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ARCHAEOLOGY FOR EDUCATION

Science, Not Black Magic: Metal and Glass Production in Africa

Foreman Bandama · Abidemi Babatunde Babalola

Abstract Ongoing research continues to show that ancient Africans had their own versions of science that were embedded in local contexts. The apparent lack of writing systems in most of the continent, especially south of the Sahara, was used to undermine the continent's scientific achievements. Rather than relegate Africa to a simple receiver of science and technology, ancient Africans should be celebrated for their successful improvisation and experimentation. We discuss processes of metal and glass production in western and southern Africa to reveal key aspects of the scientific method in these ancient African technologies and situate the knowledge within an appreciation of inclusive education that embraces diverse ideas and practices of science and technology.

Résumé Les recherches en cours continuent de montrer que les anciens Africains avaient leurs propres versions de la science qui s'inscrivaient dans des contextes locaux. Le manque apparent de systèmes d'écriture et de laboratoire de type occidental a été utilisé pour saper les réalisations scientifiques du continent. Plutôt que de reléguer l'Afrique à un simple récepteur de science et de technologie, les anciens Africains devraient être célébrés pour leurs innovations et expérimentations réussies et qui ont été accomplies sans l'aide de laboratoires et d'appareils de style occidental. Nous discutons des processus de production du métal et du verre en Afrique subsaharienne afin de dégager les aspects clés de la méthode scientifique appliquée dans ces anciennes technologies africaines. Cette discussion permet également de replacer les connaissances dans le champ général de l'éducation inclusive qui englobe à la fois les conceptions occidentales et non occidentales de la science et la technologie.

Keywords Metallurgy · African science · Science and technology · Glass production · Science education

Introduction

Metals and glass served utilitarian (practical use), expressive (signifier of power, beauty, religious beliefs), and even medicinal functions in human history. These can be found in natural forms (native), but they are mostly made by using complex transformative technologies that involve careful control of fire. Metal and glass fall within the matrix of science and

F. Bandama
The Field Museum, 1400 S Lake Shore Dr, Chicago,
IL 60605, USA

F. Bandama (✉)
University of Illinois at Chicago, 1007 West Harrison St.,
2102 BSB, Chicago, IL 60607, USA
e-mail: fbandama@fieldmuseum.org

A. B. Babalola
The British Museum, Great Russel Street,
London WC1B 3DG, UK
e-mail: ababalola@britishmuseum.org

technology. The modern scientific method, with its six pillars (observation, hypothesis, experimentation, analysis, conclusion, and repeatability), is a twentieth-century product of thousands of years of Greek, Persian, and Islamic scholarship and scientific and technological discoveries (Shuttleworth, 2009). Accordingly, the terms are now mostly understood from Western definitions. For example, the Oxford Learner's Dictionary defines science as "knowledge about the structure and behavior of natural and physical world based on facts that you can prove by experiments," and technology is defined as "scientific knowledge used in practical ways in the industry in designing new machines." In understanding how science and technology developed and the variations in their complexities, Africa south of the Sahara has long been relegated to a simple recipient of science and technology rather than a contributor and maker. In place of science, magic has been put forward as the explanation for African technologies. Magic can be defined as the power of apparently influencing events using mysterious or supernatural forces (Oxford Learner's Dictionary).

The view of Africa without science is partly due to racist and misinformed perceptions about the meaning of these terms and the attempt to universalize definitions and experiences from the Global North (also known as the West), particularly as these unfolded during the Industrial Revolution. However, a careful survey of global cultures reveals that science and technology do not (always) have the same meaning everywhere (Mavhunga, 2017). An attempt to force one's meaning as the "true" definition only silences other people's meanings and impoverishes "science" everywhere. In this article, we highlight novel African metal and glassworking technologies that fit the mold of the building blocks used to develop the scientific method in the West. Our approach stems from the understanding that science and technology are not independent of each other, and this knowledge should be passed down to students in the classroom. Educators have a role to play in how scientific knowledge is transferred, and African archaeology can prove helpful in reforming science curriculum (see Gwekwerere et al., 2013; Gwekwerere & Shumba, 2021).

As archaeologists of African origin, we combined our experience of schooling in Africa, our knowledge of indigenous systems, and our training in archaeological science to demonstrate that people across Africa for centuries were engaging in science, experimenting, improvising, inventing, and innovating technologies and technological processes. Without exhausting all technical processes, we highlight only those forms of metal and glass making in southern and western Africa that speak to the pillars of the scientific method. Our second goal is to provide resources that support teaching for sustainable development in relation to the UN Sustainable Development Goals (see this volume's introduction). This breaks from the long tradition of restricting archaeological knowledge about Africa to the academy and discipline specialists.

To chart this path, we need to define some of the scientific terms that occur throughout the rest of this article. **Pyrotechnology** refers to heat-mediated processes (such as metal and glass production) that involve controlled high temperatures (above 1000 °C) during manufacture or post-manufacturing treatment. Metals and glass require some form of minerals as base raw materials, such as ores in the case of metal. **Ores** are rock or sand mineral sources from which valuable matter can be extracted. Ores are either collected from the surface or dug up from the ground in a process known as **mining**. The search for ore bodies is called **prospecting**. When fired under certain conditions, the ores or, in the case of glass, siliceous (silica-rich) quartz pebbles or sand react and produce metal or glass. The by-product of this process for metal is called **slag**. **Fluxes** are minerals added to the base ingredient for metal and glass to reduce the melting temperature. Every raw material has its **elements**, which are simple substances that cannot be broken down into smaller parts or changed into another substance. These elements lose oxygen (**reduction**) or gain oxygen (**oxidation**) to achieve a stable state during heat-mediated transformations, called smelting. **Smelting** can also be defined as the process of winning iron metal from the ores. Smelting typically happens in a reaction chamber known as a **furnace** (Fig. 1).

African iron smelting technology focuses on melting impurities, which leaves spongy iron metal called a **bloom**. This solid reduction technology, also known as **bloomery technology**, achieved temperatures high enough to melt impurities but still below the melting point of iron (1538 °C). Furnace temperature partly depended on the flow of oxygen (required for combustion/firing). The first method involves the use of

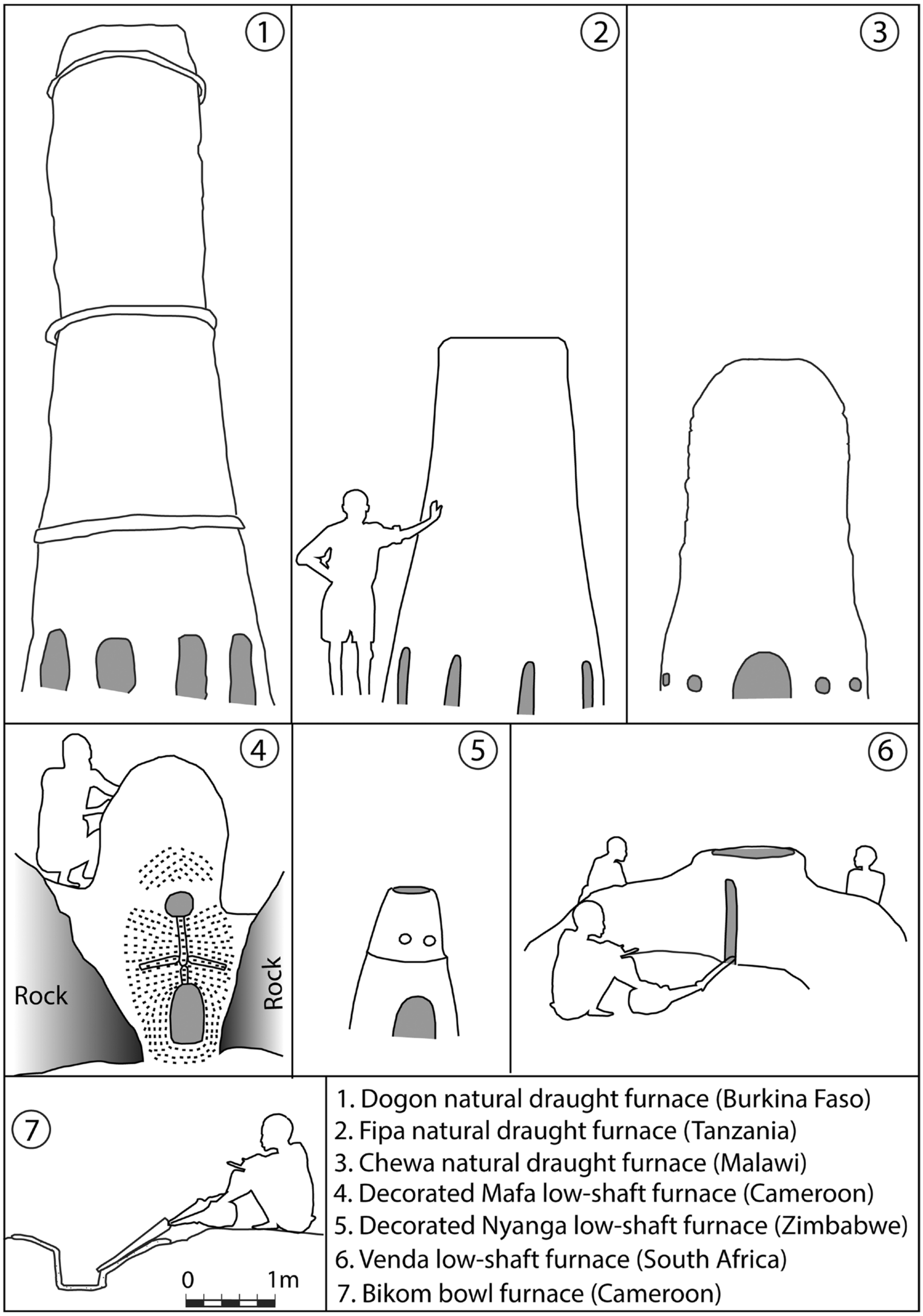

Fig. 1 Examples of African bloomery furnace types. Redrawn after Junod (1927), David et al. (1989), Childs (1989), Leloup (1994), Killick (2015), and Chirikure and Bandama (2014)

the principle of convectional currents in which cold air at the bottom of the furnace is heated and becomes less dense (lighter), causing it to rise before escaping through the top, while cold air is naturally sucked in through the tuyere holes and the process is repeated. Furnaces using this technology are called **natural-draught** or tall furnaces (Fig. 1). The second method involves forcing oxygen into the furnace using **bellows** (apparatus for pumping air) connected to tuyeres. Accordingly, furnaces using this technology are called **forced-draught** or low-shaft furnaces.

After smelting, the metal bloom may be cleaned and traded like that or be shaped into a usable object by recycling finished metals, which is called **smithing** or **forging** through **hammering** (use of a hammer and anvil to strike and shape an object), **annealing** (heating and allowing the metal/glass object to cool slowly), **normalization** (air cooling of a reheated object relatively faster than the annealing process), and **quenching** (rapid cooling of reheated metals, which is done by dipping hot metal in oil or water) techniques. Other forging techniques, such as wire drawing, relate to non-ferrous (not made of iron) metals and alloys such as gold, bronze, and brass. The process of transformation of raw materials into glassy materials is called **vitrification**.

We will now demonstrate that pre-industrial Africans, like ancient people in other parts of the world, employed scientific processes to discover and invent things. As we will illustrate, African peoples adopted somewhat different methods based on similar Western “scientific” principles to make things.

What We Know: Science in Metalworking

Africans produced metals for thousands of years. In fact, some early Eurasian explorers considered African metals much better in quality than in their places of origin. The discovery that certain rocks or sand contained enough elements that, when fired under certain conditions, could react and produce metal must involve stages now associated with the “modern” scientific method. During the early years of contact, in Western cultures, these stages are often documented in written form, and work is done in controlled environments known as laboratories (Chirikure, 2017). No such written recipes exist for much of Africa. Also, information is stored and communicated using non-written forms such as songs, physical observations, and accompanying rituals.

About ten thousand years before the present, some communities in Egypt, the Middle East, and adjacent regions were using rich and colorful copper ores such as malachite to manufacture bodily ornaments like beads. They discovered that heating these metal-rich rocks could lead to the production of metals. Archaeologists in Eurasia used metals to classify and order major time episodes into the Copper Age (5000–3000 BCE), Bronze Age (3000–1500 BCE), and Iron Age (from about 800 BCE onwards). The start of these “Ages” marked the point when the use of these metals began to predominate. South of the African pyramids, the metallurgical chapter begins with the simultaneous discovery of iron and copper. Gold, tin, and cuprous alloys (mostly bronze and brass) were then worked after centuries of ongoing iron and copper metallurgy (Chirikure, 2015). This differed from the Eurasian pattern in which the transitions from relatively easier (to smelt) copper to bronze and eventually to difficult (to smelt) iron were a very gradual process. Without any shred of evidence, Sub-Saharan metallurgy was once considered a borrowed technology from Eurasia because researchers could not explain why Africans mastered in a short period what it took Eurasians millennia to accomplish.

The beginning of the science and technology of metal production had multiple centers of origin, as reported in West, East, and Central Africa. Some very early iron dates include 1895–1370 BCE at Tchire Ouma 147 in the Termit Massif region of Niger; 2631–2458 BCE at Lejja in Nsukka region, Nigeria; 1297–1051 BCE at Dekpassanware in Bassar, Togo; and 2136–1921 BCE at Obui in Central Africa Republic (Chirikure, 2015; see Fig. 2 in the introduction). The earliest sites with African metallurgy occur in the interior of the continent (not the coastal areas), making this an indigenous technology. Although southern Africa is the last region to receive metal technology, several inventions and innovations are unique to this sub-continent.

Pre-industrial African metallurgy involved several metals and alloys (iron, copper, tin, silver, gold, bronze, and brass) with distinct histories and roles. Each metal or alloy has a unique production process (a chain of events that archaeologists call an **operational sequence**), but technological cross-borrowing

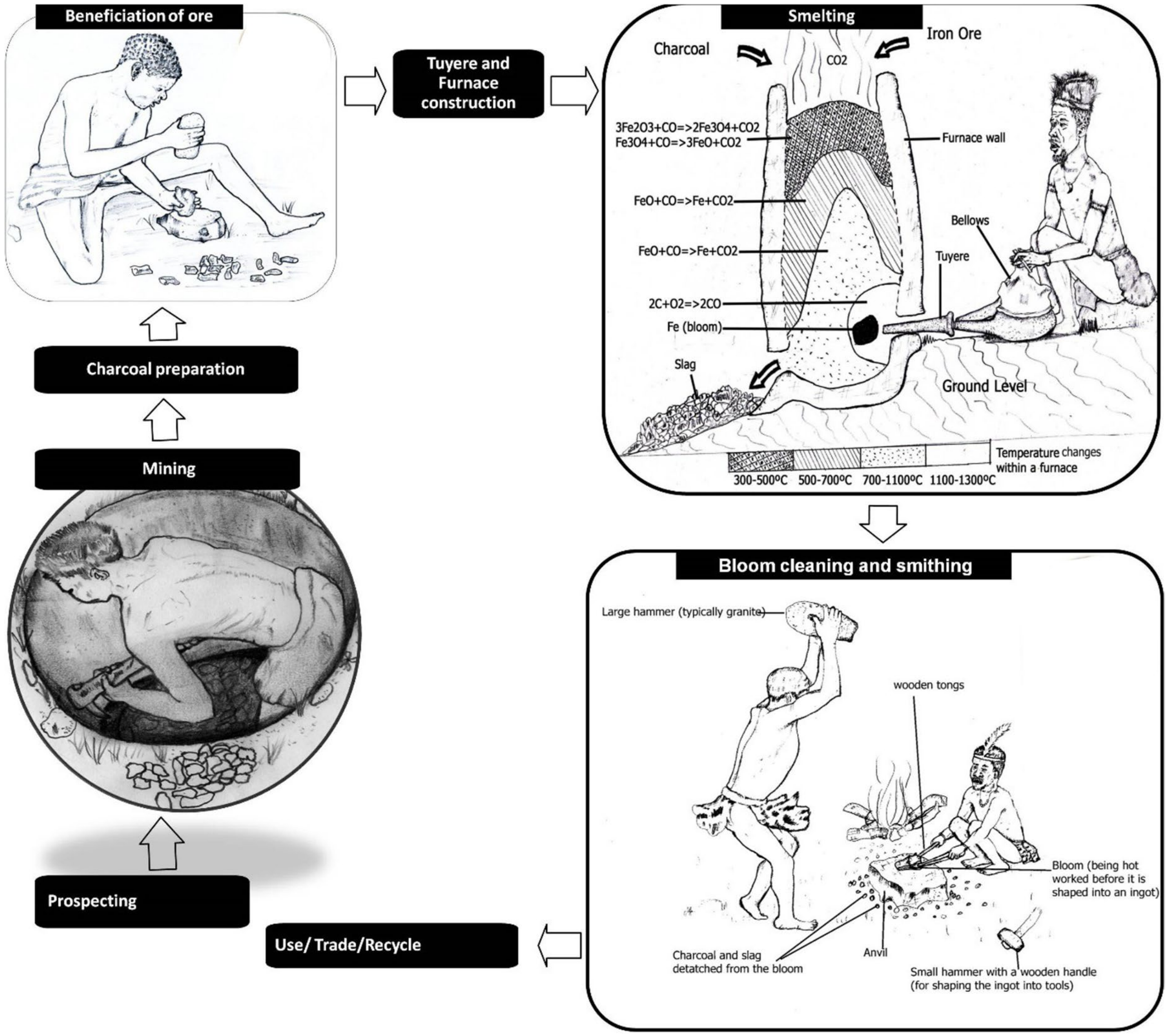

Fig. 2 Typical bloomery iron production operational sequence starting with acquiring raw materials through smelting and smithing. Modified after Bandama (2020)

across the different metals is also evident. In some cases, the finished products were also chemically mixed (alloyed) or physically combined to make composite tools or objects. Perhaps the most complex operational sequence is that of bloomery iron technology. It incorporates all the stages in other metals and alloys except for the casting and alloying stages in non-ferrous metals. Figure 2 illustrates the operational sequence of bloomery iron production, which involved prospecting, mining, ore processing/furnace construction, smelting, smithing, and the use, discard, and recycle stages.

Complex scientific reactions took place in the bloomery furnace as different phases of iron were forced to separate from oxygen (O), which reacted with carbon monoxide (CO). CO is a very unstable gas that needs to combine with oxygen to produce CO_2. Carbon monoxide has one carbon atom and one (mono-) atom of oxide (oxygen), while dioxide has two (di) atoms of oxide (oxygen). CO gas is produced by **incomplete combustion**, which happens when fire burns in an area without sufficient oxygen. In Fig. 2, the initial reactions in the smelting furnace show hematite (Fe_2O_3) reacting with carbon monoxide

(CO) to produce magnetite (Fe_3O_4) and carbon dioxide (CO_2). The continued incomplete combustion produces more carbon monoxide, which reacts with the oxygen in magnetite to produce wustite (FeO) and more CO_2. Carbon dioxide continues to escape through the top of the furnace once formed, and more carbon monoxide is produced by continued reducing conditions in the furnace. The pattern continues as unstable CO removes oxygen from wustite to leave metallic iron (Fe). This is why iron smelting is considered a reduction process because carbon monoxide reacts with oxygen from different phases of iron.

Ancient African Metallurgical Science of Observing and Testing

Starting with prospecting, ancient African metallurgists had sophisticated methods of searching for ores. The principal method involved reading the geology, soil, and vegetation of an area (Bandama, 2013). Metallurgists knew that certain trees could be signs of ores because they grow in soils formed from decaying rocks associated with those ores. The same is also true for water taste, which can be influenced by the geology in the catchment of the rivers and lakes. Rivers and lakes also receive certain ores as alluvial (water-borne) deposits, and a careful prospector can trace these deposits to the source area. Ores and associated soils and water have distinctive qualities that can be picked up by testing them against the tongue. The pinpoint accuracy of ancient African metallurgists is evidenced by the fact that in countries such as Zimbabwe, South Africa, Ghana, and Zambia, rich ore bodies were exploited before modern prospecting (Summers, 1969).

Ancient miners in southern Africa created **stopes** (small openings on the ground leading into underground mine shafts) to aid with ventilation and lighting. For mining alluvial deposits, they employed the panning technique. This is a density separation technique used to collect heavy ores such as cassiterite (a source of tin) and gold. Because these ores are heavier than typical sand in the riverbeds, a scoop of the alluvial deposits is held just below the water surface and then shaken to allow heavy pieces to pull down on their weight while lighter materials rest on top. In ancient Ghana (West Africa), some communities dived to scoop alluvial gold deposits from the bottom of rapid streams and rivers, after which they panned on the surface of the water (Barbot, 1732). This is a traditional type of **dredging**, a technique of bringing up material from a body of water with a dredge.

Examples of Experiments and Tests in African Metallurgy

Archaeological and ethnographic evidence documents the widespread use of fire setting as a common mining technique in Africa's underground iron, copper, tin, and gold mines. Fire setting is the process of softening or cracking the rock surface by the action of fire only or fire combined with rapid cooling with water. Heating causes nearly all minerals to expand, while rapid cooling (heat shock) can be achieved by throwing water on heated rock surfaces. Heating may also lead to rapid loss of water (evaporation) that may be already present in the rocks. Fire settings, therefore, can exploit existing weaknesses or create them. Because rocks are rarely homogenous (made of one mineral of the same structure and density of particles), their mixture in specific locations creates different thermal behavior, which is a major factor when inducing internal stress using fire.

Archaeologists have also found evidence of how African metallurgists developed solutions for working with low- and high-grade ores. The Chewa people of Malawi are known to have smelted low-grade laterite ores (about 40% iron) that are not considered economical today. They invented a unique two-stage smelting process that combined two types of furnaces. The first stage was done in a primary furnace of the natural draught type, which only rose to about 1.5 m. This height was not tall enough to allow complete melting of impurities since its internal temperature only reached around 1250°C (Killick, 2015). The resulting product was a sintered (incompletely melted) slag-rich sponge mass with small pieces of iron metal. They solved this technical problem by re-smelting the material in a smaller secondary furnace of the forced draught type to produce the iron bloom.

On the opposite end of the spectrum, communities in northern South Africa found ways to smelt very high-grade magnetite iron ores (over 90% iron) in low-shaft furnaces. To aid the slag formation, they added sand as a flux and sacrificed some of the iron retained in the slag. As was also the case in northern Tanzania, this high-grade magnetite-ilmenite ore contained up to 25% (by mass) titanium, which is way above the 2% upper limit for modern blast furnace technology. Titanium presents a challenge because, when partially smelted, it makes the slag viscous and hard to drain away. However, African smelters could use bloomery technology to smelt high-titanium iron ores because they operated at lower temperatures, which left the titanium oxide unreduced. Using bloomery furnaces enables them to manipulate these challenging ores in a process by which titanium is not reduced and combined with iron and silicon oxide to make a fluid slag (Killick & Miller, 2014).

Archaeological science shows us that African metallurgists achieved technical feats later mastered in other world areas. For example, modern blast furnace technology cannot handle iron ores containing phosphorus or arsenic because they dissolve in molten iron, making the metal brittle on impact. However, around 300 BCE, iron smelters at Meroe in Nubia (now modern Sudan; Fig. 3 in the introduction) successfully targeted and smelted these types of ores, taking advantage of their benefits related to hardiness, resistance to corrosion, and etching properties (Abdu & Gordon, 2004). They could do this because their solid-state bloomery technology does not make phosphorus and arsenic concentrate at iron grain boundaries. Meroitic ironworkers then etched their finished objects with an acid to create decorative swirls of lighter and darker metal. Etching was done by briefly applying a strong acid that attacked (cut into) the unprotected parts of the metal surface to create designs, leaving the resistant layers containing arsenic and phosphorus unetched (Killick, 2015). The etched areas appear darker, while the uncut areas appear lighter.

Not all ancient African metallurgical experiments were successful. At Kanshanshi in Zambia, ancient smelters unsuccessfully attempted to use a natural draught furnace to smelt copper. This experiment was not attempted again at the site or anywhere else. The highly reducing natural draught furnace is likely

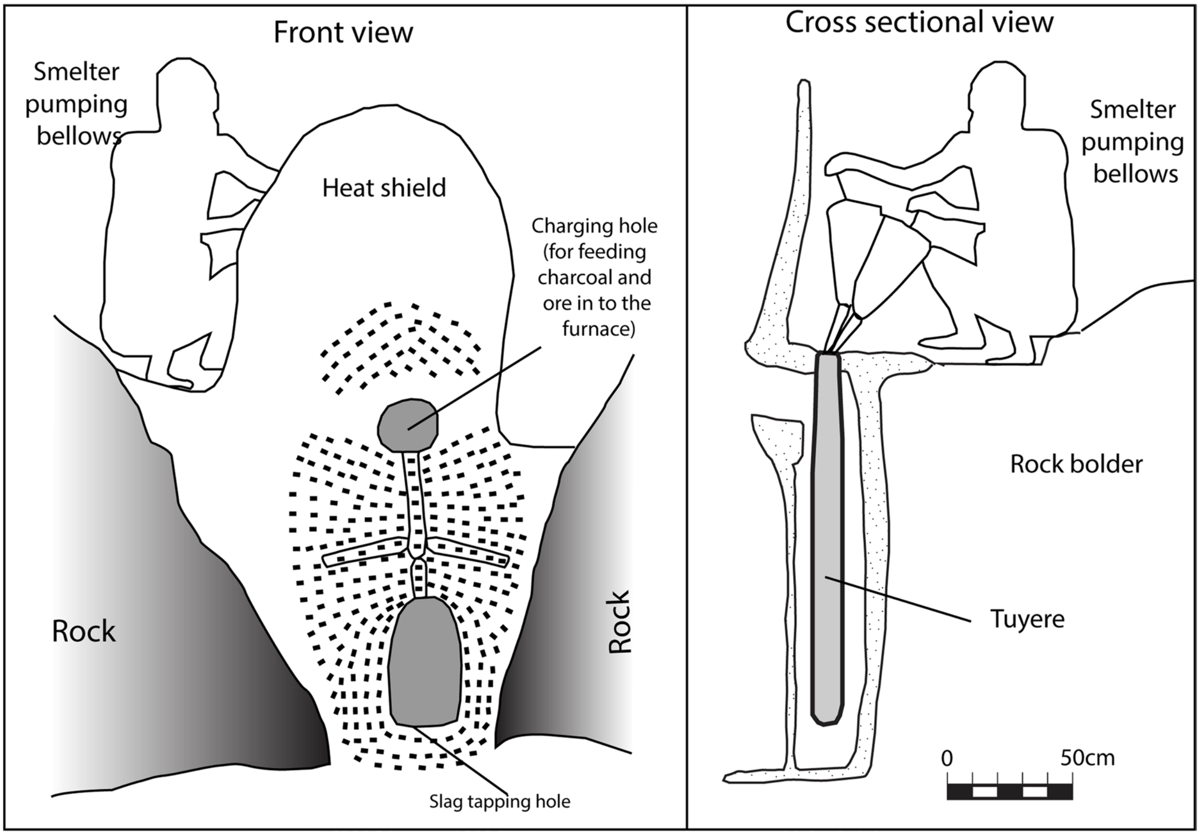

Fig. 3 Front and side view of the Mafa down-draught type of low-shaft furnaces. Redrawn after David et al. (1989)

the reason for the failure of the experiment because it would have co-smelted iron together with copper, leading to an undesirable iron-copper alloy (Chirikure & Bandama, 2014).

Ancient African bloomery furnaces exhibit remarkable diversity (Fig. 1), suggesting constant improvisation and innovations. The most amazing unique bloomery low-shaft furnace is that of the Mafa people of northern Cameroon (Fig. 3). This type relied on a single extraordinarily long (1.7 m) ceramic tuyere inserted vertically rather than horizontally, typical of bloomery furnace tuyeres (David et al., 1989). Because the tuyere was inserted deep into the furnace, part of the ceramic material was sacrificed as it melted away to facilitate slag formation. Compared to the limited range of bloomery smelting furnace types documented for ancient Europe, the diversity of furnace types is astonishing, particularly so because Africa has seen far less research than Europe.

What We Know: Glass Production

Compared to ceramics and metal, glass appeared later in the history of ancient African technology. However, like pyrotechnology materials, glass making is sophisticated and embedded in scientific knowledge. The attributes of glass, with its ability to appear in different colors, its shininess and translucency, and its reminiscent of precious stones, made it a desirable material among many ancient societies. Like metallurgy, glass production is grounded in scientific principles, including experimentation, observation, innovation, and improvisation (see Henderson, 2013; Shortland & Rehren, 2020, for details on the science of glass making). Globally, early evidence of glass dates to approximately four thousand years ago, with the earliest convincing evidence of industrial-scale production coming from Egypt, where raw materials for making glass were mostly locally sourced for almost the first one thousand years after its discovery.

It was only in the mid-first millennium BCE that the first glass in the form of a fragment of an eye bead appeared in Sub-Saharan Africa at Nin-Bere 3 in southern Mali (Giachet et al., 2019), but without evidence of production. Glass objects, in the form of beads, were traded to all parts of Africa in the past three millennia. Only recently have archaeologists confirmed that glass making also took place in Tropical Africa, especially in the southwestern part of modern Nigeria (see Babalola, 2022, for more on glass and glass beads in West Africa). Before looking at the evidence of the science and technology of glass, let us consider briefly what glass is.

What Is Glass?

The Oxford Learner's Dictionary defines glass as a hard, usually clear substance for making windows and bottles. For archaeological scientists, glass is more than a material used to make other objects. Unlike metals, glass is non-crystalline, meaning its atoms do not align into a regular structure. The term can refer to both its solid and liquid forms and a combination of different elements, all of which leave their signature on the glass. This means that a piece of glass bears the signature of a bigger sample. This explains why studying the science, technology, and production of glass from a small fragment recovered from archaeological sites is possible.

Glass can also be defined by the major constituents of its raw materials, which are almost entirely natural. Thus, the raw materials for glass are grouped into three categories: formers, modifiers, and stabilizers (Table 1). Combining these and subjecting them to high heat transforms these constituents into vitreous (glassy) material. Silica is the major forming constituent, mostly from quartz sand or stone. It requires up to 1700 °C to melt; hence, a **flux** is introduced to reduce the melting temperature. Glass can also be modified using **colorants**, **decolorants**, and **opacifiers**, which change the look of the finished glass. These additives give glass its main attributes—color and shininess. Combining different minerals with additives requires a lot of effort, observations, and scientific knowledge. Recent work has demonstrated that glass workshops existed in Sub-Saharan Africa, at least from the eleventh century AD.

Glass Making in Ile-Ife

Recent archaeological research at Ile-Ife, southwest Nigeria (see Fig. 2 of the introduction to this issue), has repositioned West Africa in the global understanding of the science and technology of glass. Ile-Ife was an urban center that gained significant prominence between the eleventh and fifteenth centuries CE. Ile-Ife

Table 1 Raw materials for forming, modifying, and stabilizing glass and their basic functions

Base raw materials			Enhancing materials		
Former	Siliceous sand or quartz stone	The main source of silicate needed for glass	Colorants	Copper oxide (Red, turquoise, or pale blue) Cobalt oxide (Dark and bright blue) Manganese oxide (Pink, black) Iron oxide (Green, black) Lead-tin oxide (Yellow)	Final color depends on certain manipulation of the furnace heat
Modifier	Soda (Natural natron, plant based) Potash (Wood) Lead oxide (Litharge)	Ingredient to lower the melting temperature of the silica	Decolorants	Manganese oxide Antimony oxide	Take out the natural color in the glass batch and make it colorless, like a wine glass.
Stabilizer	Alumina Lime	For fluidity, viscosity, and to prevent corrosion	Opacifier	Tin oxide Antimony-calcium oxide	Creates dense mass to make a milky non-translucent effect

is the ancestral settlement of the Yoruba people, one of the largest ethnic groups in West Africa. Their origin is traced to the Niger-Benue confluence area of Nigeria, dated to over two thousand years ago (Ogundiran, 2020). The Yoruba speaking people are present in today Republic of Benin, Togo, and parts of Ghana with a significant diasporic presence in the Americas, the Caribbean, and Europe. The ancient city of Ile-Ife was home to a range of specialized craft production activities, among which glass making was popular.

The glass workshops at Ile-Ife were located in an industrial park, an open space on several hectares of land in the northern section of the city, during the eleventh through fifteenth century. The park was close to a water source that traversed the northern edge of the workspace. Undoubtedly, the water source was important to glass production for mixing raw materials, quenching unwanted fire ignition, and drinking to stay hydrated. The park had furnaces for glass making and smaller fire-points for modifying glass artifacts, especially beads. The furnaces took the form of pits with clay walls surrounding them. These furnace pits were connected with channels in which clay pipes (possibly, **tuyere**) would have been placed as conduits to blow air into the furnace. In terms of design, the furnaces at Ile-Ife differ from the large tank or dome furnaces used in the Levant and South Asia. However, they were as effective in containing the heat to transform the raw materials into colorful glass and were used for centuries.

The glass makers at Ile-Ife sourced raw materials from within the vicinity. They applied the same scientific principle we know from other parts of the world in prospecting and processing raw materials. Like metallurgy, the processes involve experimentation and observation through experience and knowledge of the local geology. But, unlike a geologist prospecting with machines, the glass makers of Ile-Ife relied on their naked eyes combined with experimentation or testing to identify good sources of optimum sand, colorants, and fluxes.

Fig. 4 Crucible fragment from Ile-Ife, Nigeria, with semi-finished glass stuck to the bottom

Evidence of **semi-finished glass** stocked in the bottom of a crucible fragment from Ile-Ife (Fig. 4) convincingly supports primary glass making. The glass makers at Ile-Ife used feldspar-rich pegmatite sand mixed with calcareous material, specifically snail shells. The shell acted as both flux and stabilizer. The selection of these raw materials reflects technological choices made by the glass makers, and the combination of these raw materials formed a unique chemical composition that resulted in glass with high lime, high alumina, commonly called HLHA (Babalola et al., 2018; Lankton et al., 2006). No other known glass from around the globe has this composition. Hence, the HLHA glass is a uniquely Sub-Saharan African invention resulting from the engagement of its makers in the scientific process. HLHA glass was made in blue and green using cobalt and iron as colorants, respectively. A colorless variety also excluded manganese and antimony as evidence for intentional addition of decolorants. This suggests that craftspeople carefully selected and processed raw materials with fewer impurities for this group of glass. Experimentation did not end with the production of raw glass. The raw glass was worked into artifacts through the process called "**secondary glass working**."

Primary and secondary production were carried out at most glass making sites in early societies at different workshops. In Ile-Ife, both activities were conducted within the same industrial space. While making glass consists of gathering raw materials and sourcing the fuel needed to make raw glass, glass working involves a new level of innovation and skill. It involves the forming of things from the manufactured material. Throughout Yoruba history and more broadly across western Africa, beads have been significant objects of trade, exchange, ritual, power and authority, and personal adornment. Therefore, it is not surprising that beads were the main objects manufactured from locally made glass at Ile-Ife (Fig. 5).

The process of glass bead making involves science and technology. Knowledge of fire and heat chemistry is important for manipulating raw glass to make beads and perforating them. The quantity and varieties of glass beads found at Ile-Ife, and the quantity of production waste from the site affirm the presence of both glass making and secondary glass working at the site. After making raw glass, molten glass was drawn from the crucible for making glass beads through the process researchers call a "**drawn technique**."

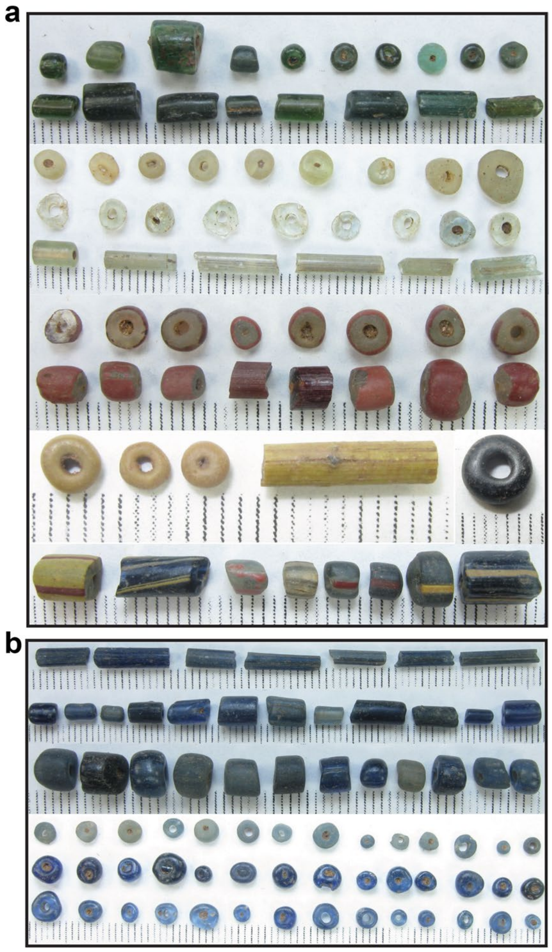

Fig. 5 Glass beads of different colors and shapes from Ile-Ife, Nigeria; those with sharp cut edges are unfinished or untreated, indicating glass working

The drawn technique involves gathering molten glass on the tip of a hollowed iron rod, then drawing out the molten glass until the desired length of the glass tube is reached. Before the molten glass is pulled, a pointed rod is inserted into the hollowed rod holding the molten glass to create a bubble, which becomes the perforation. This process could be done by two people pulling the glass apart or by one craftsperson pulling to the maximum reach of his or her hand length. Here timeliness, accuracy, and repetitiousness are important to maintain the perforation while forming long glass tubes. Once glass tubes are made, they are cut into the required sizes and treated to smooth the sharp cut edges. The outcome was well-rounded "donut-shaped" and cylindrical glass beads.

The drawn technique has greater antiquity in India than Africa (Francis, 1990), but there is no convincing evidence that it was transferred from India into Ile-Ife. While there are other techniques for making glass beads (Babalola, 2022; see the link to a YouTube video in the Learn More section below), the drawn technique has the advantage of allowing for mass production. Archaeological evidence from Ile-Ife shows that each crucible could make several tens of thousands of glass beads (Babalola et al., 2018). Having existed for several centuries, the glass industrial park in early Ile-Ife would have made millions, if not billions, of glass beads of different colors and sizes during its heyday.

While there is still a lot to learn about the implications of the development of the science and technology of glass at Ile-Ife on early societies in Sub-Saharan Africa, a few things are certain. First, Ile-Ife has changed the narrative about Egypt as Africa's epicenter of science, technology, and innovation. Ile-Ife was a regional center for sophisticated indigenous West African glass making. The glass makers exploited local materials to invent a new form of glass through the scientific process of creativity, improvisation, experimentation, and observation (Babalola, 2021). Second, it yielded the first evidence of the complete sequence of glass bead making in Sub-Saharan Africa, from glass making to bead production, indicating that glass beads are not always exotic items only modified in the region but are rather made from scratch. The mass-produced glass beads from Ile-Ife supplied wider commercial networks. Archaeological evidence and results of compositional analysis of glass beads from Gao and Essouk in Mali, Igbo-Ukwu in Nigeria, Bura in Niger, and so on have shown that Ile-Ife glass beads were transported along the River Niger corridor to reach other early West African market towns and cities from the eleventh century CE (Babalola et al., 2018). We now know that exchange and long-distance trade in West Africa was never unidirectional but rather multidirectional, with the southern communities contributing prestige goods to the commercial networks.

Concluding Remarks: Why the Science of Ancient African Metal and Glass Is Important to Know?

As Africans, we attained most of our education on the continent. Despite the obvious resource differences, our experiences in science classes were similar to those of students in the West; learning science rules and laws modeled after Western epistemologies. Our educational systems in Nigeria and Zimbabwe were inherited from colonial institutions originally designed to produce graduates fit for employment in primary industries such as mining, agriculture, or forestry. To provide the labor force for these industries, learners had to be trained in Western style "sciences" that equipped them with skills like operating Western style machinery. For impressionable young minds, a pattern was created in which everything associated with African technology was implicitly backward, while those brought by the colonialists were thought to be advanced. There appeared to be a widespread pattern of equating "being white with supremacy." Few people would admit it publicly, but many Africans of our time also had Ndukuyakhe Ndlovu's (a South African archaeologist) childhood dream of wanting to be white (Ndlovu, 2009, p. 179). African perceptions of science and technology and the practices that demonstrate the dynamics and uniqueness of African traditions were of less priority. It also took us years of reflection and reinforcement to make the connections that some of the ongoing African crafts in our communities were technically science, without needing to fit the Western mold of science.

The view of science as "embedded practice," intimately connected with ritual, for example, is considered "ascientific," "pseudo-science," or "magic" in Western perspective. In Africa, there is a strong connection between the physical and the terrestrial worlds. The deities and gods are the emissaries of the supreme God and the patrons in charge of the workability of the processes involved. In the Ile-Ife pantheon, for example, *Olokun*—the goddess of wealth—is considered the patron of the glass industry and is therefore consulted. Sacrifices are offered to appease her for a successful run. The same is true for ironworking. Current scholarship has reinforced the contributions of ancient Africa to the global history of science and technology.

Whether in reference to glass making at Ile-Ife or evidence of ancient metallurgy across Africa, archaeology challenges the notion that technological inventions and innovations are determined by race or geography (Mavhunga, 2017). Regions today considered part of the Global South played a significant role in understanding the global history and archaeology of science, technology, and innovation. The use of different apparatuses and methods of recording, reading, and measuring aspects of technical processes should not take away from what ancient Africans were capable of achieving. As producers of science and technology, they achieved technical feats, some of which are still beyond modern technology. In Ogundiran and Ige's (2015, p. 751) words, "our [African] ancestors were material scientists."

Beyond knowing about African science and technology, what are the implications for learning? How we incorporate this knowledge into school learning is equally important. Returning to the UN SDGs, meeting the goals of sustainable quality education (SDG 4) means we must embrace systems of knowledge production that differ from normative ways. Everything has a history. Learning about the long histories of Indigenous science and technology in Africa, which are stories of resilience and improvisation, holds promise to inspire tackling today's challenges through observation, inference, and experimentation grounded in place-based knowledge (e.g., Gwekwerere & Shumba, 2021).

Learn More:

To learn more about glass bead making, the Corning Museum of Glass, Corning, New York, provides examples of techniques for making glass beads, available at https://www.youtube.com/watch?v=DGvtWCX8QD4.

To learn more about iron working, based on experimental work and archaeology at ancient Meroe (Sudan) by UCL Qatar, see "Ancient Iron, Experimental Archaeology in Sudan (UCL Qatar)" https://www.youtube.com/watch?v=SPU8Uwa-jBQ.

On the role of science teachers as change agents, see

Gwekwerere, Y. N., Mushayikwa, E. & Manokore, V. (2013). Empowering teachers to become change agents through science education in-service teacher training project in Zimbabwe. *Canadian and International Education/Education canadienne et international, 42*(2), Article 3. https://doi.org/10.5206/cie-eci.v42i2.9228.

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