# Snapshots in time: MicroCT scanning of pottery sherds determines early domestication of sorghum (*Sorghum bicolor*) in East Africa

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**Declarations of Interest: None**

**Key Words**

**Abstract**

MicroCT imaging of organic inclusions within pottery sherds from Khashm el Girba 23 (KG23), Sudan, reveals domesticated sorghum (*Sorghum bicolor* subsp. *bicolor*) at c. 3700-2900 BC. The percentage of non-shattering spikelet bases was c. 73% of identifiable visualizations, with c. 27% representing wild types. These analyses demonstrate the domestication of sorghum is significantly earlier than suggested by previous archaeological

research. These results also demonstrate that microCT scanning is a major qualitative and quantitative advance on pre-existing methods for the investigation of crop remains in pottery sherds, which hitherto have been reliant on surface impressions; it is non-destructive, provides higher resolution 3D imaging of organic inclusions, and enables greater recovery of inclusions within a sherd. MicroCT analysis of ceramics, mudbrick and other building materials has considerable potential for improving the chronologies and resolution for the domestication of other cereals in the past.

**Introduction**

Sorghum (*Sorghum bicolor*) is one of the most important cereal crops cultivated globally, yet current archaeobotanical evidence for the timing and location of sorghum domestication is limited in comparison with other major cereal crops, such as maize (*Zea mays*; Kistler et al., 2018), wheat (*Triticum* spp.; Allaby et al., 2017), barley (*Hordeum vulgare*; Allaby et al., 2017) and rice (*Oryza sativa*; Fuller et al., 2016). Until recently, the earliest evidence for domesticated sorghum dated to c. 2000-1500 BC from India (Fuller, 2003), even though it has long-been been considered an African domesticate (Harlan & Stemler, 1976; Kahlheber & Neumann, 2007). Recent research at two sites in the Sudan, Khashm el Girba 23 (KG23) and Mahal Teglinos K1, used impressions of sorghum husks and rachillas in pottery sherds to provide an initial chronological framework for understanding the character and duration of the domestication episode for sorghum extending beyond 3000 BC (Winchell et al., 2017: Beldados et al., 2018). In addition, domesticated sorghum grains and chaff dating from between 2500 and 2000 BC have been recovered by flotation at the site of Jebel Moya, south of Khartoum (Brass et al., 2019). Here we use microCT scanning to virtually reconstruct sorghum husks and rachillas, as well as other organic remains embedded within pottery sherds from the earliest of these sites, KG23. The higher quality and greater quantity of archaeobotanical information recovered by microCT scanning in comparison to previously employed methods reveals the domestication of sorghum had occurred by c. 3700-2900 BC, much earlier than previously inferred.

**A Note on Sorghum Taxonomy**

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The determination of species and subspecies in archaeobotanical remains of sorghum (*Sorghum bicolor*) is often problematic. Recent taxonomy and genetics recognize three subspecies of *Sorghum bicolor*: wild (ssp. *verticilliflorum*), domesticated (ssp. *bicolor*) and inter-subspecific weedy hybrids (ssp. *drummondii*) (Wiersema & Dahlberg, 2007; Teshome & Feyssa, 2013; also see Wang et al., 2020). Both wild and domesticated forms of sorghum are cross-pollinating and therefore some mixing of types would be expected even in fully domesticated populations. As early as 1936, Snowden noted the presence of intermediate forms of wild sorghum growing in the vicinity of cultivated populations. These intermediate forms were likely exploited in the past. Examples of such intergrading forms are evident in the proportions of spikelet base types found in some modern collections where domestication traits, e.g. non-shattering spikelets with open glumes can be seen within single wild populations (see Winchell et al., 2017).

Archaeobotanical assemblages of sorghum should be differentiated into three phenotypic categories based on spikelet base morphology (Fig. 2): smooth (wild), torn rachilla (domesticated or immature) and rip scar (domesticated) (Winchell et al., 2017; Beldados et al., 2018). Wild sorghum spikelets, which naturally disperse by detaching from the rachilla, possess a smooth and even abscission scar. Domesticated-type sorghum spikelets, must be forcefully separated manually, for example by threshing, and possess a rachilla that is typically torn below the spikelet base leaving a stub; although some domesticated-type spikelets possess a "rip-scar" where the spikelet base is completely removed (noted only in modern domesticated reference material). While the "rip-scar" is exclusively found in domesticated populations it is in the minority, while the torn rachilla is the typical dominant form in domesticated populations, but might possibly result sometimes from the harvesting of green (or immature) wild plants. Nevertheless, domesticated-type spikelets are further differentiated from immature-type spikelets by the presence of a fully-filled grain or signs of grain removal through de-husking, such as an empty glume or spikelet fork; whereas the grains of immature types are not fully filled, smaller in size and flattened. Examples of immature grains and spikelets have been illustrated in carbonized macro-remains from the site of Mahal Teglinos K1 (Beldados et al 2018). Immature-type spikelets are expected to occur in significant numbers within populations undergoing pre-domestication cultivation, during which harvesting most likely occurred while the panicle was still ripening, to retain

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the maximum possible grain yield without the loss of wild-type spikelets to natural dispersal (Fuller, 2007). Domesticated sorghum is conventionally divided into five cultivated races, but early domesticated forms should all fall within the race *bicolor*, which shares tight-fitting hulls with its wild ancestor (Harlan & Stemler, 1976; Fuller & Stevens, 2018).

**The Archaeobotany of Sorghum Domestication**

The Eastern Sahelian region has long been considered the most likely location for the origin of sorghum cultivation and its subsequent domestication (Harlan, 1971; Harlan & Stemler, 1976; Haaland, 1999). The modern distribution of the wild progenitor crop, *Sorghum bicolor* ssp. *verticilliflorum,* is widespread across Africa; specifically*,* race aethiopicum is regarded as ancestral to domesticated forms, which occurs across semi-arid savanna and the southern Sahelian zone from Mauritania to western Ethiopia (De Wet and Harlan 1971; Dahlberg 1995; Fuller & Stevens, 2018). Prior to 2017 the earliest identified archaeobotanical evidence for domesticated sorghum populations came from India dating to between c. 2000-1500 BC (Fuller, 2003; Kahlheber & Neumann, 2007). Available evidence from Africa, including Early and Middle Holocene Sudan, the Egyptian desert and southern Libya, was restricted to morphologically wild forms, suggestive of wild sorghum gathering from 7500 BC to 3750 BC (Fuller & Stevens, 2018; Mercuri et al., 2018). Therefore, archaeobotanical evidence was required from East African contexts earlier than 2000 BC to document the domestication process before transference eastward to India.

Since the end of the Pleistocene, the Sahel and bordering regions were home to a large number of wild summer rain-fed cereals and grasses (Harlan, 1971; Clark, 1980; Marshall & Hildebrand, 2002; Neumann, 2005), which were exploited by ceramic-bearing hunter-gatherer groups during the early to mid-Holocene (Stemler, 1990; Wasylikowa, 1992; Wasylikowa & Dahlberg, 1999; Barakat & Fahmy, 1999; Mercuri, 2001, 2008; Barich et al., 2014; Mercuri et al., 2018). Species associated with such contexts include wild sorghum, as well as a number of small millets comprising *Pennisetum, Digitaria, Panicum, Echinochloa* and *Brachiaria*. Wild sorghum appears in large concentrations alongside these smaller millets at a number of archaeological sites spread across a wide region, including the Western Desert of Egypt at Nabta Playa (8000-7000 BC; Wasylikowa & Dahlberg, 1999), Southern Libya during the Late Acacus Period (c. 7500-7100 BC; Wasylikowa, 1992;

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Castelletti et al., 1999; Mercuri, 2001, 2008; Olmi et al., 2011), and Central Sudan (c. 5700-3750 BC; Abdel-Magid, 1989, 2003; Stemler, 1990; Sadig, 2010). Until recently, there had been no research to reveal evidence for a protracted period of pre-domestication cultivation of sorghum, or the domestication episode, which occurs prior and leads to the fixation of phenotypic and genetic changes associated with domestication, such as non-shattering spikelet bases in early archaeobotanical assemblages of other major cereal crops (Fuller et al., 2014).

Recently the examination of impressions of chaff tempering preserved on the surface of ceramic sherds has provided new evidence for the appearance of domesticated morphotypes of sorghum in the eastern Sahelian region. Archaeobotanical assemblages at two sites, KG23 (Winchell et al., 2017) and Mahal Teglinos K1 (Beldados et al., 2018), contained sorghum spikelets of both wild (*verticilliflorum*) and domesticated (*bicolor*) types, as would be expected of populations undergoing domestication under cultivation. Both sites are located in the Southern Atbai, the area between the Atbara, Gash River and Gash River Delta in modern day Sudan (Fig. 1). Today, it is a featureless semiarid steppe best known for mobile pastoral livelihoods, but summer rain-fed grasses provide potential gathered foods, and traditional low-rainfall cultivation of millets or sorghum is practiced (Sadr, 1991; Nixon et al., 2011; Winchell et al., 2017; Lancellotti et al., 2019). Under wetter climatic conditions during the middle Holocene, zones of potential cultivation or wild grass stands would have been more extensive (Lezine 2017; Hopcroft et al 2017). Subsequently with gradual drying these grasslands contracted, especially between 4000 and 2000 BC (Shanahan et al., 2015; Lezine 2017; Hildebrand et al., 2018).

The cultural materials at KG23 and Mahal Teglinos K1 are both affiliated with the Atbai Ceramic Tradition (ACT) of the Sothern Atbai region (Fattovich et al., 1984; Marks et al., 1986; Marks & Fattovich, 1989; Sadr, 1991; Fattovich, 2010; Manzo, 2012; Winchell, 2013), which is divided into seven major cultural groups: the Amm Adam Group (c. 6th-5th millennia BC); the Malawiya Group (c. 5th-4th millennia BC); the Butana Group (c. 4th-3rd millennia BC), which includes KG23; the Gash Group (c. 3rd-2nd millennia BC), which includes Mahal Teglinos K1; the Mokram Group (c. 2nd-1st millennia BC); the Hagiz Group (c. mid 1st millennium BC-mid 1st millennium AD); and, the Gergaf Group (mid 2nd millennium AD)

(Shiner, 1971; Sadr, 1988; Fattovich, 1989; Abbas & Jaeger, 1989; Sadr, 1991; Manzo et al., 2011; Manzo, 2012; Winchell, 2013). ACT sites, particularly those of the Butana Group, show increases in site area and thickness of cultural deposit over time, representing longer and more intense occupation than at earlier sites (Fattovich et al., 1984; Mbutu, 1991; Winchell, 2013). The Butana Group sites are considered to represent a change from a mobile hunter-gatherer subsistence strategy to more sedentary practices (Sadr, 1988; Grove, 2007; Winchell, 2013), even though faunal remains suggest a continuation of hunting wild game until at least the 3rd millennium BC (Peters, 1986; Manzo, 2012). The ACT sites may be of particular relevance to the spread of African cereal domesticates due to Gash Group sites, such as Mahal Teglinos K1, revealing evidence of complex administrative systems with long-distance trade links to Egypt, the Red Sea and the Arabian Peninsula (Manzo, 2012; Fattovich, 2010, 2012; Bard & Fattovich, 2013). These trade links present a possible geographic and economic route for the transference of African crops, including sorghum and pearl millet (*Pennisetum glaucum*), to the Indian sub-continent sometime during the late 3$^{rd}$ or early 2$^{nd}$ millennium BC (Boivin and Fuller 2009; Winchell et al., 2018).

Sorghum remains at KG23 and Mahal Teglinos K1 were identified in the form of plant impressions on the surfaces of ceramic vessels and baked clays, supplemented by a small number of macro-remains at Mahal Teglinos K1 (Bedaldos et al 2018). The 117 sorghum surface impressions from both sites were analysed by viewing silicone casts of the ceramic surfaces under SEM and then comparing spikelet morphologies to modern reference collections of wild and domesticated sorghum species (Winchell et al., 2017; Beldados et al., 2018).

The sorghum assemblages at KG23 and Mahal Teglinos K1 were previously interpreted to represent plant populations still undergoing domestication due to the presence of both domesticated and wild-type spikelets, implying that morphological domestication traits were not yet fixed. Within these initial studies, sorghum at Mahal Teglinos K1 (2000-1700 BC; Beldados et al., 2018) appeared further along the evolutionary path to domestication than at KG23 (3600-3100 BC; Winchell et al., 2017), due to the slightly higher percentage of domesticated spikelets; namely, 39-60% (including indeterminate and excluding indeterminate in percentage calculations, respectively) compared with 31% at KG23. Given

the chronological gap between the sites of approximately 1000-1500 years, these results suggested the domestication of sorghum occurred over a protracted time period of millennia, comparable to other major cereals (Fuller et al., 2014).

Unfortunately, the number of specimens from the pre-domestication cultivation phase of sorghum is small in comparison to those used to construct domestication sequences for other major crops (Winchell et al., 2018). Only 51 sorghum spikelets were identified at KG23 and 66 at Mahal Teglinos K1 XI.  The development of a new protocol utilising microCT imaging for the visualisation of organic remains within pottery sherds has been shown to provide an innovative way to increase archaeobotanical yield by maximising analytical coverage of previously excavated and/or analysed materials (Barron et al., 2017; Barron & Denham, 2018). In an effort to increase the number of sorghum spikelet bases associated with pre-domestication cultivation assemblages available for analysis, this protocol was applied to a selection of pottery sherds from the site of KG23, which had previously been subjected to surface impression analysis and determined to contain sorghum as temper (Winchell et al., 2017).

**Methods**

The site of KG23 is the largest of the Butana Group sites, an occupation mound covering 12 hectares comprised of midden deposits up to 2 m thick, which was excavated by the Southern Methodist University in the 1980s (Fattovich et al., 1984). Other than sporadic occurrences of surface finds, all artefacts (consisting almost entirely of lithics and ceramics) recovered from the midden deposit were characteristic of the Butana Group cultural tradition demonstrating that the occupation at KG23 consisted of a single cultural component (Mbutu 1991; Winchell 2013).  Three locations within the occupation deposit were systematically excavated (KG23a, KG23b and KG23c) in 5 cm spits.

Two wood charcoal samples from Area C and a third from Area A were radiocarbon dated and calibrated to between 3700-2900 BC (Table 1; Winchell et al., 2017), suggesting the site was occupied for a discrete period of around 500 years. However, the large standard deviations for two radiocarbon ages (SMU-1155 and SMU-1201) produce broad two sigma (95.4%) calibrated date ranges for probable occupation of the site between c. 3900-2500 cal

BC (rounded to nearest century). Despite the lower confidence level, the one sigma (68.3%) calibrated date ranges are suggestive of occupation between c. 3700-2900 cal BC and are used here to provide a chronology for interpretation of the archaeobotanical findings. Given the radiocarbon samples were all wood charcoal, they may include an 'old wood effect' and thus provide maximum dates for occupation of the site. The duration of occupation within this 800 year time period cannot be accurately determined, although the range of the median calibrated dates hints it could be less than three hundred years. These dates together with the pottery at KG23 provide a relatively robust chronological framework for occupation of the site, and align with radiocarbon and relative dating of other Butana Group sites to c. 3800-2700 cal BC (Sadr, 1991; Manzo, 2012; Winchell, 2013).

During excavation, clear internal stratigraphic zonation was not observed in the sediments across the site (Fattovich et al., 1984; Winchell, 2013). Consequently, only a relative chronology based on depth within the deposit can be used to broadly periodise finds within the period of occupation. Following a comprehensive ceramic analysis for Area KG23c, Winchell (2013) constructed a relative chronological sequence based on a statistical seriation among the major ceramic types through the deposit, which differentiated between an early (levels 11-28) and late interval (levels 1-10). Although a systematic ceramic analysis was not conducted within the other two areas excavated at KG23, this chronostratigraphic pattern between an early and late interval was also present at six other Butana Group sites where the ceramic types were analysed (Winchell, 2013: 66-70).

Following the in-depth analysis of the ceramic assemblage (Winchell, 2013), surface impressions on a selection of 91 Khordhag Plain sherds were analysed for organic inclusions (Winchell et al., 2017). Out of all the ceramic types defined within the Butana Group, only Khordhag Plain type sherds present evidence for organic tempering in the form of visible surface impressions and dark residues left from the combustion of organic materials (Winchell, 2013: 189-192). Twelve of these Khordhag Plain sherds, representing stratigraphic positions throughout the occupation deposit in Area C (Table 1), were selected for Heliscan high-resolution microCT scanning (Latham et al., 2008; Myers et al., 2011) at the National Laboratory for X-ray Micro Computed Tomography (CTLab), Australian National University.

Four sherds were mounted in each of three aluminium tubes (55 mm diameter) and stabilised using packing foam. Each tube was then imaged at 100 kV and 65 mA with a 3 mm aluminium filter for a duration of between 11-13 hours, resulting in voxel sizes of between 20-22 μm. The resultant datasets were rendered using the open source visualisation software Drishti (v. 2.6.5) and Drishti Paint (v. 2.6.5) (Limaye, 2012). The distribution of organic inclusions identified by X-ray attenuation values lower than the surrounding clay matrix was visualised in low-resolution (1/64th) (Fig. 3) before individual inclusions were identified, segmented and visualised in high-resolution (see Barron & Denham, 2018). Individual inclusions identified as sorghum spikelets were assigned to one of four categories: wild, immature, domesticated and indeterminate, based on the morphology of their spikelet bases as well as grain shape and size (following Winchell et al., 2017; Beldados et al., 2018). These new results were considered alongside available comparable datasets to provide an updated time series of evidence relating to the sorghum domestication process.

**Results**

All twelve sherds contained organic temper, including significant quantities of unidentifiable plant fragments, possibly leaf and stem chaff, as well as morphologically distinct *Sorghum* spp. spikelets*.* The majority of spikelets appeared to be empty husks, suggesting they were likely waste material from the dehusking process. Quantities of fragmentary chaff material in all sherds and the presence of spikelet forks in one sherd (C2-13 29) reinforce this interpretation. Significantly, these finds indicate that harvested sorghum was being bulk processed to separate the edible grains from chaff; the resultant by-product of this routine food processing activity was then used as ceramic temper. This suggests that sorghum was a major dietary component in the same community that produced chaff-tempered ceramics. There were also a small number of spikelets that appeared as voids within the sherds, making it difficult to determine if they were included as empty husks or had contained grains that had combusted during the firing process. While it is also possible that the empty but intact domesticated-type spikelets could also come from free-threshing sorghum races, we expect those husks to differ in shape (generally being broader) and have a different angle of attachment to the rachis (see Fuller & Stevens, 2018).

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A total of 82 sorghum spikelets were identified in the 12 sherds: 57 torn rachis domesticated-type (69%), 21 smooth wild-type (26%), no obvious immature types and 4 indeterminate (5%) (Fig. 4; Table 2; see SOM Presentation S1 of all visualised spikelets). All domesticated types had mature glumes due to a rounded morphology and small length-to-width ratios, whereas no immature types were identified with only partially filled glumes. Also, no domesticated type spikelets possessed a rip scar, which is consistent with the findings of Winchell et al. (2017; 679). Beldados et al. (2018; 521) suspected rip scars may only appear in later domesticated populations or following changes in threshing techniques. The wild types were clearly identifiable due to significantly larger length-to-width ratios and smooth abscission scars. The morphologies of inclusions that were assigned indeterminate status were partially obscured by overlapping chaff or sherd edges, were fragmentary, or had features belonging to more than one of the three other categories. The 82 identified spikelet bases significantly augment evidence for early morphological change in sorghum (Fig. 5), suggesting completion of domestication by the 3rd Millennium BC at the latest.

Four sherds contained entirely domesticated sorghum remains (C2-1 129, C2-6 81, C2-28 114, C3-3 83); two sherds contained entirely wild-type sorghum (C3-9 36, C3-19 126); and the remaining six sherds contained both domesticated and wild-type spikelets with domesticated-types outnumbering wild in four of those sherds. Three *Echinochloa* grains were also identified in two sherds (C3-3 83 and C3-13 106).

**Discussion**

*Augmented archaeobotanical recovery*

Previous studies have highlighted ceramic sherds as under-utilised sources of archaeobotanical evidence (McClatchie & Fuller, 2014), but this research highlights how high quality archaeobotanical data is missed through conventional study of only surface impressions. Primarily, macrobotanical remains visible on pottery surfaces have been imaged in order to identify taxa and sometimes determine domestication status (e.g. Abdel-Magid, 1989; Stemler, 1990; Fuller et al., 2007; Manning et al., 2011; Winchell et al., 2017; Beldados et al., 2018). This method has been particularly useful when archaeobotanical preservation of charred macro-remains is poor or field sampling has been limited.

The microCT results, comprising 82 spikelets in 12 sherds, equates to an average recovery rate of 6.83 spikelets per sherd and vastly outstrips the efficiency of previous surface impression studies. Winchell et al. (2017) utilised surface impressions in 91 sherds from KG23 to identify 51 sorghum spikelets, equating to a recovery rate of only 0.56 sorghum spikelets per sherd. The application of microCT has increased the yield of spikelet bases per sherd by over 1000 % compared to the surface impression method.

MicroCT visualisation also significantly increases the quality of archaeobotanical recovery, because it enables three-dimensional reconstruction of the entire spikelet, whereas surface impressions are often partial resulting in indeterminate morphology of the abscission scar (compare microCT images in SOM Presentation S1 to surface impression photomicrographs in SOM Presentation S2). In the twelve sherds analysed, 20 out of 31 surface impressions were indeterminate, whereas only 4 out of 82 microCT visualisations were indeterminate (Table 2).

The increased quantity of spikelets identified is particularly significant because the total quantity of spikelets associated with the cultivation of early domesticated forms of sorghum across Africa is extremely low. Indeed, these microCT results from KG23 comprise the largest and earliest assemblage of domesticated spikelets for sorghum. Even though these conclusions are based on only a handful of pottery sherds from one site, these results show the potential of using microCT analysis to document the domestication of cereals, as well as other crops, using previously excavated pottery sherds from across Africa. The results from KG23 also warrant re-examination of the Mahal Teglinos K1 assemblage to potentially increase the quantity and quality of spikelet base data.

There are a number of reasons why quantities of early sorghum remains are currently fewer than other major cereal domesticates, including poor preservation rates, lack of archaeobotanical sampling as well as decreasing access to the region due to geopolitical instability. Reasons such as these make early sorghum cultivation in Africa the perfect case study for the application of newer analytical techniques, such as microCT, which do not require further fieldwork but rather can be applied to extract larger quantities of data from extant but limited archaeological pottery assemblages. MicroCT is non-destructive and can

be applied to other already collected pottery assemblages from the Eastern Sahelian zone in order to flesh out the chronological and contextual narratives of sorghum domestication.

*Domestication Episode for Sorghum*

The increased number of spikelets identified and analysed at KG23 through microCT not only increases the dataset size, but also significantly increases the proportional counts of domesticated spikelet types. The proportion of domesticated-type spikelets (as a percentage of those identified to wild and domestic) increased from 31% in surface impressions to 73% (57 of 78) in microCT analysis, while the wild-types decreased from 35% to 27% (21 of 78; Fig. 5). MicroCT results include many fewer classed as indeterminate. The larger microCT dataset indicates that a larger proportion of sorghum plants exploited at KG23 had the domesticated morphology than previously estimated. With more than 73% displaying domesticated morphology, the sorghum crop can be regarded as domesticated, with domesticated morphology nearing or at fixation. Furthermore, this implies that cultivation began earlier than previously estimated.

Although the new data indicate that the domestication of sorghum had likely occurred by 3700-2900 BC, the location and timing of initial cultivation are unknown. The high proportion of the domesticated form at KG23 suggests that domesticated sorghum was introduced to the area during the Butana Group occupation, rather than providing evidence for *in situ* domestication in the vicinity. Comparable evidence is needed from older sites to establish whether domestication, and pre-domestication cultivation, were taking place in the region during the earlier Malawiya/ Saroba Phase (5th millennium BC) and the Malawiya-Butana transition (4000-3800 BC).

Based on these new findings, the relatively low proportion of domesticated forms reported from Mahal Teglinos K1 requires re-evaluation. The percentage of domesticated spikelets at KG23, c. 73%, is higher than that estimated at Mahal Teglinos K1, c. 60% (Beladados et al., 2018), despite being c. 1000-1500 years older. However, the sample size at Mahal Teglinos was small and has not been studied by the improved microCT methods reported here. Also the material comes from fragments of baked clay used in the construction of fixed storage

vessels (Beladados et al., 2018), and as such might not be representative of routine food processing activities.

Nevertheless, current data raise questions about how a later site appears to have a lower proportion of domesticated forms in its assemblage. Although these sites are only ~50km apart, the drop-off between the sites could represent different sorghum exploitation patterns, either with a diverse range of sorghum populations at differing stages of the domestication process, or including larger contributions of wild sorghum gathering in some areas, like Mahal Teglinos. Further, recent flotation samples from Jebel Moya, some 350 km to the southwest of KG23, indicated a domesticated sorghum assemblage dating between 2500 and 2000 BC, also earlier and apparently more advanced than the Mahal Teglinos assemblage (Brass et al., 2019). Comparisons might be drawn with evidence from the Southern Levant where shattering, wild-type barley rachises continue to dominate some assemblages after 7000 BC despite the occurrence of domesticated (>80% non-shattering) barley over most of Western Asia by ca. 7500 BC (Fuller et al., 2018). Together these discrepancies highlight the need for analysis of more archaeobotanical assemblages from more sites and phases to better capture the dynamics of sorghum domestication in the eastern Sahel.

*Snapshots of early cultivation*

The increased number of sorghum spikelets identified in this study provides a nuanced view of *Sorghum bicolor* populations growing in the Southern Atbai region at 3700-2900 BC, as well as the ways in which they were being processed for consumption and utilised as pottery temper. The ability to visualise all the sorghum spikelets in each sherd provides a 'pot-by-pot' snapshot of sorghum use at KG23, which reveals that different sorghum populations were being exploited and used as temper for different ceramic vessels. The variations in the types of sorghum present in different sherds at the site potentially represents social and spatial variations in the types of plant exploitation practiced by different households or segments of the community that were supplying chaff to various potters living in the vicinity at the same time.

Some sherds are tempered with entirely wild sorghum. The sorghum in these sherds could represent the continued exploitation of wild sorghum populations, cultivation of non-domesticated plants by some communities living locally, or the utilisation of wild stands in years when crops failed. Other sherds contain only morphologically domesticated sorghum spikelets, which are indicative of a plant population that has undergone a significant period (c. 1500-2000 years) of human-mediated selection resulting in fixation of the loss of natural dispersal mechanism and increase in grain size; these sherds represent cultivation of domesticated sorghum in the vicinity of the potters' community.

Some communities seemingly exploited wild sorghum stands more heavily than others, perhaps persistently, whereas for others wild sorghum was probably only a fall-back following crop failure or a ritual requirement. Other communities were reliant to varying degrees on the cultivation of domesticated plants, or admixed assemblages of wild and domesticated plants; they produced tempering assemblages high in the chaff of the domesticated form, or mixed domesticated and wild forms, respectively. Alternatively, some subtle differences in scheduling may account for the variations between sherd assemblages, with wild sorghum harvests taking place some weeks prior to harvesting of cultivated populations; consequently, only slight scheduling differences in when pots were made would have affected the forms of sorghum chaff available as temper. There is also the possibility that a mixed subsistence strategy, combining cultivation as well as gathering of wild sorghum using baskets or ground collection, resulted in the observed variations between sherds.

All of the sherds imaged were of Khordhag Plain type with no apparent differences in composition, form or decoration between the pottery sherds containing wild-type spikelets and those with domesticated-type spikelets (Winchell, 2013).. There is some indication for a rise in the percentage of domesticated types versus wild types within sherds from the two chronostratigraphic zones identified by Winchell (2013) at KG23: domesticated types account for 70% (42 of 60) in levels 11-28 (early interval) and 83% (15 of 18) in levels 1-10 (late interval). However, interpretative caution is needed given the small sample size of sherds analysed here, and limited stratigraphic control through excavation in spits. Irrespective of stratigraphic position, though, some sherds represent the continued

exploitation of wild types, whereas others represent the exploitation of domesticated forms or mixed populations. The resultant window on early sorghum cultivation suggests a mosaic of practices and types of plants exploited in the vicinity of the site throughout the several hundred years of occupation. Given that each pottery sherd contains its own discrete archaeobotanical assemblage, it is possible that with more data from sites across northern Africa we will be able to disentangle the socio-spatial character of early sorghum domestication.

**Conclusion**

The application of microCT scanning to organic-tempered pottery sherds has previously been shown to reveal morphological details required to differentiate between domesticated and wild-type cereal remains. The protocol developed by Barron & Denham (2018) can be applied to assemblages of organic-tempered pottery to compile proportional counts of morphological types in order to evaluate the domestication status of cereal populations being exploited by people in the past. When applied to pottery sherds from KG23, the greater analytical coverage provided by microCT significantly increases the number of organic remains available for study relative to previous analyses restricted to surface impressions (Winchell et al., 2017).

The microCT analysis reveals a high proportion (c. 73%) of spikelets at KG23 were domesticated by c. 3700-2900 cal BC, and that these remains can be clearly linked to dehusking of grains for consumption. Given comparative evidence for the rate of cereal domestication (Allaby et al., 2017; Fuller et al., 2014), we can estimate that sorghum cultivation and domestication are likely to have begun some 1500-2000 years earlier (ca. 5500-5000 BC). While these results suggest that sorghum cultivation was well-established in the Southern Atbai by 3000 BC, they also suggest that the exploitation of morphologically wild sorghum populations continued from earlier periods. Earlier sorghum assemblages in Africa, such as Nabta Playa site E-75-6 in Egypt (8100-7900 BC), or) and Takarkori in Libya (7500-6400 BC), consist of entirely wild type sorghum remains (Wasylikowa & Dahlberg, 2001; Mercuri et al., 2018). The vastly increased quantity and quality of archaeobotanical recovery using microCT relative to surface impressions greatly increases the potential of ceramic assemblages already excavated from archaeological sites across northeastern Africa

to clarify the chronologies and social processes associated with the domestication of sorghum.

**Acknowledgements**

**Table 1.** AMS radiocarbon dates for wood charcoal from Khashm el Girba (KG23; Winchell et al., 2017). Calibrations undertaken using CALIB rev. 7.1.0 (Stuiver and Reimer, 1993) and Intcal20 calibration dataset (Reimer et al., 2020).

| Test Unit | Depth (cmbs) | Lab Code | Radiocarbon Age (BP) | Calibrated Date (BC) 68.3% | Calibrated Date (BC) 95.4% | Median Probability (BC) |
|---|---|---|---|---|---|---|
| KG23a | 90 | SMU-1155 | 4527 ± 253 | 3527-2906 (100.0) | 3893-3882 (0.2) 3798-2568 (99.2) 2527-2497 (0.6) | 3214 |
| KG23c | 115 | SMU-1188 | 4519 ± 67 | 3357-3306 (22.4) 3302-3282 (8.3) 3276-3266 (4.5) 3243-3102 (64.9) | 3492-3463 (2.2) 3375-3010 (96.5) 2979-2964 (0.7) 2948-2936 (0.6) | 3211 |
| KG23c | 135 | SMU-1201 | 4727 ± 154 | 3703-3679 (3.5) 3656-3337 (94.2) 3210-3194 (2.3) | 3912-3877 (1.1) 3804-3022 (98.9) | 3482 |

**Table 2.** MicroCT data for sorghum inclusions within twelve pottery sherds excavated from Test Units C2, C3 and D3 within Area C at Khashm el Girba (KG23), Sudan. MicroCT (mCT) and surface impression (SI) data are given for each sherd (7), with '?' indicating potential identifications. Sherd code represents test unit, level (excavated in 5 cm thick spits) and the designated sherd number within that level (in parentheses).

| Depth (cm) | Sherd | Torn | | Smooth | | Immature | | Indeterminate | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mCT | SI | mCT | SI | mCT | SI | mCT | SI | mCT | SI |
| 0-5 | C2_1 (129) | 3 | | | | | | | 3 | 3 | 3 |
| 10-15 | C3_3 (83) | 4 | 1? | | | | | | | 4 | 1 |
| 25-30 | C2_6 (81) | 7 | | | | | | | 3 | 7 | 3 |
| 40-45 | C3_9 (36) | | | 2 | 2? | | | 2 | 2 | 4 | 4 |
| 40-45 | D3_9 (13) | 1 | | 1 | | | | | 1? | 2 | 1 |
| 55-60 | C2_12 (79) | 7 | | 1 | 1 | | 3 | | | 8 | 4 |
| 65-70 | C2_13 (29) | 1 | | 7 | 1 | | | | 2 | 8 | 3 |
| 65-70 | C3_13 (106) | 4 | | 1 | | | | 1 | 1+2? | 6 | 3 |
| 70-75 | C2_15 (116) | 6 | | 1 | | | | | | 7 | 0 |
| 90-95 | C3_19 (126) | | | 5 | | | | | 1? | 5 | 1 |
| 90-95 | D3_19 (90) | 16 | | 3 | 1 | | | 1 | 5 | 20 | 6 |
| 135-140 | C2_28 (114) | 8 | 2 | | | | | | | 8 | 2 |
| **Totals** | **12** | **57** | 3 | **21** | 5 | **0** | 3 | **4** | 20 | **82** | 31 |

**References**

Abbas, S. & Jaeger, S.E. 1989. The early ceramic of the Eastern Butana (Sudan). In: Krzyzaniak, L. & Kobusiewicz, M. (Eds.), *Late prehistory of the Nile Basin and the Sahara*. Poznań Archaeological Museum, Poznań, pp. 473–480.

Abdel-Magid, A., 1989. *Plant domestication in the Middle Nile Basin—An archaeobotanical case study.* British Archaeological Reports International Series 523, Oxford.

Abdel-Magid, A., 2003. Exploitation of food-plants in the Early and Middle Holocene Blue Nile area, Sudan and neighbouring areas. *Complutum* 14: 345–372.

Allaby, R.G., Stevens, C., Lucas, L., Maeda, O. & Fuller, D.Q., 2017. Geographic mosaics and changing rates of cereal domestication. *Philosophical Transactions of the Royal Society B: Biological Sciences* 372(1735): 20160429. https://doi.org/10.1098/rstb.2016.0429

Barakat, H. & Fahmy, A., 1999. Wild grasses as 'Neolithic' food resources in the eastern Sahara: A review of the evidence from Egypt. In: van der Veen, M. (Ed.), *The exploitation of plant resources in ancient Africa*. Kluwer Academic/Plenum Publishers, New York, pp. 33-46.

Bard, K. & Fattovich, R., 2013. The Land of Punt and recent archaeological and textual evidence from the pharaonic harbour at Mersa/Wadi Gawasis, Egypt. In: Chrisomalis, S. & Costopoulos, A. (Eds.), *Human expeditions: Inspired by Bruce Trigger*. University of Toronto Press, Toronto, pp. 3–11.

Barich, B., Lucarini, G., Hamdan, M.A. & Hassan, F.A., 2014. *From lake to sand: The archaeology of Farafra Oasis, Western Desert, Egypt.* All'Insegna del Giglio, Florence.

Barron, A., Turner, M., Beeching, L., Bellwood, P., Piper, P., Grono, E., Jones, R., Oxenham, M., Kien, N.K.T, Senden, T. & Denham, T., 2017. MicroCT reveals domesticated rice (Oryza sativa) within pottery sherds from early Neolithic sites (4150-3265 cal BP) in Southeast Asia. *Scientific Reports* 71. https://doi.org/10.1038/s41598-017-04338-9

Barron, A. & Denham, T., 2018. A microCT protocol for the visualisation and identification of domesticated plant remains within pottery sherds. *Journal of Archaeological Science: Reports* 21: 350–358. https://doi.org/10.1016/J.JASREP.2018.07.024

Beldados, A., Manzo, A., Murphy, C., Stevens, C. & Fuller, D.Q., 2018. Evidence of sorghum cultivation and possible pearl millet in the second millennium BCE at Kassala, Eastern Sudan. In: Mercuri, A.M., Hohn, A. & D'Andrea, A.C. (Eds.), *Plants and people, Progress in African archaeobotany.* Springer, New York, pp. 503-528.

Boivin, N. & Fuller, D.Q., 2009. Shell middens, ships and seeds: Exploring coastal subsistence, maritime trade and the dispersal of domesticates in and around the ancient Arabian Peninsula. *Journal of World Prehistory 22*(2): 113-180.

Bouchaud, C., Clapham, A., Newton, C., Tallet G. & Thanheiser, U., 2018. Cottoning on to Cotton (Gossypium spp.) in Arabia and Africa During Antiquity: Progress in African Archaeobotany. In: Mercuri, A.M., Hohn, A. & D'Andrea, A.C. (Eds.), *Plants and People in the African Past. Progress in African Archaeobotany, Arabia and Africa during antiquity.* Springer, New York, pp. 380-429.

Brass, M., Fuller, D.Q., MacDonald, K., Stevens, C., Adam, A., Kozieradzka-Ogunmakin, I., Abdallah, R.M.J., Alawad, O.K., Abdalla, A.A.M., Gregory, I.V., Wellings, J., Hassan, J. & Abdelrahman, A.M., 2019. New findings on the significance of Jebel Moya in the eastern Sahel. *Azania* 54(4), 425-444. https://doi.org/10.1080/0067270X.2019.1691845

Castelletti, L., Castiglioni, E., Cottini, M. & Rottoli, M., 1999. Archaeobotanical analysis of charcoal, wood, and seeds. In: Di Lernia, S. (Ed.), *The Uan Afuda Cave. Hunter-gatherer societies of Central Sahara*. Arid Zone Archaeology Monographs 1 All'Ilnsegna del Giglio, Florence, pp. 131–148.

Clark, J., 1980. The origins of domestication in Ethiopia. In: Leakey, R. & Ogot, B. (Eds.), *Proceedings of the Eighth Pan African Congress of Prehistory and Quaternary Studies*. International Louis Leakey Memorial Institute for African Prehistory, Nairobi, pp. 268-270.

Dahlberg, J., 1995. Dispersal of sorghum and the role of genetic drift. *African Crop Science Journal* 3: 143–151.

De Wet, J.M.J. & Harlan, J.R., 1971. The origin and domestication of *Sorghum bicolor*. *Economic Botany* 25: 128–135. https://doi.org/10.1007/BF02860074

Fattovich, R., 1989. The late prehistory of the Gash Delta (eastern Sudan). In: Kryźanyak, L. (Ed.), *The late prehistory of the Nile Basin and the Sahara.* Poznań Archaeological Museum, Poznań, pp. 481–498.

Fattovich, R., 2010. The development of ancient states in the northern Horn of Africa, c. 3000 BC–AD 1000: An archaeological outline. *Journal of World Prehistory* 23: 145–175.

Fattovich, R., 2012. The southern Red Sea in the 3rd and 2nd millennia BC: An archaeological overview. In: Agius, D., Cooper, J., Tradakas, A. & Zazzaro, C. (Eds.), *Navigated spaces,*

connected places. *Proceedings of the Red Sea Project V held at the University of Exeter, 16– 19 September 2010.* British Archaeological Reports, Oxford, pp. 39– 46.

Fattovich, R., Marks, A. & Mohammed-Ali, A., 1984. The archaeology of the eastern Sahel: Preliminary results. *African Archaeological Review* 2: 173–188.

Fuller, D.Q., 2003. African crops in prehistoric South Asia: A critical review. In: Neumann, K., Butler, A. & Kahlheber, S. (Eds.), *Foods, fuel and fields: Progress in African Archaeobotany*. Heinrich-Barth Institut, Cologne, pp. 239-271.

Fuller, D.Q., 2007. Contrasting patterns in crop domestication and domestication rates: Recent archaeobotanical insights from the Old World. *Annals of Botany* 100: 903–924. https://doi.org/10.1093/aob/mcm048

Fuller, D.Q. & Stevens, C., 2018. Sorghum domestication and diversification: A current archaeobotanical perspective. In: Mercuri, A.M., Hohn, A. & D'Andrea, A.C. (Eds), *Plants and people, Progress in African archaeobotany*. Springer, New York, pp. 427-452.

Fuller, D.Q., MacDonald, K. & Vernet, R., 2007. Early domesticated pearl millet in Dhar Nema (Mauritania): Evidence of crop processing waste as ceramic temper. In: Cappers, R. (Ed.), *Field of change. Proceedings of the 4th International Workshop for African Archaeobotany.* Groningen Archaeological Studies, Groningen, pp. 71–76.

Fuller, D.Q., Denham, T., Arroyo-Kalin, M., Lucas, L., Stevens, C., Qin, L., Allaby, R. & Purugganan, M., 2014. Convergent evolution and parallelism in plant domestication revealed by an expanding archaeological record. *Proceedings of the National Academy of Sciences* 111(17): 6147–6152. https://doi.org/10.1073/pnas.1308937110

Fuller, D.Q., Weisskopf, A.R. & Castillo, C., 2016. Pathways of rice diversification across Asia. *Archaeology International* 19: 84-96. http://doi.org/10.5334/ai.1915

Fuller, D.Q., Lucas, L., Gonzalez Carretero, L. & Stevens, C., 2018. From intermediate economies to agriculture: trends in wild food use, domestication and cultivation among early villages in Southwest Asia. *Paléorient* 44: 61-76. https://doi.org/10.1371/journal.pone.0063195

Grove, M., 2007. *A walk in the dust: Linking paths and places in pastoralist archaeology.* Paper given at annual conference, University of York, December 14th-16th.

Haaland, R., 1999. The puzzle of the late emergence of domesticated sorghum in the Nile Valley. In: Gosden, C. & Hather, J. (Eds.), *The prehistory of food. Appetites for change*. Routledge, London, pp. 397-418.

Harlan, J., 1971. Indigenous African Agriculture. In: Cowan, C. & Watson, P.J. (Eds.), *The origins of agriculture: An international perspective*. Smithsonian Press, Washington, pp. 59-70.

Harlan, J. & Stemler, A.B., 1976. The races of sorghum in Africa. In: Harlan, J. (Ed.), *Origins of African plant domestication.* Mouton Publishers, The Hague, pp. 465-478.

Hildebrand, E., Garcea, E.A.A., Florenzano, A. & Mercuri, A.M., 2018. Multiscalar perspectives on Holocene climatic and environmental changes in the Sahara and Nile Corridor, with special consideration of archaeological sites on Sai Island, Sudan. In: Mercuri, A.M., Hohn, A. & D'Andrea, A.C. (Eds.), *Plants and people, Progress in African archaeobotany*. Springer, New York, pp. 215-245.

Hopcroft, P.O., Valdes, P.J., Harper, A.B., & Beerling, D.J., 2017. Multi vegetation model evaluation of the Green Sahara climate regime. *Geophysical Research Letters* 44(13): 6804-6813. https://doi-org.virtual.anu.edu.au/10.1002/2017GL073740

Kahlheber, S. & Neumann, K., 2007. The development of plant cultivation in semiarid West Africa. In: Denham, T., Iriarte, J. & Vrydaghs, L. (Eds.), *Rethinking Agriculture: Archaeological and ethnoarchaeological perspectives*. Left Coast Press, California, pp. 320-345.

Kistler, L., Maezumi, S.Y., De Souza, J.G., Przelomska, N.A., Costa, F.M., Smith, O., Loiselle, H., Ramos-Madrigal, J., Wales, N., Ribeiro, E.R., Morrison, R.R., Grimaldo, C., Prous, A.P., Arriaza, B., Thomas, M., Gilbert, P., de Oliveira Freitas, F. & Allaby, R.G., 2018. Multiproxy evidence highlights a complex evolutionary legacy of maize in South America. *Science* 362(6420): 1309-1313. https://doi.org/10.1126/science.aav0207

Lancelotti, C., Biagetti, S., Zerboni, A., Usai, D., & Madella, M., 2019. The archaeology and ethnoarchaeology of rain-fed cultivation in arid and hyper-arid North Africa. *Antiquity* 93(370): 1026-1039.

Latham, S., Varslot, T. & Sheppard, A., 2008. Automated registration for augmenting micro-CT 3D images. *ANZIAM Journal (CTAC 2008)* 50: C534–C548. https://doi.org/10.21914/anziamj.v50i0.1389

Lézine, A.M., 2017. Vegetation at the time of the African Humid Period. In *Oxford Research Encyclopedia of Climate Science.* Oxford University Press, Oxford. https://doi.org/10.1093/acrefore/9780190228620.013.530

Limaye, A., 2012. Drishti: a volume exploration and presentation tool. *Proceedings of SPIE: Developments in X-Ray Tomography* VIII: 8506. https://doi-org.virtual.anu.edu.au/10.1117/12.935640

Manning, K., Pelling, R., Higman, T., Schwenniger, J.-L. & Fuller, D.Q., 2011. 4500-year-old domesticated pearl millet (Pennisetum glaucum) from the Tilemsi Valley, Mali: New insights into an alternative domestication pathway. *Journal of Archaeological Science* 38: 312–322.

Manzo, A. (Ed.), 2012. *Italian archaeological expedition of the Eastern Sudan of the University of Naples L'Oriental. Report of the 2011 field season.* Università degli studi di Napoli L'Orientale, Naples.

Manzo, A., Coppa, A., Beldados, A. & Zoppi, V., 2011. *Italian archaeological expedition to the Sudan of the University of Naples 'L'Orientale': 2010 field season.* Universita degli studi di Napoli "L'Orientale", Naples.

Marks, A., Mohammed-Ali, A. & Fattovich, R., 1986. The archaeology of the Eastern Sudan: A first look. *Archaeology* 39: 44–50.

Marks, A. & Fattovich, R., 1989. The later prehistory of the Eastern Sudan: A preliminary view. In: Krzyaniak, L. & Kobusiewicz, M. (Eds.), *Late prehistory of the Nile Basin and the Sahara*. Poznań Archaeological Museum, Poznań, pp. 451–458.

Marshall, F. & Hildebrand, E., 2002. Cattle before crops: The beginning of food production in Africa. *Journal of World Prehistory* 16(2): 99-143.

Mbutu, S., 1991. *The Butana Group lithic industry: Its implications on regionalism during the Neolithic Period in Northeastern Africa*. PhD dissertation, Southern Methodist University, Dallas.

McClatchie, M. & Fuller, D.Q., 2014. Leaving a lasting impression. In: Stevens, C., Nixon, S., Murray, M.A. & Fuller, D.Q. (Eds.), *Archaeology of African Plant Use*. Left Coast Press, California, pp. 259-266.

Mercuri, A.M., 2001. Preliminary analysis of fruits, seeds and few plant macrofossils from the Early Holocene sequence. In: Garcea, E. (Ed.), *Uan Tabu in the settlement history of the*

*Libyan Sahara*. Arid Zone Archaeology Monographs 2 All'Insegna del Giglio, Florence, pp. 189-210.

Mercuri, A.M., 2008. Human influence, plant landscape evolution and climate inferences from the archaeobotanical records of the Wadi Teshuinat area (Libyan Sahara). *Journal of Arid Environments* 72(10): 1950–1967. https://doi.org/10.1016/j.jaridenv.2008.04.008

Mercuri, A.M., Fornaciari, R., Gallinaro, M., Vanin, S. & di Lernia, S., 2018. Plant behaviour from human imprints and the cultivation of wild cereals in Holocene Sahara. *Nature Plants* 4(2): 71–81. http://dx.doi.org.virtual.anu.edu.au/10.1038/s41477-017-0098-1

Myers, G., Kingston, A., Varslot, T. & Sheppard, A., 2011. Extending reference scan drift correction to high-magnification high-cone-angle tomography. *Optics Letters* 36: 4809–4811. https://doi-org.virtual.anu.edu.au/10.1364/OL.36.004809

Neumann, K., 2005. The romance of farming: Plant cultivation and domestication in Africa. In: Stahl, A. (Ed.), *African archaeology: A critical introduction*. Blackwell Publishing, Oxford, pp. 249-275.

Nixon, S., Murray, M.A., & Fuller, D.Q., 2011. Plant use at an early Islamic merchant town in the West African Sahel: the archaeobotany of Essouk-Tadmakka (Mali). *Vegetation history and archaeobotany* 20(3): 223-239.

Olmi, L., Mercuri, A., Gilbert, M., Biagetti, S., Fordyce, S., Cappellini, E., Massamba N'Siala, I., & Di Lernia, S., 2011. Morphological and genetic analyses of early and mid-Holocene wild cereals from the Takarkori Rockshelter (Central Sahara, Libya): First results and prospects. In: Fahmy, A., Kahlheber, S. & D'Andrea, A.C. (Eds.), *Windows on the African past. Current approaches to African archaeobotany.* Africa Magna Verlag, Frankfurt, pp. 175–184.

Peters, J., 1986. *Bijdrage tot de Archeozoologie van Soedan en Egypte.* PhD dissertation, Fakulteit der Weternschappen, Rijksuniversiteit, Gent.

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards. R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., & Talamo, S. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 cal kBP) *Radiocarbon* https://doi.org/10.1017/RDC.2020.41.

Sadig, A.M., 2010. *The Neolithic of the Middle Nile region: An archaeology of central Sudan and Nubia*. Fountain Publishers, Kampala.

Sadr, K., 1988. *The development of nomadism: The view from ancient northeast Africa*. PhD dissertation, Southern Methodist University, Dallas.

Sadr, K., 1991. *The development of nomadism in ancient northeastern Africa.* University of Pennsylvania, Philadelphia.

Shanahan, T.M., McKay, N.P., Hughen, K.A., Overpeck, J.T., Otto-Bliesner, B., Heil, C. W., King, J., Scholz, C.A. & Peck, J., 2015. The time-transgressive termination of the African Humid Period. *Nature Geoscience* 8(2): 140-144. https://doi.org/10.1038/ngeo2329

Shiner, J., 1971. *The prehistory and geology of northern Sudan.* National Science Foundation, Dallas.

Snowden, J.D., 1936. *Cultivated races of Sorghum*. Adlard and Sons, London.

Stemler, A., 1990. Scanning electron microscopic analysis of plant impressions in pottery from sites of Kadero, El Zakiab, Um Direiwa and El Kadada. *Archéologie du Nil Moyen* 4: 87–106.

Stuiver, M. & Reimer, P.J. 1993. Extended 14C data base and revised CALIB 3.0 14C age calibration program*. Radiocarbon* 35: 215-230.

Teshome, M. & Feyissa, T., 2013. Genetic diversity of wild sorghum (*Sorghum bicolor* ssp. *verticilliflorum* (L.) Moench) germplasm from Ethiopia as revealed by ISSR Markers. *Asian Journal of Plant Sciences* 12: 137-144.

Wang, J., Hu, Z., Upadhyaya, H.D. & Morris, G.P. 2020 Genomic signatures of seed mass adaptation to global precipitation gradients in sorghum. *Heredity* 124: 108-121.

Wasylikowa, K., 1992. Exploitation of wild plants by prehistoric peoples in the Sahara. *Würzberger Geographische Arbeiten* 84: 247–262. https://doi.org/10.1017/S0003598X00085835

Wasylikowa, K. & Dahlberg, J., 1999. Sorghum in the economy of the early nomadic tribes at Napta Playa, southern Egypt. In: van der Veen, M. (Ed.), *The exploitation of plant resources in Ancient Africa*. Kluwer Academic/Plenum Press, New York, pp. 11–32.

Wasylikowa, K. & Dahlberg, J., 2001. Sorghum remains from site E-75-6. In: Wendorf, F,. & Schild, R. (Eds.), *Holocene settlement of the Egyptian Sahara: Volume 1: the archaeology of Nabta Playa*. Springer/Plenum, New York, pp 578–587.

Wiersema, J.H. & Dahlberg, J., 2007. The nomenclature of *Sorghum bicolor* (L.) Moench (Gramineae). *Taxon* 56(3): 941–946.

Winchell, F., 2013. The Butana Group ceramics and their place in the Neolithic and Post-Neolithic of Northeast Africa. *Cambridge Monographs in African Archaeology 83.* British Archaeological Reports, Oxford.

Winchell, F., Stevens, C., Murphy, C., Champion, L. & Fuller, D.Q., 2017. Evidence for sorghum domestication in Fourth Millennium BC eastern Sudan: Spikelet morphology ceramic impressions of the Butana Group. *Current Anthropology* 58(5): 673-683. https://doi.org/10.1086/693898

Winchell, F., Brass, M., Manzo, A., Beldados, A., Perna, V., Murphy, C., Stevens, C. & Fuller, D.Q., 2018. On the origins and dissemination of domesticated sorghum and pearl millet across Africa and into India: A view from the Butana Group of the Far Eastern Sahel. *African Archaeology Review* 35: 483–505. https://doi.org/10.1007/s10437-018-9314-2
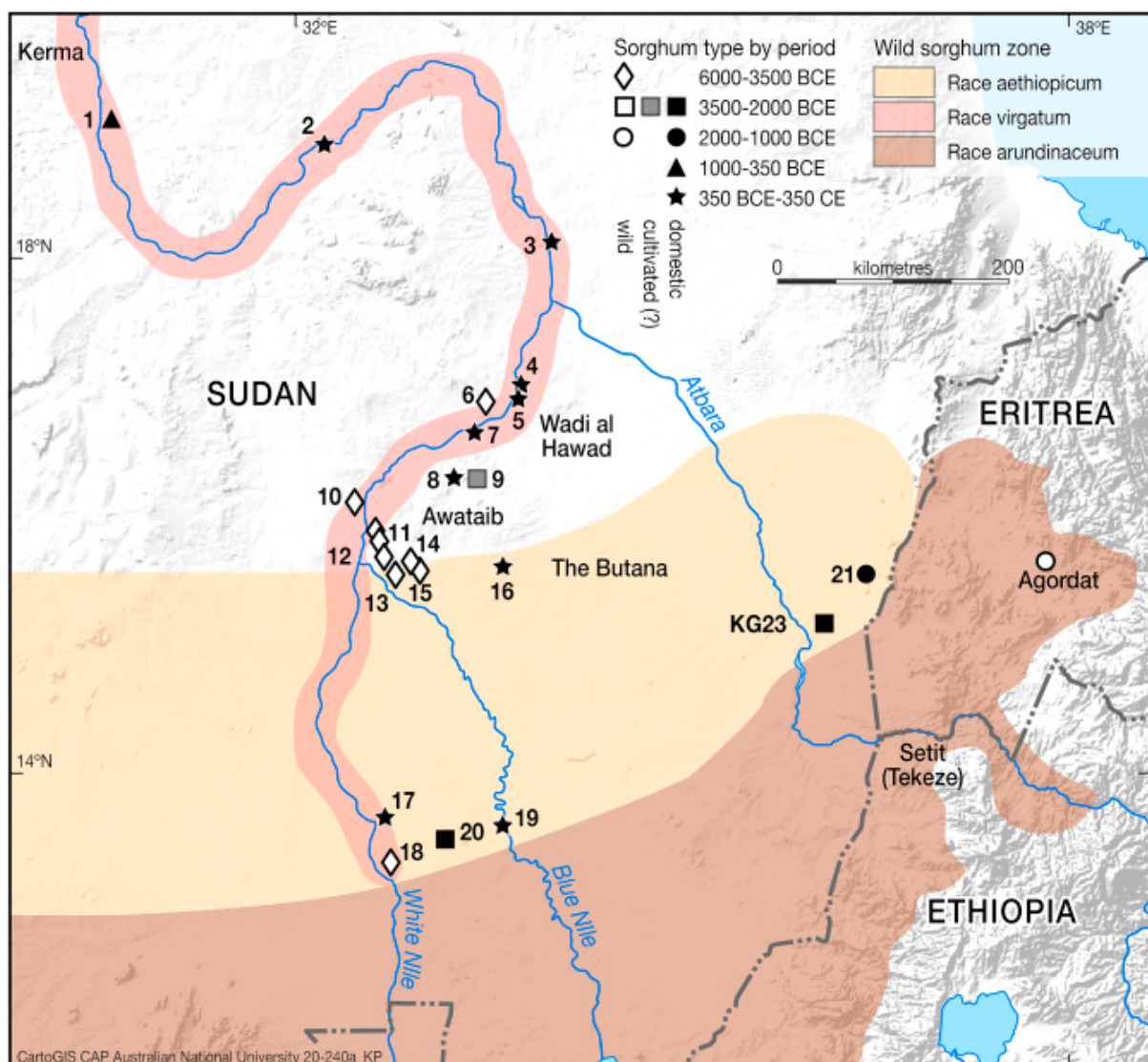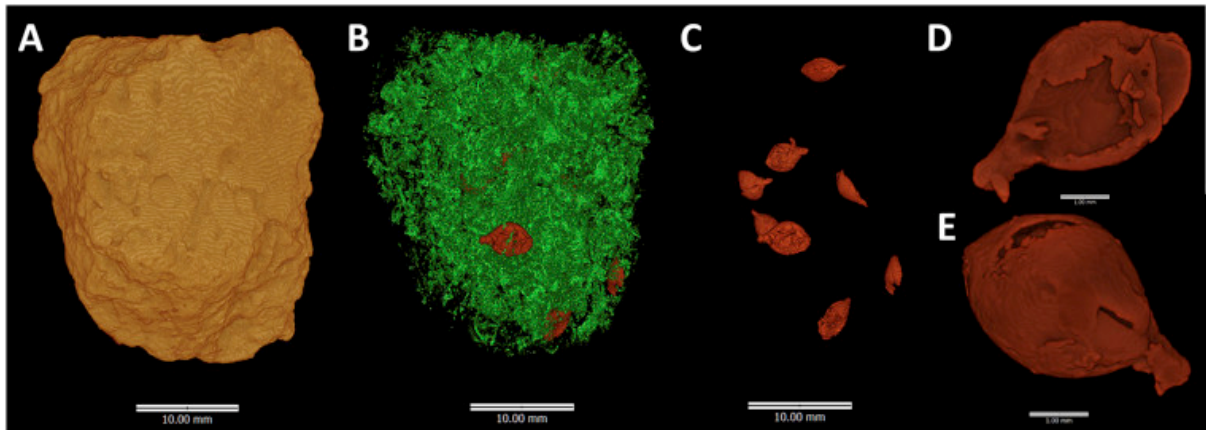
**Figures**



*Figure 1.* Map with location of Khashm el Girba 23 (KG23) in relation to other sites with archaeological evidence of sorghum (wild, cultivated, and domesticated); domesticated status indicated for sites with majority non-shattering evidence. Map indicates approximate potential modern extent of wild sorghum races (after Harlan & Stemler, 1976; Fuller & Stevens, 2018). Sites numbered: (1) Kawa; (2) Umm-Muri; (3) Dangeil; (4) Meroe City; (5) Hamadab; (6) El Kadada; (7) Muweis; (8) Naqa (art) (9) Shaqadud; (10) Shaheinab; (11) El Zakiab and Kadero; (12) Umm Direiwa; (13) Sheikh Mustafa; (14) El Mahalab; (15) Sheikh el Amin; (16) Jebel Qeili (art); (17) Jebel Tomat; (18) Rabak; (19) Abu Geili; (20) Jebel Moya; (21) Kasala K1 [Mahal Teglinos] (Updated from Winchell et al., 2017; Bouchard et al., 2018; Fuller et al., 2018; Brass et al., 2019).
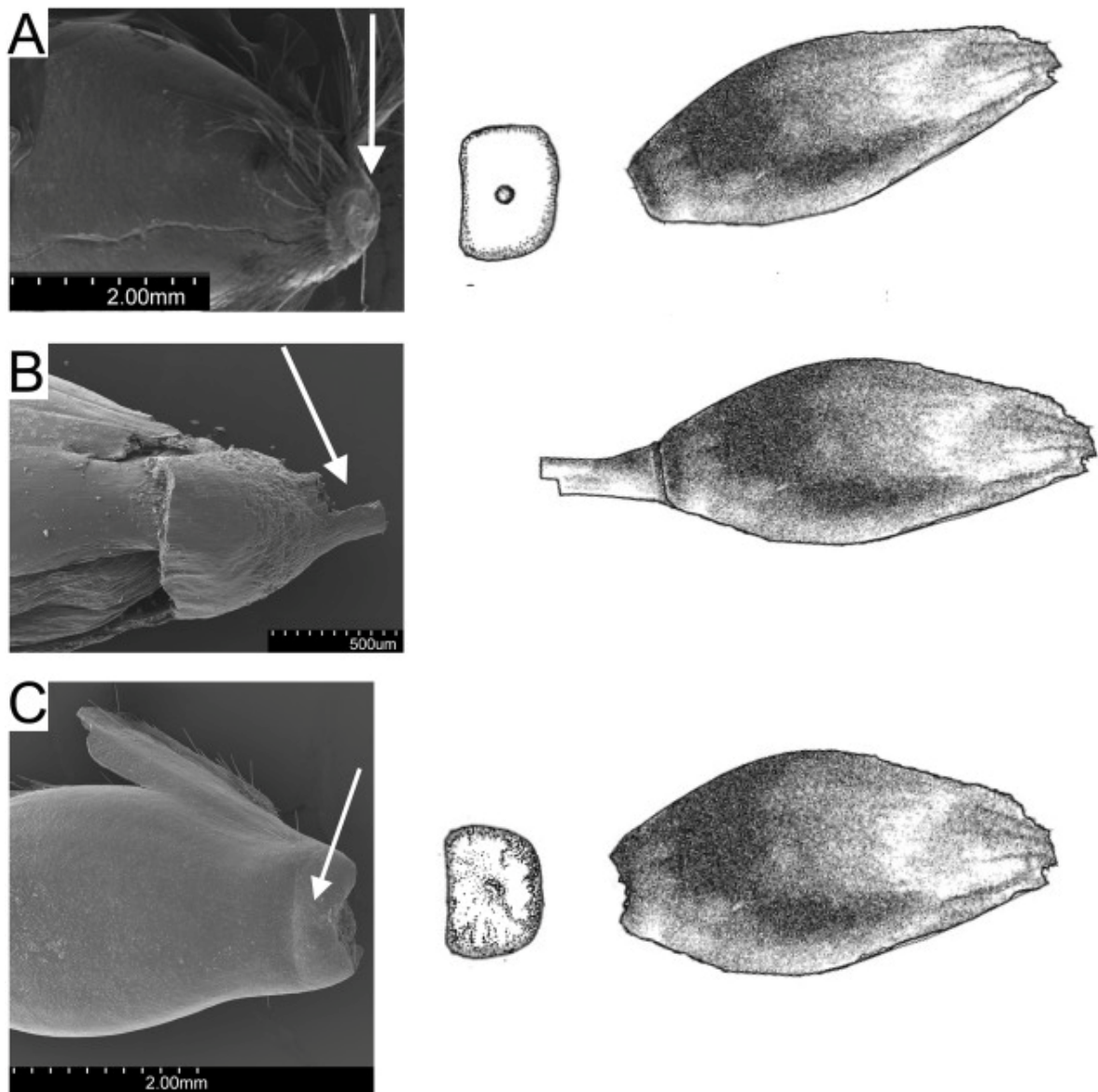
*Figure 2*. Comparative SEM (left) and hand illustrated (right) images of reference specimens showing: A – smooth scar in wild-type; B – torn rachillas (30-100%) in domesticates and immature (green-harvested) wilds; C – "rip scar" (up to 70% in domesticates).

*Figure 3.* MicroCT images of Sherd C2-12 (79). A: Clay fraction. B: Organic inclusions rendered in green with whole sorghum spikelets rendered in red. C: Sorghum spikelets isolated from the ceramic matrix. D-E: Detail of Inclusion 11, domesticated-type sorghum spikelet. See SOM Animation 1 – methodological summary of microCT visualisation of included sorghum remains.
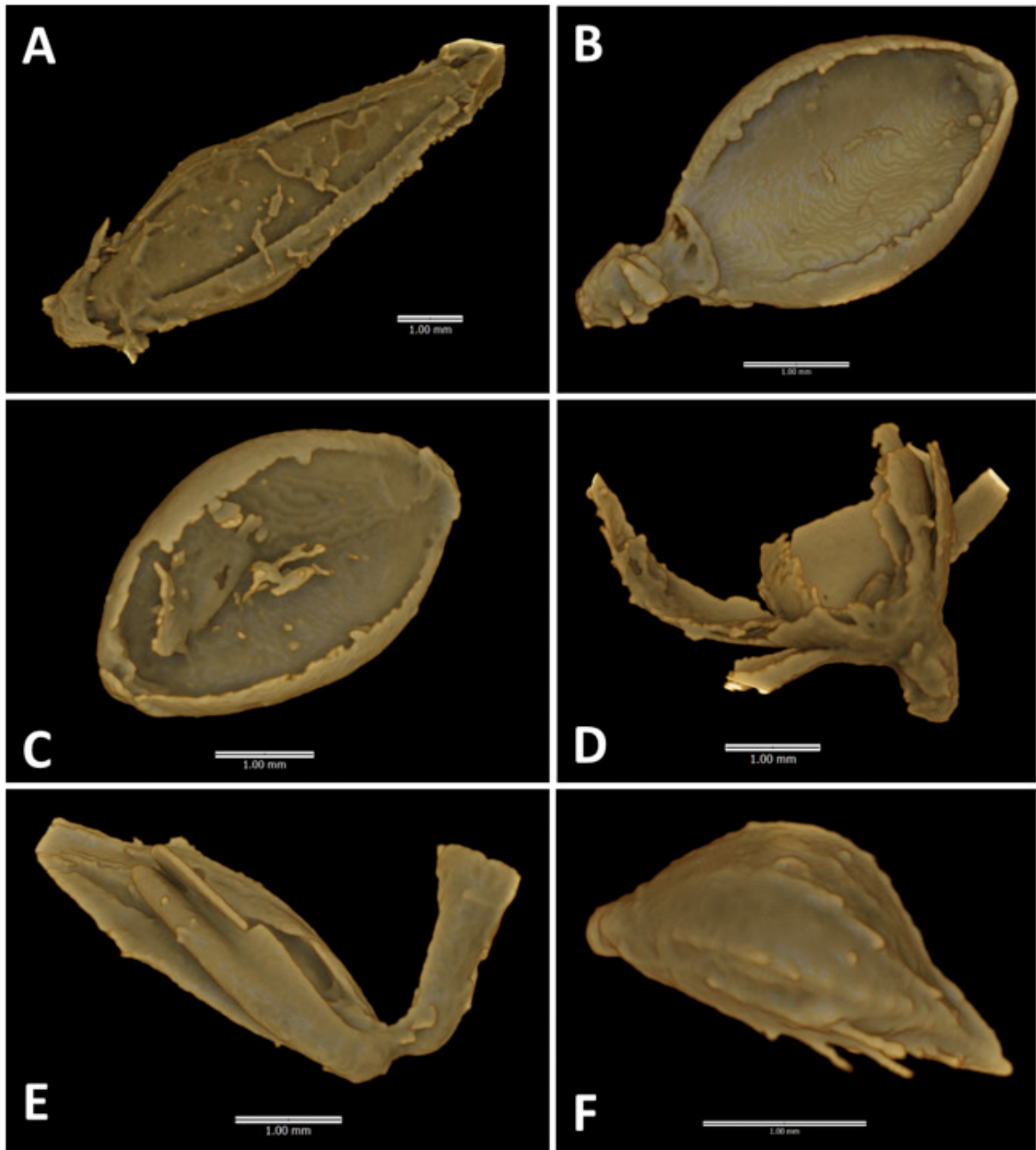
*Figure 4.* MicroCT images of botanical inclusions within pottery sherds from KG23c. A: Wild-type sorghum spikelet, Sherd C3-9 (36) Inclusion 3. B: Domesticated-type sorghum spikelet, Sherd D3-19 (90) Inclusion 4. C: Wild-type spikelet, Sherd D3-19 (90) Inclusion 23. D: Domesticated-type spikelet fork, C2-15 (116) Inclusion 8. E: Wild-type spikelet fork, Sherd C2-13 (29) Inclusion 9. F: *Echinochloa* grain, Sherd C3-13 (106) Inclusion 13. See SOM Animation 2 – virtual excavation of sorghum spikelet, Inclusion 6, within sherd C2-12 (79).
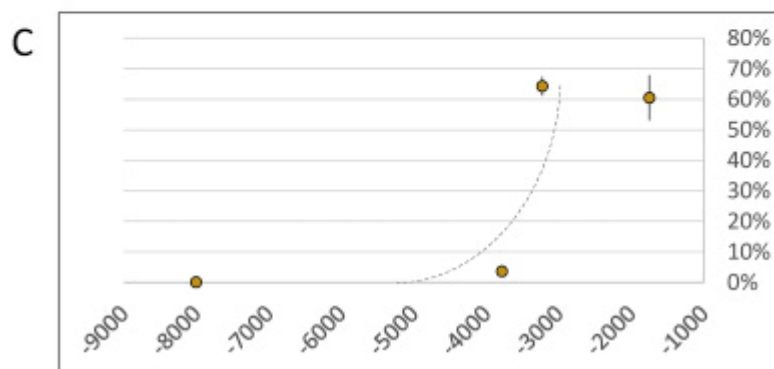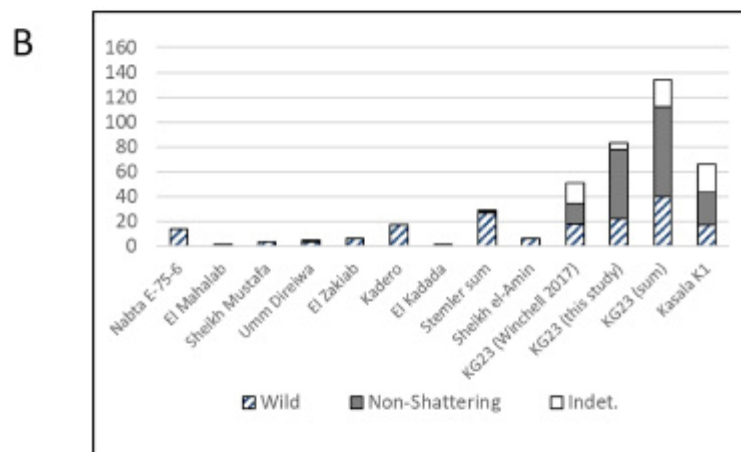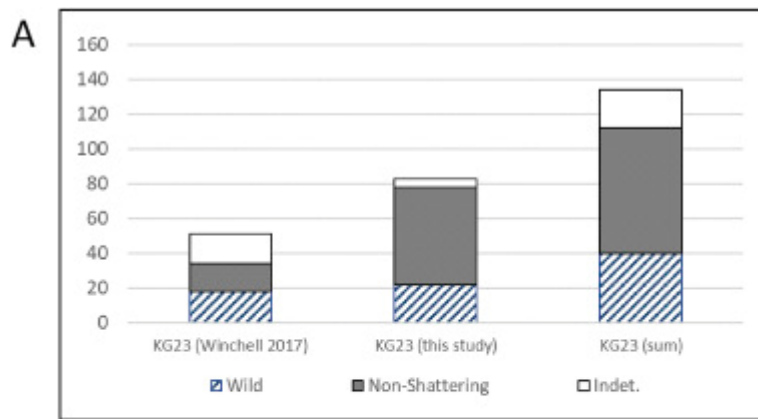
*Figure 5.* Contribution of new sorghum impressions to quantitative domestication data on Sorghum. Panel A. Counts/proportions of spikelet base types from: SI = surface impressions (Winchell et al., 2017); mCT = microCT scans (this study); and, Total = the two datasets combined. Panel B. The total KG23 dataset compared to other quantified data (from Abdel-Magid, 1989; Stemler, 1990; Wasylikowa & Dahlberg, 1999; Winchell et al., 2017; Beldados et al., 2018; see Table *S1*). C. The estimated percentage of domesticated vs. wild types is plotted (excluding indeterminates) (as per Fuller et al., 2014; see Table *S1*). Assemblages included are Nabta E-75-6 (Wasylikowa & Dahlberg, 1999) (n=14), all four Stemler (1990) sites

summed (n=29), KG23 summed (n=134), Mahal Teglinos K1 (Beldados et al 2018) (n=66). Dashed curve of domestication rate is impressionistic.

*Table 1.* AMS radiocarbon dates for wood charcoal from Khashm el Girba (KG23; Winchell et al., 2017). Calibrations undertaken using CALIB rev. 7.1.0 (Stuiver and Reimer, 1993) and Intcal13 calibration dataset (Reimer et al., 2020).

*Table 2.* MicroCT data for sorghum inclusions within twelve pottery sherds excavated from Test Units C2, C3 and D3 at Khashm el Girba (KG23), Sudan. MicroCT (mCT) and surface impression (SI) data (from Winchell et al., 2017) are given for each sherd, with '?' indicating potential identifications. Sherd code represents test unit, level (excavated in 5 cm thick spits) and the designated sherd number within that level (in parentheses).

**SOM Captions**

**Table *S1*.** Current data on sorghum non-shattering from Egypt and Sudan: KG23 in comparative context.

**Animation *S1***. Methodological summary of microCT visualisation of included sorghum remains demonstrating the virtual extraction of sorghum spikelets from Sherd C2-12 (79). Initial images show clay fraction (rendered in brown), then sequentially revealing organic inclusions (rendered in green) and whole sorghum spikelets (rendered in red), and concluding with detailed visualisation of Inclusion 11, a domesticated-type sorghum spikelet.

**Animation *S2***. Demonstration of virtual excavation of sorghum spikelet, Inclusion 6, within sherd C2-12 (79). The visualisation shows the virtual excavation of the sorghum spikelet (rendered in red) from the surrounding clay matrix (rendered in brown).

**Presentation *S1***. Virtually reconstructed sorghum spikelets embedded as inclusions and impressions within pottery sherds from Khashm el Girba (KG23). All 82 spikelets reconstructed.

**Presentation *S2***. Photomicrographs of surface impressions of sorghum in the surface of pottery sherds at Khashm el Girba (KG23).