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► **To cite this version:**

Gamal Younes, David Kaniewski, Nick Marriner, Christophe Morhange, Hader Sheisha, et al.. The construction of the Giza pyramids chronicled by human copper contamination. *Geology*, 2024, 52 (10), pp.774-778. 10.1130/G51965.1 . hal-04659321

HAL Id: hal-04659321

<https://hal.science/hal-04659321v1>

Submitted on 23 Jul 2024

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The construction of the Giza pyramids chronicled by human copper contamination

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ABSTRACT

Although the construction of the Giza necropolis necessitated the creation of an extensive array of metal tools, the significance of these early instances of metallurgy, and the contamination they left, has been overlooked in favor of understanding pyramid building techniques. We geochemically analyzed a sediment core from the Khufu harbor to track the construction of the Giza necropolis, with a particular focus on copper contamination deriving from metallurgical activities. We found that significant local contamination

32 **occurred during the regnal years of Kings Khufu, Khafre and Menkaure, consistent with**
33 **metalworking during the preparation and construction of the edifices. While the pyramid**
34 **complex led to the creation of an outstanding cultural legacy for humanity, it also marked**
35 **the onset of significant man-made metal contamination at Giza.**

36

37 **INTRODUCTION**

38 The pyramids of Giza, one of the world's most iconic cultural landscapes, are monumental
39 edifices that served as the final resting place for kings of the Old Kingdom's 4th Dynasty
40 (Lehner and Hawass, 2017; Verner, 2021). The Great Pyramid of Giza, an architectural marvel
41 constructed under the reign of King Khufu (first regnal year: 2613-2577 BCE; Bronk Ramsey
42 et al., 2010), stands as an enduring testament to human ingenuity and holds a well-deserved
43 place among the Seven Wonders of the Ancient World. The second edifice was built by King
44 Khafre (first regnal year: 2586-2548 BCE; Bronk Ramsey et al., 2010) and the final pyramid
45 was erected by King Menkaure (first regnal year: 2564-2524 BCE; Bronk Ramsey et al., 2010).
46 King Khufu reigned for 26-30 years (Gautschy et al., 2017; Jüngling and Höflmayer, 2023) and
47 it has been estimated that the Great Pyramid was nearly completed during his reign. According
48 to the journal of inspector Merer, at the end of King Khufu's reign, the white limestone blocks
49 for cladding his pyramid were still brought from Tura (Tallet and Lehner, 2022). The building
50 of the Great Pyramid, which required a massive workforce and support services such as scribes,
51 stonemasons, metalworkers, carpenters and foremen, is partly detailed in the Wadi el-Jarf
52 papyri (Tallet, 2021). The population necessary to complete the project on-site probably ranged
53 from 7,000 to 20,000 people (Smil, 2020).

54 The construction activities carried out on the Giza plateau must have resulted in a significant
55 increase in contamination, particularly due to the widespread production and utilization of
56 metallic tools (Odler et al., 2016; Odler and Kmošek, 2019; Odler et al., 2021). Archaeological
57 artifacts reveal that craftsmen used copper tools for various tasks (work on limestone, textile,
58 wood), sometimes alloying copper with arsenic to improve their properties, particularly
59 hardness (Rademakers et al., 2020). Despite decades of research and archaeological
60 discoveries, geochemical tracers have never been used at Giza to probe the site's long
61 metallurgical history before, during and after the Old Kingdom, notably during the Naqada
62 period. While acknowledging potential limitations, particularly regarding the spatial extent and
63 intensity of metalworking activities at Giza, utilizing the evolution of contaminants is a valuable

64 method for reconstructing the local production of metal tools over thousands of years and
65 encompassing various archaeological time periods.

66

67 **METHODS**

68 We reconstructed copper contamination in the Giza area (Fig. S1 and Fig. S2) from the
69 Neolithic to the New Kingdom, spanning approximately 3,200 years (6465±80 to 1225±80
70 BCE). This record is based on sediments from the Khufu harbor (core GIZA 3; Younes et al.,
71 2024), which was overlooked by the pyramid complex (Lehner, 2020). Preserved in a
72 refrigerated container, the core underwent sediment subsampling for geochemical analyses.
73 Sediments were digested and analyzed for copper (Cu), aluminum (Al), iron (Fe), titanium (Ti)
74 and arsenic (As) using an Inductively Coupled Plasma Mass spectrometry (ICP-MS quadrupole
75 Perkin Elmer Nexlon 300X). Copper concentrations, expressed in ppm, were evaluated against
76 refractory Crustal Elements (CE) ratios, defining an Enrichment Factor (EF). The EF revealed
77 anthropogenic copper contamination, notably from the onset of Cu use in the Nile valley. The
78 reconstruction of copper contamination coupled with arsenic (Fig. S3a-b), using z-scores, PCA
79 (Fig. S4), and chronological interpolation provides a detailed picture of metalworking activities
80 and their environmental impact across millennia. The laboratory methods are detailed in the
81 Supplemental Material.

82

83 **RESULTS AND DISCUSSION**

84 **Naqada IIIA-III B occupation**

85 The Predynastic rise in copper contaminants (-0.86 to 3.26, Fig. 1 and Fig. 2a-b) and arsenic
86 (up to 7.4 ppm, Fig. S3), from 3265±80 to 3185±80 BCE, appears consistent with a Naqada
87 IIIA-III B occupation (Dee et al., 2013) of the Giza plateau, also supported by an early
88 intensification in local agropastoral activities (Fig. 2b; Sheisha et al., 2023). The sharp increase
89 in metallurgy and copper contamination (score of 3.26, Fig. 1), providing evidence of local
90 metalworking during this period, is a compelling indication of late Predynastic activity at the
91 site, which is, however, absent from current archaeological records. The only confirmed late
92 Predynastic remains in the area are 13 graves from the small family cemetery of Kafr Ghattati
93 north of Giza (Engles, 1990), with the beginning attributed to Naqada III B (Hendrickx and
94 Brink, 2002). Local settlements, if present, were probably destroyed when the 4th Dynasty
95 pyramids were erected. There was probably a Naqada population practicing metallurgy at Giza,
96 predating evidence from the Memphite region. Inscriptions (Tallet and Laisney, 2013) also

97 attest to mining expeditions and the use of copper from the Naqada III culture (Hauptmann,
98 2007). The elevated peak of arsenic observed during this period (Fig. S3) could potentially be
99 linked to its use in alloying with copper, given that arsenic has been detected in Egyptian
100 metalwork since at least the Naqada II period. A high contamination (Fig. S3) probably means
101 less control over the arsenic in the metalworking compared to the Dynastic period. However,
102 with the exception of Maadi, scant information exists regarding Predynastic metalworking
103 workshops (Odler, 2023).

104

105 **First Dynasty of Egypt**

106 The second notable increase, observed as a shift from 3035 ± 80 to 2945 ± 80 BCE (-0.58 to 2.20,
107 Fig. 1), is believed to be associated with the construction of tombs on the Giza plateau. This
108 period coincided with the final phase of high-water levels in the Khufu branch of the Nile (Fig.
109 2a and Fig. S5a). This period likely represents a significant phase in the construction of Early
110 Dynastic monuments, particularly on those sites that would eventually form the pyramid fields.
111 At Giza, anything below the Old Kingdom pyramid and tomb complexes would have been
112 largely destroyed, but Early Dynastic tombs, ranging from the First to the Third Dynasties have
113 been uncovered in the southern part of the Giza necropolis (Martin, 1997). The peaks in copper
114 contamination with arsenic up to 5.9 ppm (Fig. S3), attributed to the First Dynasty, are most
115 probably connected to the construction of tombs of high officials at Giza and in its vicinity.
116 Copper contamination places the early stage of funeral constructions at 3035 ± 80 BCE,
117 providing new chronological evidence, based on geochemistry, that complements and
118 reinforces the archaeological record.

119

120 **Second Dynasty**

121 A significant increase in copper contamination occurred between 2795 ± 80 and 2715 ± 80 BCE,
122 during the Second or Third Dynasty (see Fig. 1). Archaeological findings at Giza have
123 uncovered tombs of prominent officials from both the Second and Third Dynasties (Martin,
124 1997), hindering further refinement regarding the specific origin of the copper and arsenic
125 contamination although a Second Dynasty attribution is most likely based on current ^{14}C
126 chronologies. This episode coincides with both a major drop in the Khufu branch level (Fig. 2a
127 and Fig. S5a) and a strong development in agropastoral activities (Fig. 2b and Fig. S5b). At
128 Giza, evidence of metalworking abruptly declined around 2715 ± 80 BCE, suggesting a partial

129 abandonment of metallurgy on the plateau until the reign of King Djoser. This suggests that
130 socio-economic parameters before the Third Dynasty influenced local human behavior.

131

132 **The Giza pyramid complex**

133 The first major phase of copper contamination, with more control on arsenic in metalworking
134 (average of 2.5 ± 0.1 ppm), dates from 2615 ± 80 to 2485 ± 80 BCE (1.2 to 4.5, Fig. 1), a
135 chronological range that corresponds to the construction of the Giza necropolis. The building
136 of the Great Pyramid has been previously dated either indirectly by the accession date of King
137 Khufu and the length of his reign, or directly by astronomical observations. The proposed
138 chronology extends from 2636-2606 BCE (Gautschy et al., 2017; Tallet and Lehner, 2022) to
139 2480 ± 5 BCE (Spence, 2000), including several possibilities such as 2613-2577 BCE (Bronk
140 Ramsey et al., 2010), 2589 BCE (Shaw, 2000), 2554 BCE (Beckerath, 1997) and 2509 BCE
141 (Hornung et al., 2006). A completion date for the Great Pyramid has also been estimated at
142 2559-2518 BCE (Dee et al., 2009). Copper contamination dates the onset of massive
143 metalworking on the Giza plateau to 2615 ± 80 BCE, a date supporting the hypothesis of an
144 extensive occupation of Giza and edifice construction beginning in the late 27th century or early
145 26th century BCE. The discernible increase in contamination levels at Giza is coherent with
146 significant copper-tool findings, including chisels, needles, axe blades, clamps/nails and awls,
147 that have been discovered and identified as artifacts utilized in the construction of the Khufu
148 and Khafre edifices and related projects (pyramids and the Great Sphinx; Odler et al., 2021).
149 Copper contamination moderately declines at 2545 ± 80 BCE (Fig. 1), which may correspond to
150 the reign of King Djedefre who built his pyramid at Abu Roash, not on the Giza plateau
151 (Gautschy et al., 2017). Completion dates have been estimated for the Pyramids of King Khafre
152 (2527-2463 BCE) and King Menkaure (2456-2370 BCE; Dee et al., 2009). The second increase
153 in copper contamination is centered on 2485 ± 80 BCE (from 2545 ± 80 to 2415 ± 80 BCE; Fig.
154 1), in line with the length of the reigns of King Khafre and King Menkaure (24 and 19 years
155 respectively; Gautschy et al., 2017). Metallurgy on the Giza plateau did not stop after the
156 construction of the pyramids and the site remained active throughout the Old Kingdom with
157 numerous tombs attributed to royal officials of high, middle and low ranking (Porter et al.,
158 1994; Odler et al., 2016) (Fig. 3). A sharp decline in metalworking, however, was recorded
159 after 2155 ± 80 BCE (Fig. 1), at the onset of the First Intermediate Period (~ 2150 BCE;
160 Seidlmayer, 2000).

161

162 **First Intermediate Period and Middle Kingdom**

163 During the First Intermediate Period, the Giza plateau went through a phase of abandonment of
164 the building area and copper metallurgy, followed by a prolonged period of decline throughout
165 a significant portion of the Middle Kingdom (Zivie-Coche, 1976). However, the presence of a
166 few known artifacts from these periods offers compelling evidence in support of minor tombs
167 in the area (Zivie-Coche, 1976). During the 12th Dynasty, the pyramids and tombs were
168 plundered, while the causeways and temples were repurposed as quarries by pharaohs for their
169 own building projects (Zivie-Coche, 1976; Gilli, 2009). During this period, traces of copper
170 working weaken at Giza (3.6 to 1.7, Fig. 1), with an overall drop in contamination throughout
171 the 11th and 12th Dynasties (Fig. 3). The remaining activity on the plateau (Fig. 1) probably
172 resulted from workers removing stone from the Giza necropolis. A significant decline in
173 agriculture and an extension of grazing has also been elucidated on the floodplain surrounding
174 the harbor (Fig. 2b; Sheisha et al., 2023). However, a revival of copper metallurgy occurred
175 after 1755±80 BCE, during the 13th Dynasty, probably during the reign of King Sobekhotep I
176 (first regnal year: 1777-1712 BCE; Bronk Ramsey et al., 2010) or his successors. This activity
177 is clearly identified by metal contamination and probably corresponds to a limited occupation
178 of the Giza plateau. These limited constructions in the area are recorded by rare archaeological
179 artifacts (Zivie-Coche, 1976). Following the decline of the Middle Kingdom and the onset of
180 the Second Intermediate Period, there was a notable decrease in contaminants at Giza (4.4 to
181 2.85, Fig. 1). This downturn suggests a decrease in metallurgical activity in the pyramids field.

182

183 **New Kingdom**

184 Around 1565±80 BCE and the onset of the New Kingdom and the reign of King Ahmose (first
185 regnal year: 1566-1552 BCE; Bronk Ramsey et al., 2010), Giza remained an active site and
186 copper-arsenic contamination from the plateau rose again (2.85 to 3.65, Fig. 1). The higher
187 peak was attained at 1445±80 BCE (4.5, Fig. 1), most probably during the regnal years of king
188 Amenhotep II (first regnal year: 1441-1431 BCE; Bronk Ramsey et al., 2010) who built the
189 Temple of Hauron-Haremakhet to the north-east of the Sphinx, and erected a stela (Pasquali,
190 2009; Bassir, 2017). A chapel may have been built before by King Thutmose I (first regnal
191 year: 1520-1507 BCE; Bronk Ramsey et al., 2010) but its origin remains unclear (Porter et al.,
192 1994). Copper contamination remained high during the reign of King Thutmose IV (first regnal
193 year: 1414-1403 BCE; Bronk Ramsey et al., 2010) who erected the “Dream stela” and built an
194 enclosure wall around the Sphinx to protect the statue (Zivie-Coche, 1976; Bassir, 2017).

195 During the reign of King Tutankhamun (first regnal year: 1349-1338 BCE; Bronk Ramsey et
196 al., 2010), a structure now referred to as the king's resthouse was built (Porter et al., 1994). King
197 Seti I (first regnal year: 1307-1296 BCE; Bronk Ramsey et al., 2010) made additions to the
198 Temple of Hauron-Haremakheth (Porter et al., 1994). A significant resurgence in contamination
199 levels, marked by a sharp rise following a period of decline centered on 1315 ± 80 BCE (-0.5,
200 Fig. 1), occurred during the reign of Ramesses II (first regnal year: 1292-1281 BCE; Bronk
201 Ramsey et al., 2010) who erected a stela and usurped the king's resthouse (Porter et al., 1994).

202

203 **CONCLUSION**

204 The geochemical analysis of sediments from Khufu harbor has unveiled a rich history of
205 Predynastic and Dynastic Egypt on the Giza plateau and its vicinity, highlighted by
206 metallurgical evidence and copper contamination (Fig. 1). This analysis also pinpointed a
207 Predynastic Naqada occupation within the area. These new findings provide valuable insights
208 for future research on the plateau, especially regarding the Predynastic period. The
209 contamination record also shows that the development of Giza as a necropolis was directly
210 influenced by a drop in Nile levels (Fig. 2a). The historical tapestry of Giza reveals that the
211 plateau was shaped by a multitude of communities, including ancient traces of agropastoralism
212 (Fig. 2b). However, the most conspicuous imprint is undoubtedly the pervasive metallic
213 contamination that originated from extensive metalworking activities associated with the
214 construction of the necropolis, subsequent looting and the addition or renovation of later
215 buildings (Fig. 3). The construction of the pyramid complex was a crowning achievement of
216 the ingenuity and ambition of Dynastic Egypt. However, it is essential to acknowledge that this
217 monumental endeavor also left an indelible mark on the Giza plateau in the form of the first
218 major man-made metal contamination.

219

220 **ACKNOWLEDGEMENTS**

221 Drilling permission was obtained with the help of the National Research Institute of Astronomy
222 and Geophysics (NRIAG, Helwan, Egypt). Financial support was provided by: CEREGE
223 laboratory (APIC Research project), MITI-CNRS (AQUASANMARCO project), ARKAIA
224 Institute (GIZA project), National Natural Science Foundation of China (Grant n°42106161
225 and Grant n°42261144741) and MSHE - Université de Franche-Comté (GIZAPORT Project).

226

227

228 **FIGURE CAPTIONS**

229 **Figure 1.** Metallurgy and man-made copper contamination at Giza from the Copper Age to the
230 New Kingdom. Copper contamination is shown as PCA-Axis 1 scores (with a 200-year moving
231 average and a 95% confidence interval) and compared with the intensity of human occupation
232 on the plateau. The primary periods of contamination align closely with attested historical
233 events. The First Intermediate Period (FIP) and Second Intermediate Period (SIP) are marked
234 with an arrow.

235

236 **Figure 2.** Copper contamination compared with the Nile level and agropastoral activities at
237 Giza. Copper contamination, shown as PCA-Axis 1 scores, is compared with (a) the level of
238 the Khufu branch of the Nile and (b) the evolution of agropastoral activities on the Giza plateau.

239

240 **Figure 3.** Evolution of copper contamination by archaeological/historical period. Boxplots
241 showing the evolution of copper contamination from the Neolithic to the New Kingdom. The
242 phases of increased copper contamination from the Predynastic Period to the Old Kingdom are
243 indicated as calibrated ¹⁴C dates (with the associated 2σ - 95% probability) plotted in relation
244 to major archaeological events at Giza.

245

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