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CONTRIBUTION TO THE SPELEOLOGY OF STERKFONTEIN CAVE, GAUTENG PROVINCE, SOUTH AFRICA

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ABSTRACT
The authors present more data about the speleological aspect of the Sterkfontein Cave, famous for its bone breccia which yielded abundant hominid remains. They also briefly review the previous voluminous studies by numerous authors, which are mainly dealing with the paleontology, stratigraphy and sedimentology of the breccia. The present investigations were oriented to hitherto poorly investigated aspects such as detail mapping of the cave, its country rock stratigraphy and recording the underground extension of the basal part of the breccia body.
The cave consists of a complex network of phreatic channels, developed along joints in Neoarchaean cherty dolostone over a restricted surface of 250x250m. The combined length of all passages within this area amounts to 5,23km. The system extends over a height of about 50m and the dry part of it is limited downwards by the water-table appearing as numerous static pools. The fossiliferous breccia (= Sterkfontein Formation) forms an irregular lenticular mass 75x25m horizontally by 40m vertically, which is included within the passage network. It crops out at surface and in the cave, and resulted from the filling of a collapse chamber, which was de-roofed by erosion.
The present investigation confirmed that the cave and the Sterkfontein Formation are part of a single speleogenetic event. The breccia resulted from cavity filling by sediments introduced from a pit entrance, whereas many of the phreatic passages around it, which are developed at the same elevation, were only partly filled or remained entirely open up to present. This filling took place mainly in a vadose environment.
Taking into account the age of the Sterkfontein Formation (>3,3-1,5 My, from base to top), the geomorphic evolution of the landscape and the context of other caves in the region, it seems that the cave might have started to form 5 My ago. It has been continuously developing up to present as a result of a slow drop of the water-table.

Introduction

Sterkfontein Cave is situated 35km to the NW of Johannesburg (Fig 1) and is well known internationally for the hominid fauna found in a paleokarst filling associated with it. It is the most important site among other comparable deposits clustered in the Kromdraai area, which represents a small portion of the regional karst. The numerous publications on Sterkfontein deal mainly with the paleontology, archaeology and

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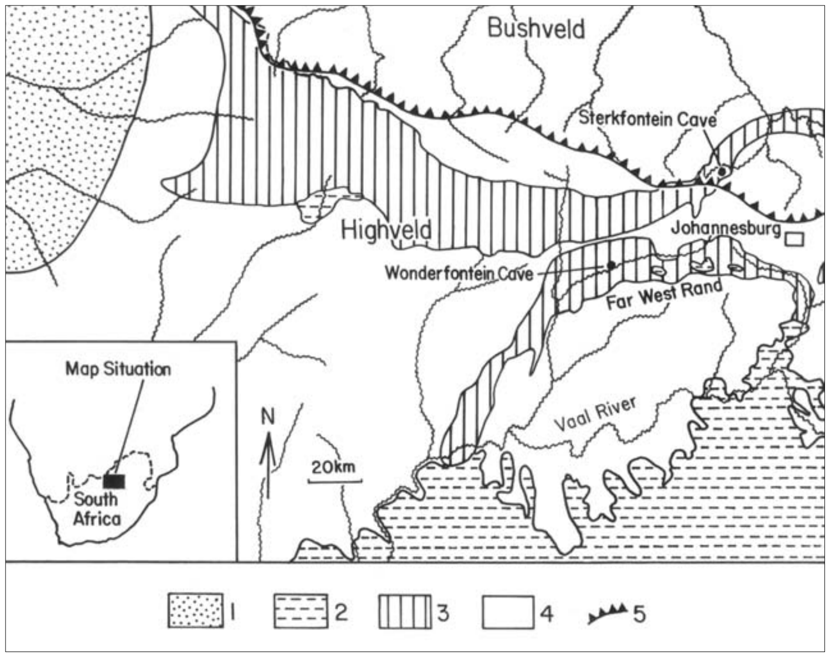

Fig. 1. Situation, basic geological and geomorphic data: 1) Kalahari Basin (Upper Cretaceous to Recent sandy sediments); 2) Karoo Basin (Permian shale, sandstone and minor discontinuous tillite at base); 3) Malmani Subgroup (Neoarchean dolostone and chert); 4) other older or younger terrains; 5) escarpment.

sedimentology of this filling, and less with the cave itself. In this paper only the titles most relevant to the former topics are referenced.

The present study focussed on a detailed topographic survey of the cave, its geology and speleogenesis. Indeed the previous map produced by the University of the Witwatersrand, although accurate, did not record finer details and many passages have not been plotted. The new survey consisted of theodolite measurements along the tourist route between the two entrances and along a few side passages, in particular the one leading to Ravjee Lake (Fig 2). The remainder of the passages were surveyed by the usual "compass, tape and clinometer" method performed by the cavers. The map and the sections depicted in Figures 2 and 3 represent the main data gathered during this investigation. Due to the complexity of the system, passage overlap in plan projection and due to a lack of definite cave levels, it was unfortunately not possible to produce a map that is easy to read.

History of the discovery, explorations and scientific highlights of the Sterkfontein Cave

The fossiliferous deposits of cave-fill breccia and flowstone formation deposits in the "Transvaal Dolomite" were first brought to scientific notice at the inaugural

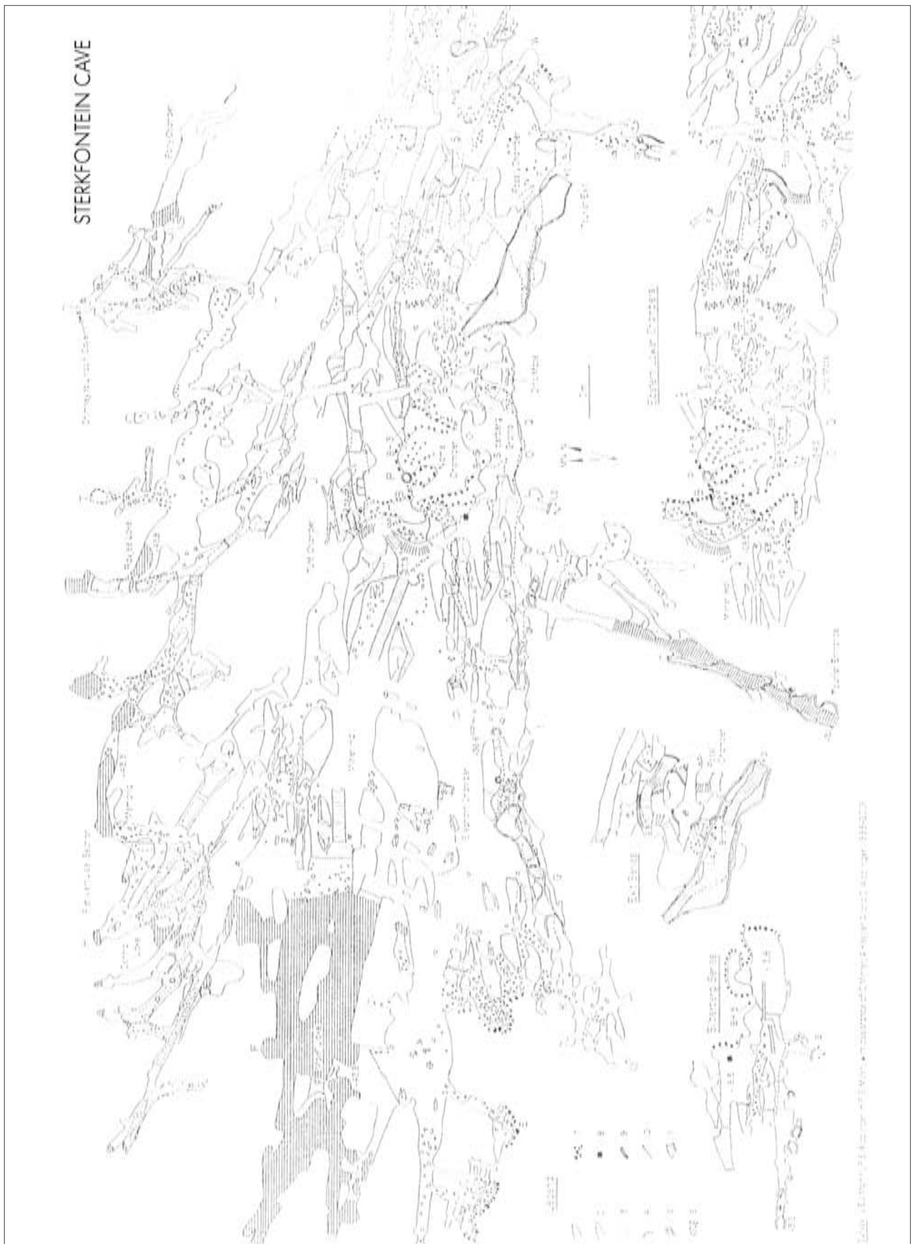

Fig. 2. Map of Sterkfontein Cave. *<u>Legend</u>: 1) cavity outline; 2) cavity outline under single overlay; 3) cavity outline under double overlay; 4) scarp and edge of pit in cave; 5) scarp and edge of pit at surface (=entrance); 6) blocks and scree; 7) walls of breccia and boulder blockages; 8) Australopithecus skeleton; 9) masonry wall; 10) gates and fences; 11) flight of stairs.*

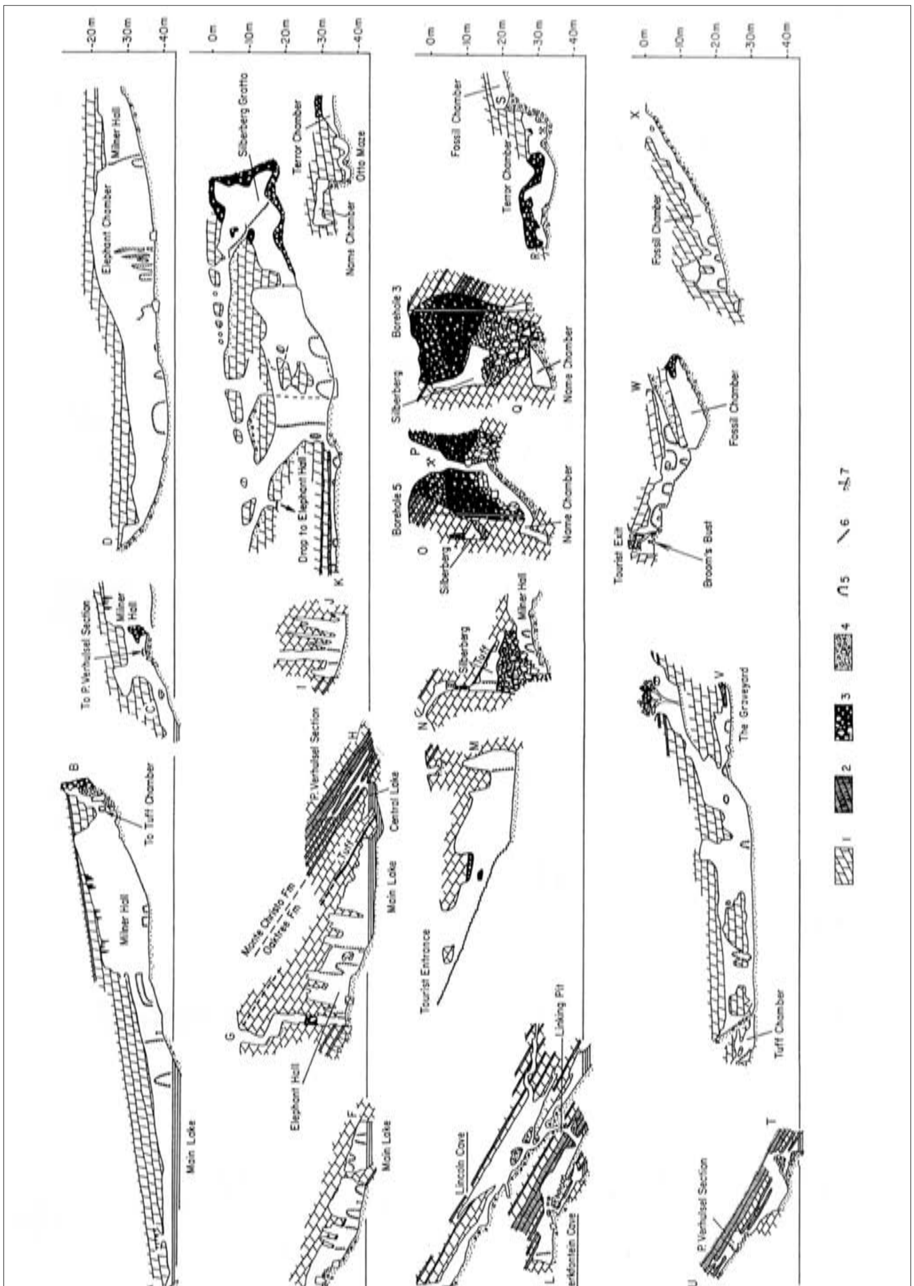

Fig. 3. Sections of Sterkfontein Cave. Positions indicated by capital letters on map Fig 2. Legend: 1) dolostone; 2) chert; 3) calcified old breccia and silt; 4) unconsolidated scree, silt and sand; 5) outline of side passage; 6) flight of stairs; 7) fence or gate.

meeting of the newly formed Geological Society of South Africa by its first Secretary, David Draper on 8 April 1895 (Draper 1896). C.K. Brain (1981) is of the opinion that Draper was describing the exposed cave sediments on Sterkfontein Hill.

The actual cave opening was first discovered by Mr. G. Martignalia after a blast. He was mining the Sterkfontein Hill calcite flowstone outcrop in 1896. He termed the opening a "wondergat" (marvelous hole). The cave was immediately explored and was found to be very beautifully decorated by flowstone formations. The beauty of the caves attracted wide interest and articles appeared in both South African and overseas journals.

The spectacular beauty of the cave had come to the attention of several geologists in the former Transvaal Republic. In 1898 Draper stated at a meeting of the Geological Society that he had taken steps to preserve the cave for the benefit of the public by approaching the owners, who appeared to be cooperative. However, the protection of the cave was not to last long and the cave was irreparably damaged between 1918 and 1920. At this time the owner, Mr. E.P. Binet was leasing the cave to a Mr. Nolan. Binet was not prepared to extend the lease on expiry. This greatly infuriated Nolan, who then proceeded to blast the flowstone formations with explosives.

During the 1920s the cave was exploited for calcite flowstone by the Glencairn Limestone Company. The operations were managed by Mr. G.W. Barlow, who sent specimens of fossils recovered to various scientists.

In 1935 the already famous Dr. Robert Broom was appointed as paleontologist at the Transvaal Museum in Pretoria. He immediately proceeded with his search for adult hominid remains, which would accord with the famous Taung Child discovered in 1924 by R. A.Dart. He was conducting excavations in the same area (Skurweberg and Gladysvale sites), when students of the University of the Witwatersrand showed him some fossil baboons that had been found at Sterkfontein. Broom immediately made arrangements and visited Sterkfontein on 17th of August 1936 where he discovered a large portion of a skull and intact upper dentition of an adult *Australopithecus* (Broom 1936).Subsequent regular visits by Broom to Sterkfontein returned a number of other australopithecine fossils as well as a wealth of other mammalian material.

Shortly before World War II in 1939 mining of calcite was curtailed at Sterkfontein due to a drop in the price of lime and with that the paleontological work also came to an end for the duration of the war.

In 1947 Broom, assisted by Dr. J.T Robinson resumed excavations at Sterkfontein using funding arranged by the then Prime Minister of the Union of South Africa, General Jan C. Smuts, who was greatly fascinated by Broom's remarkable discoveries. Soon afterwards the most complete australopithecene skull was blasted out. This skull subsequently became known as Mrs. Ples.

Operations at Sterkfontein were again curtailed in 1949 when the digging team was moved to Swartkraans, another hominid deposit nearby.

In 1959 the owners of the farm Sterkfontein donated the 20 morgen containing the Sterkfontein cave to the University of the Witwatersrand and the area became known as the Isaac Edwin Stegman Nature Reserve. Excavations at Sterkfontein resumed in

1966 under the direction of P.V. Tobias and A.R. Hughes and continued with great success under the direction of Tobias and R.J. Clarke up to the present. More than 500 *Australopithecus* specimens have been discovered to date.

The two most spectacular discoveries were:

1. A specimen of *Homo habilis* (Stm. 53) found by Hughes in 1976.
2. Little Foot - some hominid foot bones which were discovered in a box marked baboon postcranial by R.J.Clarke in 1994. He found that the bones fitted together to produce the most complete australopithecene foot known to date. The bones originated in the so-called Silberberg Grotto. In 1997 Clarke decided to search for the remainder of the specimen and sent two technicians with casts of the foot for possible fit to search for the remainder of the fossil in the grotto. Within a day they located the site where the original foot bones had been found. Clarke then commenced to excavate the bones and to everybody's surprise found a near-complete skeleton with a complete skull. This excavation is currently still on-going and the find may represent a new taxon.

Sterkfontein is as yet the richest hominid site in South Africa and has the potential to yield a wealth of fossils to scientists for many years to come.

As far as caving exploration is concerned, it seems that most sections were already known shortly after discovery, as they are easily accessible. This represented a cumulated length of passages amounting to about 2km. In 1984 a diver (P.Verhulsel) disappeared in the Main Lake and was found dead of starvation 6 weeks later, in a chamber hitherto unexplored into which he had emerged (see details in Sefton *et al* 1985). During the rescue attempt, the members of the South African Spelaeological Association discovered and surveyed 892m of new passages. Only minor new sections were found during the survey by the authors, like for instance the Otto Maze (Fig 2).

Two other caves occur immediately north of Sterkfontein, partly overlapping it: Lincoln and Fault Caves. They were discovered and explored at the same time as Sterkfontein and have been mapped by the University of the Witwatersrand, probably in the early seventies (Wilkinson 1973). In the same period and later, in 1984, the members of the South African Spelaeological Association discovered new passages in Lincoln Cave. In 1989-90, both Lincoln and Fault Caves were re-surveyed in more detail and visually connected through a narrow, but impenetrable tube (Boshoff *et al* 1990). Linking with Sterkfontein had been attempted several times in the past, albeit without success. In April 2001, however, after completion of the project it appeared from the survey that two passages in both caves, overlapping each others, were separated by a floor only a few metres thick. By digging from below in a narrow chimney filled with rubble and then from above, a connection could be established, thus integrating the Lincoln-Fault cave system with Sterkfontein Cave (Fig 3 and 4).

Geological context

The Sterkfontein Cave is developed in the Malmani Subgroup of late Archaean

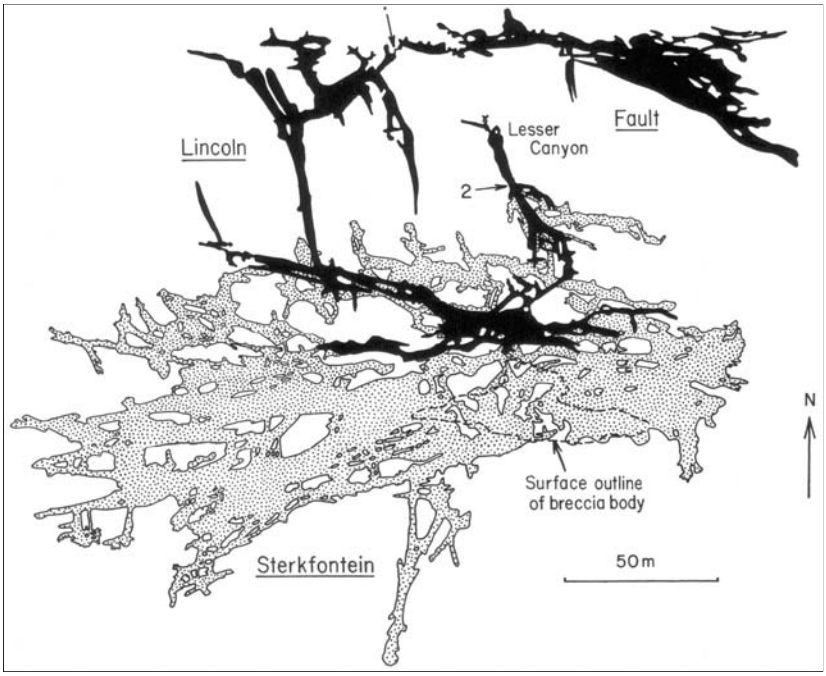

Fig. 4. Simplified map of Sterkfontein Cave (grey, overlays and details omitted) and Lincoln-Fault System (black). 1= Lincoln-Fault link; 2= Lincoln-Sterkfontein link. Map of Lincoln-Fault after Boshoff et al (1990).

age (2,5-2,6 billion years), which has been deposited in the intracratonic Transvaal Basin (Button 1973). The lithology consists essentially of shallow marine stromatolitic dolostone with a variable amount of chert. The dolomite mineral is typically rich in Fe and Mn (up to 3% combined). Its thickness reaches 1450m in the Sterkfontein area (Eriksson and Truswell 1974). Based on the abundance of chert, the subgroup has been subdivided into 6 formations. The Oaktree Formation (180m thick) represents the basal unit, characterised by its very chert-poor nature. The overlying unit, the Monte Christo Formation (700m thick) is rich in chert. It has thin but spectacular oolitic beds at its base. Sterkfontein Cave straddles the boundary between the two formations, but Lincoln and Fault caves are entirely hosted by the Monte Christo Formation (Fig 3). Two stratigraphic markers have been identified in the cave. The first one is a tuff seam, up to 30cm thick, interstratified in the Oaktree dolostone 8-10m below the top of the formation (Fig 3and 6). Macroscopically it appears as a pale greenish-grey shale with ghosts of glass shards visible in thin sections. It is widespread throughout the Transvaal Basin and has been successfully used for geochronometric dating (Walraven and Martini 1995). Another tuff seam, thinner and more sporadically developed, has been indentified a few metres lower down. The second marker is a 4-5m thick chert bed, with minor interstratified dolostone seams, 3-4m above the base of the Monte Christo Formation (Fig 3).

The strata dip about 30° to the NW. The only significant tectonic feature is represented by a long, subvertical, silicified fault running N-S, skirting the cave system to the East (Wilkinson 1973). Dolerite dykes and sills are numerous in the area; a sill is developed immediately below Sterkfontein, but has not been observed in the cave.

Geomorphic setting

The cave entrances are located on top of a small hill (1491m) and 45-50m above a broad valley with a stream flowing to the NE. The scenery is hilly rolling country dissected by valleys, situated in the upper reaches of a zone forming the escarpment

Fig. 5. Tourist Exit and bust of Broom contemplating an Australopithecus skull.

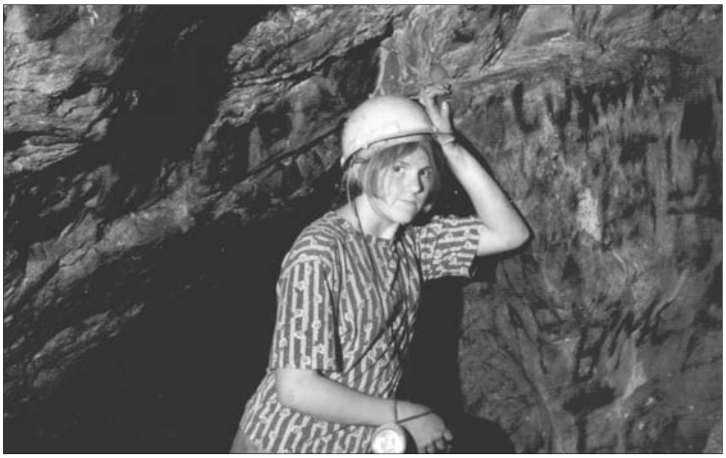

Figure 6. 25cm thick tuff seam, dipping to the left, base on top hard hat. In Tuff Chamber.

separating two natural regions: the Highveld (1500-1600m) in the south, from the Bushveld in the North (1000-1100) . These two regions represent surfaces peneplaned by erosion cycles. The Highveld corresponds more or less to the African Surface, which started to develop after a continental uplift during the Cretaceous, whereas the Bushveld coincides in part with the Post-African I Surface generated after Early Miocene uplift and south-westwards tilting of the African Surface in the area under consideration (Partridge and Maud 1987).

Due to the long existence of the African Cycle, the African Surface had been well peneplaned and covered with a thick weathering crust. During the development of the Post-African I Cycle, the African Surface underwent erosion by river systems flowing both to the southwest (to the Atlantic) and to the north (to the Indian Ocean). On the northern system the erosion was more aggressive, with the development of an escarpment incising the Highveld. The southwestern erosion was more moderate resulting in the formation of a low-relief landscape not associated with an escarpment as spectacular as in the northern case. This suggests that the renewal of erosion was mainly the result of an increase of the talweg gradient of the African Surface by tilting of the peneplain. This led to widespread degradation of the latter surface. 200km to the west, both surfaces merge into the Kalahari Basin. Here sedimentation dominates over erosion (Fig 1).

About 1km to the north of the cave, the flat bottom of the valley has been incised by a stream down to a depth of 8m (Robinson 1962, Wilkinson 1973), leaving gravel terraces on both sides. This entrenchment is possibly due to a recent erosion renewal.

Generalities on the karst of the Transvaal basin

It is necessary to summarize the nature of the regional karst as it differs from the classic models. One characteristic is the deficiency in surface features like doline, polje, swallow-holes and disappearance of the surficial fluvial network. The latter morphology is only observed, although it is not spectacular, on the very flat plateaus of the southwestern quarter of the basin (Martini and Kavalieris 1976, Marker 1980). Elsewhere the dendritic network of streams is always well developed. The residual cover can be very thick, in places exceeding 100m.This is as a result of the large percentage of insoluble impurities in the dolostone (Brink and Partridge 1965, Brink 1979).

In contrast with the deficiency of surface karst morphology, caves are well developed. They are of the hyperphreatic type, forming generally labyrinthic networks of passages which are controlled by joints, or broad flat chambers, the result of the dissolution of chert-free beds sandwiched between cherty dolostone (Martini and Kavalieris 1976). Chambers formed by ceiling breakdown after excessive dissolution are also common. The caves do not seem to form well integrated systems, but rather develop open channels only in zones where the dissolution for some reason was more intense. The latter characteristic is suggested among others by the restricted extension of the cave systems: the most remote places are not more than a few hundreds metres distant from the entrances, whereas the cumulated lengths of all passages may be over 10km.

The flow of ground-water through the karst is very slow and where the water-table is reached it forms pools that are apparently static. Perennial underground streams are practically absent. According to measurements of the karst porosity, speleogenesis is maximal just under the water-table, amounting to several per cent, and decreases rapidly deeper (Enslin and Kriel 1969). Penetrable caves still occur occasionally at greater depth, however, for instance at 79m below the water-table, as observed by exploration after artificial de-watering of aquifers (Moen and Martini 1996). An important and well documented characteristic of the karst aquifer of the Transvaal Basin is its subdivision into compartments, separated by impervious subvertical dykes of dolerite and syenite, as well as by silicified faults.

Two types of detrital cave sediments may be distinguished. In the deep parts, not directly influenced by the surface, sedimentation is minimal and limited to autochtonous material. The reason is that the phreatic flow is too slow to transport particulate material. The sediments consist of chert debris and dark-brown wad pellets detached from the ceiling and the walls, and having accumulated on the floor. The material known as wad is the residue left in a quiet phreatic environment after incongruent dissolution of dolomite, which releases Mn and Fe oxides. During this process, these oxides concentrate on the crystal junctions. As a result, after complete disappearance of the carbonate, these oxides form a micro-boxwork pseudomorphing the dolostone texture (Martini and Kavalieris 1976). When a cavity "bursts" up to the surface, by ceiling breakdown or suffosion through the residual cover, alluvials are introduced into the caves by occasional floods during storms. Most often, these alluvials consist of chert fragments, reddish silt and sand eroded from surface soils.

Description of the cave

Sterkfontein is a three-dimensional hyperphreatic maze of fissure passages typical of the karst of the Transvaal basin. Its 25 entrances are the result of the intersection of phreatic channels by the surface. These passages retain the same morphology down to below the water-table, i.e. over an elevation of about 50m (Fig. 2 to 4). The cave system is restricted to a 200x250x50m volume. However, the cumulative passage development of Sterkfontein, including Lincoln Cave, amounts to 4,73km. This figure increases to 5,23km if Fault Cave is added, although it is not yet conventionally linked to the system, as only visual connection was achieved. Mining of calcite did not considerably alter the morphology of the passages, except in the Silberberg Grotto. Here a particularly voluminous stalagmite and a flowstone sheet (the "Boss") have been removed. This suggests that the chamber is mostly man-made. The map indicates that the passages of the whole system follows two main directions of subvertical joints: the dominant one is mostly W to WNW and the subordinate one varies from N to NNE (Fig 2). The passage morphology is also controlled by the lithology of the country rock. In the chert-poor Oaktree Formation, in which the greater part of the cave is developed, the passages belong dominantly to the fissure type. Here passages reach heights of 15m, while the widths are in the order of a few metres only. Large chambers can form by dissolution of partitions separating swarms of tightly spaced passages. This is typically the case for the Elephant Chamber (Fig 7), where

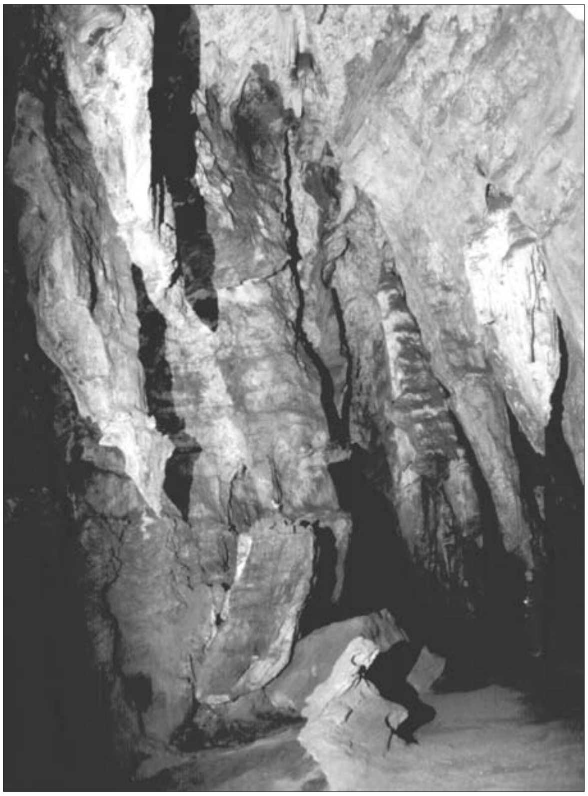

Fig. 7. Elephant Chamber. Note long roof pendants. Person to the left gives scale.

the remnants of these partitions are left as long roof pendants reminiscent of trunks. Passages are often superimposed, adding more complexity to the map. This splitting into several levels in a same joint is often due to "false" floors composed of rubble and flowstone blockages, rather than undisturbed country rock. Compared to other regional caves, the development by ceiling breakdown is relatively minor. The main voids of this latter type are Terror (alias Jacovec) and Fossil Chambers.

In the northern part of Sterkfontein Cave, i.e. in the P. Verhulsel Section, the area to the east of the latter, and in part of the Lincoln-Fault Cave System, the passages display a different morphology. They are still joint-controlled, but as they are developed in the Monte Christo Formation, chert seams up to 30cm thick separate "stacks" of low (0,5-1m) but broad (2-5m) passages. For instance in the P.Verhulsel Section, up to 4 crawlways levels are in places superposed over a stratigraphic interval of only 3-4m (Fig 3). These levels often merge into two or more passages by breakdown of the chert floors and develop into "canyons". In this section, and further eastwards, it appears from the map that most passages stop against a same WSW-ENE line marked by pools. The latter represents the position where the 5m thick chert marker dips under the water-table. This prominent chert bed seems to have acted as a barrier, impeding passage development between Sterkfontein Cave and the Lincoln-Fault System. Only in the eastern part of the cave, on account of an unusual, complete breakdown of the chert ceiling, a connection could be established (April 2001 connection). In the Lincoln-Fault Cave System, the splitting of passages by chert layers is still observed, but is less characteristic than in Sterkfontein. The reason for this is that the dolostone is less siliceous.

From the survey it appears that the volume of voids remains approximately constant from the surface down to the water-table, that is over an elevation difference of about 50 m. It is also obvious, that the longitudinal axes of the passages, even in the Oaktree Formation, are generally inclined sub-parallel with the apparent dip of the country rock. These observations preclude the presence of preferential dissolution levels. This is not the rule everywhere in the karst of the Transvaal Basin. Cases are known where phreatic mazes strictly developed at specific elevations: for instance in Wonderfontein Cave (Fig 1), a 9,4km passage network which is restricted to an elevation range of only 3-4m (Kent *et al* 1978).

The nature of the original tensional joints controlling passage development has been observed in several places on the chert ceilings, for instance in the P.Verhulsel Section . Since chert is practically unaffected by karst dissolution, it is particularly favourable for the preservation of these cracks. The recorded width of these cracks varies from fractions of a millimetre to one centimetre (Fig 8). The walls of the joints

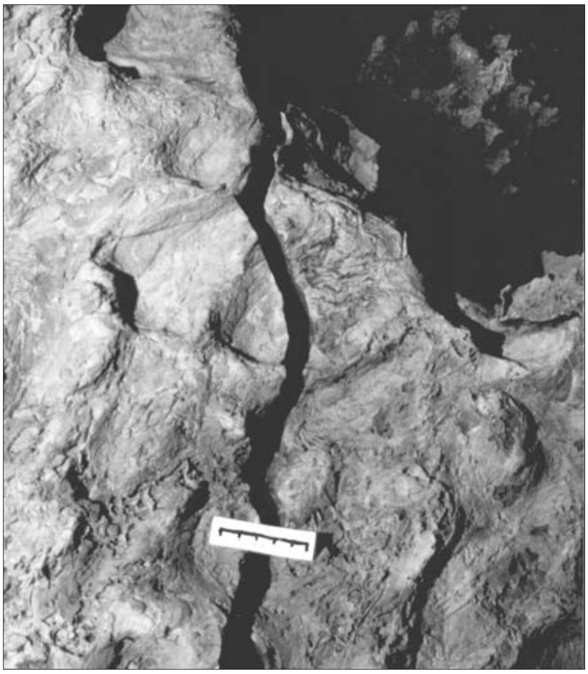

Fig. 8. Open joint at chert ceiling in Lesser Canyon, Lincoln Cave. Scale in centimetres.

are coated with tiny secondary quartz crystals which have grown before speleogenesis. Open joints in dolostone, which are unaffected by dissolution are rare. Where these have been observed their surfaces are also coated with minute quartz crystals. The latter mineral sometimes impregnates the dolostone over a few millimetres on both sides of the joint. Such open joints have been observed in most other caves in the region and will be the subject of another article. It was proposed that they have formed during the important tensional event associated with the flood basalt volcanism,which affected the entire sub-continent during the Early Jurassic (Kavalieris and Martini 1976).

In rare cases, passages are not controlled by subvertical joints, but by moderately inclined fractures, like the eastern part of the long passage linking the tourist route with Ravjee Lake. This fracture is possibly a very minor compression fault, along which the initial cavities developed as primal voids having rhombic cross-sections.

Hydrology

About 30 static pools have been reported in the cave system, the most important by far being the Main Lake (Fig 9). With the exception of a small perched pool at the eastern end of the P.Verhulsel Section, they all mark the water-table. The depth of the pools has not been thoroughly investigated, but diving in the Main Lake and in the pools of the P.Verhulsel Section, indicates maxima of not more than 4m. Obviously

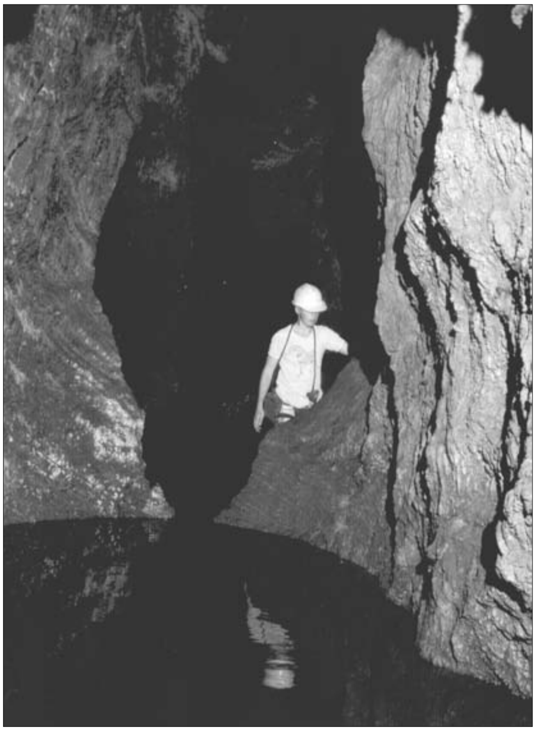

Fig. 9. Fissure passage, half-flooded at water-table level. Western end of Main Lake.

greater depths have been estimated in Lincoln Cave. The water level of the lakes fluctuates slowly according to the preceding rainfall pattern. At present this is within a range of about 2m. Apparently the water flows to a spring situated 900m to the north of the cave. This spring is situated in the talweg of the broad valley mentioned previously. The position of the resurgence seems to be controlled by the damming effect of the N-S silicified fault, which was mentioned in the geology section and which prevents ground-water to flow eastwards. The spring elevation is very close to that of the Main Lake (Wilkinson 1973).

Against this apparently simple and logic hydrological model, for previous levelling of other pools has indicated great differences in elevation (Wilkinson 1973). For instance Ravjee Lake would be 4m lower than the Main Lake. The pool in Fault Cave, the most distant, would be 9m lower. According to the present levelling, the respective discrepancy for Ravjee Lake amount to –0.5m. The exploration by diving (Wits Diving Club)also proved that the Main Lake and the pool situated immediately to the north of the P.Verhulsel memorial must be on the same level, since they have been connected by diving (Sefton *et al* 1985). Careful levelling between the pool at the end of the "Lesser Canyon" in Lincoln Cave, and the pool under the linking chimney in Sterkfontein (April 2001 connection) indicated that the latter is 18cm lower than the former. This difference is probably within the margin of error. Both pools are therefore probably on same the level, although separated by the barrier formed by the chert marker. It seems that the elevation differences between the other pools are not more than decimetric rather than metric. A more accurate survey would be desirable to confirm this conclusion.

Speleothems

Although the most massive speleothems have been removed by mining, remnants of flowstone or dripstone of calcite or aragonite are still present. The latter mineral has generally reverted to calcite. Evaporite-type speleothems are represented by popcorn and aragonite frost on the walls. Sometimes these are associated with chalky microcrystalline hydromagnesite. These three carbonate minerals are very common in other caves in the Transvaal Basin. The frequency of aragonite is related to the Mg-rich nature of the ground-water (ex: Martini and Kavalieris 1978, Hill and Forti 1997).

Flowstone and stalactites are corroded up to a height of about 6m above the water-table, especially in the vicinity of the Main Lake (Fig 10). The intensity of this dissolution increases with depth. No speleothems are observed below 2-3m above the lake surface. Some inactive, "old" speleothems in the upper reaches of the cave, for instance in Fossil Chamber, also show signs of re-solution . In these cases the origin of the corrosion is not known. Various factors have been suggested in other caves (Martini and Kavalieris 1976 and 1978): rise of the water-table, dripping solutions undersaturated in calcite, condensation, bat guano and ammonia oxidation by *Nitrobacter* (Martini and Kavalieris 1976 and 1978).

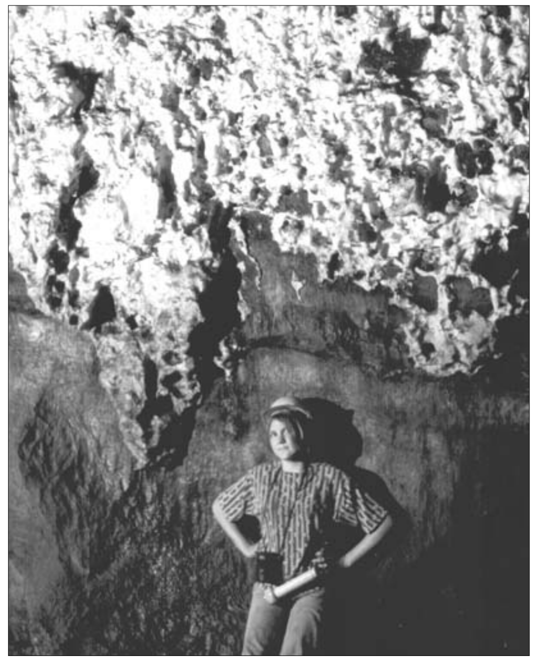

Fig. 10. Corroded flowstone adherent to the wall at western extremity of Milner Hall, near Main Lake.

The main fossiliferous body

The fossiliferous body is exposed at surface over an area of 70m and a maximum north-south width of 25m (Fig 4). Excavation in this body yielded Upper Pliocene to Pleistocene fauna including hominid remains. It seems to extend at least to a depth of 40m below the surface (Fig 3). Its elongation is conformable with the orientation of the cave passages surrounding it. The fossiliferous breccia has been opened and stripped of its overburden by extensive diggings, first during calcite mining and later for paleontological purposes. This breccia body is widely accepted as the filling of a cave of which the roof has been largely removed by erosion. It has been extensively studied by a number of authors, mainly from the surface diggings, but also from an exposure within the cave (Silberberg Grotto) and from 5 boreholes drilled for stratigraphic purposes.

In general the breccia consists of dolostone, chert and flowstone clasts of variable size and abundance, set in a calcite and loam-silt matrix. Induration affects all lithological types and is due to the development of calcite, which often constitutes more than 50% of the matrix. A stratigraphic succession has been established, which has been termed the Sterkfontein Formation and is subdivided into 6 members (Partridge 1978, Partridge and Watt 1991). As these members result from the deposition of cave sediments, extreme irregularity in thickness and rapid lateral facies changes are the rule. From base to top, the lithological units are as follows:

Member 1. 0-20m thick, consisting of occasionally voluminous blocks set in a dark-brown manganiferous matrix. It also contains stalagmitic and lenticular flowstone masses, and is paleontologically practically barren. This megabreccia represents the conical accumulation of debris from ceiling breakdown at a stage when the cave had no entrance, or only a distant one. It is exposed in the Silberberg Grotto, in the upper parts of the Name Chamber and at the eastern end of the Milner Hall. It was intersected in the 5 boreholes.

Member 2. 0-8m thick, consisting of stratified pale reddish-brown, silty loam with rare rock debris and flowstone lenses. Bones are locally abundant. The detrital sediments have been introduced from a pit entrance above and deposited by stream action, sometimes in a subaqueous environment. The member is exposed in the Silberberg Grotto (Fig 11) and has been intersected by 3 of the 5 boreholes.

Fig. 11. Base Sterkfontein Fm at the eastern extremity of Silberberg Grotto. Note dolostone to the right with a pocket of wad pellets (black) covered by flowstone (white), representing the very reduced Member 1 at the southern edge of the breccia body. The flowstone is overlain by reddish and brown silt of Member 2.

Member 3. 5-11m thick. It starts with a flowstone sheet, which is relatively regular and widespread across the breccia body. The flowstone is overlain by reddish-brown, clayey, silty sand with scattered angular rock fragments and in places abundant bones. These sediments represent colluvial material, possibly with an aeolian component, and were introduced from the surface. It is mainly exposed in the Silberberg Grotto, where remnents left after mining can be observed at mainly inaccessible height on the northern wall. At surface the top of this member is visible in the eastern portion of the breccia body. It has been intersected in the 4 boreholes.

Member 4. Up to 9m thick. It contains abundant rock debris, reaching large boulder size, in a dominantly calcitic matrix at the base and reddish-brown to yellowish loam in the upper part, with local pockets of loam and calcite lenses containing minor rock fragments at the top. The sediment originates from colluvium introduced by floods, and blocks detached from the ceiling. An increase in ^{13}C in calcite suggests better ventilation of the cave, due to enlargement of the entrance subsequent to more ceiling collapse. The member is mainly exposed at surface and has been intersected by 4 boreholes. This is the main fossiliferous horizon, having produced abundant hominid remnants.

Member 5. Up to 5m thick, this unit rests unconformably on Member 4, which was already calcified since the latter has been observed as boulders included in Member 5 (Robinson 1962). It consists of reddish-brown sandy loam with rock debris, occasional bones and stone tools. The mode of deposition is the same as that of Member 4. At surface it is exposed in the western part of the breccia body.

Member 6. Up to 1,5m thick. It is comparable with the previous unit, but the matrix is dark reddish-brown. It also contains some bones and stone artifacts, probably introduced by early man. This member forms only a small outlier in the western part of the breccia body.

In the surface diggings, Members 3 to 6 display a gentle WNW dip, assumed to represent the sedimentation slope. This suggests a detrital origin, from an entrance towards the east (Robinson 1962, Partridge 1978) and also indicates that this filled paleocave was inclined westwards, like many present-day passages in the cave below. A similar inclination is also suggested by ceiling remnants observed only in the western side of the breccia body. The morphology of the ancient ceiling is typical of an origin by breakdown (Robinson 1962).

As the breccia is calcite-rich, it was subsequently subjected to karst dissolution at the surface. This resulted in the formation of narrow vertical tubular pits ("makondos") and de-calcification associated with subsidence of the residuals into a "swallow hole". The latter contains mainly soft residuals from Member 4 and 5 and was extensively excavated. Extraction of paleontological and archeological material was greatly facilitated by the soft nature of the material (Clark 1994). By digging deeper during the paleontological excavation, the "swallow hole" broke into the Name Chamber (Fig 1 and 2).

Other paleo-fills in the cave

Apart from the exposures in the Silberberg Grotto, the Name Chamber and the eastern end of the Milner Hall, which are directly and obviously part of the breccia body (= Sterkfontein Formation) described previously, comparable occurrences of indurated cave fill have been observed in many other places in the Sterkfontein Cave System. Stratified siliciclastics consisting of gravel and silt, plus flowstone layers, are sticking to the side wall and to the ceiling of the southern side of Terror Chamber. In this chamber breccia also fills fissure passages, forming clastic veins exposed in the ceiling. As these occurrences are situated practically under the main breccia body and at the same elevation as the lower part of this body, it is very likely that they represent more distal sediments of the Sterkfontein Formation. It is not possible, however, to speculate which member they might belong to.

Three occurrences of cave filling to the west of the Elephant Chamber are located mainly at the ends of passages. Access to this filling is difficult due to obstruction by large boulders, the result of ceiling breakdown. By inspection of the map (Figure 2) it seems possible that these boulder chokes are part of the same large, E-W elongated zone of collapse, which does not have an obvious surface expression. Calcification is well developed only in the eastern site.

Twelve metres to the northwest of "G" (Fig 2), calcite mining exposed the bottom of an ancient fissure passage (Fig 12). Here one observes wad pellets (see gen-

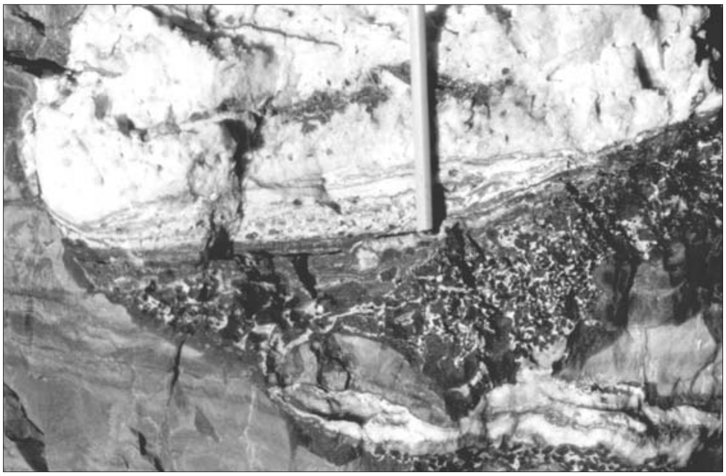

Fig. 12. Base of filled passage, revealed after calcite mining. Note wad fragments (black) detached from the wall representing phreatic residual, in calcite matrix subsequently deposited in the vadose zone, overlain by flowstone. Note disconformity with dolostone. Pen as scale. In passages to the SW of Elephant Chamber.

eralities about the karst of the Transvaal Basin), which were detached from the wall and gently accumulated onto the floor in a quiet phreatic environment. Later, after lowering of the water-table, the pellets were cemented by carbonate in a subaerial environment. This type of fossil sedimentation, contemporaneous with the speleogenesis, has been frequently observed by the authors in other prospecting pits of the Kromdraai area.

Ten metres to the northwest of the previous occurrence, in a small maze, remnants of a flowstone floor form ledges on the walls and bridges splitting the passages in two levels. In places relics of breccia in a silty brown matrix are sticking to the underside of the flowstone (Fig 13). This suggests that the detrital material was friable. It could therefore be drawn down by further cave development at a lower level. The observed remnents are the result of calcification. Moreover it seems that the flowstone marks the end of detrital deposition since it is not overlain by other sediments. Similar occurrences are observed in Fossil Chamber, the Graveyard, and at the northwest side and the eastern end of Milner Hall.

An informative occurrence of the previous type is observed in the central part of the maze of fissure passages developed south of the eastern end of Milner Hall, 10m to the SSW of point -27,3 (Fig 2). Calcified silty sediments containing minor rock fragments which are irregularly covered by a flowstone floor, separate the passage in two levels. At the ceiling of the lower level, it appears that the removal of the calcified silt was not only mechanical, but accompanied by dissolution (Fig 14). The floor of the upper level above this point represents more or less the top of the cave fill. Beyond a sharp turn to the left, this upper level can be followed eastwards along a short passage (15m) giving access to the lower part of the Silberberg Grotto where an *Australopithecus* skeleton has been found (Fig 2). As the slope is even and upwards, this suggests that the sediments merge into Member 1 or 2. This conclusion is further supported, if after returning to the starting point, the upper level is followed to the northeast. After 10m the passage leads to a broad balcony dominating the eastern extension of Milner Hall. The edge of the balcony is made of a 50cm thick flowstone sheet. Under the balcony, it appears that the flowstone sheet rests on coarse breccia, which merges eastwards into the large boulder breccia of Member 1 (Fig 3 and 3). As no sediments younger than Member 2 entered the upper level, it appears therefore that in the upstream direction, towards the main breccia body, the debris slope reached the ceiling during deposition, thus blocking further detrital influx. This is the "hopper" effect well described by Wilkinson (1974).

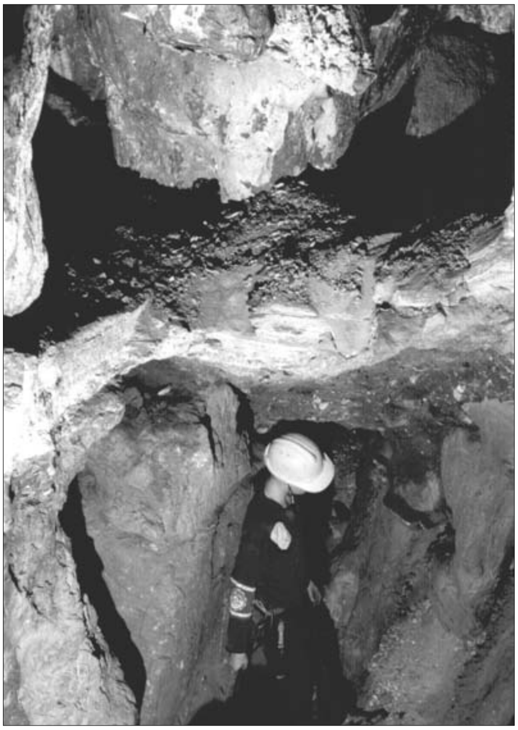

Fig. 13. Flowstone floor (white) covered with some Recent rubble, splitting fissure passage in 2 levels, with remnant of breccia sticking underneath. In maze at the western end of Elephant Chamber.

Practically no typical calcified breccia and finer sediments, as described up to now, have been observed in the P.Verhulsel Section, in the series between Ravjee Lake and Fairy Chamber, and in Lincoln Cave. In Fault Cave, however, an important body of such sediments is visible at the ceiling of Bone Passage (Boshoff *et al* 1990).

With the exception of the deposits in Terror Chamber and in the maze of fissure passages south of the eastern extremity of Milner Hall, which are likely linked with the Sterkfontein Formation, it seems obvious that the other occurrences reviewed in this section are not connected to the latter formation. A common characteristic of all the calcified breccias, however, is that they do not occur less than 10m above the water-table. This means that the possibility remains open that they are contempora-

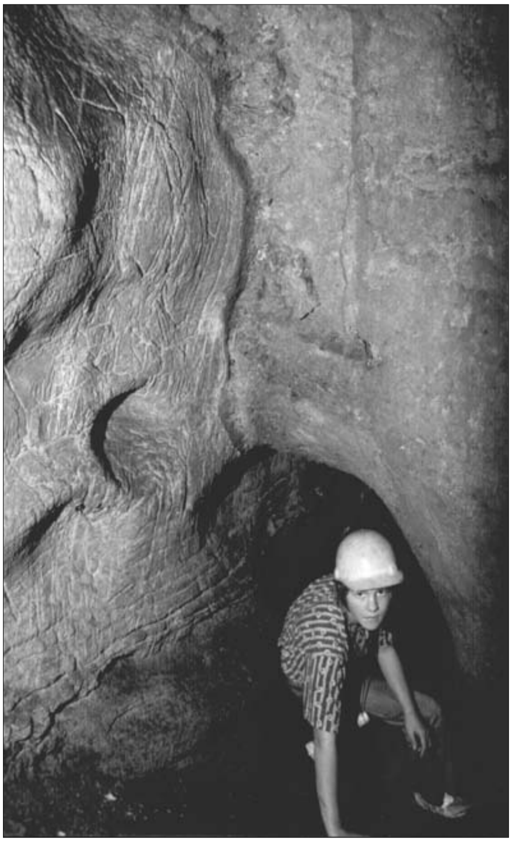

Fig. 14. Re-dissolved calcified silt (Member 1 or 2). Note dolostone to the left, calcified silt to the right and wad band (dark) marking the contact. Above person, note arched ceiling continuous with the dolostone as evidence of re-solution. In maze south of eastern end of Milner Hall.

neous with the main breccia body. Attention was focussed on the possibility of rejuvenation of the passage joints into old flowstone and well calcified breccia. In most places no extension of the joints could be observed, or only irregular very thin fractures with no measurable opening. The latter may perhaps be due to blasting. In the upper part of the Lesser Canyon, in Lincoln Cave, an old corroded flowstone, untouched by the miners, completely chokes a passage and was apparently cracked by joint reactivation, producing a 2-3mm wide opening. It is not certain, however, that the fracture is not due to sagging of the chert seam forming the ceiling of a cavity immediately underneath and supporting the flowstone. In conclusion, it seems probable that the joints have not been substantially rejuvenated after the deposition of the Sterkfontein Formation.

Post-Sterkfontein Formation detritals

Detrital sediments obviously younger than the calcified breccia are represented by unconsolidated and unsorted rubble forming the floor of most passages down to below the water-table. They mostly represent, on the one hand, residual chert plates and wad, and on the other hand, boulders, gravel and silt reworked from older, poorly consolidated breccia described previously. To a variable extent this material has been transported by colluvial creep and by ephemeral streams after storms. A deposit of this type is the steep fan of debris in the northern side of the Name Chamber, which consists of boulders, gravel and silt originating from under the pit linking the cave to the paleontological diggings at surface (Fig 2 and 3). It is mainly the result of reworking of the de-calcified breccia (Clark 1994). Another debris fan originates from approximately the same spot, but spread into the eastern side of Milner Hall, extending to the west and splitting in two lobes separated by a large block (Fig 2). In the middle of Milner Hall and the Elephant Chamber, the slope of both lobes progressively flattens into a plateau at 5 to 7m above the Main Lake (see sections in Fig 3). A comparable terrace-like surface is observed to the southwest of Ravjee Lake, but its edge is only at 4m above the water-table. At this place, however, water lines, well marked on the wall, are visible 6m above the present lake surface.

Age of the Sterkfontein Formation

The oldest fossiliferous unit, Member 2, has not been extensively worked yet. Nevertheless it yielded a hyena, suggesting a Pliocene age "substantially" older than Member 4, paleontologically documented by Tobias 1979, Partridge *et al* 1999. In the lower reaches of the Silberberg Grotto, the remarkable discovery of a near complete australopithecine skeleton embedded between flowstone floors in Member 2, is adding more clues (Clarke 1998). As the fossil is not completely extracted yet, the results are only preliminary. Nevertheless it indicates a species other than *Australopithecus africanus*, which is common in Member 4. Four inclined calcite flowstone layers, two above the skeleton and two below it, have been sampled for paleomagnetic study (Partridge *et al* 1999). It was concluded that the *Australopithecus* was deposited during the Mammoth Reversal and an age of 3,3 My was proposed. This age is a subject of controversy, however, as it was suggested in a recent publication (Berger Lacruz and de Ruiter, 2002), that these sediments might be younger than 3 My.

Member 3, although fossiliferous , has not been investigated yet and no date can be proposed. Member 4 has been extensively excavated and produced a rich fauna, including the great majority of the 600 australopthecine remains found at Sterkfontein. An age of 2,6-2,8 My was estimated by comparison with faunal assemblages of East Africa (McKee 1993). In a recent publication Berger *et al* (2002) reported a maximum age of 2,5 My for Member 4, also based on faunal correlation. Member 5 yielded remains of *Paranthropus robustus* and *Homo habilis*, plus stone tools of the Oldowan culture (2,0-1,7 My) in the base and of the Early Acheulean (1,5 My) above (Clarke 1994).

Speleogenesis

As accepted by all authors, Sterkfontein Cave formed by dissolution along joints in a phreatic environment, a process leading in places to ceiling breakdown when the cavity reached a certain size. Only the details have to be discussed here. Since the passage sizes remained practically constant over the entire vertical span, it seems that during the secular drop of the water-table the dissolution intensity remained approximately the same at any elevation above the present phreatic zone. Therefore the model of a spasmodically falling water-table (Partridge 1978) can be accepted only if it occurred in increments small enough to have no sensible effect on the passage morphology.

The restricted extent of the easily penetrable passages, forming a dense network, is a characteristic shared by the majority of caves of the Transvaal Basin, but is difficult to explain. It might be due to zones of initial joints wider than usual, but this hypothesis needs to be demonstrated. Another possibility would be that the cave systems developed where deep water wells up and mixes with ordinary ground-water close to surface. This model is suggested by comparison with the caves of northern Namibia, which also show restricted surface extension, but where there is evidence of such upwelling for some of them (Martini and Marais 1996, Martini *et al* 1999).

The age of the initial speleogenesis is also difficult to estimate. This process is still active today since no Ca-carbonate is deposited at present under the water-table. For the oldest, most elevated passages, like the Silberberg Grotto and the upper part of Lincoln cave, the presence of Member 2 suggests that they might be older than 3,3 My,provided that the age found by Partridge *et al* (1999) is accepted. Partridge (1973) calculated the age of de-watering of the cave after the time necessary for the nick point of the Post-African I erosion cycle to reach it. He determined an age of 3,26 My, a figure which would fit well with the age of the oldest fossiliferous sediments (Member 2). At that time, however, at least half of the cave was already dry, which suggests that the de-watering and speleogenesis of the top levels must be even older.

Up to now the nine cave breccias investigated in the Malmani Subgroup of the Transvaal Basin have not revealed faunas older than Upper Pliocene (ex. Bamford 1999). The absence of pre-Pliocene ages seems to indicate that older caves favourable for trapping mammals did not form, or had been eroded. Indeed on the karst of the Transvaal Basin, the African Surface has been lowered to variable degrees (Partridge and Maud 1987).

Another possibility to explain the lack of paleocave fillings older than Upper Pliocene, would be that during the African peneplanation most of the dolostone was protected from dissolution by a cover of impervious shale and sandstone of the Ecca Formation (Permian) of the Karoo Basin (Fig 1).There is evidence that a widespread Permian cover existed over the Malmani Subgroup not far above its present exposures. Remnants of this formation are widely distributed over the lowered African Surface in the southwestern quarter of the Transvaal Basin. In other words, in this area the African Surface nearly coincides with the pre-Permian erosion surface. On the Malmani dolostone they form relatively large patches indicated on the geological maps, numerous discrete remnants are hidden under red soil and have been discovered by drilling (ex. Wilkins *et al* 1987), and a few paleocave fillings have been observed in quarries (Marker 1974) and in caves (observations by the authors).

Keeping uncertainty in mind, a possible cave development scenario may be proposed. Erosion was renewed after continental uplift and tilting of the African Surface, an event which started about 18 My ago (Partridge and Maud 1987) and led to reactivation of karst development. After these considerations and the age of the breccia, the beginning of the speleogenesis might date to the end of the Miocene (~5 My).

A future possibility to directly date the speleogenesis of Sterkfontein, would be to use the $^{40}Ar/^{39}Ar$ method on cryptomelane in wad, provided that the latter contains this mineral. Future investigations should thus focus on wad forming delicate microboxwork directly released from dolomite dissolution (see previously).

About the younger speleogenetic phases, the Sterkfontein Formation is informative, as it indicates that 3,3 My ago the cave was already de-watered at 20-25m above the present water-table. That the secular drop of the water-table was irregular, comprising temporary rises, is evidenced by re-solution of calcified silt and breccia about 12m above the water-table (Fig 14). These oscillations might be linked to climatic variations or to more local "accidents" in the evolution of the surficial drainage system. Similarly, speleothems are corroded up to 6m above the Main Lake (Fig 10). This oscillation was perhaps controlled by the resurgence, when at one stage the stream channel might have been choked by alluvium, thus forcing a localised rise of the water-table, as suggested by the 8m gravel terrace.

Conclusions and comparisons

The mapping conducted during this project provides more data about the configuration of the cave, added new passages and was an opportunity to clarify the details of the local stratigraphy of the Malmani Subgroup. The most significant contribution, however, is a better understanding of the basal part of the Sterkfontein Formation. Indeed at this level the main breccia body, a filled chamber generated by ceiling collapse, partly splits into clastic veins, which are infillings of phreatic fissure passages. These observations also confirmed that the latter formation is not a paleokarst filling independent from the actual cave. This misleading impression has been induced by the general calcification of both breccia and siltstone by dripping water, also depositing stalactites, stalagmites and flowstone floors, thus rendering it resistant to undermining by continuing speleogenesis and vadose erosion. This also explains the absence of soft sediments contemporaneous with the Sterkfontein Formation. It also appeared that the collapse chamber hosting this formation is contemporaneous with the phreatic passages of the upper part of the cave, although they remained open up to now. These parts of the cave were not filled up, because of blockages ("hoppers") preventing introduction of detritals from surface. A model of cave development is presented at Figure 15.

Sterkfontein is an example of a cave still open and in formation after probably more than 5 My and having escaped complete removal by surface ablation. One factor in favour of such a long preservation is a slow rate of karst evolution, a condition which is still met today: although the rainfall is about 80cm/y, the groundwater recharge amounts to only 15% due to high evapo-transpiration (Enslin and Kriel 1967). Old caves which remained open up to present are known elsewhere in the world, like for instance the highest ones in the Guadalupe Mountains, New Mexico. These caves are located in a semi-arid environment and formed by sulphuric speleogenesis, an event dated at 12 My by $^{40}Ar/^{39}Ar$ method on alunite (Polyac *et al* 1998).

Another factor favouring long preservation is an entrance on the top of a hill, where ablation is weak and where only minimal residual material can enter the cave. In contrast, where the topography is flat, larger volumes of alluvium are engulfed and the caves are rapidly filled up as soon as entrances form by suffosion in residual

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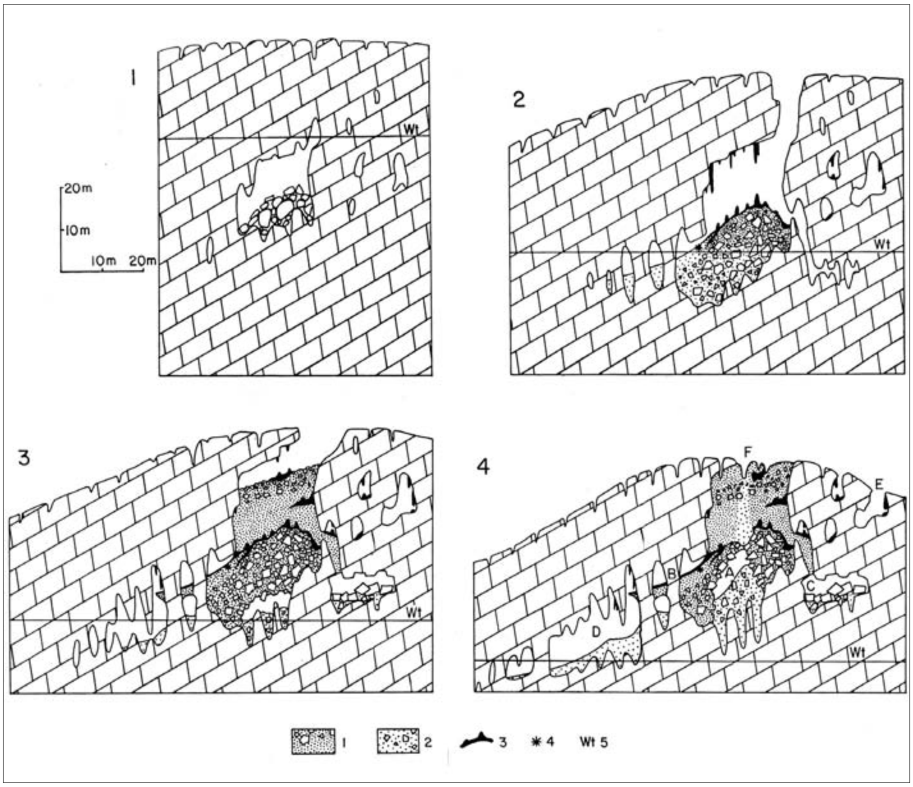

Fig. 15. Idealised speleogenetic model of Sterkfontein Cave. Passages shown as cross-sections, phreatic residuals and surface soils not marked. Elevation of paleo-surfaces assumed after ablation rate of ~5m / My (Gams 1989). Legend: 1) indurated detrital fill from ceiling breakdown and reworking from surficial soils; 2) cf 1, but unconsolidated; 3) flowstone; 4) Australopithecus *skeleton; 5) water-table. Evolution phases: 1) at about 5 My or older, formation of cave in phreatic environment with no penetrable entrance; note dissolution, roof collapse, blocks accumulation ; 2) at 3,3 My, after water-table drop and opening to surface, introduction of detritals and animal remains; note formation of speleothems due to better ventilation, and calcification of detritals above water-table (deposition of Member 2 and basal Member 3); 3) at about 2 My, after deposition of Members 3 and 4, due to continuing drop of water-table, dissolution and reworking of older calcified breccia, often left as bridges and relic ledges; 4) actual setting; de-roofing of breccia body, karstification and de-calcification of breccia. Comments for letters A to F : A) sedimentation in Name Chamber; reworking of loose detritals, as a result of continuous speleogenesis and later of suffosion in de-calcified breccia; B) deposition of Member 2 and 3, followed by re-solution and mechanical reworking (cf. eastern part of Milner Hall); termination of sedimentation due to "hopper" effect; C) filling of Terror Chamber by detritals arbitrarily attributed to Member 3, then after induration, continuous speleogenesis by solution-collapse leaving "clastic dykes" exposed at ceiling; D) in Milner Hall and Elephant Chamber, recent sedimentation mainly originating from reworking of older detritals; formation of "alluvial terrace"; E) old phreatic passage, unfilled, intersected by surface; F) formation of the "Swallow Hole" by subsidence of decalcified breccia.*

cover or by rock ceiling collapse. An informative and well dated example is the paleokarst of the Quercy, in southern France (Pélissier *et al.* 1999, and references therein). This paleokarst reached a mature stage, with a thick soil cover, during the Lower Eocene and was eventually fossilised under Middle Miocene basin sediments. During this 30 My span, karst activity was reduced, but potholes opened periodically and were filled by bone-rich sediments almost instantly, geologically speaking. Indeed the paleontological content of more than 100 of these potholes indicated that each of them contains a geochronologically punctual faunal assemblage, although the overall ages vary from Lower Eocene to Lower Miocene. Where the African Surface developed on the Malmani dolostone, with regard to its protracted existence, a similar mature karst might have formed, but would probably have been eroded in the Sterkfontein area. Only 200-250km to the west of the cave, where sedimentation supersedes erosion, paleokarst deposits related to the African Surface might be discovered. They should yield Upper Cretaceous to Miocene faunas and thus indirectly contribute to a better understanding of the evolution of the karst of the Kromdraai area, including Sterkfontein Cave.

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