difficult to ascertain in the absence of detailed historical and epigraphic records, as is the case in eastern Ethiopia, but is potentially accessible through the study of human remains using bioarchaeological techniques, such as strontium isotope analysis.

Excavations completed in eastern Ethiopia, as part of the *Becoming Muslim* project, recorded small quantities of human remains in a burial mound at Sofi, and in the abandoned town of Harlaa. Limited previous research on human skeletal remains dating to the last 2000 years in Ethiopia has focused on Aksumite, 1st to 7th century material (e.g. Leclant 1959, 6–10; Munro-Hay 1989, 324–328; Cook 2000), and more chronologically relevant post-Aksumite medieval Christian contexts (e.g. Gleize et al. 2015; Seifu 2016), or on burial monuments linked with indigenous religions, post-dating the 7th century (e.g. Bouville 1995; Bouville and Cros 2007; Boisserie 2012; Farago-Szekeres 2012; Cros 2014). None of the published studies from the Aksumite or post-Aksumite periods have included strontium isotope analysis. The only reference found to its use, on hair and teeth samples from Christian mummified remains, is in an unpublished PhD thesis (Seifu 2016, 186–189).

Here, we report the results of strontium isotope analyses carried out on human and faunal teeth from Harlaa – the first such application of this technique to human remains from an Islamic site in Ethiopia – and also a human tooth from a non-Muslim burial at Sofi. The aims were to:

- Characterise the strontium isotope context for the Harlaa site, in a part of the world where very little isotopic research has so far been conducted;
- Test for different mobility patterns in Muslim and non-Muslim human individuals
- Explore the possibility that some of the individuals buried at Harlaa were first generation immigrants to the area

This investigation measured strontium isotope ratios in teeth using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS). Laser ablation analyses generate data at very high spatial resolutions yet questions remain about how best to target the analyses when sampling tooth enamel (Müller et al. 2019). An additional aim was therefore to test how the choice of sampling location affects results obtained using laser ablation sampling techniques in human teeth, achieved by measuring five human teeth twice in different locations. Multiple teeth from the same individual were also analysed to assess intra-individual variability in enamel that mineralises simultaneously in different dental elements.

The sites and the burials

Harlaa (9°29’10.22"N, 41°54’36.96"E). Harlaa is located approximately 40 km north-west of Harar and 15 km southeast of Dire Dawa (Figure 1), at 1700 m ASL on the edge of the main fault escarpment of the southern Afar margin underneath the modern Oromo village of Ganda Biyo on the Dire Dawa to Dengego road. The archaeological name, Harlaa, is related to the common appellation “Harla” given by the Oromo to ruined stone-built towns and funerary monuments in the region, whose origins are ascribed to a legendary ancient people of giant status who occupied the region before the Oromo arrived, beginning in the mid-16th century (Joussaume and Joussaume 1972, 22; Chekroun et al. 2011, 79). The Oromo are unconnected with the former inhabitants of Harlaa, having migrated into the region, probably as a consequence of the instability resulting from the *jihad* of Ahmad Gragn, referred to previously. This may have been the culmination of a chain of Oromo movements, possibly starting in the 12th century, when under pressure from the Islamised Somali, the agricultural Oromo (Bareituma) moved from the Somaliland region into the Harar plateau and the nomadic Oromo (Borana) migrated into southwest Ethiopia (Beckingham and Huntingford 1954, lxxii-lxxiii).

Harlaa was a large urban centre (Figure 2), covering a maximum area of approximately 900 m north to south by 500 m east to west, excluding outlying cemeteries (Khalaf and Insoll 2019). It is composed of several elements including at least three mosques, a central settlement area, workshops, wells, lengths of fortification wall, and cemeteries to the north, east, and west. Prior to the start of the current investigation of the site, previous archaeological research had consisted of limited survey and surface collections (e.g. Patassini 2006; Chekroun et al. 2011).

Since 2015, excavations have been completed in a mosque (Area A), workshop complex (Area B), cemeteries (Areas C and D), a house with associated industrial/kitchen facility (Area E) – part of an extensive building complex, with a defensive wall, and what may have been a reception hall (Area F) – and a well-preserved complex of merchant’s or artisan’s houses (Area G) (Insoll et al. 2017; Khalaf and Insoll 2019; Insoll et al. in press). Human remains were recovered from areas B, C, and D. Area B has provided the longest chronology at Harlaa with 14 AMS dates obtained spanning the period between the mid-6th and early 15th centuries (Table 1) (Insoll in preparation). The workshops appear to have been used primarily for jewellery manufacture, particularly marine

Figure 1. The locations of Harlaa and Sofi (Ganda Harla) within Ethiopia (prepared by N. Khalaf).

shell (*Strombus tricornis*) bead making and cowry shell (*Cypraea moneta* and *annulus*) processing, as well as hard stone (agate, carnelian, quartz, rock crystal) and glass bead manufacture, and copper metallurgy.

Trade, including in beads, was of significant importance to the inhabitants of Harlaa with wide-ranging contacts attested archaeologically, including with South Asia, the Arabian Peninsula, Egypt, and indirectly, the Far East (Insoll et al. in press; Insoll in preparation). A site total of 2,441 beads were found (excluding Area G, which awaits analysis), with approximately 2,000 glass and 400 stone beads recorded. The agate beadmaking techniques at Harlaa resemble those of Gujarat in western India in their use of heat treatment, diamond drill bits, and bow drills (cf. Roux 2000; Kenoyer 2017). South Asian technological transfer is also suggested by the shell bangles, with the same sawing techniques and waste generated as, for example at Mantai, Sri Lanka, where it was dated to the sixth to twelfth centuries (cf. Waddington and Kenoyer 2013). Beads, bracelets, and cowry shells were likely exported from Harlaa throughout the surrounding region. International trade patterns were manifest by 160 sherds of Chinese and Southeast Asian/Chinese origin ceramic vessels, as well as 145 sherds of Middle Eastern ceramics, including of

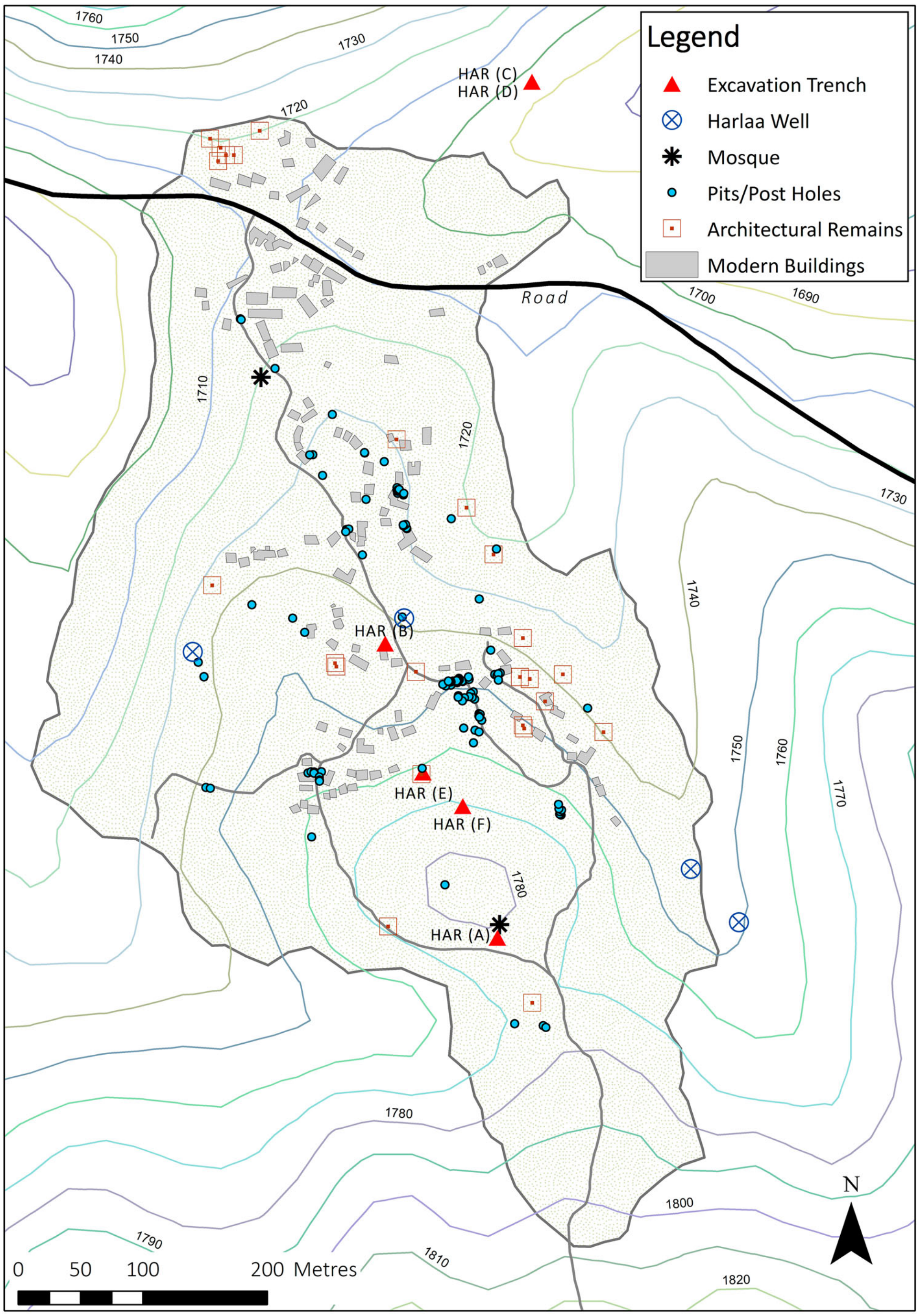

Figure 2. The locations of Areas B, C, and D within Harlaa (prepared by N. Khalaf).

Yemeni, Egyptian, and Iranian provenance (Insoll in preparation). Fragments of imported glass vessels, and copper coins, including two Ayyubid *fals* from the Cairo mint, and dated to 623-635/1226-1237 (D. Nicol pers. comm. 20/2/19) provided further evidence for participation in Red Sea and Indian Ocean commerce. The evidence from Harlaa thus amplified archaeological understanding of Indian Ocean networks over the last two millennia (e.g. Insoll 2003; Rougeulle 2015; Wynne-Jones 2016; Lambourn 2018), by indicating that these extended deep into the Ethiopian interior.

Dietary evidence was also indicative of trade connections. All fish bones found were from oceanic/Red Sea/Gulf of Aden species. The sole presence of post-cranial elements in phases 1–4 (7th to early 14th centuries) suggested that they were imported in preserved form, either dried or salted (Gaastra and Insoll 2020). The majority of fauna came from domestic species with the most common sheep/goat (52.4%), followed by cattle (23.9%), and transport livestock, particularly horse/donkey (7.9%), but also camel (3.6%). Remains of domestic chicken and guinea fowl were also present (11.4%). The possibility that some animals were imported to Harlaa is discussed below based on strontium isotope analysis of five herbivore teeth. The proportions of the goat, cattle, and sheep, and butchery evidence concur with

Table 1. Cumulative AMS radiocarbon dates from Areas B, C, and D at Harlaa, and AMS and TL dates from Sofi.

Context number	Date and laboratory number
HAR 15 (B) 6	Cal AD 1155–1260 (2 sigma calibration; Beta – 419526)
HAR 15 (B) 10	Cal AD 1165–1265 (2 sigma calibration; Beta – 419527)
HAR 16 (B*) 6	Cal AD 1290–1410 (2 sigma calibration; Beta – 451581)
HAR 16 (B*) 7	Cal AD 1255–1290 (2 sigma calibration; Beta – 451582)
HAR 16 (B*) 9	Cal AD 1190–1275 (2 sigma calibration; Beta – 451583)
HAR 17 (B) 6 – Hearth	Cal AD 1220–1285 (2 sigma calibration; Beta – 461299)#8232;
HAR 17 (B) 10#8232;	Cal AD 1035–1215 (2 sigma calibration; Beta – 461300)
HAR 17 (B) 15#8232;	Cal AD 535–620 (2 sigma calibration; Beta – 461301)
HAR 17 (B) 24 – Hearth	Cal AD 775–975 (2 sigma calibration; Beta – 461302)
HAR 17 (B) 24 – Under Wall	Cal AD 1015–1050 and Cal AD 1080–1150 (2 sigma calibration; Beta – 461303)
HAR 18 (B) 6	Cal AD 1256–1306 (2 sigma calibration; Beta – 490904)
HAR 18 (B) 13	Cal AD 1152–1260 (2 sigma calibration; Beta – 490905)
HAR 18 (B) 24	Cal AD 776–971 (2 sigma calibration; Beta – 490906)
HAR 18 (B) 26	Cal AD 684–780 (2 sigma calibration; Beta – 490907)
HAR 17 (C) Burial 1 – Upper	Cal AD 1330–1340 and Cal AD 1395–1440 (2 sigma calibration; Beta – 461292)
HAR 17 (C) Burial 2 – Lower	Cal AD 1220–1285 (2 sigma calibration; Beta – 461293)
HAR 17 (D) 1#8232;	Cal AD 1165–1265 (2 sigma calibration; Beta – 461294)
TUM 15 (A) 1	Cal AD 1275–1385 (2 Sigma calibration; Beta-421104)
TUM 14 (A) 2 (TL)	AD 1224+/-80 (W4824)

that found across multiple Islamic period sites in Arabia, Mesopotamia, and Iberia, and is suggestive that some of the population was following an orthodox Muslim diet in Harlaa. However, the presence of either warthog (*Phacochoerus sp.*) or bushpig (*Potamochoerus sp.*), which was unlikely to be consumed by observant Muslims, suggests a mixed religious community or religious non-observance (Gaastra and Insoll 2020).

The establishment of a Muslim community at Harlaa, the earliest in eastern Ethiopia, can be reconstructed based on the AMS dates from the mosque and the Muslim burials described below, as in existence by the mid-twelfth century (Insoll in preparation). Additional correlation is provided by Arabic inscriptions, with one with a date of 657 AH (1259–1260 AD) (Bauden 2011, 296) and another the partial date of 44x AH (Schneider 1969, 340), calculated as 1048–1057 AD (Chekroun et al. 2011, 79). Islam co-existed with indigenous religions that were followed by the majority of the local population. What these religions were, is little understood, their having left no historical records, and having only been partially investigated archaeologically with reference to their most tangible aspect, funerary practice.

As part of the wide range of materials recovered from the workshops, six human teeth were found. These were conceivably one of the materials worked, but more likely were incorporated either accidentally, or perhaps because the workshop occupants either functioned also as "dentists" or lost teeth themselves over the approximately 800 years the area was in use. The absence of any other human remains in the deposits indicates they were not associated with burials. In contrast, Areas C and D were in part of a cemetery northeast of the settlement area and workshops. Two AMS dates were obtained from the burials in Area C, and one AMS date from the burial in Area D (Table 1). Usually, Muslim burials cannot be excavated because of understandable Muslim prohibitions on disturbing the deceased (Insoll 1999, 169; Petersen 2013, 253). In this instance, permission to investigate two graves was given by the Ethiopian authorities (Authority for Research and Conservation of Cultural Heritage and Dire Dawa Culture and Tourism Office) and the local Harlaa community, as one (D) was already damaged and had exposed human remains, and the other (C) was suffering from erosion with loss of part of the southern edge of the terrace the grave was located on. Additional impetus was added by the local community wanting to ascertain if the dead were giants of Harlaa legend (Insoll et al. 2017, 34).

A double burial, one above the other, was exposed in Area C. The burials were within an approximately rectangular enclosure with internal dimensions of 138 × 100 × 140 × 123 cm, and formed of travertine slabs laid on edge (Figure 3). This was one of a series of similar structures contained within the partial remains of a building constructed from massive stone boulders. The grave was marked with unworked and uninscribed head and foot stones and each burial was found laid beneath a series of angled stone slabs, six for the upper burial (HAR 17 [C] Burial 1 [Upper]), and seven for the lower (HAR 17 [C] Burial 2 [Lower]) (Figure 3). The use of the slabs covering the bodies in the grave is suggestive of the *Shiqq* or *Shaqq* type grave where the corpse was placed inside a human-sized trench closed off with planks, or slabs within a larger rectangular pit, rather than the alternative *lahd* grave, where the body was placed inside a shelf-like niche cut into the pit edge, and blocked off with a wall. The function of slabs and wall being to prevent the face of the dead having direct contact with the earth (cf. Petersen 2013, 246). Within their graves both individuals were lying on their sides, oriented northeast to southwest with their heads at the northeast and faces slightly to the northwest. The

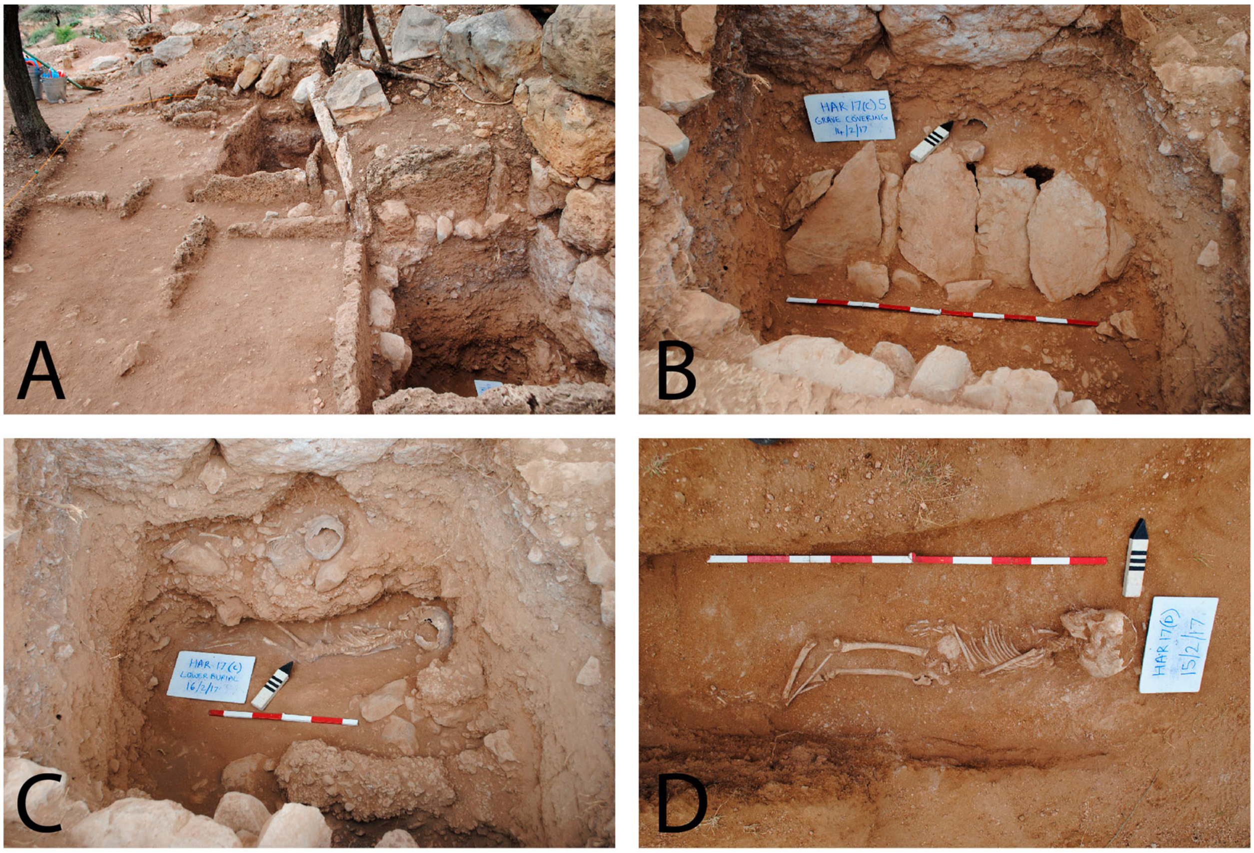

Figure 3. (A) HAR 17 [C]. The rectangular grave enclosures. (B) HAR 17 [C]. The stone slabs covering the upper burial. (C) HAR 17 [C]. The double burial. (D) HAR 17 [D]. The single burial (photos: T. Insoll).

right arm of the upper burial was in front of the face and the arms were extended in front of the body in the lower burial (Figure 3). The only artifacts associated with the burials were a single *Olividae* marine shell, a sheep/goat tooth, and a glass bead from the layer (HAR 17 [C] 2) above the stone slabs over the upper burial. These items could not be interpreted as grave goods and the absence of the latter, associated with the grave form, the position in the grave, and the close orientation to the *qibla* (the direction of Mecca), almost directly north at Harlaa, indicates these were Muslim burials (cf. Insoll 1999, 170–173; Petersen 2013, 248). The single burial excavated in Area D (HAR 17 [D]) was also Muslim, as indicated by orientation and position of the body. The individual was buried oriented east–west, with head to the east, and face directly north, i.e. toward the *qibla*, on their side, with hands in front and arms extended along the sides of the body (Figure 3). There were no associated artifacts, and because of erosion the type of grave cannot be determined. The human remains from the three burials are described below.

Sofi (9°15'36.1"N 42°08'45.8"E). Non-Muslim burial was under stone cairns or tumuli, *Daga Tuli*, sometimes with circular burial chambers (Joussaume 1980, 2014). Within the vicinity of Harlaa, these types of monuments have not been found, but numerous examples exist in the Tchercher mountains, as at Sourré-Kabanawa, some 40 km southwest of Harlaa, where radiocarbon dates indicated comparable chronology to Harlaa with two *Daga Tuli* with circular chambers dated to Cal AD 980–1180 (Monument 1) and Cal AD 770–950 and Cal AD 930–1080 (Monument 3) (Joussaume 1980, 102). Harlaa could have been the source of some of the grave goods recovered including *Cypraea annulus* cowry shells, *Olividae* marine shells, copper bracelets and large numbers of small blue, green, red, and yellow glass beads (cf. Joussaume 1980, Pl. XII-XIV).

Other *Daga Tuli* have been recorded around the city of Harar on the Somali Plateau. An example, TUM 15 (A), was excavated at Sofi 8 km southeast of Harar (Figure 1), at approximately 1900 m ASL (Insoll, MacLean, and Engda 2016). The mound measured 13 m southeast to northwest by 14.2 m northeast to southwest and was about 1.5 m in height. It was located west of the road in the valley below. Permission to complete the excavation of the mound at Sofi was given at three levels: national, represented by the Authority for Research and Conservation of Cultural Heritage; regional, by the Harar Culture and Tourism Bureau; and local, by the community in Sofi. The tumulus was built of unworked stone with an inner core of large boulders and an outer layer of smaller stone pebbles and cobbles. A radiocarbon date from charcoal obtained from between the

Figure 4. TUM 15. The *Daga Tuli* (burial mound) at Sofi. The fragmentary human remains were recorded next to the upright stone slab in the foreground (photo: T. Insoll).

two stone layers, and a thermo-luminescence date from a potsherd from the internal basal large boulder layer indicated an overall chronology of the 13th to 14th centuries (Table 1) (Insoll, MacLean, and Engda 2016, 29–30), and thus that the tumuli had been constructed after Islam was well-established in Harlaa. A single fragmentary human burial oriented north to south was found at the base of the mound next to an upright stone slab (Figure 4). This was located near the northern edge of the mound approximately 4 m from the centre. The burial had been destroyed by stone collapse, exacerbated by poor bone preservation caused by the soil conditions (Insoll, MacLean, and Engda 2016). The condition rendered osteological analysis impossible. Whether grave goods were present was unclear as only a few pot sherds were recovered, but the orientation of the burial and grave form indicate it was non-Muslim, thus providing a suitable comparison to the Muslim individuals from Harlaa.

The human remains from Harlaa

The human remains were recorded using standardised skeletal and dental inventory tables and in diagrammatic form (Buikstra and Ubelaker 1994; Antoine 2017). No duplicated skeletal elements or teeth were identified, indicating, on the basis of the material that was available for assessment, that each assemblage contained one individual (MNI = 1). The inventories and subsequent analyses were based on a limited number of extracted teeth and one bone sample (TUM15 (A) 2 = one tooth; HAR15 (B) = one tooth; HAR 17 [C] burial 1 (upper) = seven teeth; HAR 17 [C] burial 2 (lower) = ten teeth, one fragment of left maxilla; HAR 17 (D) = five teeth). Due to the fragmented condition and very poor completeness of each of the skeletal assemblages assessed, the osteological analyses of the individuals were limited in scope. However, age-at-death determinations were estimated using standard dental development and eruption criteria (AlQahtani 2009; AlQahtani, Hector, and Liversidge 2010; AlQahtani, Hector, and Liversidge 2014; Antoine 2017; Buckberry and Brickley 2017). The results are presented in Table 2. Two individuals were represented by loose teeth not directly extracted from skeletal remains, meaning only minimum ages could be determined of >11.5 years old for TUM15 (A) and >3.0 years old for HAR15 (B). The other three individuals are non-adults, with individual HAR 17 (C) burial 1 (upper) having died between 2.5 and 3.5 years old, individual HAR 17 (C) Burial 2 (lower) having died between 4.5 and 6.5 years old, and individual HAR 17 (D) having died between 2.5 and 6.5 years old. Although the classification of these individuals as non-adults is reliable, the age

Table 2. Age-at-death estimations.

Individual	Burial	Dentition present	Age-at-death estimation
Human 1 (Non-Muslim tumuli burial from Sofi)	TUM 15 (A)	Mandibular premolar 2, left, fully formed crown but missing the root base.	>11.5 yrs *Justification:* Adult 2nd premolars are fully formed (root apex closed) by 13.5 years of age. As the root base is not present in this tooth, a more conservative estimate of minimum age was used.
Human 2 (Muslim burial)	HAR 17 (C) Burial 1 (upper)	*Maxillary Dentition:* Central incisor, left, deciduous, fully formed. Lateral incisor, left, deciduous, fully formed. Lateral incisor, right, deciduous, fully formed. Canine, right, deciduous, fully formed. Molar 1, permanent, crown only *Mandibular Dentition:* Molar 1, mandibular, right, deciduous, fully formed. Molar 1, mandibular, permanent, crown only.	2.5- 3.5 years old *Justification:* Before 2.5 years old, the deciduous teeth are not completely formed, and the permanent 1st molar crowns are not yet formed. After 3.5 years old, the permanent 1st molar (mandibular and maxillary) would begin to exhibit evidence of root formation which was not identified.
Human 3 (Muslim burial)	HAR 17 (C) Burial 2 (lower)	*Maxillary Dentition (Deciduous):* Canine, left, fully formed. Molar 1, left, fully formed. Molar 2, left, fully formed. *Maxillary Dentition Permanent:* Central incisor, left, crown only. Lateral incisor, left, crown only. Canine, left, crown only. Premolar 1, left, crown only. Premolar 2, left, crown only. Molar 1, left, crown formed, initial root formation evident and tooth is beginning to erupt. Molar 2, left, crown only.	4.5-6.5 years old *Justification:* Before 4.5 years old, the permanent, maxillary, 1st molar does not initiate root formation or erupt, and the permanent crowns of the 1st and 2nd maxillary premolars and 2nd maxillary molar are not yet formed. After 6.5 years old, the permanent 1st maxillary molar would have fully erupted and completed root formation. In addition, the permanent, maxillary, central and lateral incisors, canine, and 1st and 2nd premolars would have initiated root formation, which was not identified.
Human 4 (Muslim burial)	HAR 17 (D)	*Maxillary Dentition:* Central incisor, left, deciduous, fully formed. Canine, left, deciduous, fully formed. *Mandibular Dentition:* Central incisor, right, deciduous, fully formed. Lateral incisor, right, deciduous, fully formed. Canine, right, deciduous, fully formed.	2.5-6.5 years old Justification: Before 2.5 years old, the deciduous teeth are not completely formed. By 6.5 years old, the permanent, mandibular, central incisor erupts, and in turn, removes the deciduous, mandibular, central incisor from the dental arch. This was still present.
Human 5 (Non-burial context in a workshop complex)	HAR 15 (B)	Canine, deciduous, fully formed crown but missing the root base.	>3.0 years old *Justification:* Deciduous canines are fully formed (root apex closed) by 3.5 years of age. As the root base is not present in this tooth, a more conservative estimate of minimum age was used.

ranges provided may not reflect their "true" chronological age. This is because population-specific and period-specific dental development criteria for this geographic region, population, and archaeological period do not exist and were therefore not used (Hillson 2005, 211; Adams et al. 2018; Smith 2020). Moreover, the exact time and rate at which individual teeth undergo the mineralisation process has been shown to vary both between and within individuals, thereby reducing the effectiveness of tooth formation for estimating the age-at-death for samples originating from an unstudied archaeological population (Montgomery 2010; Hillson 2005; Evans, Chenery, and Fitzpatrick 2006; Akkus et al. 2016; Adams et al. 2018; Esan, Mothupi, and Schepartz 2018).

Due to the non-adult statuses of the individuals, sex determinations were not attempted as reliable osteological methods have not yet been developed (Buikstra and Ubelaker 1994, 16; Brickley 2004, 23; Brickley and Buckberry 2017, 33). However, the potential impact of biological sex on the results and subsequent interpretation must be kept in mind, as non-adult females are commonly c.1-6 months ahead of their male counterparts in overall dental development, and up to c.11 months ahead in terms of the development of their canines (Demirjiajn and Levesque 1980; Hillson 2005, 210; Lewis 2007, 38; Liversidge 2009). The pathological assessments of the individuals revealed no evidence of disease or trauma, although no reliable inferences could be made regarding the health statuses of the individuals due to the lack of skeletal and dental remains available for examination. Evaluations of dental non-metric traits (D-NMT), i.e. non-pathological morphological variants in dental anatomy, were also completed (White and Folkens 2005; Saunders and Rainey 2008, 553). Only one individual exhibited evidence of a D-NMT. HAR 17 (C) burial 2 (lower)'s left, maxillary, central incisor had slight elevations on the mesial and distal aspects of the lingual surface of its crown; this represents a mild ("semi") expression of the non-metric trait referred to as a "shovel-shaped" incisor (Hanihara 1961). This particular D-NMT has been used as a marker of ancestral origin, with it being most often identified in individuals of mongoloid decent, with Bernstein (1997, 308) reporting an 85–99% occurrence rate in mongoloid dentitions. However, it can also be found, albeit less often, in individuals of negroid and caucasoid descent (El-Najjar and McWilliams 1978, 75; Kharat, Saini, and Mokeem 1990). Therefore, the presence of this trait cannot be used to proffer a reliable determination as to the ancestral origin of the individual.

Strontium isotope analysis

The analysis of stable and radiogenic strontium isotopes in human and faunal tooth enamel is widely used in archaeology to study mobility patterns of past populations (Bentley 2006; Hrnčíř and Laffoon 2019; Montgomery 2010), including recent applications studying long distance mobility in large ancient cities (Perry, Jennings, and Coleman 2017; Wong et al. 2018) and in other Islamic contexts (Allen et al. 2020). Strontium isotope ratios of bedrock geology vary according to the age of the rocks and the chemical composition at the point of rock formation, specifically the initial $^{87}Sr/^{86}Sr$ and proportion of radioactive rubidium ^{87}Rb, which decays on geological timescales to radiogenic but stable strontium ^{87}Sr (Faure and Mensing 2005). As these bedrock geologies erode their products are passed to surface geologies, sediments and soils and from there, bioavailable (water soluble) strontium enters the food chain as it is absorbed by plants or consumed directly by animals and humans in drinking water (Ericson 1985; Capo, Stewart, and Chadwick 1998; Price, Burton, and Bentley 2002).

Strontium is incorporated into bones and teeth during growth by substituting for calcium in the bioapatite crystal lattice. While archaeological bone and tooth dentine is known to be susceptible to contamination by strontium absorbed from the burial environment, tooth enamel is hard and dense and thus retains the original biogenic signal laid down when the tooth first formed (Hoppe, Koch, and Furutani 2003), potentially over millions of years (Copeland et al. 2011). Enamel formation occurs in two phases, beginning with matrix production and ending with enamel mineralisation (Hillson 2005). While matrix formation occurs incrementally along a leading edge, the maturation phase, when enamel becomes heavily mineralised, is less systematic and may proceed at different speeds in different parts of the tooth over a period of days, weeks or months (Suga 1982; Hoppe et al. 2004). All strontium isotope measurements in tooth enamel, however tightly spatially resolved they may be, are therefore time-averaged and will incorporate strontium consumed over the whole period of enamel formation which may vary in duration in different parts of the tooth (Bendrey et al. 2015). Nonetheless, the pattern of enamel formation remains broadly sequential, beginning at the tooth crown and ending at the enamel-root junction, meaning a time series can be produced by sampling progressively along the tooth cusp (e.g. Mays et al. 2018; Gigleux et al. 2019). In this way, it is possible to use changes in the strontium isotope ratio along the tooth cusp as a proxy for mobility over time, according to the different geologies encountered during the period of enamel mineralisation (Bentley 2006; Ericson 1985; Slovak and Paytan 2011).

The human individuals excavated at Harlaa are juveniles or young adolescents meaning only deciduous teeth that start forming *in utero* or earlier-forming permanent teeth (formation starts <1 year of age) were available for analysis. Such teeth are commonly analysed in strontium isotope mobility studies (reviewed in Hrnčíř and Laffoon 2019) but are potentially more complex to interpret than later-forming teeth due to possible interferences caused by strontium recycling from maternal body tissues during pregnancy and lactation (Blakely 1989; Montgomery 2010). Strontium recycling describes the process whereby strontium from maternal body reservoirs, particularly bones and teeth, is resorbed into the blood stream during foetal growth and passed to the growing child. This has led to concerns that strontium recycling has the potential to buffer or perhaps entirely overprint the geochemical signature passed up the food chain from the local geology, however the extent of these impacts on the strontium isotope composition of the infant are still not well understood (Lugli et al. 2019; Montgomery 2010). Some elements, such as lead, are particularly susceptible to recycling effects and remobilised lead from maternal reservoirs has been shown to dominate the isotopic signature in foetal tissues over dietary sources (Gulson et al. 1999). Yet the situation with strontium is less clear and questions remain about the residence time and turnover of strontium in the body, the proportion of strontium contributed to a growing foetus from dietary vs maternal body tissue sources, and how these things may vary across different species (Lugli et al. 2017; Lugli et al. 2019; Montgomery 2010). Many previous studies have measured and successfully interpreted strontium isotope data from deciduous human teeth (reviewed in Hrnčíř and Laffoon 2019; Knipper et al. 2018; Knudson et al. 2016; Lugli et al. 2017; Lugli et al. 2019) and earlier-forming permanent dentition that likely overlaps with the breastfeeding and weaning period (Evans, Chenery, and Fitzpatrick 2006;

Table 3. Harlaa teeth sampled for strontium isotope analysis. Enamel formation periods in human teeth are approximate and given according to White and Folkens (2005). Enamel formation periods in animals are given according to Brown et al. (1960), Jones and Sadler (2012), and Makarewicz and Pederzani (2017).

Code	Burial / find number	Species/ individual	Tooth	Enamel formation period	Age at death	Muslim / non-Muslim burial
HG1		Cattle	Maxillary P4	Approx. 1.0 - 2.5 yrs		
HG2		Cattle	Mandibular M1	in utero – 3 months		
HG3		Goat	Maxillary M2	2 - 12 months		
HG4		Cf. Cattle	Maxillary molar (M2?)	birth – 13 months		
HG5		Goat	Maxillary M2, erupting	2 - 12 months		
HG6	TUM15 (A)	Human 1	Mandibular PM2 (left) adult	2 - 7 yrs	>11.5 yrs	Non-Muslim tumuli burial at Sofi
HG7	HAR17 (C) burial 1 (upper)	Human 2	Mandibular m1 (right) decid.	in utero – 6 months	2.5-3.5 yrs	Muslim burial
HG8		Human 2	Mandibular M1 adult	birth – 36 months		
HG9*	HAR17 (C) burial 2 (lower)	Human 3	Maxillary M2 (left) decid.	in utero – 11 months	4.5-6.5 yrs	Muslim burial (section of maxilla)
HG10		Human 3	Maxillary M1 (left) adult	birth – 36 months		
HG14		Human 3	Maxillary m1 (left) decid.	in utero – 6 months		
HG15*		Human 3	Maxillary canine (left) decid.	in utero – 9 months		
HG11*	HAR17 (D)	Human 4	Mandibular di1 (right) decid.	in utero – 4 months	2.5-6.5 yrs	Muslim burial
HG12*		Human 4	Mandibular di2 (right) decid.	in utero – 4 months		
HG13*		Human 4	Maxillary canine (left) decid.	in utero – 8 months		
HG16	HAR15 (B) 3	Human 5	Canine decid.	in utero – 9 months	>3.0 yrs	Non-burial context in a workshop complex

Note: * – Teeth analysed twice at different places around the tooth cusp.

reviewed in Hrnčíř and Laffoon 2019; Müller et al. 2003). More broadly, earlier-forming teeth such as 1st molars are routinely used for research into the mobility of past populations using other isotope systems such as $\delta^{18}O$ (Prowse et al. 2007) despite similar concerns about fractionation effects caused by breastfeeding (Wright and Schwarcz 1998). For the present analysis, earlier-forming permanent teeth and deciduous teeth that form partly *in utero* or during the first year of life were both included and provide information primarily about the mobility of the mother during pregnancy and breast feeding (Table 3).

Method

Teeth from two goats and three cattle found in the workshop complex at Harlaa (Area B) were analysed to investigate $^{87}Sr/^{86}Sr$ ratios in source regions for foods consumed at Harlaa. As a large trading centre, it is likely that animals would have been imported to Harlaa from various locations across the hinterland around the city and potentially also from further afield, and no assumption was made that these animals would reflect "local" Harlaa geology. Teeth from five human individuals were also selected for analysis, including multiple teeth from three Muslim burials (Areas C and D), one tooth from the non-Muslim tumuli burial from Sofi, and an individual tooth found in the workshop complex alongside the animal remains (Area B) (Table 3).

Enamel-dentine segments approximately 3–5 mm wide were cut parallel to the axis of growth from each sampled tooth (Figure 5), in each case retaining some of the dentine core that was also used for analysis (see below). In four cases – HG11, HG12, HG13 and HG15 – a full half-section of the tooth was taken instead to allow multiple analyses to be made on opposite sides of the tooth cusp (Figure 6). Additionally, two enamel segments were collected about 3 mm apart from the dm2 from human 3 (HG9) and analysed separately (Table 3). These data were used to test whether the $^{87}Sr/^{86}Sr$ profile varied according to choice of sampling location in the tooth.

Strontium isotope ratios were measured along the centre-line of enamel cross-sections by Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry (LA-MC-ICPMS), using a New Wave 193 nm excimer laser ablation system (UP193FX) coupled to a Thermo Scientific Neptune MC-ICP mass spectrometer located in the Plasma Mass Spectrometer Laboratory, National Oceanography Centre, University of Southampton, UK. Untreated tooth segments were first embedded on edge in Epofix© epoxy resin and then sanded using 35 μm and 15.3 μm grits to create a flat surface ready for analysis. Tuning protocols focused on minimising oxide production (monitored as $^{254}(UO)^{+}/^{238}U^{+}$), thereby reducing the impact of the $^{40}Ca^{31}P^{16}O+$ and $^{40}Ar^{31}P^{16}O+$ molecular ions, which are isobaric on mass 87, to negligible levels (Lewis, Coath, and Pike 2014; Willmes et al. 2016). The enamel to be analysed was pre-ablated to remove surface contaminants. For data collection, the laser, with a beam diameter of 150 μm, was set to pulse at 15 Hz while traversing across the sample at 10 $\mu m s^{-1}$. The ablated sample was swept from the laser cell using helium gas, which was then mixed with argon and nitrogen gas flows before entering the plasma ion source. $^{87}Sr/^{86}Sr$ was measured in static collection mode with an integration time of 1.049 s. All corrections were applied offline, cycle by cycle. We correct for krypton impurities present in the argon gas by subtracting a 60 s on-peak gas blank (Lewis, Coath, and Pike 2014), and for mass bias using an $^{86}Sr/^{88}Sr$ ratio of 0.1194 (Nier 1938),

Figure 5. Fragment of maxilla from Human 3 (Har 17 [C] lower burial), following sampling of adjacent teeth to remove enamel-dentine wedges 3–5 mm wide. From left to right, sampled teeth are dc1, dm1, dm2 and M1. In the right hand image the canine has been removed and is lying on the scale bar (photos: A. Pryor).

according to an exponential mass fractionation law (Russell, Papanastassiou, and Tombrello 1978). Rubidium interference was corrected using the natural $^{87}Rb/^{85}Rb$ ratio of 0.385617 (Faure 1986). Following Woodhead et al. (2005), calcium dimers and argides were corrected when calculating $^{84}Sr/^{86}Sr$ ratios using the natural abundances of calcium isotopes and by monitoring mass 82 for $^{40}Ca(or\ ^{40}Ar)^{42}Ca+$.

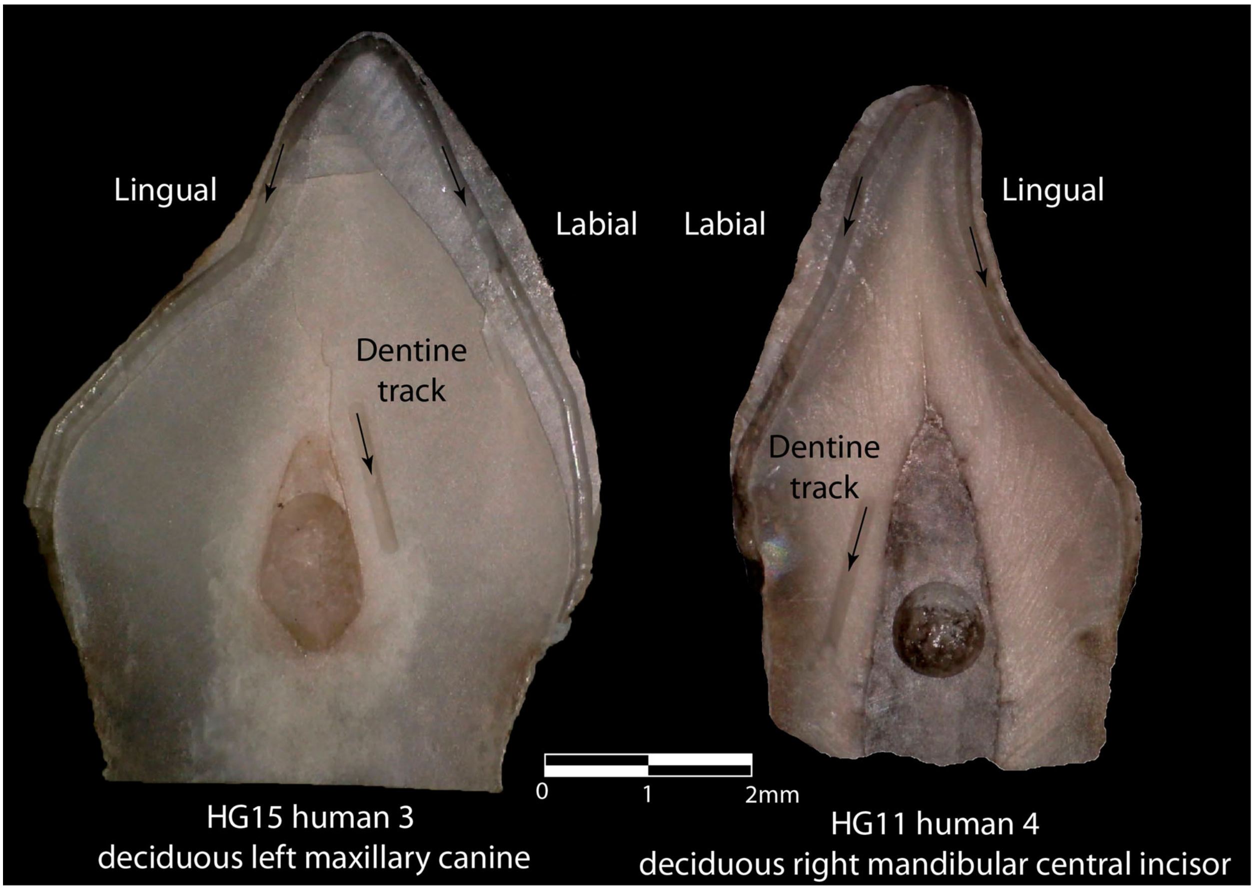

Figure 6. Human teeth from Harlaa sampled twice for LA-MC-ICPMS, along the labial and lingual cusps respectively. The laser tracks are indicated by arrows in the enamel and dentine of each tooth (photos: A. Pryor).

Rare earth element contamination was monitored using ^{89}Y as a proxy, and data showing significant concentrations were rejected as diagenetic (Woodhead et al. 2005; Lewis, Coath, and Pike 2014).

Accuracy and reproducibility of the approach was monitored using a series of five in-house enamel standards derived from pigs fed controlled diets, and containing similar strontium concentrations to that typically observed in bioapatite (~30–300 parts per million (ppm)). All have previously been characterised for their $^{87}Sr/^{86}Sr$ through Thermal Ionisation Mass Spectrometry (Lewis et al. 2017). Repeat analyses of one of these enamel standards at intervals throughout the analytical session gave a mean $^{87}Sr/^{86}Sr$ of 0.709104 ± 0.000085 (1 S.D.), equating to a mean offset of +36 ± 119 parts per million (ppm; 1 S.D.) for the laser ablation analyses over the TIMS values. This is consistent with previous laser ablation studies where small positive offsets from known $^{87}Sr/^{86}Sr$ values are usually observed due to molecular interference on ^{87}Sr of $^{40}Ca^{31}P^{16}O^{+}$, which is the primary constituent of the enamel matrix, and $^{40}Ar^{31}P^{16}O^{+}$ (e.g. Lewis, Coath, and Pike 2014; Willmes et al. 2016). This offset is, however, well within both the internal precision of individual measurements of 200–600 ppm and the total variation between the teeth of >8000 ppm, and is therefore considered insignificant to our interpretation of the data. It should be noted that the impact of the interferences on ^{87}Sr will be greater for samples containing lower concentrations of strontium (Nowell and Horstwood 2009). However, the beam intensity of ^{88}Sr in our samples was almost always higher than that of our standards (0.76–0.99 V), suggesting equivalent or greater concentrations of strontium were present in the archaeological teeth. The in-house standards are therefore an appropriate demonstration of the study's accuracy and reproducibility.

The "local" bioavailable strontium isotope context at Harlaa was characterised using measurements of tooth dentine collected from all analysed teeth. Like bone, dentine becomes contaminated with diagenetic strontium absorbed from the environment after burial, which is useful for determining the strontium isotopic composition of sediments in the vicinity of the buried tooth. Nonetheless, dentine data must be assessed carefully when determining the "local" range as the extent of diagenesis can be variable between teeth buried in different places around a site, and even in different places within a single tooth (Budd et al. 2000). Plans were also made to collect plant samples from the broader region around Harlaa during the 2018 and 2019 field seasons to build a strontium base map for the area, however this proved impossible due to difficult security conditions that made it dangerous to travel.

Bioavailable strontium variability around Harlaa was therefore estimated following a literature review of published data for similar geological contexts across Ethiopia. This review revealed only a single measurement representative of bioavailable strontium from the wider east Ethiopian region, from the tooth dentine of an elephant thought to have lived in the west Afar region in the vicinity of the modern Awash National Park, approximately 200 km west of Harlaa (Coutu et al. 2016). Measured $^{87}Sr/^{86}Sr$ is low at 0.70675, likely reflecting the mixed undifferentiated Pleistocene alluvium occurring widely in this region and derived from weathering of all the different geologies found nearby, thus representing a mixed geochemical signal. In the absence of further data, reflecting the paucity of stable isotope research in eastern Ethiopia, further inferences were made based on bulk bedrock values. Bioavailable $^{87}Sr/^{86}Sr$ may differ from values observed in bedrock due to differential erosion/dissolution of different mineral components, inputs from atmospheric sources, or movement of groundwaters (Capo, Stewart, and Chadwick 1998; Price, Burton, and Bentley 2002). We therefore make an assumption that the relative positioning of geologies with low, middle or high strontium isotope ratios will be broadly reflected in the soluble strontium component, without necessarily falling within the exact ranges quoted below. The resulting predictions are sufficient for suggesting an initial interpretation of the Harlaa strontium data, which can be improved and refined as more data become available in future.

Results

Geological context

Harlaa is located at 1700 m above sea level on the northern margin of the Somali plateau, close to the main fault escarpment of the southern Afar margin. The region is part of the Ahmar Mountain chain. The highest peak of Gara Muleta, which is located close to Harlaa, reaches 3,381 m above sea level and the area is characterised by deeply incised valleys stretching more than 20 km. Basement geology around Harlaa is comprised of Precambrian deposits of high grade gneisses and migmatites (Teklay et al. 1998; EIGS 1985; GSE 2010), however these are only extant at the surface in localised areas. This includes outcroppings near Harlaa that can be reached within a kilometre or so to the south, and within 5–10 km to the east, west and north (Figure 7). Across most of the study region, however, these old basement geologies are entirely buried by Mesozoic marine and terrestrial deposits and younger Tertiary sediments. Harlaa itself is situated on Middle Jurassic limestones of the Hamanlei Formation that were deposited during a marine incursion that flooded much of the horn of Africa (Abbate, Bruni, and Sagri 2015). These limestones are present extensively throughout

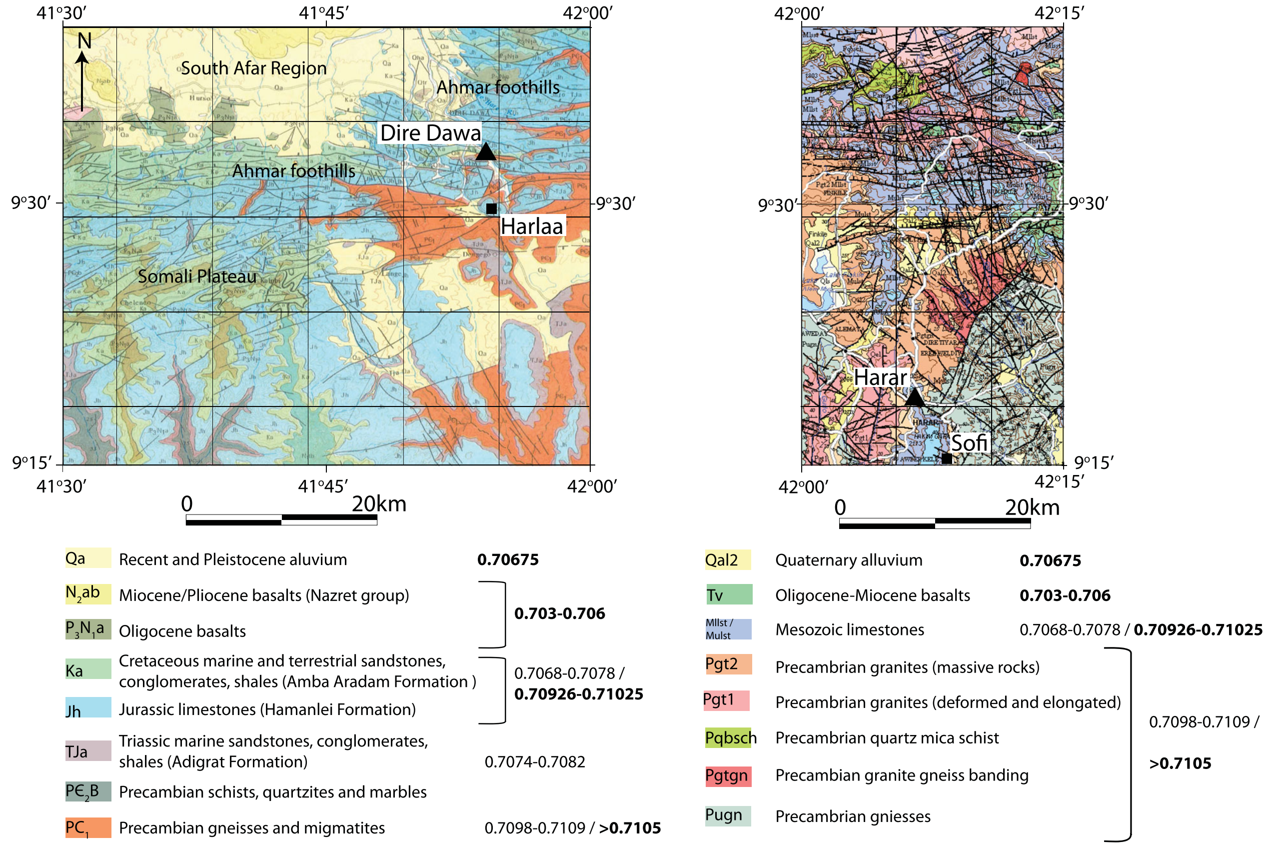

Figure 7. Geological maps of Harlaa and surrounding area at 1:250,000 resolution. Strontium isotope ratios are given as whole-rock (plain text) and predicted bioavailable (bold text) values (see Results). Left: part of geological map number NC37-12 prepared by the Ethiopian Institute of Geological Surveys (EIGS 1985); Right: part of geological map number NC38-9 prepared by the Geological Survey of Ethiopia (GSE 2010). The two maps are contiguous but were drawn using different colour schemes and therefore shown as two separate regions.

the Harlaa region occurring in deposits up to 1000 m thick and comprising the major depositional component of the Ahmar Mountains. Rare small areas of earlier Triassic/Jurassic Adigrat Sandstone Formation, comprising sandstones, conglomerates and shales deposited in fluvial and shallow marine deltaic environments, are also present throughout the Ahmar Mountains including a small outcropping a few kilometres south of Harlaa (Figure 7). Further small outcroppings of slightly younger Cretaceous sandstones, conglomerates and shales of the Amba Aradam Formation (mixed marine and terrestrial deposits) are located <10 km north and west of Harlaa, becoming more prevalent in a westerly direction. Beyond about 30 km west of Harlaa these Cretaceous deposits alternate frequently with substantial volcanic deposits of much younger Alaji Basalts of Oligocene age before being completely replaced by the latter geologies at approximately 80–90 km distance from the site. Soils throughout the region around Harlaa reflect the local geological context, being derived from Mesozoic sandstones and limestones, flood basalts and, subordinately, from Precambrian basement rocks (Billi 2015, 5).

Around 10 km north of Harlaa a major geological boundary between the Somali plateau and the Afar region is marked by a transition to recent undifferentiated Pleistocene alluvial sediments with outcroppings of Miocene-Pliocene Stratoid basalts and rhyolitic and trachytic domes and flows of the Nazret Group. Much further north lies the Main Ethiopian Rift system that cuts through the Afar Depression, at approximately 150 km distance from Harlaa.

Bioavailable strontium

Cross-referencing with the strontium isotope marine curve indicates that the Jurassic-Cretaceous marine deposits of the Hamanlei and Amba Aradam Formations which predominate in the area around Harlaa should have whole-rock isotopic compositions in the range of 0.7068–0.7078, while the Triassic-period Adigrat Formation should range between 0.7074 and 0.7082 (McArthur, Howarth, and Shields 2012). These values equate to low-middling bioavailable strontium ratios in the east-Ethiopian context. Direct measurements of granitoid Precambrian gneisses and migmatites located all around Harlaa produced whole-rock $^{87}Sr/^{86}Sr$ ratios of 0.7098–0.7109 (Teklay et al. 1998). This is relatively higher than the limestones, which is expected due to the higher initial Rb/Sr ratio and greater age of the granites. For the purposes of interpretation, any values above 0.7105 were taken as indicating probable interactions with the Precambrian geologies (consistent with the dentine values discussed below), as soluble strontium from Precambrian granites is known to rise to 0.713 or higher in other contexts. Meanwhile, strontium isotope measurements of recent Miocene-Pliocene volcanic basalts located in the Main Ethiopian Rift valley system approximately 250 km west of Harlaa produced very low values ranging between 0.7035 and 0.7043 (Ayalew et al. 2016). This agrees well with measurements of between 0.703 and 0.706 made on groundwater from aquifers and flood basalts of the same geological age in the Aksum region in northern Ethiopia (Alemayehu et al. 2011). Good agreement between whole rock and soluble strontium isotopic ratios in young basalts is unsurprising, due to very low initial Rb/Sr ratios in basalts and a relatively short decay time for the different mediums to diverge (Alemayehu et al. 2011 and references therein). Therefore, it seems likely that the young Miocene-Pliocene basalts located approximately 25 km north of Harlaa in the south Afar region should also have similarly low $^{87}Sr/^{86}Sr$ values of around 0.703–0.706, and that this signature should also be found in plants and animals that lived in there.

Tooth dentine and bioavailable strontium at Harlaa and Sofi

Dentine $^{87}Sr/^{86}Sr$ ratios in 16 teeth from Harlaa and Sofi were measured 3144 times by laser ablation (Figure 8). Beginning with Harlaa, dentine for HG16 (Human 5) found in the workshop complex showed much more radiogenic values than all other teeth and similar to the enamel values measured for this individual, indicating that the dentine had not equilibrated with the burial environment and reflecting good preservation of the tooth. Dentine from one of the goats (HG3) also stands out as having a clearly more radiogenic signature than all other samples, despite being found together in a group with the other four measured herbivores from the workshop complex (HAR B). This is another case where the dentine has most likely not fully equilibrated with the local burial environment and dentine data from HG3 and HG16 were excluded from further analysis. The strontium isotope range at Harlaa site was therefore defined as 0.70926–0.71025, calculated using the median ± 1.5* the inter-quartile range of all remaining tooth dentine measurements (0.70975 ± [1.5*0.00033]). This is higher than the "whole rock" range of 0.7068–0.7078 predicted for the limestones of the Hamanlei Formation upon which Harlaa lies, and gives a first indication of the $^{87}Sr/^{86}Sr$ ratio in soluble strontium from these deposits. Specifically, bioavailable strontium at Harlaa may be elevated by contributions from the relatively more radiogenic Precambrian granites immediately adjacent to the site, so the tooth dentine data probably reflect the upper end of the total bioavailable range for the Hamanlei Formation deposits. This interpretation is supported by dentine results from the single human

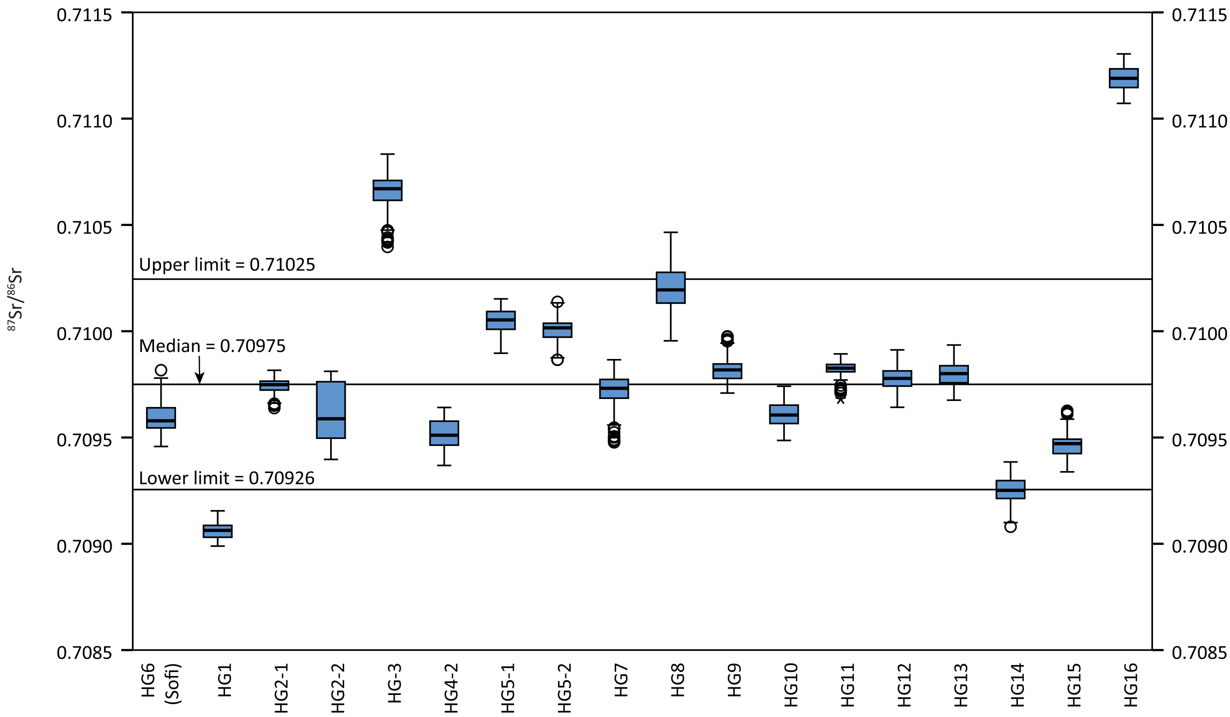

Figure 8. Strontium isotope measurements of tooth dentine from Harlaa and Sofi. Upper and lower limits to the 'local' strontium isotope range at Harlaa were calculated as the median ± 1.5* the inter-quartile range of all measurements from teeth considered to be fully equilibrated with the local burial environment (see text).

tooth from Sofi (HG6,) which also lies on Hamanlei limestones close to Precambrian granites around 50 km south-east of Harlaa and ranged between 0.70946-0.70982. This is indistinguishable from the bioavailable strontium range observed at Harlaa. Overall, the dentine data therefore place the Hamanlei Formation, and likely the other Mesozoic marine rocks in the region, intermediate between the Cenozoic basalts with very low $^{87}Sr/^{86}Sr$ ratios and the Precambrian granitic deposits which are predicted to display much higher values (Figure 8).

Herbivores

Two goats and three cattle each spent a large part or the entirety of the period of tooth growth living on less radiogenic geologies than that of the burial environment at Harlaa (Figure 9; Table 4; Supplementary Information). It is immediately clear that none of the animals were born on the Precambrian granites found in the hills immediately surrounding Harlaa, or on the recent basalts found variously to the west on the Somali plateau or in the south Afar plains. Cattle HG4 is the only animal to show significant overlap with the range identified for Harlaa from the dentine data, occurring in the latter part of the M2 between approximately 6–12 months of age. This implies that HG4 is the only animal which may have grown up in the immediate vicinity of the site, although a remote origin on an isotopically similar geology is also possible. Of the other two sampled cattle, HG1 grew up in a much less radiogenic location showing a consistent isotopic signature of 0.70744–0.70800 throughout the period of tooth growth. Meanwhile, $^{87}Sr/^{86}Sr$ ratios in the sampled M1 cattle tooth (HG2) change from approx. 0.7085 to about 0.7080 around half way down the tooth (Figure 9). Cattle M1 teeth mineralise partly *in utero* and continue growing up to ~3 months of age (Brown et al. 1960) and are potentially problematic for reconstructing mobility due to the possible effects of strontium recycling from maternal reservoirs, although the magnitude of any impact and how this might vary between species is not currently clear (Montgomery 2010). It is therefore not possible to say whether the step change in $^{87}Sr/^{86}Sr$ ratios at about 14 mm from the enamel root junction (ERJ) reflects a change in maternal metabolism/strontium recycling associated with giving birth and the start of lactation, or dietary change of the mother, or genuine mobility of both mother and infant. However, data from the lower half of the tooth between 14 and 0 mm from the ERJ, which formed post-birth, does indicate that the mother and calf lived on geologies with $^{87}Sr/^{86}Sr$ ratios of about 0.7080 during this period of tooth formation, very similar to the range observed in cattle HG1. Overall, the data suggest that all three cattle probably grew up in either the Ahmar Foothills or the Somali Plateau area. These regions both comprise a mix of Oligocene basalts with very low ratios and the Amba Aradam and Hamanlei formations, with predicted values more similar to those at Harlaa, a mix of which may well produce bioavailable values such as those observed in the cattle. The Quaternary sediments of the Afar Plains also remain an outside possibility specifically for cattle HG1 given the low ratios measured for this individual. Each of these possible source regions are located at distances of around 10–30 km from Harlaa, consistent with the importation of cattle from the local hinterland around the site.

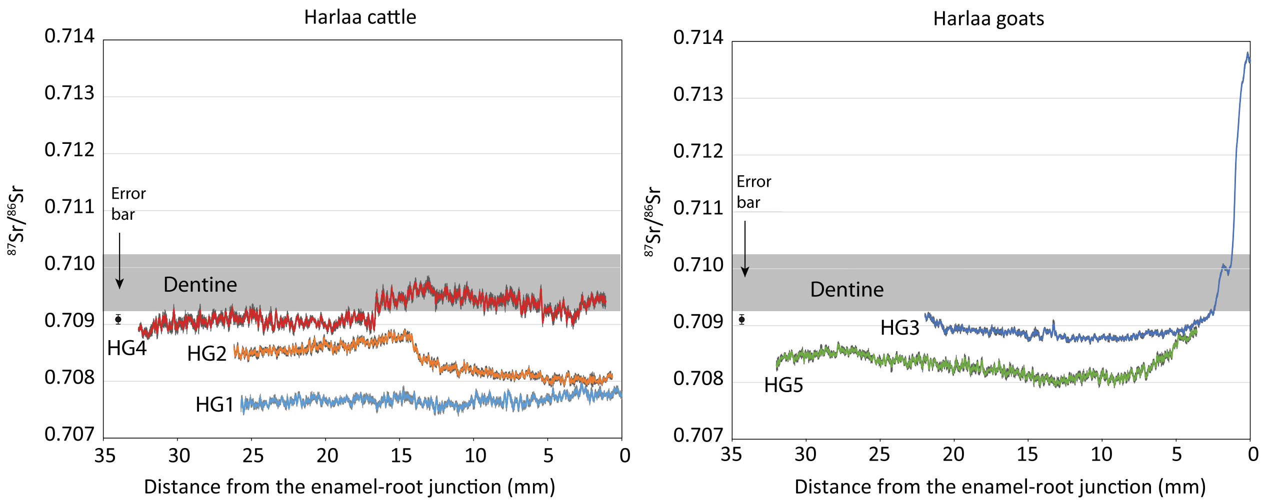

Figure 9. Stable strontium isotope ratio profiles measured on five herbivores from Harlaa. Lines indicate the 10-point mean moving average of the individual laser ablation measurements (collected approximately every 10 µm along the tooth cusp). Dark grey shading around these lines indicates uncertainty, calculated as the standard mean error. The baseline defined for the Harlaa site using the tooth dentine data is marked in light grey. Measurement error is indicated by the error bar, which represents the reproducibility of the pig enamel standard at 1σ (see Methods).

Concerning the two goats, HG3 and HG5 both grew up on geologies characterised by $^{87}Sr/^{86}Sr$ ratios between approximately 0.7080–0.7090, the same isotopic range as identified for the cattle (Figure 9). Additionally, HG3 shows clear evidence of mobility in the final weeks or months of the tooth growth period characterised by a rapid change in $^{87}Sr/^{86}Sr$ from about 0.7090 to above 0.7135. This change occurs without any increase in ^{89}Y that would indicate contamination by REEs. Additionally, the $^{87}Sr/^{86}Sr$ is dramatically different to that recorded in the tooth dentines, ruling out diagenetic contamination by strontium from the local burial environment; and the ^{88}Sr beam intensity falls from around 16 volts to 9 volts in step with the change to higher ratios (see Supplementary Information), whereas contamination with diagenetic strontium would be expected to have increased the ^{88}Sr beam intensity. These data therefore indicate movement away from pastures on Mesozoic deposits where the animal HG3 was reared to different geologies, with different soil and vegetation types, once the animal had matured. The other analysed goat, HG5, also shows hints of starting a similar movement at the same point during tooth growth. However, the final 4 mm of enamel in this individual was contaminated with diagenetic strontium (visible as simultaneous sharp increases in ^{89}Y and ^{88}Sr, and $^{87}Sr/^{86}Sr$ that converged with the average for Harlaa defined in the tooth dentines) meaning this movement cannot be confirmed. $^{87}Sr/^{86}Sr$ readings as high as 0.714 in individual HG3 are clearly associated with older Precambrian granites, such as those found in the hills which immediately surround Harlaa, and may indicate that seasonal vertical transhumance of goats was being practiced.

Humans

Laser ablation repeated measurements of the same tooth

Paired $^{87}Sr/^{86}Sr$ profiles in five teeth analysed twice showed largely indistinguishable isotopic ratios and very similar trends and intra-tooth changes along the axis of growth (Figure 10; Table 4). No wiggle-matching was undertaken when aligning the isotopic curves, data were simply aligned based on the enamel-root junction in each case. Short areas of minor disagreement are present, most likely caused by (1) small variations in the timing of enamel formation between the more vertical labial and more curved lingual sides of the tooth; (2) discrepancies in the exact position of the laser track within the width of the enamel strip, as well as (3) noise in the laser ablation signal (see Methods). In no case do these fluctuations significantly affect the interpretations of the strontium isotope data regarding mobility of the human individuals. The magnitude of the differences is similar to that observed previously between paired bulk-enamel samples of left and right dental elements from the same individual (Knudson et al. 2016). Profiles of ^{88}Sr and ^{89}Y that are routinely monitored and used to help interpret laser ablation data (Supplementary Information) also display excellent agreement between tooth cusps, indicating similar patterns of diagenetic interference affecting the thinnest enamel close to the enamel-root junction in each tooth/tooth profile (these sections were removed as part of the data reduction process and are therefore not included in the summary data in Table 4 or shown in Figure 10). The results demonstrate that laser ablation measurements of enamel $^{87}Sr/^{86}Sr$

Table 4. Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ profiles measured by laser ablation.

Species / Individual	Tooth	Mean	Std. Deviation	Median	Interquartile Range	Minimum	Maximum	Range	Mean standard error
Cattle	HG1	0.70767	0.00008	0.70766	0.00011	0.70744	0.70800	0.00055	0.00005
Cattle	HG2	0.70837	0.00027	0.70839	0.00049	0.70793	0.70889	0.00096	0.00005
Goat	HG3	0.70916	0.00093	0.70889	0.00017	0.70871	0.71378	0.00507	0.00003
Cf. cattle	HG4	0.70923	0.00022	0.70918	0.00038	0.70877	0.70975	0.00098	0.00007
Goat	HG5	0.70832	0.00020	0.70832	0.00032	0.70794	0.70893	0.00099	0.00005
Human 1	HG6	0.70888	0.00009	0.70889	0.00016	0.70867	0.70908	0.00041	0.00009
Human 2	HG7	0.70983	0.00017	0.70983	0.00025	0.70933	0.71020	0.00087	0.00012
	HG8	0.70991	0.00014	0.70990	0.00019	0.70958	0.71036	0.00078	0.00011
Human 3	HG9 (1)	0.71010	0.00020	0.71008	0.00026	0.70964	0.71067	0.00103	0.00013
	HG9 (2)	0.71018	0.00015	0.71020	0.00017	0.70966	0.71057	0.00091	0.00011
	HG10	0.71055	0.00018	0.71057	0.00023	0.70984	0.71098	0.00114	0.00015
	HG14	0.71038	0.00027	0.71039	0.00041	0.70987	0.71108	0.00121	0.00014
	HG15 labial	0.70998	0.00018	0.70998	0.00023	0.70947	0.71048	0.00101	0.00016
	HG15 lingual	0.70997	0.00020	0.70996	0.00029	0.70939	0.71043	0.00105	0.00015
Human 4	HG11 labial	0.71077	0.00018	0.71078	0.00028	0.71031	0.71123	0.00092	0.00012
	HG11 lingual	0.71083	0.00021	0.71083	0.00029	0.71030	0.71139	0.00109	0.00018
	HG12 lingual	0.71083	0.00022	0.71086	0.00035	0.71019	0.71127	0.00108	0.00014
	HG12 labial	0.71065	0.00021	0.71066	0.00031	0.71020	0.71119	0.00099	0.00011
	HG13 labial	0.71173	0.00024	0.71171	0.00039	0.71123	0.71219	0.00096	0.00013
	HG13 lingual	0.71171	0.00026	0.71175	0.00036	0.71107	0.71226	0.00119	0.00013
Human 5	HG16	0.71135	0.00010	0.71134	0.00013	0.71110	0.71167	0.00057	0.00009

Note that the mean standard error relates to the 10-point moving mean average for each tooth (represented in Figures 9 and 10 as dark grey shading around the $^{87}Sr/^{86}Sr$ profiles). It is approximately twice as large for the human teeth compared to herbivore teeth, reflecting a higher strontium concentration in the herbivores. See Supplementary Information for further details.

profiles are repeatable in human teeth at different positions around the tooth cusp and that the specific sampling position around tooth cusps in humans does not significantly affect the outcome of the measurements, despite differences in tooth morphology. This suggests that other factors should take precedence when deciding where to sample human teeth for strontium isotope analysis, for example the condition of the enamel in different places around the crown, location of cracks through the tooth, or ease of access for drilling a sample when teeth are still fixed in the jaw.

Comparisons between teeth sampled from the same individual

Multiple teeth with overlapping periods of enamel mineralisation were sampled in humans 2, 3 and 4. Enamel mineralisation is a complex two-stage process resulting in a degree of time-averaging that varies in duration in different places of the same tooth, and in two different teeth that formed simultaneously in the same individual (Montgomery 2010). Additionally, individual molar elements mineralise at different speeds in different individuals with important differences between males and females (Adams et al. 2018; Esan, Mothupi, and Schepartz 2018; White and Folkens 2005; Hillson 2005, 210–214; Demirjiajn and Levesque 1980). This means that the mineralisation period in human teeth can only be stated approximately, which complicates the process of aligning isotopic data measured at high resolution by laser ablation from multiple teeth from the same individual. Nonetheless, $^{87}Sr/^{86}Sr$ ratios in enamel that forms simultaneously will be related (Anders, Osmanovic, and Vohberger 2019; Knudson et al. 2016), and isotopic profiles in teeth with overlapping formation periods from the same individual are expected to show similar trends.

Overall, teeth from the same individual with overlapping growing periods show a good level of agreement, however some differences were also observed. In Human 2, a deciduous M1 shows indistinguishable $^{87}Sr/^{86}Sr$ ratios to those measured in the earliest-forming enamel in a permanent M1 (Figure 10). However, Human 4 shows a more mixed pattern, whereby deciduous central and lateral incisors that form simultaneously show excellent agreement but a deciduous canine, which is predicted to form partly simultaneously, shows no overlap in the $^{87}Sr/^{86}Sr$ profile. In this case it appears that mineralisation of the mandibular incisors finished early and/or the mineralisation of the maxillary dc1 was late starting, eliminating the period of overlap in formation entirely. Finally, in Human 3, three simultaneously-forming deciduous teeth (dm1, dm2 and dc1) show good overall agreement although a small section of more enriched values in dm1 is expressed to a lesser extent in dm2 and not at all in dc1. Meanwhile, a permanent M1 from the same individual aligns well with the more enriched values of dm1 but shows little or no overlap with the simultaneously-forming dm2 and dc1. The patterning in Human 3 is more difficult to explain as changes to the tooth formation periods due to the long period of predicted overlap, and probably results from the various time-averaging effects introduced during enamel growth and mineralisation and the exact positioning of the laser track on the M1 tooth cusp.

Human mobility

Strontium isotope profiles in 11 teeth from five humans reveal different and distinct mobility patterns in each analysed individual (Figure 10; Supplementary Information). Three individuals were found in Muslim burials. Human 2 (HAR17 (C) upper burial) is represented by teeth that form *in utero* through to around three years old (one dm1 and one M1). The enamel strontium profiles show consistent isotopic ratios indistinguishable from the "local" Harlaa signature throughout the period of growth. The consistency of the signature indicates a seasonally-uniform and stable geographic source of food and water to mother and baby for the entire 3+ years duration of tooth growth, including the period of formation *in utero* represented in the dm1. The most parsimonious explanation for these patterns is that the mother was consuming food and water derived from Harlaa and the surrounding similar limestone geologies during pregnancy and, following birth, the infant baby and mother continued to live in the same area during the formation of the deciduous teeth, up to at least 3 years of age. Assuming that liquids other than breast milk and solid foods were introduced prior to the infant dying, this weaning diet had the same strontium isotopic composition as the food and water consumed by the mother during pregnancy and lactation after giving birth.

Human 3 (HAR17 (C) lower burial) is represented by four teeth that formed *in utero* through to about three years of age. The earlier-forming teeth, mineralising up to approximately 11 months of age, mostly show ratios indistinguishable from the local Harlaa range, apart from a short section of dm1 that has values between 0.7105-0.7110. The permanent M1, which forms between birth and three years of age, shows isotopic ratios in the same range as the elevated section of dm1. Isotopic differences in Human 3 between teeth that are predicted to grow simultaneously prevent a detailed interpretation for this individual. Instead, we tentatively suggest that, as with Human 2, the mother appears to have mostly consumed food and water derived from Harlaa and surrounding similar geologies while pregnant; this diet continued for mother and baby after birth up to the end of growth in dm2, *circa* 11 months of age. The more radiogenic values in dm1 occur at around or just after the time of birth, and could reflect dietary change associated with childbirth and the start of breast feeding, or possibly indicate a visit lasting a few weeks made by the pregnant mother out of the city to an older Precambrian geology in the hills near Harlaa. The more consistently enriched values in the adult M1 almost certainly indicate further movement after the deciduous teeth finished forming, also into an older Precambrian geology in the hills near Harlaa, but at what age this movement occurred is not currently known.

Human 4, the third Muslim burial (HAR17 (D)), has more enriched isotopic profiles than the other Muslim burials, derived from deciduous central and lateral incisors and a deciduous canine (Figure 10). The sampled enamel formed partly *in utero* up to around eight months of age, over which time the $^{87}Sr/^{86}Sr$ ratios rise from about 0.7104 to about 0.7121. The enamel strontium profiles fall entirely within the range estimated for the older Precambrian geologies found near Harlaa, and are notably higher than the range assigned to the Hamanlei formation upon which Harlaa itself lies. This indicates that the mother of Human 4 consumed food and water sourced from Precambrian geologies during pregnancy and while breast feeding after birth. The progressive enrichment over the first eight months of life indicates either a change in the source of food and water, mobility to a different area within the Precambrian geologies, or both. Precambrian geologies are found widely within a few kilometres of Harlaa in the hills near the site and also in more distant locations to the south and east (Figure 7).

The $^{87}Sr/^{86}Sr$ profiles of Humans 1 and 5 indicate that both individuals consumed food and water sourced from geologies different to Harlaa during the period of tooth formation (Figure 10). Human 1 (TUM15 (A) 2) from the non-Muslim *Daga Tuli* burial tumuli at Sofi, represented by a 2nd premolar, spent their early childhood between 2 and 7 years of age in a single geological territory with a strontium isotope profile between 0.7085 and 0.7090. Human 1 is therefore distinct from all other analysed human teeth and is also the only one of the five investigated humans to have a strontium isotope profile showing significant overlap with the analysed fauna. This might indicate

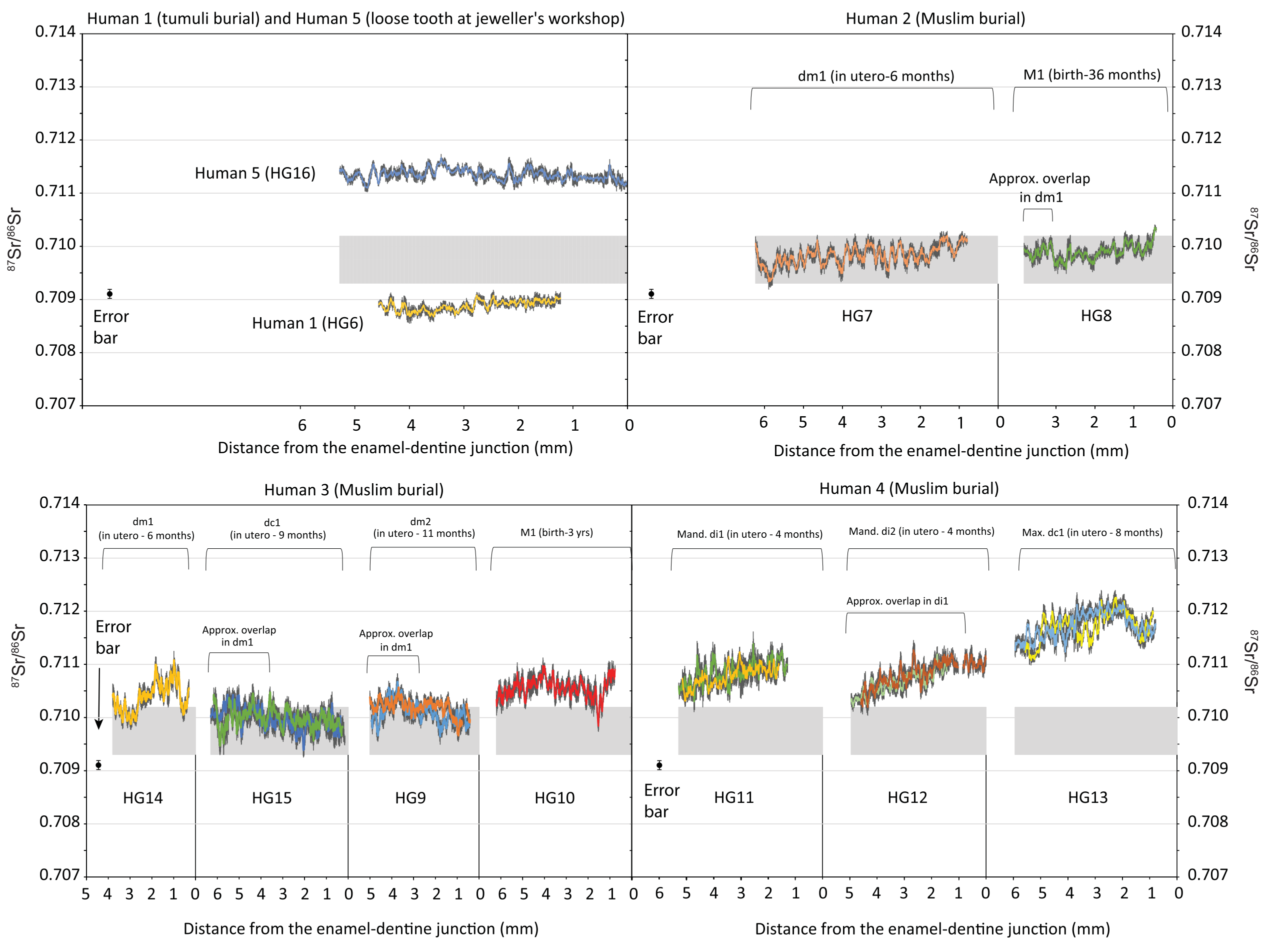

Figure 10. Strontium isotope data for the human teeth excavated at Harlaa and Sofi. Double tracks for HG11, HG12, HG13 and HG15 reflect double-sampling along the labial and lingual cusps of each tooth (see Methods). Double track for HG9 reflects two separate samples collected *c.*3 mm apart. Further explanation of the data plots is given in the legend of Figure 9.

a chance association with isotopically similar but geographically separated geological contexts, but a more direct association is also possible; for example, this individual might have lived or worked with shepherds during childhood. The geology within a 10 km radius of the tumuli burial at Sofi contains a mix of Precambrian gneisses/granites with relatively high bioavailable $^{87}Sr/^{86}Sr$ and Mesozoic limestones expected to produce lower isotopic ratios similar to the tooth dentine data. Beyond a 10 km radius, the region is extensively dominated by Precambrian deposits, mixed with smaller areas of more recent Quaternary deposits predicted to have very low $^{87}Sr/^{86}Sr$ ratios. If the individual buried at Sofi was a local, he must therefore have grown up in the limestone hills region lying immediately south of the modern city of Harar, which stretches for more than 20 km N-S (Figure 7). Alternatively, as Human 1 did not die for at least four years after the measured PM2 enamel finished mineralising, it is possible this individual spent the earlier years of their life further west on the Somali Plateau where Mesozoic limestones and other marine-derived deposits are present much more extensively. This would imply either a movement into the local area near Sofi in the years prior to death, or that the individual was taken to Sofi after death for the explicit purposes of burying them there. Meanwhile, Human 5, represented by a loose deciduous canine found in the workshop complex (HAR15 [B] 3), shows a more radiogenic signal between 0.7110 and 0.7115, reflecting the diet of the mother during pregnancy and immediately after birth. These strontium isotope values can be correlated with the same radiogenic geologies encountered by Humans 3 and 4, namely the Precambrian deposits found in the hills near Harlaa and beyond.

Discussion – Islamisation and mobility

The strontium isotope results provide a first insight into the diverse origins of the Harlaa community in the absence of historical sources, and provide information on Islamisation. Three infants buried in cemeteries in Harlaa following Muslim traditions have been measured, providing clear evidence of locally born Muslim infants. These include one that was born and died in Harlaa aged approx. 3.5 years (Human 2); one that shows evidence of mobility between Harlaa and the hills near the site throughout their 6.5 years of life (Human 3); and one who was born and spent at least the first 8 months of life in the hills region but was subsequently buried in Harlaa aged around 6.5 years (Human 4). This indicates that the Muslim community was well-established in Harlaa, and among families living in the surrounding rural environment within a few km of Harlaa. This is significant for it suggests a religious community that was not purely focused inside Harlaa, an urban population directly involved with and influenced by international trade networks. Rather, those following Islamic practices were also fully integrated among the indigenous rural community in the hinterland surrounding Harlaa, suggesting either that immigrants following the Islamic religion had settled throughout the area near Harlaa, or that members of the indigenous population had converted to Islam. The loose tooth from the workshop complex (Human 5) is from another individual who grew up in the hills surrounding Harlaa. Nothing else is known about the provenance of this tooth or the individual it belonged to, except that their tooth was either extracted as part of dental work, fell out and was lost, or formed part of the wide range of material used in the workshops.

The individual buried in Sofi (Human 1) attests different origins. They probably grew up either in the limestone hills near the tumuli site, or further west in the Ahmar foothills/Somali Plateau region. In either case, the isotopic range is distinct from that shown by the Muslim individuals and correlates with the source of some of the animals consumed at Harlaa. Burial under a tumuli was a non-Muslim practice, and the possibility that this individual was a pastoralist/shepherd is important in questioning the hypothesis that pastoralists were always amongst the first groups to convert to Islam for reasons such as the ease of worship that Islam requires, equating well with a mobile lifestyle, or that they were exposed early to the religion through acting as guides for Muslim merchants (e.g. Trimingham 1959, 1968). Rather, a more complex pattern is suggested (cf. Insoll 2003, 2017), where some urban population (Harlaa), some rural population (around Harlaa) and some pastoralists were Muslim, but equally, other components of these groups were not Muslim, and it suggests that both Muslims and non-Muslims co-existed in the region, as they do today. Furthermore, the possibility that Human 1 may have been taken to Sofi specifically for burial would correlate with the large numbers of burial mounds reported by the local population for the Sofi region, indicating that it, like parts of the Tchercher Mountains east of Harar (cf. Joussaume 1980, 2014), may have been a locale chosen for this role, for reasons now unknown.

Alongside being tied into international trade networks, Harlaa was also a centre for local trade, with clear evidence for the importation of animal foods and/or other by-products from the wider region. The strontium ratios measured in the goats and cattle are consistent with having grown up in the rural areas around Harlaa, on the marine-derived deposits found in the foothills of the Ahmar Mountains and the Somali Plateau within distances of 0–30 km of the site. This amplifies the zooarchaeological data showing that Harlaa cattle were mostly retained into adulthood

(Gaastra and Insoll 2020), as the isotopic data indicates that they were kept away from the site at least while growing up. Conversely, the zooarchaeological studies indicate that goats were more actively managed for their meat, with around 50% slaughtered as sub-adults between 18 months – 3 years of age (Gaastra and Insoll 2020). The isotopic data have now suggested another way in which goats were actively managed, moving them from locations where they were calved into the hilly upland areas formed of Precambrian granites at around 12 months of age. Finally, it would appear important that four of five analysed humans show substantially different $^{87}Sr/^{86}Sr$ profiles to the five investigated animals. Although the numbers of individuals investigated remains small so far, if this pattern is representative of the broader circumstances at Harlaa, it would suggest that families following Muslim traditions may not have been engaged in farming /livestock rearing activities. Instead, it is possible that they were primarily involved in other activities such as mining, trade, and craft production, evidence for which is represented in all areas of Harlaa.

Conclusions

Further work is required to understand bioavailable strontium variability across the varied geologies that surround Harlaa to test the interpretations presented here. It is already clear that a potentially large range in bioavailable strontium isotope values exists around the site, and while this offers great potential for distinguishing local and regional movements across the Ahmar Mountains and eastern Ethiopia more generally, it will also make it harder to detect very long distance international migrants to Harlaa who immigrated from abroad, which is also a probability based on the presence of technologies and materials from the Arabian peninsula and western India, for example (Insoll et al. in press). Improvements to the strontium base map could be achieved by collecting plant and sediment samples once the security situation improves sufficiently to allow travel through remote areas, alongside analysis of both modern and archaeological, and wild and domestic fauna, that will average some of the natural variability encountered across the study region. Analysis of small mammals such as rodents would help pin down the isotopic signal from discrete geologies and specific parts of the landscape. Together with the data presented here, such analyses will help clarify the "local" isotopic range and, particularly, whether it is possible to confidently distinguish different parts of the Mesozoic marine-derived rocks on the one hand, and the Precambrian granites and gneisses on the other. Our results have taken the first step in elucidating the composition of the Harlaa community and provide a platform for further future work.

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