A Review of the Geomorphological Context and Stratigraphy of the Sterkfontein Caves, South Africa

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Abstract

The Sterkfontein Caves, located in the southwest of the Cradle of Humankind, Gauteng, is the world's richest *Australopithecus*-bearing locality and has yielded iconic fossils like Mrs Ples (StS 5) and Little Foot (StW 573), as well as *Paranthropus robustus*, *Homo ergaster* and *Homo habilis* fossils and large Earlier Stone Age lithic assemblages. The cave deposits have also yielded enormous assemblages of associated fossil fauna and document over three and a half million years of landscape, environmental, faunal and hominid evolution. These fossiliferous cave deposits represent a more recent episode of a geological history spanning 2.6 Ga years, beginning with the deposition of the dolomites, to the commercial exploitation of the caves by lime miners in the early twentieth century. The location and morphology of the karst caves is a result of a combination of factors including lithological variation within the two host dolomite formations, an early karstification and infilling of the dolomites over two billion years ago and local dolomite fracturing. Vadose zone collapse in densely fractured areas has enlarged chambers and passages, and played a major role in the location and nature of the openings to the landscape. When open to the landscape, a broad range of geomorphological processes, including re-dissolution of interred deposits, creates dynamic sedimentary environments with complex stratigraphic histories. This article reviews the geomorphological history of the Sterkfontein Caves in an effort to consolidate this information as we press forward with new stratigraphic and geomorphological work at the site.

Keywords

Sterkfontein • Dolomites • Karst geomorphology • Paleocave deposits • *Australopithecus*

1 Introduction

The Cradle of Humankind World Heritage Site covers an area of approximately 800 km^2 in the northwest of Gauteng Province, South Africa (Fig. 1). The boundaries of the Cradle of Humankind (hereafter Cradle) partially enclose the exposed and karstified dolomite, which hosts the prolific hominid-bearing caves. The densest group of excavated fossil-bearing sites, including Sterkfontein, is located in the south-western area of the Cradle near the Blaauwbank river valley (Fig. 1). The Blaauwbank River, which is now an ephemeral stream, wanders through gravel and floodplain deposits, relics of its more energetic past.

The site of the Sterkfontein Caves occupies the top of a low hill about 300 m south of, and rising 50 m above (1491 m asl), the Blaauwbank River. Paleoanthropological attention was brought to Sterkfontein, while speleothem mining was displacing large quantities of fossil-bearing

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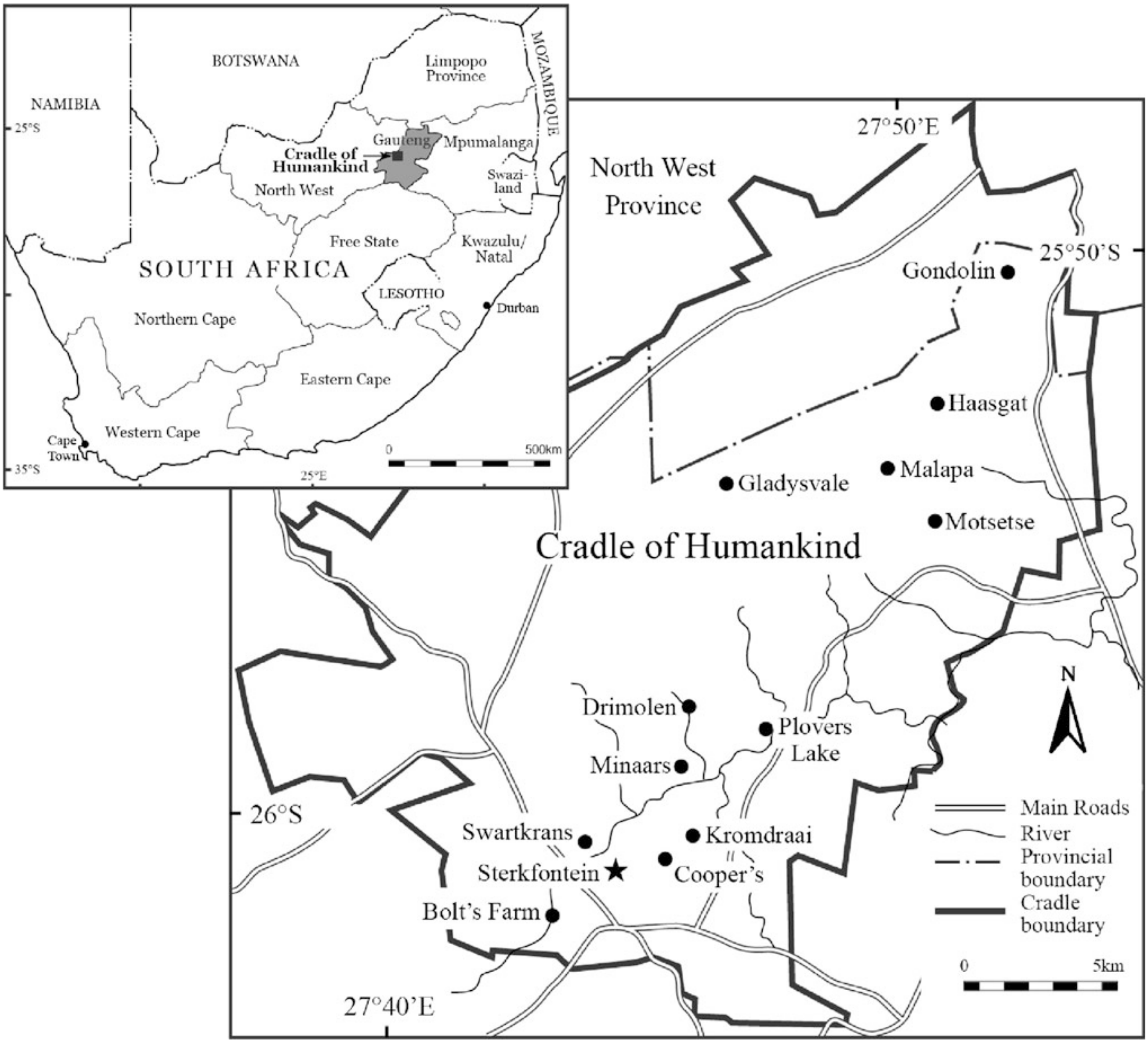

Fig. 1 Sterkfontein and other key fossil sites within the Cradle of Humankind, Gauteng, South Africa

sediments associated with large stalagmites, stalactites and flowstones that were exposed on the landscape surface after the erosion of the cave roof. The by-product of the mining was the creation of large fossil-bearing dumps. It was in one of these dumps (Dump 18) that the first hominid fossil was found in 1936 (Broom 1936). The Sterkfontein site remains one of the most prolific and long-studied fossil hominid localities in the world, yielding over 800 hominid specimens. Key finds include the first adult cranium of an *Australopithecus* found in 1936 (TM1511), the first complete adult *Australopithecus* cranium (StS 5) (Broom 1947), affectionately known as Mrs Ples, three partial *Australopithecus* skeletons (Sts 14; StW 431; StW 573) (Broom et al. 1950; Tobias 1987; Clarke 1998), and the most complete skeleton of an *Australopithecus* yet discovered (StW 573) (Clarke 1998, 2013). This article reviews the geomorphological history of the Sterkfontein Caves in an effort to consolidate this information as we press forward with new stratigraphic and geomorphological work at the site (e.g. Bruxelles et al. 2014; Stratford et al. 2014, 2016).

2 Geological Setting

The dolomites that host the caves of the Cradle of Humankind, and Sterkfontein, have an extensive geological history that has influenced the formation and geomorphology of the caves as well as the deposits accumulated within them.

The karst caves of the Cradle of Humankind formed within the dolomites of the Malmani Subgroup which were deposited under epeiric conditions (Eriksson et al. 1995) between 2550 and 2423 Ma, and reach a thickness of 1450 m close to Sterkfontein (Truswell and Eriksson 1975). A range of tidal, deep water and chemical depositional environments accumulated the dolomite and chert beds within a general carbonate ramp model (Truswell and Eriksson 1975; Sumner and Grotzinger 2004). The Sterkfontein Caves have formed within and across the boundary of the two lower formations of the Malmani Subgroup (Eriksson et al. 1995; Martini et al. 2003) (Fig. 2). The basal member, the Oaktree Formation, is poor in chert bed density and is overlain by the Monte Christo Formation, comparatively rich in chert beds (Martini et al. 2003). The difference in chert bed density between these two formations has played an important role in the formation and geomorphology of the current cave system. At Sterkfontein, the dolomite dips between 25° and 30° northwest, a result of the uplift of the Johannesburg Dome to the southeast (Eriksson 1988), and intracratonic basin sag caused by thermal subsidence within the Transvaal Basin to the north (Eriksson et al. 2001).

The depositional history of the Transvaal Basin since the deposition of the Malmani dolomites is complex and ends with the 2050 Ma deposition of the Bushveld Igneous Complex (Eriksson et al. 1995). In this 400 Ma post-Malmani period, processes include basinal tectonic extensional subsidence and thermal subsidence with cycles of epeiric drowning. It is these kinds of basin development and rifting processes that may have provided ideal circumstances for rising hydrothermal solutions to penetrate the dolomites and develop hypogene caves. The dominant basinal processes are punctuated by pre-rift uplift and base-level falls which resulted in subaerial exposure, erosion and accumulation of associated deposits into the early karst (Ryan 1986; Eriksson et al. 1993). It is likely that over the long period between the formation of the dolomites and their burial beneath the Bushveld Complex, several phases of karstification took place through either epigenic or hypogenic processes. The subaerial exposure, karstification and

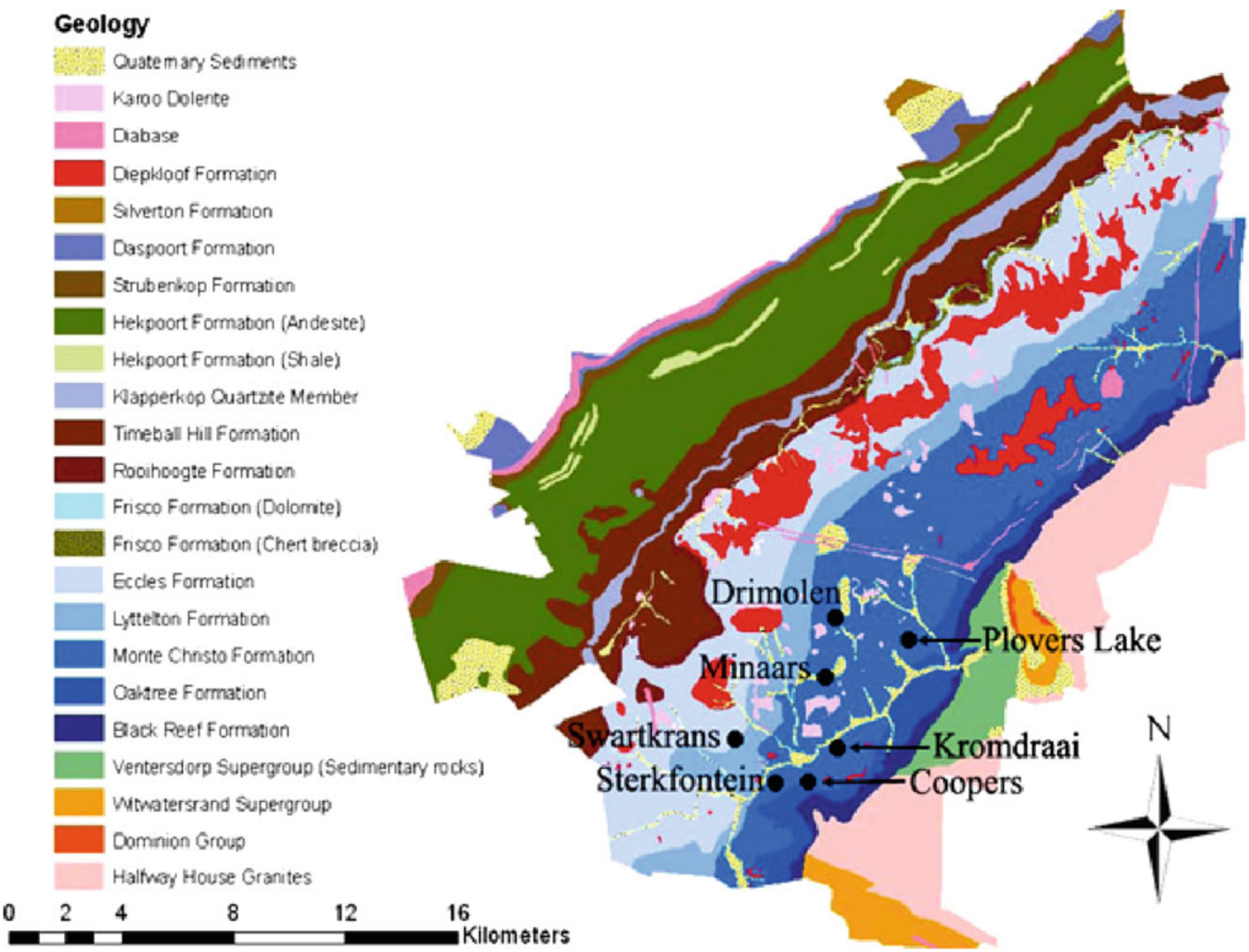

Fig. 2 Geological map of the Cradle of Humankind (adjusted from Obbes 2000)

denudation of the dolomites between 2423 and 2200 Ma (Button 1973) removed the upper beds of the Malmani Subgroup leaving just the Oaktree and Monte Christo formations around the south-western Cradle and Sterkfontein.

In the Sterkfontein area, some of the early karst forms and open faults and fractures in the Monte Christo Formation were filled by the chert breccias of the Rooihoogte Formation (Eriksson 1988; Dirks and Berger 2013). This formation represents the proximal and medial portions of extensive alluvial fans formed from the weathering of the uplifted dolomite landscape (Catuneanu and Eriksson 2002). It must be noted, however, that there may be other genetic processes contributing to the development of the Rooighoogte Formation. The silicious cement that binds the chert breccia may have formed through hydrothermal activity. Remnants of this chert breccia paleokarst fill are found in close association with the cave sites of Coopers Cave, Gladysvale, Kromdraai, Malapa, Sterkfontein and Swartkrans. Where this association is found, it is clear that the unconformities formed by the chert breccia-filled paleokarst and dolomite provided the focus for the next generation of karstification, as the dolomites were again exposed and weathered.

The age of the formation of the Sterkfontein Caves is difficult to estimate. Erosion of the African land surface during the Cretaceous contributed significantly to the removal of Karoo Supergroup sediments that had buried the Malmani dolomites (Partridge 1973; Martini 2006). The following uplift and south-westward tilting associated with the onset of the Post-African I erosion cycle, starting in the Miocene (Partridge 2010), facilitated further river incision, and perhaps started to expose the dolomites on the landscape, thereby renewing karstification (Partridge 1973; Beukes et al. 1999). Martini et al. (2003) suggest a date of between 5 and 18 Ma for the start of the formation of the Sterkfontein Caves, based on the Miocene uplift, erosion and exposure, and the oldest deposits yet found in the caves. Alternatively, it has been proposed that the caves formed below covering Karoo sediments only to be opened when those deposits were eroded and the dolomites exposed at about 2 Ma (Dirks and Berger 2013). This has recently been revised by Dirks et al. (2016) who propose that the dolomites were exposed in the Miocene but caves were not forming until a rapid karstification and opening in the Pleistocene—as judged by the absence of Miocene or Early Pliocene deposits (Dirks et al. 2016). This is an odd assumption to make given that the extensive and multilevel caves have to form underground before they can open to the surface and accumulate sediments, two processes that may take significant amounts of time. Martini et al. (2003) proposed a more parsimonious model with the caves starting to form underground, as the dolomites were exposed in the Miocene, and then only starting to open in the Late Pliocene. The rolling hills of the Blaauwbank river valley are characteristic of landscapes produced by the rivers of the Post-African I erosion cycle draining to the southwest (Martini et al. 2003) and suggest an earlier exposure than the Plio-Pleistocene.

3 Karstification and Cave Geomorphology

3.1 Karstification

There have been several works that have focused on the specific karstification process that formed the Sterkfontein Caves (e.g. Partridge 1978; Wilkinson 1983; Martini et al. 2003). The hyperphreatic model of cave formation has received greater support over the history of geological research at the site (Partridge 1978; Pickering and Kramers 2010). The classic hyperphreatic model proposes that lowering piezometric surface will form successively deeper parts of the cave network as water moves through deeper parts of the system (Palmer 2007), creating progressively deeper and younger karst galleries. This model is supportive of the lowering water table levels relating to uplift and erosion cycles as proposed by Partridge (1973). Accordingly, Partridge (1978) and Partridge and Watt (1991) placed the base of their allogenic deposit sequence, named 'Member 2' of the 'Sterkfontein Formation', within the mid-level Silberberg Grotto. Following the hyperphreatic model, the 4.5 km of passages beneath the Silberberg Grotto formed more recently and necessarily contain younger or reworked sediments. The relatively rapid downcutting of the rivers, and associated surface erosion rates, found in the northern part of the Cradle (Dirks et al. 2010—erosion rates have been recently reassessed in Dirks et al. 2016) may provide the hydrological scenario for such a formation process, but the same geomorphological situation is not found in the southern area of the Cradle where landscape erosion rates and river incision are significantly slower (Granger et al. 2015).

Contrastingly, Wilkinson (1973, 1983, 1985) proposed a 'deep phreatic' karstification process, suggesting the entire vertical extent of the cave system was developed by the time the caves opened to the surface through a period of vadose zone collapse. This is based on detailed geomorphological mapping of the cave network and tracking autogenic and allogenic colluvial deposits to the base of the system.

A further alternative could be hypogenic karstification—i.e. cave formation through rising water flow (Martini et al. 2003; Klimchouk 2007). This may have contributed to the earliest karstification of the dolomites (2423–2200 Ma), when hot water may have risen close to the landscape surface during periods of thermal subsidence of the Transvaal Basin (Eriksson et al. 2001). Large quartz nodes have been found near chert breccia deposits (Rooihoogte Formation) associated with the early phases karstification found across the Cradle and may be related to rising thermal water (Pers. Obs). In more recently formed carbonate basins in Namibia, large quartz formations can be found at the base of some complex, deep cave systems suggesting a definite relationship between recent karst formation and rising thermal water. The role of hypogenic process in the development of the most recent (Miocene) karst in the Cradle is difficult to assess for two main reasons, first—extensive infilling of sediments and associated localized erosion has obscured many informative karstification features, and second—extensive mining of speleothem has damaged the walls and ceilings of the cave and removed informative mineral deposits that documented the early formational stages. We have to be conscious of the potential for the contribution of multiple karstification processes represented on the Cradle landscape and in single cave networks over the very long geological history of these dolomites.

Recent geological studies have identified another possible karstification process involving the in situ chemical alteration of the dolomite into 'ghost rock' (Bruxelles et al. 2009; Dubois et al. 2014). This process creates pseudophreatic karst morphologies but differs in the process of dissolution and final removal of the dolomite. Residual dolomitic alterite is removed as base levels (piezometric surface) drop, leaving vertically fully developed karst networks as the caves open to the surface through vadose zone collapse. Low penetration of meteoric recharge, near-static groundwater (Martini et al. 2003) and observed in situ remnant dolomitic alterite in fine powder or boxwork structures preserved at all levels of the caves support this formation model, and work is ongoing to test this theory.

Identification of the specific development model and the stages and timings of base-level lowering in the Sterkfontein Caves has important implications for the maximum age of the interred fossil and artefact-bearing deposits, a subject that remains a source of significant and continued debate (e.g. Berger et al. 2002; Clarke 2002; Walker et al. 2006; Pickering and Kramers 2010; Herries and Shaw 2011; Granger et al. 2015; Dirks et al. 2016). The hyperphreatic model suggests that fossiliferous deposits found in the deepest areas must be younger than, or reworked from, older upper chambers following several significant base-level lowering stages, even while the caves where open to the surface. In contrast, both the ghost rock model and Wilkinson's (1985) model propose that some of the deepest deposits may be the oldest and could date to well in excess of three million years. This requires the base level to have lowered to near its current elevation prior to the caves opening to the surface. The maximum proposed date by Wilkinson for the lower deposits has been supported by some work (Partridge et al. 2003; Granger et al. 2015), but challenged by others (Berger et al. 2002; Pickering and Kramers 2010; Herries et al. 2013). Recent renewed geomorphological and stratigraphic work at Sterkfontein supports Wilkinson's (1983, 1985) observations of early allogenic sediments being deposited at the base of the system, with remnants of preserved taluses found in some deep chambers (Stratford et al. 2014), but has not yet succeeded in providing new absolute dates for these early sediments.

There are several clues in the hydrology of the system that support the latter scenario of karstification. First, there is an absence of hierarchical convergent 'branchwork' passages (Palmer 2007), suggesting that slow groundwater flow is likely to have prevailed throughout the formation of the current generation of caves. Second, there is a dominance of fissure flow through secondary porosity features as the main regime for recharge. Diffuse flow is minimal and restricted to the deepest chambers, and flow through conduits is generally restricted to vertical passages and fractures. The dominance of tall and narrow passages suggests fracture control on groundwater flow and speleogenesis. The dominance of the fissure flow also accounts for the slight variation seen in the water table level in different areas of the caves (Gillieson 1996). Conduit enlargement through mechanical removal is minimal but was likely to have contributed slightly more significantly during the removal of the alterite and early opening of the caves, as evidenced by fine gravels, rounded sands and shallow channel erosion features found in deep deposits.

3.2 Cave Geomorphology

The vertical amplitude of the karst network at Sterkfontein is difficult to estimate as passages descend below the piezometric surface. Martini et al. (2003) propose an amplitude of around 50 m. Lateral karst development is guided by dominant and subordinate fracture systems within the heavily fractured dolomites. Figure 3 shows Wilkinson's reconstruction of major fracture systems at Sterkfontein in relation to the passages and chambers of the Sterkfontein network. Figure 4 shows the same fracture zones in relation to the surface-exposed deposits and several major hominid fossil finds. The insert in Fig. 4 shows an infrared image of the southern surface-exposed deposits. Warm air rising from the cave shows openings and permeable sediments filling openings. The infrared image illustrates the continued influence of the fracture zones in the distribution of fissure flow processes (further described later). High-resolution mapping of the lower cave system is ongoing (Stratford et al. 2016) and will allow more detailed modelling of upper and lower karst levels in relation to the fracture systems and hydrological processes. The high density and orientation of fracturing is a result of the long history of uplift in the southeast and subsidence to the north and northwest forming a dominant fracture system orientated roughly southwest–northeast and a subordinate system orientated north–south.

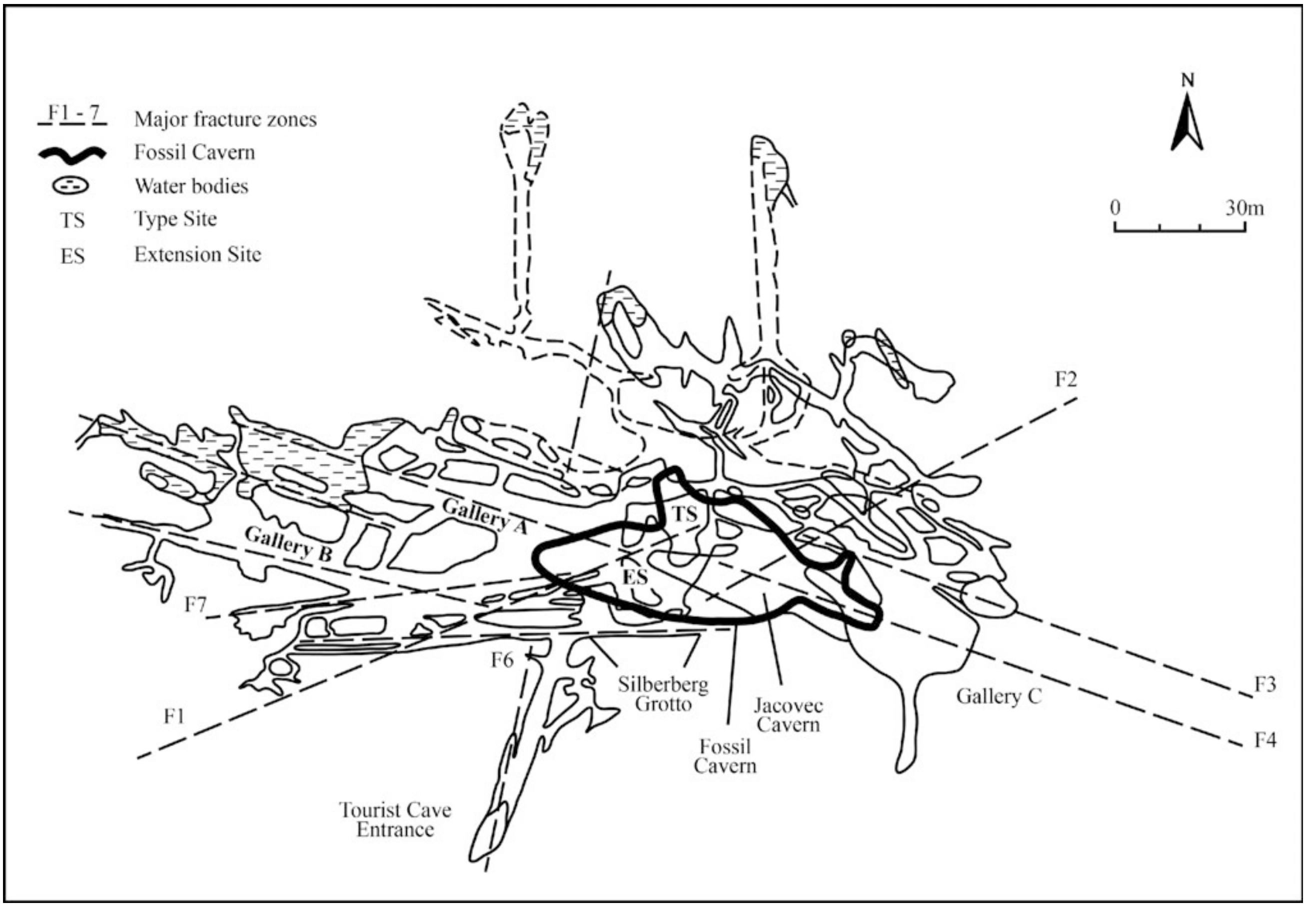

Fig. 3 Geomorphological plan of the Sterkfontein Cave system. Major controlling fracture zones are shown in relation to the upper form (Fossil Cavern *bold line*), and the lower form (subterranean area *thin lines*). From Wilkinson (1983)

The influence of these fracture zones can be seen in the roughly perpendicular intersections of the major passages and galleries. The cave network is limited to an area roughly 350 m east–west and 250 m north–south. The development of dolerite sills and dykes, and a large silicified fault to the east (Wilkinson 1973) provide weak constraints to the east–west karst development. North–south constraints are more firmly controlled by the southwest–northeast and southeast–northwest-orientated fracture zones, with few underground passages forming extensively past them.

In the phreatic zone, deep, narrow vertical fractures enable water penetration and dissolution of tall, narrow passages in chert-poor areas. In chert-rich areas, superimposed passages form between chert beds but in the same plane as the fracturing. In the vadose zone, the fractures have several influences: First, they are the focus of collapse, increasing passage height, and in some cases facilitating articulation with the landscape. Second, they provide fissure flow pathways for meteoric recharge, facilitating localized speleothem formation and localized dissolution of host rock and infills which may enlarge openings and facilitate further collapse. Allogenic sediment accumulation, erosion and speleothem growth are generally focused around these fractures, and as Wilkinson comments, '*entry points increase in number and size with proximity to the centre of the system, namely the intersection area of fracture zones* (1983, p. 519)'. The activity of these fracture systems and associated fissure flow can be seen in the spatial organization of openings, re-karstification of sediments and multiple generations of intrusive speleothem growth throughout the network.

The combination of fracture systems and different chert densities has formed two main karst morphologies at Sterkfontein, an upper and lower. An upper level is represented by a single large, deep chamber formed partly in the chert-rich Monte Christo dolomite. The contents of the upper parts of the chamber were exposed on the landscape surface after the erosion of the cave roof and contain the hominid-and stone tool-bearing localities named the 'Type Site' (TS in Figs. 3 and 4) and 'Extension Site' (ES in Figs. 3 and 4) (excavation area outlined in Fig. 3 and dark blue in Fig. 4) and were the focus of early excavations by

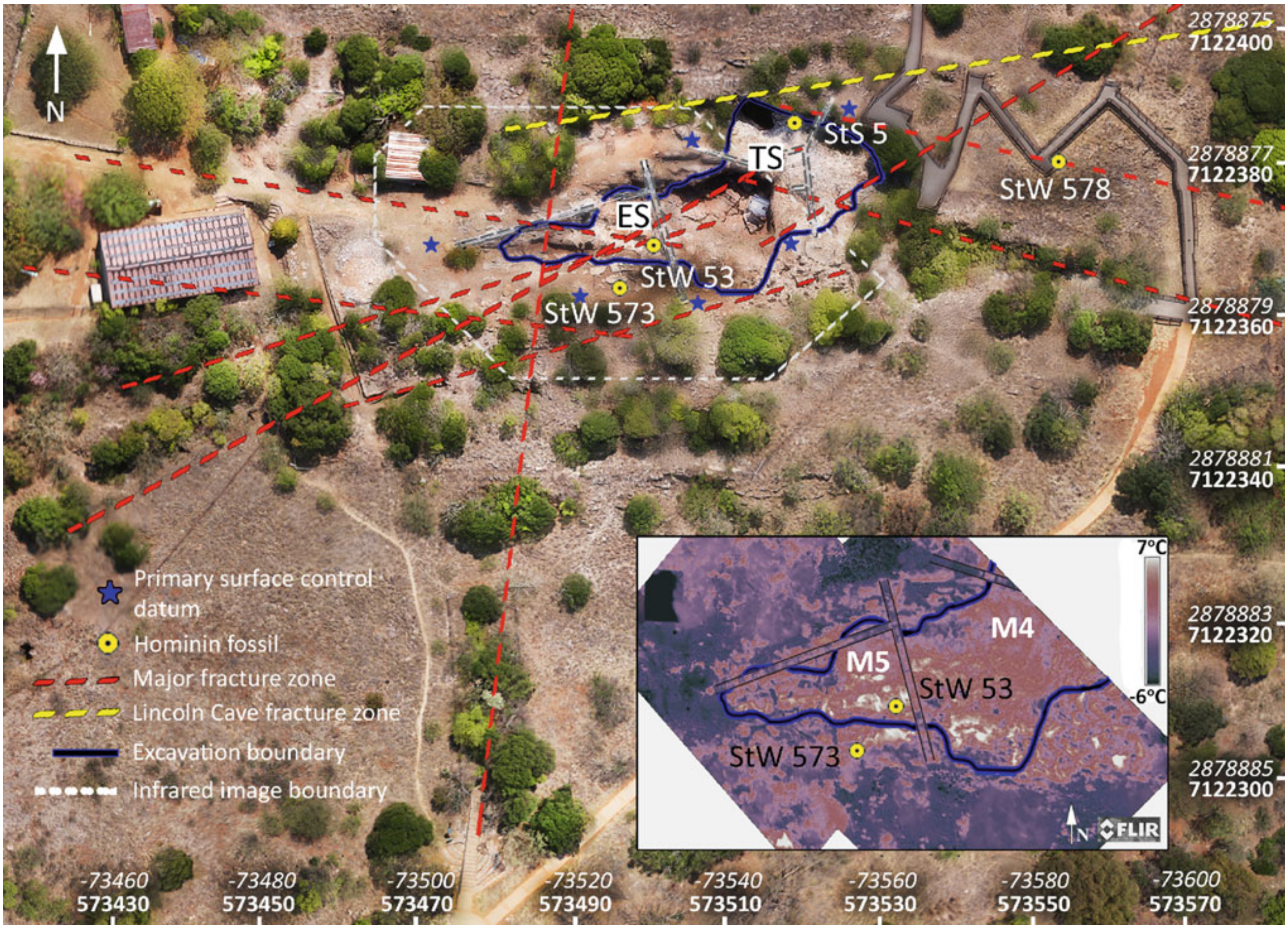

Fig. 4 Fracture zones in relation to the Sterkfontein surface excavation site and four major hominid finds—StS 5, StW 53, StW 573 and StW 578. Major zones are indicated in *red dashed lines*, and the excavation outline is marked in a *thick blue line*. Figure *inset* represents an aerial infrared photograph of an area of the southern part of the surface site which is demarcated by the same *thick blue line*. Ambient temperatures during the flight were about −6 °C. *Red* areas are warmer (3–6 °C) and *white* areas represent temperatures of greater than +7°C. The areas of Member 4 and Member 5 are indicated by 'M4' and 'M5' in the figure *inset*. 'TS' indicates the area of the type site, and 'ES' indicates the area of the extension site as seen in Fig. 3. UTM coordinates (*bold*) and local Lo27 coordinates (*italic*) are given on the *bottom* and *right* axes (aerial photograph DJ Stratford; *Inset* courtesy of L Bruxelles)

Broom (1936) (Broom et al. 1950) and later more intensive excavations by Tobias and Hughes (Tobias and Hughes 1969). Lateral dimensions of this chamber are controlled by the convergence of five fracture zones (Figs. 3 and 4). Enormous collapsed blocks in the lower areas of the surface excavations in this chamber suggest that large roof pendants (perhaps remnants of early walls) collapsed at various stages while the chamber was filling with allogenic sediments. The early morphology of this chamber, prior to any opening to the surface and under phreatic conditions, may have been characterised by short, broad passages developed between chert beds. The Silberberg Grotto, a mid-level chamber in the network, represents one of perhaps several basal portions of this large chamber and was developed within the upper Oaktree dolomite. These basal areas are now separated by, or completely filled with, a combination of authigenic and allogenic infill and speleothem. Small passages allowing the distribution of sediments and fluids into deeper areas directly from the upper (now landscape-exposed) level are abundant. The southern wall of the Silberberg Grotto represents the southern limit of the chamber and the Sterkfontein network (Wilkinson 1973; Pickering and Kramers 2010). The small perpendicular passage which extends south past this boundary (Fig. 3) and is currently used as the main tourist entrance to the caves, is not a natural passage but was created as an access for the lime miners through heavy blasting along a poorly developed north–south fracture zone.

The lower level is more extensive than the upper, with passage length in excess of 4.5 km (Martini et al. 2003). Here, passage development is influenced by fracture system direction, density and chert-poor dolomite, creating very tall, narrow, passages. Passages can generally be described as labyrinthine in the east of the lower levels where fracturing is denser but collapse in the vadose zone is less extensive. In the west, passages are more parallel, or forming parallelogram-like polygons, developing closely along dense and active compound fracture systems that are slightly more distant from one another (Gallery A and B in Fig. 3). Density of fracture system plays an important role here in the lateral dimensions of the chambers and passages, with vadose zone collapse joining spaces between tall, narrow, closely parallel passages, forming galleries, e.g. 'Gallery B' in the Milner Hall (Fig. 5). Inter-gallery passages are generally smaller and perpendicularly orientated, developing along the subordinate north–south trending fracture zones.

Fig. 5 Sterkfontein Milner Hall. Note the sloping dolomite and interbedded chert (A) and evidence of the vadose zone collapse on the cave floor (B). View looking west along 'Gallery B' in Fig. 3. Railing in background is 1 m high and roof is 13 m high (*Photograph* DJ Stratford)

4 Paleocave Deposits and Their Geomorphology

Opening of the caves to the landscape surface occurs through a combination of vadose zone collapse and localized meteoric dissolution along vertical fractures. Openings are often very deep, and in some cases connect the landscape directly to the base of the network 30 m below (Fig. 6). Generally at Sterkfontein, openings to the caves form along the southern boundaries of the network (Figs. 3, 4; Wilkinson 1973; Clarke 2006). This is evident across the system and may be in part a contribution of opening enlargement developing along 'dip tubes' (Ford 1971; Palmer 2007). The concentration of openings along the southern fracture systems has caused dynamic erosion and depositional processes. The continued focus of fissure flow near the southern fracture systems can be seen in the re-karstification of parts of the surface-exposed breccia (see Fig. 7) and in the frequency of openings and blocked openings more densely concentrated in the south of the site (see 'hot spots' across the southern area of the site in the infrared image inset in Fig. 4). Where deposits are evidently associated with a northern opening, it is most likely that they have entered via an opening on the southern boundary of another chamber. For example, the large talus deposit associated with the northern wall of the Milner Hall is likely to have developed from a southern entrance to a chamber associated with the Lincoln Cave (Fault Cave) which lies directly over the northern area of the Milner Hall (Reynolds et al. 2003; Stratford 2011).

When surface erosion has intersected with the uppermost passages, long deep gullies are opened. Typically, openings are very steep sided and represent a serious natural trap danger to animals. As a result, 'death trap' assemblages represent a common bone accumulation agent (e.g. Pickering 1999; Pickering et al. 2004; Kibii 2004). Concentration of vegetation around the cave openings, particularly the wild olive (*Olea oleaster*), is thought to have provided shelter for primates, carnivores and sometimes hominids, accounting for the high proportions of these taxa represented in the fossil assemblages.

Passages between system levels are also often characterized by narrow, steep, and sometimes vertical conduits. Oldowan-bearing deposits found in the western Fossil Cavern are joined to the underlying Name Chamber via 12 m vertical shaft. This passage provides a distributive conduit, redistributing sediments, fossils and artifacts and spreading them through a maze of connected passages in the lower level (Avery et al. 2010; Stratford et al. 2012, 2014).

Fig. 6 A typical cave opening at Sterkfontein. This particular opening articulates directly to the base of the system, some 25 m below. Notice the established vegetation around the opening (*Photograph* D. J. Stratford)

Fig. 7 Re-karstification within the stony Member 4 breccia at the western end of the surface-exposed Sterkfontein breccias. The deep vertical cavities within the eroded surface of the Member 4 deposit have been subsequently filled with stone tool-bearing Member 5 sediments. Breccia to the *left and right of the red* sandy breccia is *Australopithecus*-bearing Member 4 (*Photograph* L. Bruxelles with permission)

Once open, the caves started to accumulate allogenic sediments, animal bones, stone tools and occasionally the bones of our hominid ancestors. Sediments generally accumulate through colluvial processes with varying degrees of water interaction, developing a range of sedimentary facies related to gravity flows. Within the cave, sediments can be calcified, decalcified, eroded and reworked through multiple phases by meteoric and percolating water. In areas of high fracture density, fluid and solute introduction through fissure flow is increased, thereby intensifying localized chemical and mechanical modification. Combinations of processes can distribute sediments (and their interred bones), artefacts and chemical components vertically and laterally en masse or as separate components through the caves. This can stratigraphically isolate assemblages (Farrand 2001; Bosch and White 2004; Goldberg and Sherwood 2006; White 2007; Ford and Williams 2007) or create sorted assemblages with biased faunal, chemical and particle representations (Adams et al. 2007; Stratford et al. 2014; Val and Stratford 2015). The complex multiscale implications of these processes on sediments, fossils and artefacts create long and convoluted stratigraphic histories, a condition that is aptly demonstrated by the number of stratigraphic investigations of the Sterkfontein deposits since the first hominid discovery in 1936 (e.g. Cooke 1938; Brain 1958; Robinson 1962; Wilkinson 1983; Partridge and Watt 1991; Pickering and Kramers 2010; Herries and Shaw 2011; Stratford et al. 2014). Table 1 lists the major stratigraphic works together with the sources of data for these contributions and the associated interpretations.

The current lithostratigraphic sequence used at Sterkfontein was proposed by Partridge (1978) and comprises five major members organized in broad chronostratigraphic order. Member 1 is an autogenic deposit formed during the early vadose zone collapse of the cave. Member 2 is an extensive deposit (Stratford et al. 2014) in which the famous

Table 1 Major stratigraphic works conducted at Sterkfontein

Author	Year	Interpretations
Cooke	1938	Recognized the deposits as a single breccia body exposed at the surface and 'lower cave'
Brain	1958	Recognized the deposits as a single breccia exposed in two underground areas
Robinson	1962	Divided the breccias into 'Lower', 'Middle' and 'Upper'. Underground sediments were a single breccia except for a collapse of 'middle' breccia into the Name Chamber
Wilkinson	1973	Proposed a 'deep phreatic' karstification model from the continuous exposures of breccias through all depths of the caves
Partridge	1978	Described the five major members of the 'Sterkfontein Formation' from breccia exposures in the Silberberg Grotto and surface excavations Silberberg Grotto is considered the base of the sequence
Wilkinson	1983, 1985	Reinterpretation of the full depth of deposits in relation to the formation of the caves. Proposes the deepest deposits may be the oldest
Partridge and Watt	1991	Supports Partridge's initial interpretation that the Silberberg Grotto contains the oldest sediments from descriptions of sediment cores
Clarke	1994	Proposed three phases of formation in the M5 deposit and clarifies Robinson's (1962) hypothesis of collapsed M4 sediments in the Name Chamber
Kuman and Clarke	2000	Refined M4 and M5 stratigraphy and proposed distribution of hominid specimens in relation to the M4/M5 boundary
Clarke	2006	Proposed the erosion and collapse of the StW 573 torso and subsequent intrusion of speleothem in the resultant void
Reynolds et al.	2007	Proposed the erosion and movement of fossils and artefacts from the western Member 5 areas through an articulating tunnel into the Lincoln Cave
Ogola	2009	Proposed the continuation of M4 below the Member 5 west deposit
Pickering and Kramers	2010	Proposed a reassignment of Member 3 as distal Member 4, suggest deepest deposits in the Milner Hall and Jacovec Cavern are younger than M2 in the Silberberg
Herries and Shaw	2011	Generally proposed younger dates for the deposits and an intermediate age for the StW 53 infill between M4 and M5.
Stratford et al.	2012	Suggested a rapid and gradual reworking of the Oldowan-bearing M5 sediments into the Name Chamber and Milner Hall
Stratford et al.	2014	Suggested M2 accumulated to a depth close to the current base level thereby implying the current depth of the caves was formed when the caves opened to the surface
Bruxelles et al.	2014	Proposed a refined sequence of depositional and erosional processes active in the taphonomy of StW 573 and identified intrusive flowstone characters in speleothems around the skeleton
Author	**Year**	**Major data resources**
Cooke	1938	Faunal representation; sediment description
Brain	1958	Faunal representation; sediment description
Robinson	1962	Faunal and stone tool representation; sediment description
Wilkinson	1973	Cave geomorphology; deposit distribution
Partridge	1978	Sedimentological analysis of exposed breccias
Wilkinson	1983, 1985	Cave geomorphology; deposit distribution
Partridge and Watt	1991	Sedimentological analysis of sediment core samples

(continued)

Table 1 (continued)

Author	Year	Major data resources
Clarke	1994	Sediment description and stone tool; hominid representation
Kuman and Clarke	2000	Hominid and stone tool representation and spatial distribution; sediment description
Clarke	2006	Faunal representation; taphonomy; deposit and sediment feature description
Reynolds et al.	2007	Artefact, hominid, faunal representation; U-Pb speleothem dates
Ogola	2009	Artefact, hominid and faunal representation; taphonomy
Pickering and Kramers	2010	U-Pb dating of speleothem, longitudinal facies identification from exposed breccias and Partridge's 1989 sediment cores
Herries and Shaw	2011	Paleomagnetic seriation of siltstones and associated speleothems; faunal and artefact representation and ESR dates
Stratford et al.	2012	Deposit and sediment description, macro- and microfauna and artefact representation
Stratford et al.	2014	Sedimentological and geochemical analysis; artefact and fauna representation; taphonomy; spatial analysis of deposits
Bruxelles et al.	2014	Micromorphology, geochemistry, sedimentology

StW 573 'Little Foot' skeleton was found (Clarke 1998). Member 3 lies largely conformably on the capping flowstone of Member 2 in the Silberberg Grotto, but has not yet been systematically sampled for fossils. Member 4 was exposed on the landscape surface through speleothem mining and has yielded more *Australopithecus* specimens than any other hominid locality in the world. Member 5 contains the earliest stone tool assemblages in Southern Africa (Kuman and Clarke 2000) and examples of the earliest member of the *Homo* genus. Vertical and lateral boundaries continue to be debated across all the deposits and are generally proposed from a range of variables such as faunal taxonomic representation, core sample facies correlation and artefact presence or absence. Very little is known about the internal stratigraphy and formation processes of these deposits, although current work is focusing on increasing stratigraphic resolution. As an example, Member 4, containing the vast majority of *Australopithecus* fossils, may have taken up to 500,000 years to accumulate (dating to between about 2.6–2.1 Ma) (Cooke 1974; Herries and Shaw 2011) and documents a significant landscape, environmental and faunal evolutionary window. Geomorphological understanding of this deposit is, however, lacking, with basic boundaries, geometry and formation history still being debated. What is clear is that only residual primary depositional forms remain within a framework of diagenesis.

As the landscape surface is eroded, new openings to some of the deepest chambers have been formed and old openings have been opened again depositing new sediments across the system and at all levels. Where water has been channelled, old deposits have been undercut and locally collapsed, resulting in voids filled by later sediments or flowstones. It is exactly this process that has caused a great deal of confusion over the dating of the StW 573 *Australopithecus* skeleton in the Silberberg Grotto (Bruxelles et al. 2014; Granger et al. 2015). In some cases, re-karstification of autogenic and allogenic cave deposits has formed irregular and occasionally vertical unconformities between sediment bodies. Such a situation can be seen in surface-exposed deposits in the western area of the excavation where deep vertical cavities have been eroded into the irregular surface morphology of the stony Member 4 (Fig. 7). In this case, the cavities have been filled by stone tool-bearing Member 5 sediments, and only through dedicated stratigraphic work has this situation been recognized (Kuman and Clarke 2000). New studies suggest that highly irregular and vertical deposit contacts are frequent at Sterkfontein. These processes create dynamic depositional environments with complex intra- and inter-deposit stratigraphic histories and deposit boundaries which are difficult to predict during excavation and very difficult to reconstruct retrospectively.

5 Summary

The Cradle of Humankind World Heritage Site preserves a long and complex history of geological, landscape and environmental processes spanning over two billion years. This is highlighted with a flash of hominid evolution preserved in the cave infills of the Sterkfontein Caves over approximately the last three and a half million years. We would, however, have no information regarding the evolution of local hominid species during the Late Pliocene and Pleistocene if it were not for the timeous opening of the caves during a period of our evolution that is so intriguing. Ancient geological processes provided the lithologies, fracture zones and fluid flow patterns that have influenced the morphology of the cave network, the distribution of fauna on the landscape, when and how the cave will open, and how sediments, bones and artefacts will be deposited and distributed through the cave system. The result is a dynamic karst environment with a long and complicated infilling history.

What is clear from the continuing debate about basic stratigraphy and karst evolution at Sterkfontein is that dedicated research is needed to clarify the fundamental mechanisms and relative (followed by absolute) timings of the evolution of the karst, the landscape, and the fossiliferous deposits at Sterkfontein and throughout the Cradle of Humankind.

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