Taung and beyond: The mining history, geology and taphonomy of *Australopithecus* in South Africa

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South Africa is host to the single richest early hominin fossil record worldwide, including many examples of the endemic species *Australopithecus africanus* fossils. This species was first described by Raymond Dart in 1925 from the deposits near the town of Taung. Later, many more fossils, of different species and genera, were found in the caves of the Sterkfontein and Makapan Valleys. To understand this rich and diverse fossil record, we must understand how the landscape formed (cave formation processes) and changed (mining), when this happened (geochronology), and how the fossils were accumulated and modified (taphonomy). Here we provide a review of these themes to mark the centenary of the Taung Child discovery. We mark this moment in our field by critically reflecting on the role of extractive practices, especially centred around past mining of the Caves and the exclusion of many members of research teams. The South African Fossil Hominid sites provide a unique opportunity to expand our understanding of the intersection between human evolution and changing environmental conditions, as the karstic landscape and remnant cave systems preserve both fossils and sedimentary archives of past environmental change. We offer a perspective on future research areas: more standardised excavation practices and techniques to raise the quality of data collected from the caves and new techniques to date and extract palaeoclimate data from cave deposits themselves, to provide novel insights into the world of the early australopiths.

Significance:

This review introduces the reader to the important fossil remains and palaeoclimate archives preserved within South Africa, highlighting the key species *Australopithecus africanus* and marking the centenary of its first description from the site of Taung. We review the geological and exploration history of the South African hominin fossil sites and discuss how they are intrinsically linked. We explore the impact of past extractive practices on the fossil and palaeoclimatic archives for past, current and future research. We go on to emphasise members of research teams who have been crucial to the discovery and recovery of fossils but have often been excluded and remained unnamed.

[Abstract in* Setswana*]

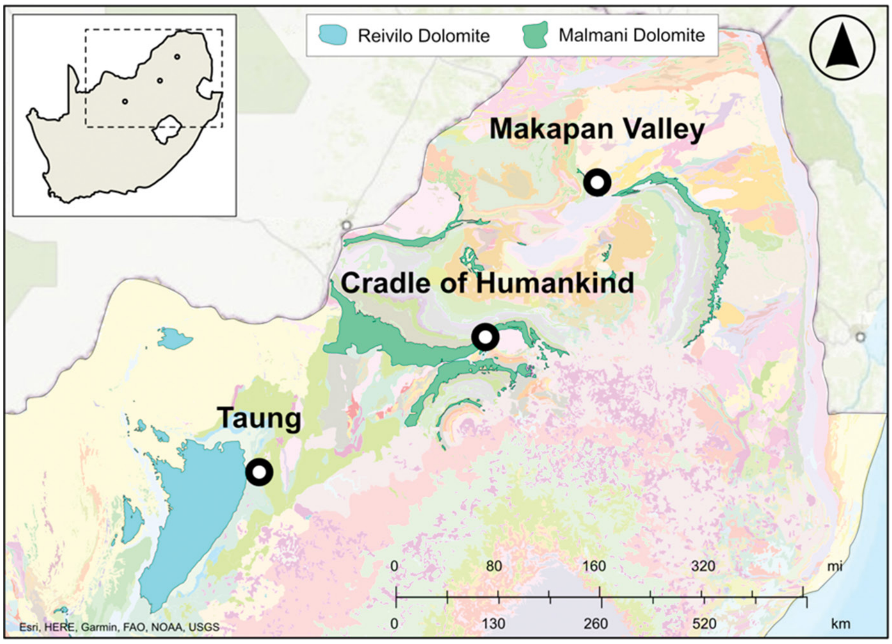
Introduction

Fossils of *Australopithecus africanus* have been recovered from three localities within the UNESCO Fossil Hominid sites of South Africa: Taung, Makapan Valley, and the cave systems of the Cradle of Humankind (hereafter referred to as 'the Cradle'). These caves and palaeocave remnants formed within the Palaeoproterozoic Malmani (the Cradle and Makapan Valley) and Reivilo (Taung) Dolomites within the Transvaal Supergroup[1] (Figure 1). In this contribution marking the centenary of the Taung Child discovery[2], we review the geological history and the early mining history of the South African australopith sites, and how these intersect. We focus on the stages of formation of the caves themselves, the processes through which material is accumulated in the caves, from fossils to speleothems (secondary cave carbonates), and how we use the caves and their contents to place *Australopithecus africanus* in context. We specifically zoom in on past extractive practices on the fossils and speleothems and how these impacted subsequent research, and emphasise people crucial to the history of scientific study who have largely remained unnamed and unacknowledged.

Historically, the bulk of early hominin research in southern Africa has been conducted in the Cradle, as it is by far the most densely packed fossil site in this region with localised cave systems, many of which have yielded hominin fossils. While this contribution marks the centenary of the Taung Child discovery, it is important to look at the wider UNESCO Fossil Hominid sites of South Africa (primarily the Cradle of Humankind and, to a lesser extent, Makapansgat Limeworks in Makapan Valley) to fully understand the history of scientific study. The bridge between the geological history and history of exploration/mining is that the specific geological processes created caves of interest to the mining industry, which, in turn, exposed the significance of the fossil material, marking the start of palaeontological research in South Africa. We go on to highlight the potential of innovative methods to further our understanding of the environmental context of the Taung Child and other key fossils within the UNESCO Fossil Hominin sites of South Africa.

Cave formation, sedimentation and climate dynamics

Previously, researchers divided up the cave sediments of the Cradle (palaeo-)caves into members based on their lithologies, leading to stratigraphies emphasising complexity.[7–12] An alternative is presented by Pickering et al.[13], Edwards et al.[14] and Pickering and Edwards[15]: a simple cave sedimentation model that can be applied to all Cradle sites (Figure 2), albeit with site-specific characteristics and nuances. They show that, at the simplest level, only two sediment types are found within the caves: externally derived, fossil-rich clastic sediments (also referred to as breccia in the older literature) and in-situ speleothems (secondary cave carbonates, including stalagmites,



Historical summary

- **19th - early 20th century:** Lime mining at most Cradle caves
- **1924** Discovery of the Taung skull
- **1925** Dart, 1925, description of Taung skull
- **1936:** Broom, 1936, Discovery of an adult australopith at Sterkfontein
- **1953** Dart, 1953, basis for the Osteodontokeratic Culture Hypothesis
- **1981** Brain, 1983, The Hunters or the Hunted.
- **1999** UNESCO World Heritage status for the wider Cradle of Humankind area, including Taung and Makapan valley
- **2019** Pickering et al. 2019, first Cradle-wide U-Pb chronology
- **2025** Taung Centenary and SAJS special issue

Source: Adapted from ArcGIS Map Viewer Classic (image attribution: Esri, HERE, Garmin, FAO, NOAA, USGS).

Figure 1: Geological map of South Africa overlain by hominin fossil sites within the UNESCO Fossil Hominid sites of South Africa, including Taung, the Cradle of Humankind and Makapan Valley. The cave sites formed with the Reivilo and Malmani Dolomites (highlighted in blue and green, respectively), which both belong to the Palaeoproterozic Transvaal Supergroup. The dashed rectangle indicates the inset. A timeline of events in the history of the caves and fossils is also provided. Publications referred to in the timeline are references [2–6].

stalactites, and flowstones). The caves we see today (Figure 2; Stage 9) are the result of speleothem and clastic deposition, erosion and sediment infill, mining and excavation. This model builds on previous work by Brain[7], Moriarty et al.[16] and Pickering et al.[13,17,18]. The mode of sedimentation dominant at any one time is closely linked to changes in the hydroclimate[6,19] and to whether the caves are open or closed to the surface above[13,16].

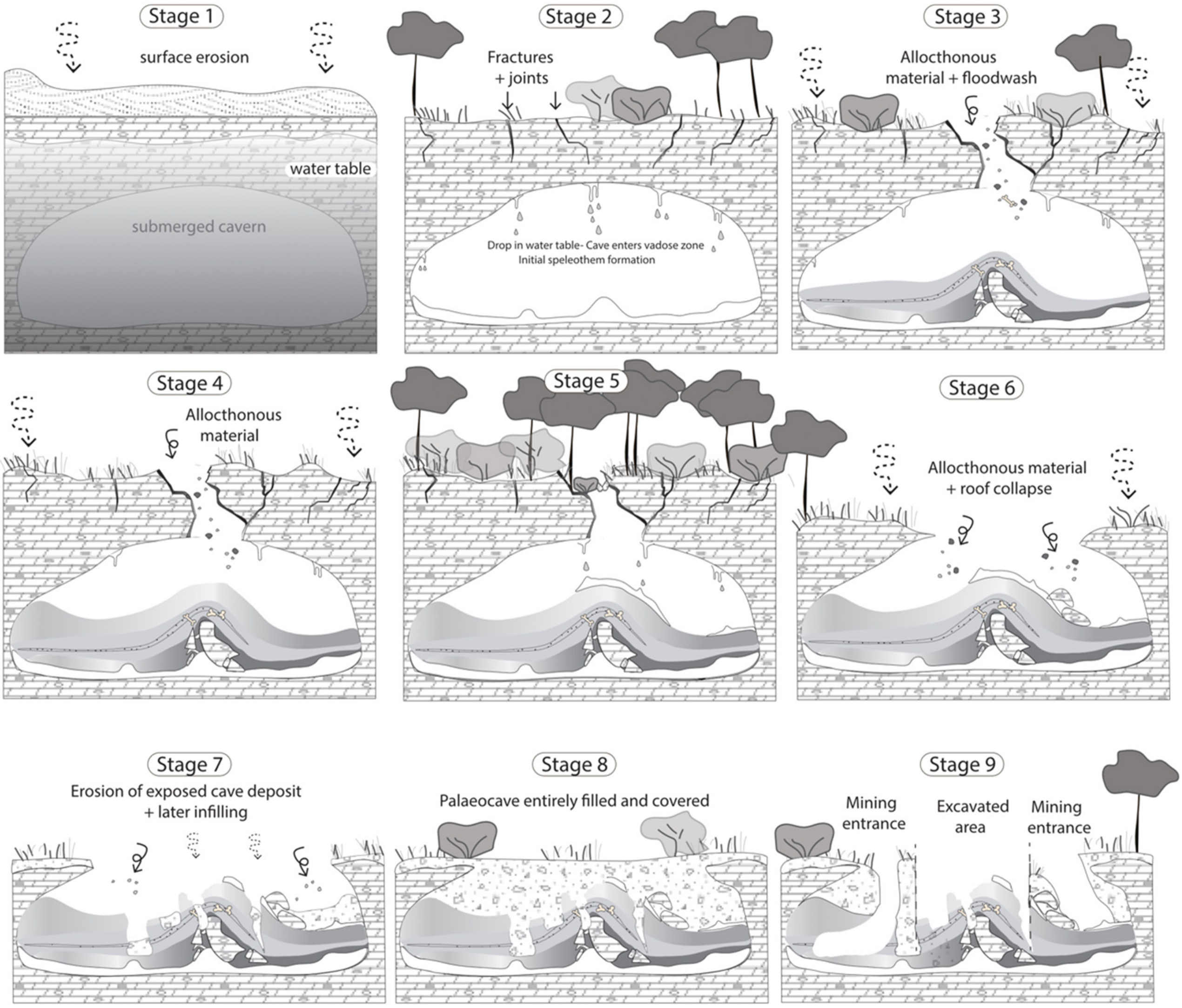
Speleothems can only form when they are uninterrupted by clastic sediment input, thus when the caves are closed or when little to no surface flooding occurs (Figure 2; Stage 2 and 5). Flowstones are horizontally bedded speleothems that form on walls and floors of caves from a central water drip source and are ubiquitous features in all Cradle caves[6,13] (Figure 3). Speleothems, including flowstones, form only under the right climatic conditions when there is sufficient vegetation cover above the cave and water infiltrating the karst. In subtropical, semi-arid regions such as the Cradle, speleothem growth is primarily linked to climatic moisture availability[20], meaning that the presence of flowstones directly indicates wet conditions in the past[13,21]. At all the cave sites considered here, these flowstone layers are interbedded with the fossil-bearing sediments (Figure 3). These externally derived clastic and bone material can, naturally, only enter the cave when there is a direct connection to the surface above the cave.[7,13,22] Such material is generally more readily available and mobilised during periods of relative aridity when sediment mobilisation and episodic flooding occurs. The presence of such material thus suggests that, during that sedimentation mode, the caves were open, and that climatic conditions were relatively dry[6] (Figure 2; Stage 3, 4, 6 and 7). By extension, the fossil record is also restricted to these dry periods, and represents short-lived, highly episodic sedimentation phases, meaning that our understanding of floral, faunal and hominin evolution is biased towards arid-adapted species.[6,13]

The evident cycles of deposition, erosion, and redeposition (Figure 2) in South African cave deposits[23–25] imply that such deposits sample multiple depositional episodes containing a ‘climate-averaged’ mix of species[25,26]. The available fossil evidence from Taung, Makapan Valley, and the Cradle of Humankind suggests that these regions experienced significant climatic fluctuations with profound impacts on the local environment, influencing the availability of resources and the suitability of the areas for various faunal and floral species survival.[27] Palaeoclimatic reconstruction using fossil fauna and flora, from different sites, points to the existence of mosaic habitats (a combination of open grassland, savannah woodland, and few patches of closed forest) (see Reynolds and Kibii[25]: Table 11) but overall agrees with the dry phase hypothesis. This combination of habitats is reflected in the speleothem carbon isotope signal from the Limeworks Member 1 Collapsed Cone and Buffalo Cave speleothem in the Makapan Valley.[28]

Fossil-bearing sediments formation, calcification and decalcification

The continued solution of dolomitic limestone by meteoric waters passing through fissures or joints leads to the formation of sinkholes and shafts that connect the ground surface to the caverns below.[29] These shafts and sinkholes can serve as natural traps through which animals or other organisms enter the cave and are unable to exit.[30] The openings also act as conduits through which organic and inorganic surface material gets incorporated into the caverns. Over time, organic material gets into contact with mineral-rich water and undergoes mineralisation, where minerals gradually replace the organic matter’s original structure, turning it into a fossil.[29] As calcium bicarbonate-rich solutions seep through fissures in cave walls, it cements together the incorporated sediments and bones.[29] Through diagenesis, loose sediment is transformed into solid rock that helps preserve organic materials incorporated within. This process spreads out from vertical drip points in the cave roof, where calcium carbonate drip waters drive the cementation and can be observed at a metre scale and at a micrometre scale in thin sections.[13]

The reverse process, sediment decalcification, occurs when calcium carbonate is removed or dissolved from sediment. Percolation of slightly acidic groundwater through the rock drives this process, leading to chemical weathering and dissolution over time. As the calcium carbonate is removed, the cementing material weakens, and the sediment may become less cohesive and more prone to fragmentation.[5] This process can alter the appearance and integrity of the sediment, potentially leading to the formation of a softer, more porous rock with void spaces. It is also possible that not all sediments become cemented, with lateral variations in levels of sedimentation away from drip points observed in cave systems such as Gladysvale.[13] Clastic sediments are sometimes reworked, leading to the loss of some material and leaving remnant



Source: Inspired by Edwards et al.[14] and Brain[7].

Figure 2: Nine-stage model for cave formation at the Cradle of Humankind following Edwards et al.[14] and Pickering and Edwards[15]. Caves first start to form by dissolution of the host dolomite under phreatic conditions (Stage 1). Once the caves enter the vadose zone, speleothem formation is initiated (Stage 2). When the caves open to the atmosphere, allochthonous material is deposited (Stages 3 and 4). The caves gradually close when increased vegetation blocks the cave entrance, after which increased effective precipitation reinitiates speleothem deposition (Stage 5). The cave deposits are eroded and exposed during Stages 6 and 7, followed by infilling and covering of the cave (Stage 8). Stage 9 shows the modern representation of the caves after mining activity and palaeontological excavation. (Flowstone layers in white; clastic sediments in grey shades.)

deposits adhering to walls – such as those observed at Swartkrans[19] – or (re-)incorporated into other sections of a cave system – as has been described at Sterkfontein Caves.[31,32]

Dating the caves, their infills and the fossils

There are several analytical techniques well suited to dating fossil cave sites and remains. The method used depends on the type of material (clastic sediment, speleothem, bone, tooth enamel) and the suspected age. Due to the limited range of methods applied to dating the Taung site, we refer to the wider UNESCO Fossil Hominid sites of South Africa (including Taung, the Cradle of Humankind and Makapan Valley).

To date, only palaeomagnetic analysis alone has provided an age for the Taung Child[33], with a depositional age of 3.03–2.61 Ma[33]. The Taung sites are formed within tufa, a secondary calcium carbonate deposit, unlike the Malmani dolomites which host the Cradle caves. From the beginning, the Taung Child skull was considered to have come from a cave named Dart Pinnacle which formed through this tufa[2], but an alternative explanation argues that fossil deposition took place during a period of tufa formation[33,34], although this has been contested[35].

Within the Cradle, fossils occur in clastic cave fill which exists in discrete packages sandwiched between extensive, horizontally bedded speleothems and are referred to as ‘flowstone bounded units’ (FBUs). In comparison, key early hominin fossils in eastern Africa are preserved between volcanic ash beds, allowing for potassium/argon (K/Ar) or argon/argon (Ar/Ar) dating, which brackets fossils and provides accurate radiogenic age estimates.[36,37] The lack of any volcaniclastics within the Cradle led many to dismiss these sites as ‘undateable’, leading to early preference for biochronological dating based on eastern African age estimates, based on the first appearance datum (FAD) and last appearance datum (LAD) of a species, from dated and secure stratigraphic contexts.[38] However, this method is not without its flaws. Biochronology is based on the assumption that the fauna and hominins in different regions existed around the same time period under similar ecological and environmental conditions, and does not consider possible variations in the biogeography of the regions. The possibility of differences in the species being compared as a result of geographic isolation and their independent evolution paths due to their respective environments is also not considered.[39,40] Finally, the existence of species appears to be affected by environmental conditions limiting the utility of

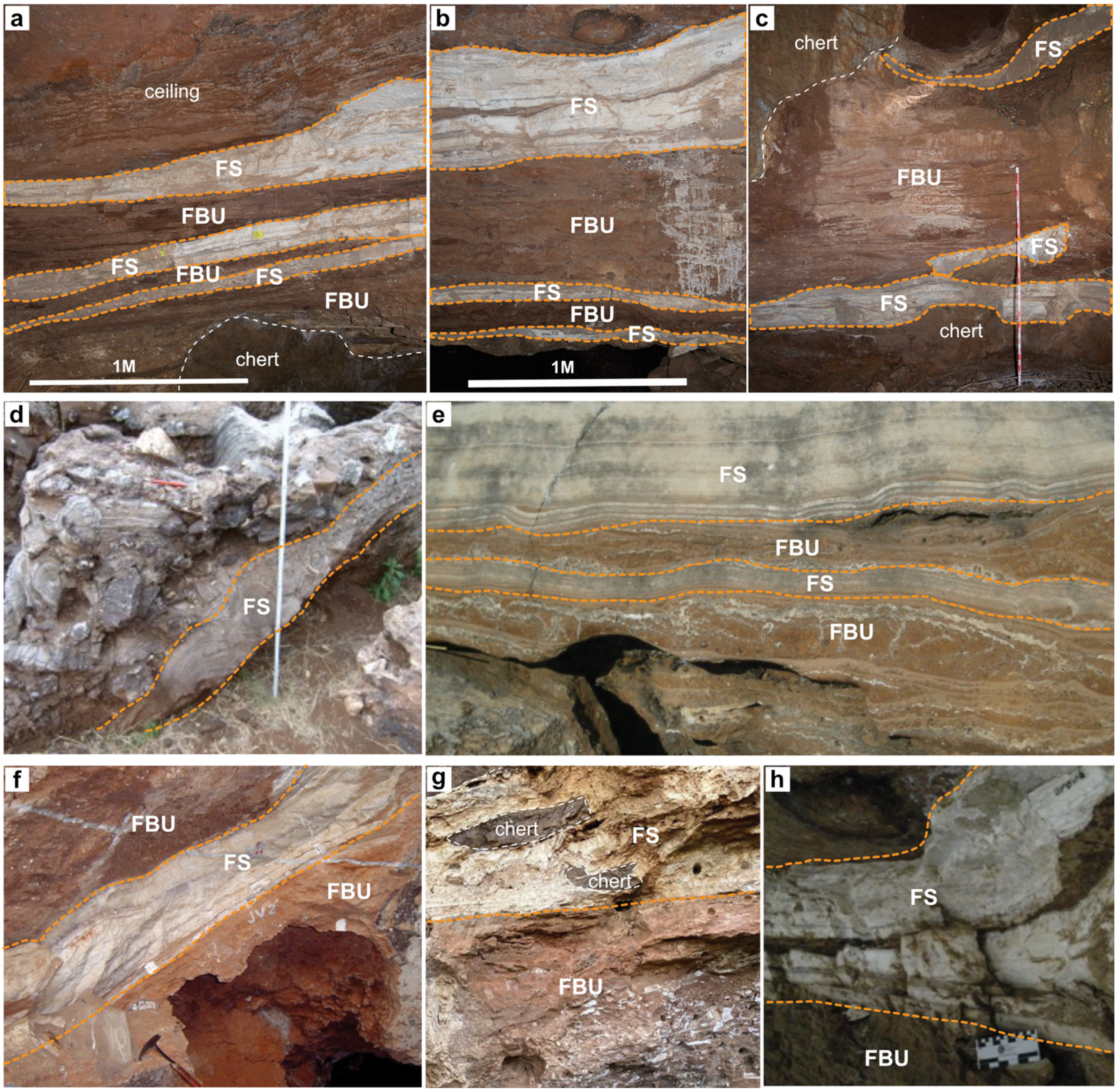


Figure 3: Flowstone-bounded units (FBUs) from fossil-bearing cave sites in South Africa. These FBUs and flowstone (FS) sequences are ubiquitous features across the Cradle and Makapan Valley: (a–c) Bolt's Farm, (d) Cooper's, (e) Makapansgat Limeworks, (f) Swartkrans, (g) Gondolin and (h) Bolt's Farm.

the fossil fauna as a dating tool.[41] Although absolute dating is preferred, biochronology remains useful to provide chronological context when multiple absolute dating methods provide inconsistent results, as shown recently by Frost et al.[42]

The most widely applied dating technique is palaeomagnetism – a correlative technique which measures changes in Earth's magnetic field as they are recorded in rocks and sediments and makes comparisons against known archives (e.g. Geomagnetic Instability Timescale [GIT] and Geomagnetic Polarity Time Scale [GPTS]). Ideally, palaeomagnetic records will be anchored by some form of radiogenic date, i.e. uranium-lead (U-Pb), electron spin resonance (ESR) dating or cosmogenic nuclide dating. The applicability of palaeomagnetic techniques relies on the completeness of a sediment package and a thorough understanding of the depositional or formational environment.[43] As well as Taung, palaeomagnetic analysis has been applied at Makapansgat[33] and a number of Cradle sites including Bolt's Farm[14,44], Sterkfontein[45], Drimolen[46], Gondolin[47], Gladysvale[48] and Kromdraai[49]. Cave deposits are often complex and multi-generational, with erosional events in a sequence.[32] Moreover, the stratigraphic sequences are often thought of as representing short time periods where few changes in magnetic polarity might be expected or numerous enough to correlate to the GIT or GPTS without help from other dating methods, such as biochronology[47,50] or absolute dating[51–53]. The results of palaeomagnetic investigation at major fossil sites over the last 20 years have, however, been remarkably uniform.[8,41,47,50,54]

Dating speleothems directly is possible with the radiometric U-Th and U-Pb technique. The U-Pb method is well established and usually applied to small resistant silicate minerals such as zircon. Indeed, the challenge was adapting the sample preparation and measurement protocols to be applicable to carbonate minerals[55] on much younger time scales, such as the last few million years[56]. Given the ubiquity of flowstones in the South African caves, and their interbedded depositional positions between the fossil-bearing sediments, they make ideal targets for dating with the U-series (U-Th for the last 500 ka and beyond this U-Pb), and can be seen as analogous to the volcanic tuff layers from the eastern African hominin sites in providing ages for the fossils sandwiched between them. The limiting factor in using this method is the initial concentration of uranium in the flowstones, which, if below a threshold value (around 1 part per million or 1 ug/g), the amount of lead produced during the relatively short time window of a few million years is below the detection limit of even the most sophisticated mass spectrometers. This issue is overcome by mapping the distribution and concentration of U and its daughter isotopes (Th and Pb), either by phosphor imaging or laser ablation trace element mapping[17,57] and selecting the ideal layers (high U, low Th and Pb) for subsequent dating. This approach has led to the successful dating of almost all the caves in the Cradle, and is best applied in conjunction with palaeomagnetic analysis of the same sequence of cave deposits (for recent examples see [6,14,44,45]). Makhubela and Kramers[58] experimented with U-Th/He dating of flowstones from various Cradle sites and offer this as an alternative dating technique for instances where U-Th and U-Pb are not suitable.

Cosmogenic nuclide dating aims to apply a chronology to the evolution of landscapes, including erosion and fluvial incision rates, sedimentary deposition and soil formation.[51] In the Cradle, cosmogenic nuclide dating has been applied, both to study landscape evolution[51] and to date fossiliferous deposits with mixed results[59–61]. An attempt to date the near complete *Australopithecus* specimen ‘Little Foot’ (StW573) from Sterkfontein via cosmogenic nuclide burial dating resulted in an age of 3.67 ± 0.16 Ma.[60] More recently, Granger et al.[61] reported a cosmogenic nuclide isochron burial date of 3.41 ± 0.11 Ma for the ‘lower middle’ of member 4 (M4), and a simple burial age of 3.49 ± 0.09 Ma for Jacovec Cavern. Later, reinterpretation of the age and burial model for StW573 concluded an age of <2.80 Ma.[62,63] This younger age was more parsimonious with the chronology previously established by radiometric (U-Pb, palaeomagnetic) and faunal age estimates (<2.80–2.20 Ma[40,41,64]). The overestimation of age estimates from cosmogenic dating of cave sediments could be linked to recycling of quartz within a multigenerational cave system.[31,62,63]

The Witwatersrand gold rush and cave exploration and mining

Palaeontological and archaeological discoveries in South Africa are heavily intertwined with gold rushes and cave exploration/mining.[65] Both have played important roles in shaping the history and culture of South Africa, and continue to be areas of interest for historians, palaeoscientists, geologists, and adventurers alike (see Ackermann et al. this issue[66]). One of the most significant gold rushes in South Africa was the Witwatersrand Gold Rush, which began in 1886 and led to the discovery of the world’s largest gold deposits.[67] The substance known colloquially as ‘lime’ was important for this early mining industry and was extracted for agriculture and for the purification of gold.[68] In the 1880s, gold minings used cyanide to separate the gold from host rocks[69], with lime used as a cost-efficient reagent for pH control[70]. The lime, also referred to as quicklime, was produced from the calcination of calcium carbonate deposits ($CaCO_3$)[70], leading to the search for local sources of carbonate and the prospecting and exploration of nearby caves (now preserved in the Cradle). To open up the caves to access the speleothems, the miners used dynamite, which was particularly destructive to fossils and also the surrounding sediment matrix.[65] While the fossiliferous blocks of sediment were not processed in the kilns, they were utilised in paving the roads for easier movement of the horse-drawn caravans, as well as in sealing entrances to speleothem-rich caves from other limestone prospectors. The blasting of the caves, though it provided easy access to the underground caverns, resulted in loss of fossils and compromised reconstruction of cave stratigraphy, in addition to complicating interpretations of cave taphonomy. Although blocks of fossil-bearing sediments were certainly not transported between caves, they were, in some instances, inadvertently mixed where the cave contained multiple depositional sequences (e.g. Bolt’s Farm[71]). To date, it has been almost impossible to associate ex-situ breccia blocks with the exact stratigraphic loci from which they originated. There has, however, been one study which recovered a fragment of a primate tooth from an ex-situ block and successfully located a remaining piece of the same tooth from in-situ sediment at Waypoint 160, Bolt’s Farm.[72]

Hierarchy in mining and its relevance to fossil discoveries

The first formal mining operations in South Africa were established in 1852[73], and South Africa saw a peak in mining activity and exploration over the turn of the 20th century, with industries including diamonds in Kimberley, gold in Johannesburg and lime in Taung.[74] As these mining operations expanded, they became micro-communities that represented the broader racial and cultural disparities across the country. Mining operations were led by white European men, whose names appear in our history books today.[75] In contrast, the remaining workforce was made up of migrant black workers from across southern Africa[76] and, from 1901 onwards, a contingent of imported Chinese men[77]. These men worked in cramped and hazardous situations, leading to over 69 000 mineworker deaths between 1900 and 1993, and more than a million were maimed or seriously injured.[78] As was characteristic of the nation at that time, these people of colour took all the risk, remained largely nameless through history, and saw very little of the subsequent economic rewards. Although they were obviously around, there is no mention of women in the literature, meaning they are also erased from these histories, and that only white men received credit for the mining and fossils, and everyone else (including women of all colours) was historically excluded.

Mining activity was divided into two factions: the ‘unskilled’ labour contingent made up of people of colour and the ‘skilled’ overseers who dictated how operations were run.[74] After the Boer War and the establishment of the new Union under the British Commonwealth in South Africa, stricter regulations were introduced, alongside broader regulations, that imposed higher taxes and the ‘pass law’ explicitly designed to force black people to accept employment at whatever wages that white people were willing to pay.[79] It was under these conditions that the Buxton-Norlim Limeworks were founded.

Quarrying at Taung began after World War 1 (c. 1918) by the Northern Lime Company, and formally closed in 1977 under the name Pretoria Portland Cement Company Limited (commonly PPC Cement). The economic boom of the country was underpinned by the discovery of both diamonds (mostly from Kimberley, discovered in 1867) and gold along the Witwatersrand Reef in Johannesburg (c. 1886[74]). The original mine workers at Taung were men from the surrounding Buxton and Norlim Villages. These supposedly unskilled workers had an integral understanding of the landscape, as their people had occupied the Taung landscape since the Batlhaping Ba-Ga-Maidi tribe first moved to the area in c. 1830.[80] Oftentimes, it was these lower-income workers whose experience determined where it was best to uncover not only precious metal seams, but later, fossil deposits as well. To date there are no details on who the workers at Taung were during the years surrounding the recovery of the Taung Child fossil.

What is known is that life for these mine workers was dangerous and short. Many migrant workers, whose families lived distantly, died in mine hospitals and were considered “unclaimed”.[81] Raymond Dart famously began amassing human bodies for the newly established University of the Witwatersrand Medical School and mining operations provided one stream of available “materials”.[82] Their names have been lost to history and their contributions have been largely ignored by European historians until recently.[82,83]

There is some shift in the ethos surrounding people considered “technicians”. For example, Stephen Motsumi and Nkwane Molefe were acknowledged for the critical role they played in the discovery of Little Foot, the *Australopithecus prometheus* partial skeleton.[84] Similarly, the Drimolen Fossil Hominid team chose to honour the long-serving site manager, Simon Mokobane, by nicknaming the *Homo* aff. *erectus* specimen, DHN 134, Simon, after him.[46] These attempts to recognise the roles that these often-unnamed persons play in the uncovering of internationally acclaimed fossil hominins is a step in the right direction; however, more needs to be done to change the long-standing status quo observed within the southern African palaeosciences[85] (see also Kgotleng et al. in this issue[86]).

Challenges and biases introduced by lime mining

Mining activities in South Africa have played a pivotal role in the discovery of fossil hominins, with finds like the Taung Child skull capturing the attention of the scientific community worldwide. However, alongside these discoveries, come ethical concerns surrounding the exploitation of natural resources and the cultural ownership of palaeontological finds. Questions arise regarding the transparency of fossil disclosure and the extent to which fossils found by miners were properly documented and donated to institutions, such as the Ditsong Museum (see Black et al. in this issue[87]).

Most Cradle sites were exploited for lime during the 19th and early 20th centuries, although there are few records of these activities during this time and almost no scientific or historical studies were done (to the best of our knowledge). Mining removed large amounts of cave carbonate, often transported and combusted in on-site lime kilns, such as those seen at caves like Gondolin and Bolt's Farm.[47,71] It was not until the discovery of an adult australopith[4], commonly known as 'Mrs Ples', that the South African caves attained a new level of importance. Focus shifted to their exploration as potential archaeological and palaeontological repositories[88], especially those subjected to lime mining as large portions had already been opened up, providing an opportunity to assess the in-situ sections and the mine dumps for fossils.[68] As much as lime mining drew attention to these caves, it also led to the extraction and damage of both the caves and fossils, with early extractions using dynamite to blast sections away.[65] The importance of fossil and archaeological material does not emerge only from their discovery, but also from their stratigraphic context providing a relation to the material with which it is found with and a baseline for other aspects of research, such as chronology and palaeoclimatic reconstruction. Some important hominin fossils have been recovered from mine dumps, such as the enigmatic Gondolin molar GDA-2; however, only inferences can be made on their possible origin.[89]

The Osteodontokeratic culture and later cave taphonomy research

Discovery of the Taung Child prompted further exploration into similar lime-rich deposits across South Africa. These included the White Limes Limited Limeworks, a crude quarry operation in the Makapansgat Caves, Limpopo Province.[90] Soon after this mining operation began, there was a push for it to be recognised as a national monument, which prompted mining operations to move elsewhere and for palaeontologists to have greater access to fossil-bearing caves.[90] By 1957, a large sample of the latter had been discovered from several of these sites, namely, Taung, Sterkfontein and Makapansgat.[90] The skeletal material recovered raised a curious question: of the hundreds of australopith bones recovered, not one was a limb bone. Rather, there was a high frequency of cranial elements[90,91] (see also Schroeder et al. in this issue[92]).

These unique assemblages, with their peculiar skeletal representations, when viewed from the lens of the researchers who had just lived through two major global wars[93] (see also Kuljian in this issue[94]), seemed like the remains of a violent butchery site. The bones of large fossil ungulates were blackened and broken. Dart used the Makapansgat Member 3 material (and augmented his argument with the associated faunal remains from the Taung assemblages[90,95]) as the basis to introduce his Osteodontokeratic Culture Hypothesis (ODK). The ODK, as it has come to be known, posited that our early ancestors were blood-thirsty apex predators, who roamed the southern African landscape killing everything in their path "slaking their ravenous thirst on the hot blood of victims and devoured livid, writhing flesh" and then using the bones, teeth and horns of their kills as weapons or tools[3(p.209)]. This was used to explain modern human violence[93]: it was an inherited behaviour from our predecessors. Dart's hypothesis was controversial[96,97], like his original hypothesis that the Taung Child represented an early human ancestor; however, in this instance, he was wrong. Washburn[96] went on to show that deposits at Makapansgat were the result of a now-extinct large hyaenid feeding (also see Maguire et al.[97]).

One researcher in particular, Charles Kimberlin Brain, began to develop alternative explanations for the accumulation of fossil bones based on his excavations at Swartkrans Cave in the Cradle. Brain revolutionised the field of taphonomy by including a range of different observational and actualistic experiments. These included not only the accumulating behaviours of hyaenids, but also expanded to show that leopards (*Panthera pardus*) were capable of amassing large ungulate fauna into cave systems below their preferred tree caches.[5] He also included work on porcupines, abiotic accumulators and human activity. This type of observational research changed the field of taphonomy and introduced a new era of actualistic taphonomy, and replaced the ODK as the conceptual framework in which fossil assemblages are assessed.

Cave taphonomy also offers perspectives on palaeoenvironments, palaeoecology, and the relationships that would have existed between living things and cave systems over time. Although earlier researchers were primarily concerned with the taxonomic composition of vertebrate remains in the caves in South Africa, the last seven decades have seen a concerted effort in reconstructing depositional histories and cave taphonomy. Reconstructing the complex taphonomic history of fossil assemblages has taken a multiproxy approach, including geochronology[9,17,40,51,98], depositional and preservation processes, taphonomic agents, and taphonomic modification[5,25,99,100]. More so, taphonomic studies have become specialised in differentiating between mammalian (leopard, hyaenid, hominin, foxes, etc.), reptilian (crocodile[101]) and avian accumulators[102], as well as abiotic accumulating agents (such as wind and waterwash[103]). The accumulating agent can contribute to variation in concentrations of fossils, laterally and/or vertically within a fossil deposit. These include carnivores, porcupines, death trap, fluvial transport, birds of prey and hominins. After deposition, faunal assemblages underwent post-depositional modifications including mineralisation, plastic deformation, and weathering prior to discovery and retrieval.[104]

Taphonomic studies on the direct impact of mining on fossils have not been done. That said, the broader impact of dynamite blasting for speleothems in caves has certainly impacted cave geology and interpretation, with nearly every site in the Cradle of Humankind preserving a fossiliferous 'miners dump'. Several of these dumps (such as that of Gondolin mentioned above[89] and those of Bolts Farm[105]) have been explored and retain critical taxonomic information, although anchoring these specimens into the broader context of the site geology and stratigraphy is near impossible. In some instances, such as *Australopithecus prometheus* 'Little Foot' and *Australopithecus sediba*, fossil finds in the dumps have been placed in actual in-situ stratigraphic locations in the caves and turned out to be the discovery of partial skeletons.[84,106] Early writers, such as Eitzman[91], recount instances of how mining operations destroyed large portions of the record and these accounts are well summarised by Dusseldorp[107]. Unfortunately, despite mining operations in the Cradle having ended many decades ago, gold mining operations further afield still impact on the integrity of the Cradle, with mine effluent threatening the local environment and waterways.[108]

The curious case of the Taung Child's taphonomy

The Taung Child is, to date, the only known hominin specimen recovered from the pink clay and siltstone (PCS, aka 'Pink Fill') deposits, formerly the Dart Pinnacle[34], which are believed to have derived from a river system bisecting the Ghaap Escarpment[109]. This is unusual in that most sites with early hominin remains have more than one specimen; many preserve near-complete skeletons (Strekfontein, Malapa, Rising Star), with occasionally even several hominin genera. The single occurrence of the Taung Child has prompted investigation into the skull itself, looking for taphonomic markers to explain it being fossilised alongside a vast array of other taxa, dominated by small primates.[2,38,96,110]

In his description of the Taung faunal assemblage[111], Dart observed four types of damage which he attributed to the hunting habits of early australopiths: depressed fractures and punctures, basi-cranium removal, cranium crushing and mandible distortion, and V-shaped nicks.

These features identified in the faunal assemblage, and the Taung Child skull itself, are now attributed to eagle activity.[112] Additional taphonomic features have now been recognised (see Baker[113] for a full list). Three extant species are suggested as potential analogues for a hypothesised Plio-Pleistocene bird of prey based on their size and ability to carry such large prey items: Verreaux's eagle (*Aquila verreauxii*); crowned eagle (*Stephanoaetus coronatus*); and martial eagle (*Polemaetus bellicosus*). Subsequent research argued that the crowned eagle left the most similar markings on the crania of small primates.[114–116] However, both Berger and Clarke[112] and Baker[113] agree that it is likely impossible to attribute the Taung Child accumulation to any one species of raptor, as there is major overlap in their taphonomic markings and also that ecological variability plays a large role in prey selection and feeding behaviours between even the same species of eagle. Similarly, without a comprehensive assessment of the large-bodied raptor populations present in southern Africa during the early Pleistocene, attributing any taphonomy to an extant raptor would be limiting. More work is required to explore the Taung faunal collections and possibly to explore the large avian materials to attempt to narrow down a possible accumulator.

Prospects of cave research and conclusions

Much of the clastic sediments and speleothems were removed or displaced during mining in the late 19th and early 20th centuries. Consequently, invaluable parts of the fossil record, within the clastic sediments, and the climatic record archived by the speleothems were lost. Nonetheless, the antiquity of *Australopithecus africanus* and other hominins is now well understood and constrained through the dating of fossil deposits and flowstones.[6,33,44]

The missing piece of the puzzle, however, is understanding how climatic and environmental change influenced the rise and demise of *Australopithecus* and other hominins. Speleothems are invaluable archives, recording such changes via multiple proxies. Despite having lost the bulk of speleothem deposits due to mining activities, flowstones are still ubiquitous features in the Cradle and Makapansgat caves and provide an under-studied resource for palaeoclimatic and -environmental reconstructions. Speleothem and fluid inclusion stable isotopes, coupled with analyses of the abundance of GDGT lipids (TEX_{86}) within the same speleothems, allow for direct comparison of the two palaeothermometry methods and thus provide robust temperature reconstructions[117,118] and will shed light on the regional temperature changes over multiple glacial-interglacial cycles and millions of years. Fluid inclusion stable isotopes also quantify rainfall amounts and source and allow for direct comparison with the Global Meteoric Water Line (i.e. the global annual average, linear relationship between oxygen and hydrogen isotope ratios in meteor water). Producing such a multi-proxy record from the already dated cave sites will allow us to test the hypotheses of earlier studies, that is, that in the wider Cradle region: (1) rainfall variability is modulated by orbital precession[119], (2) the two alternating sedimentation modes, speleothem vs. clastic, represent wet and dry conditions, respectively[6], and (3) orbital eccentricity cycles (100, 400 and 2400 ka) influenced long-term aridity trends in southern Africa[120].

Another important and recent research development is the establishment of world-class dating facilities in South Africa. Historically, the lack of such facilities in the country, and in fact on the continent, meant that all U-Th and U-Pb dating of speleothems was done overseas, where analytical costs were high and there was very limited investment in local human capacity building. The new dating capabilities at several universities (including the University of Cape Town and the University of Johannesburg) allow for in-country analysis, leading to both job and critical skills development within South Africa and the African continent.

One of the major challenges in South African cave research is the lack of standardised methodology and excavation protocols. Research teams use different methods for collecting and analysing data, making it difficult to compare results across studies/sites as different research teams bring their own experience, perspective and knowledge and thus their own way of conducting research. This leads to differences in excavation practices, sampling methods and data recording. To clarify the depositional and post-depositional histories, future studies must incorporate new technologies and analytical techniques. For instance, advances in imaging, geochemical analysis, and data modelling offer exciting opportunities for a more comprehensive understanding of past ecosystems and the processes that shaped them. The integration of advanced technologies, such as LiDAR scanning and 3D mapping, to create detailed 3D models of cave systems can provide valuable insights into their formation and development over time, and provide detailed data with which to test taphonomic interpretations.[121] Computed tomography scanning offers a non-destructive three-dimensional macroscopic and microscopic view of internal structures of sediments revealing the overall composition, frequency, location, orientation, size and alignment of constituent clasts and fossils.[122] Micromorphological analysis uses petrographic thin sections of cave sediments and flowstones and transmitted light microscopy to document site formation processes and stages of formation and is necessary as part of a multidisciplinary dating of fossil-bearing sites.[14,44,52,123]

To our best knowledge, none of these techniques described above has been applied to understanding depositional processes and environmental change at Taung. While more challenging for tufa deposits, the Taung carbonates could be dated with U-Th and U-Pb to refine the existing palaeomagnetic ages. Additionally, trace element analyses could provide valuable palaeohydrological proxy data, further improving our understanding of the environmental context of *Australopithecus africanus* at Taung. Similarly, additional work on the faunal assemblages, very little of which has been revisited in the past two decades (last assessed in McKee[124]), would be valuable to situate the palaeoenvironmental and taxonomic diversity of the western interior of southern Africa for a critically underrepresented period of the early Pleistocene. The faunal materials associated with the Taung Child have not been analysed to the same extent as those in the coeval Cradle deposits.

The history of South Africa's palaeontological and archaeological discoveries is closely linked to gold rushes and cave exploration (see Ackermann et al. in this issue[66] for more). As miners searched for lime sources, they explored caves, leading to exposure of fossiliferous deposits, including some of the world's most important hominins. The formal mining operations reflected the racial and cultural disparities across the country, with white European men leading the operations while black migrant workers from southern Africa and imported Chinese men comprised the remaining workforce. These mining expeditions caused the loss of clastic sediments and speleothems, including valuable parts of the fossil and climatic records. As the demand for lime declined and there was a recognition of the palaeontological and archaeological potential of the deposits at Taung, the Cradle and Makapansgat, research began on the cave formation processes, depositional sequences, palaeoenvironment, taxonomic compositions of fossil fauna and flora, and the taphonomy of the assemblages. Even 100 years later, there is still enormous scope for work to be done on the existing deposits, using new techniques and methods, as well as exploring for new fossil-bearing deposits. Today, South Africa is positioned to offer world-class research into speleology and fossil analysis, with the establishment of dedicated speleothem dating and 3D imaging labs that are bound to provide a more comprehensive understanding of past ecosystems and the processes that shaped them and drive us into the next century of cave and fossil research.

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Data availability

There are no data pertaining to this study/article.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare.

Authors' contributions

R.W.: Conceptualisation, methodology, writing – initial draft, student supervision, project management, funding acquisition. S.E.B.: Conceptualisation, methodology, writing – initial draft, writing – revisions, project management. T.R.E.: Conceptualisation, methodology, writing – initial draft, funding acquisition. J.K.: Conceptualisation, methodology, writing – initial draft, writing – revisions, project management. G.L.: Conceptualisation, methodology, writing – initial draft. R.P.: Conceptualisation, methodology, writing – initial draft, funding acquisition. All authors read and approved the final manuscript.

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