STERKFONTEIN CAVE SYSTEM : EVOLUTION OF A KARST FORM

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DECLARATION

I, Murray Justin Wilkinson, hereby declare that this thesis is my own work and has not been submitted for a Master's Degree at any other University.

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ABSTRACT

The Sterkfontein Cave System is a karst cave developed on the Dolomites of the Transvaal System, fifty kilometres north-west of Johannesburg in South Africa. It lies beneath a small hill and was first exploited as a source of lime. Later it became a tourist and scientific attraction of world renown when some of the first australopithecine remains were recovered from a deposit within it. This deposit has been exposed on the surface near the hill summit, by the process of surface lowering and consequent deroofing of the chamber containing the deposit. Excavations are under way to recover fossils and artefacts, to determine the extent and to clarify the stratigraphy of the deposit.

The Cave System is comprised of four separate caves: the deroofed Fossil Cave (containing the bone-bearing deposit mentioned above) lies immediately south of Lincoln's Cave. Tourist Cave, the largest in the system underlies both of these. Fault Cave is situated a short distance north-east of this complex. The system measures three hundred and fifty metres (east-west) and two hundred and fifty metres (north-south); its vertical extent is almost sixty metres. Static water bodies occupy all the lowest points in the caves.

It is hypothesised in this work that the cave system fits models of cave development established overseas, and that evidence of climatic oscillation, in the form of changes in travertine deposition and fluctuations in water body level, is preserved in the system.

The evidence for erosion throughout the system is overwhelmingly phreatic, with some features which owe their existence to aggressive percolating meteoric water. The system thus fits Davis' (1930) hypothesis that caves form phreatically and then undergo a phase of replenishment

when the water table drops. Little definite evidence for vadose erosion exists, however.

Consideration of cave plans and sections, and of surface and underground fractures and fracture zones indicates that the system may be divided into two morphological categories, namely, bedding plane passages in the northern half of the system and fracture zone caverns of great vertical extent in the southern half. The bedding plane passages adhere to Ford's theory (1971) that steeply dipping beds (i.e. where dip exceeds five degrees) are conducive to deep phreatic weathering along bedding planes (the dolomite in the vicinity of Sterkfontein dips thirty degrees north). The fracture zone caverns are determined purely by the particular structural lineaments of the area.

The water bodies appear to be poorly connected since the piezometric surface descends towards the local drainage line.

The deposits of the system consist of various kinds of speleothems in relatively small quantities, and large volumes of externally derived hillslope soil and debris. No deposits of the kind Bretz (1942) encountered in many American caves have accumulated in the Sterkfontein Cave System. The non-calcareous deposits of the System occur as large colluvial debris cones or slot fillings, the older deposits usually cemented by percolating carbonate-charged water. Many of the cemented deposits have been partially destroyed by re-solution due to rising phreatic water and/or percolating meteoric water. Generally, newer debris cones accumulate beneath the undestroyed remnants of the cemented cones, having entered apparently by the same route as the older debris material. A model to explain this sequence is presented.

The large debris deposits only occur in the large fracture controlled caverns, and many appear to be connected with deposits in higher caverns, and even with the surface Fossil Cave accumulation.

Changes in travertine deposition and fluctuations of ground water level - as shown by re-solution levels preserved against the various deposits - are best explained as responses to changes in climate. The dating of such changes is extremely approximate: they may have occurred at any time between fifty thousand and two million years ago.

LIST OF CONTENTS

PAGE

PAGE

CHAPTER 10 (Cont.)

LIST OF FIGURES

FIGURE		FACING PAGE

PART 1

INTRODUCTION AND SETTING OF THE STERKFONTEIN CAVE SYSTEM

CHAPTER 1 - INTRODUCTION

1.1 The Sterkfontein Cave System has developed in the Proterozoic Dolomite Series. It is therefore a karst cave. It lies in the Blaauwbank River valley, 50km north-west of Johannesburg.

It attracted attention originally as a source of lime for industrial purposes. However, it is now part of a protected nature reserve because its fossils have become world renowned, and also because the cave system has become a tourist attraction.

The prolific speleothems in the cave system have been mined extensively for industrial purposes and many of them have been destroyed. Mining ceased in 1939 however, when the price of lime dropped to an uneconomic level. Directly above the tourist caverns lie a mass of fossil-bearing breccias which are exposed on the surface of the hillside. The breccias have attracted the interest of archaeologists since the 1930's when Dr. Broom discovered austrolopithecine remains embedded in them. Later fossil finds aroused world wide interest.

1.2 This study aims to investigate the development of the cave system, the surface, breccia-bearing cave and the three interconnected, underground caves as a whole. In specific terms the aims of this study are twofold:- It is hypothesised that:

1. the Sterkfontein Cave System fits the models of cave development established overseas;

2. the Sterkfontein Cave System, like other cave systems in the Transvaal, preserves evidence of climatic oscillations in the variation

of calcium carbonate deposited, and fluctuations in water table levels.

1.3 The Cave System was chosen for detailed study for a number of reasons.

1.3.1 No detailed study had yet been made of the system, although the archaeological site was well documented.

1.3.2 A detailed study such as this provides an ideal opportunity for testing various models of cave development.

1.3.3 Sterkfontein, being one of the largest cave systems in the Transvaal, can be expected to yield new information on the development of caves in the Transvaal.

1.3.4 The accessibility of Sterkfontein from Johannesburg favoured it for study.

1.3.5 Work on other areas in the Transvaal dolomite outcrop has shown that caves preserve evidence of past climatic conditions. It was likely, therefore, that Sterkfontein would also contain similar evidence, which might be compared profitably with climatic sequences derived from other areas.

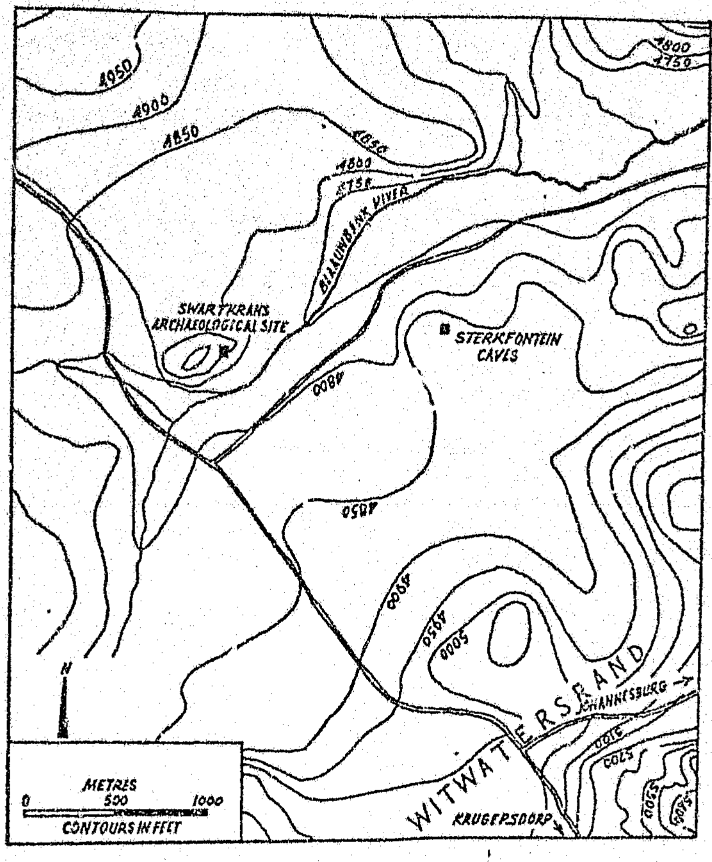

Fig. 2.1 Blaauwbank river valley in the vicinity of Sterkfontein

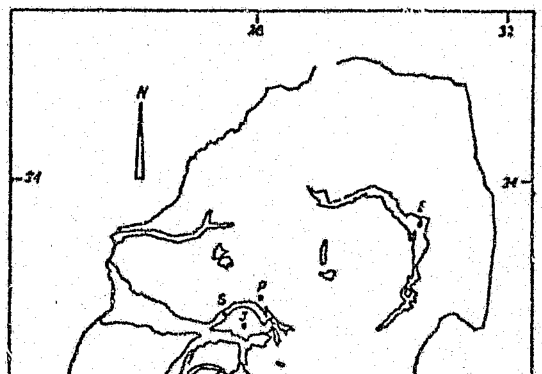

Fig. 2.2 Distribution of dolomite in the Transvaal
S : Sterkfontein Caves; E : Echo Caves; P : Pretoria
J : Johannesburg

CHAPTER 2 - THE SETTING OF THE CAVE SYSTEM

2.1 Topographic Setting

Sterkfontein is one of the many caves in the vicinity of the north-east flowing Blaauwbank River. It is situated beneath a small hillock one kilometre south of the river (Fig. 2.1.). The altitude of the top of the hill is 1485m. and that of the river bed 1450m. The Witwatersrand quartzite ridge forms high ground to the south (average elevation 1740m.), and the Timeball Hill quartzites form a belt of high ground to the north (average elevation 1600m.). The intervening Dolomite Series descends to 1450m. since the main drainage line occupies the outcrop (Fig. 2.1.). The average degree of relief of the area is 300m.

Whereas the bevelled summits of the dolomite outcrop have been attributed to a somewhat depressed 'African' erosion surface, the quartzite ridges are believed to represent a pre-Karroo bevel (Partridge, 1968). The valley incision, represented by the Blaauwbank River and its associated valley system is here assigned to the 'Post-African' cycle.

The infilled valley system is dry upstream of Sterkfontein but downstream of the spring the alluvium has been incised to a depth of 8m. The surrounding valley slopes are covered with a varying depth of soil, many metres thick in pockets, but with bedrock outcropping on more exposed sites, such as the Sterkfontein hillock.

2.2 Geological Setting

The Dolomite Series in which the Sterkfontein Cave System has developed, outcrop extensively in the Transvaal around the granite domes as well as around the Bushveld Igneous Complex (Fig. 2.2.). The width of the outcrop varies; in the Sterkfontein area the dolomite is exposed in

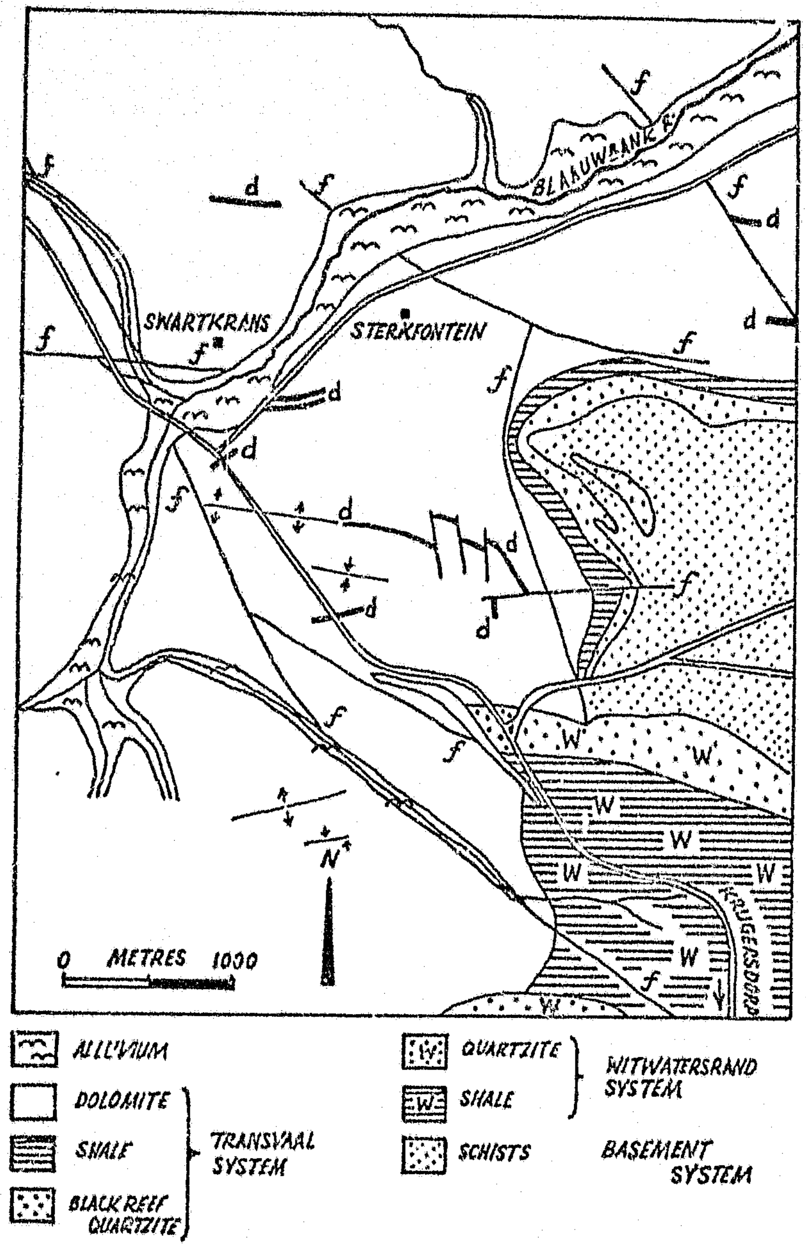

Fig. 2.3 Geology of the Sterkfontein area

a tract 16km. wide, dipping to the north.

The Proterozoic Dolomite Series, part of the Transvaal System, lies conformably on the Black Reef Quartzite, the thin basal member (20m) of the system. The Dolomite Series are overlain unconformably by the Pretoria Series, the upper member of the Transvaal System, immediately to the north of Sterkfontein. The Series is 1500m thick in this region.

The Transvaal System itself rests unconformably on the Witwatersrand System and on the Basement Schists, the oldest rocks in the area. These rocks outcrop to the South of Sterkfontein forming a prominent ridge.

The Dolomite Series is generally formed of massive dolomitic limestone, blue-grey in colour. Towards the base of the series, however, there are numerous interbedded narrow chert bands and occasional shaley layers. There is also a concentration of chert, towards the top culminating in the massive 'Giant Chert', a siliceous conglomerate marking a major erosional unconformity. Diabase sills and dykes have been intruded into the Dolomite Series. The dip of these rocks averages 30^{O}N, although the occurrence of an east-west trending syncline and anticline to the south-west of Sterkfontein affects the general dip (Fig. 2.3.). In places faulting has affected the dolomite strata and the interbedded sills. Fault breccias of dolomite blocks occur in the shatter zones, and can be seen on the surface at Swartkrans, 1km upstream from Sterkfontein.

The dolomite is 'blue-grey, compact, and minutely crystalline' (du Toit, 1962) with large proportions of magnesium carbonate added to the basic calcium carbonate constituent.

The lithology of the dolomite suggests that it was formed in a shallow sea environment; the presence of oolitic beds indicate direct precipitation. The numerous siliceous chert bands (95% silica - Brink and Partridge, 1965), indicate changing environmental depositional conditions.

Brink and Partridge (1965) elucidate the chemical reaction which occurs when dolomite dissolves: solution produces bicarbonates, in reality Ca^{++} and Mg^{++} ions in solution. Ca^{++} is precipitated as $CaCo_3$ in the form of speleothems underground. Magnesium being more soluble than Calcium is rarely precipitated as a carbonate.

$$3CaCO_3.2MgCO_3+5H_2O+5CO_2 \rightleftharpoons 3Ca(HCO_3)_2 + 2Mg(HCO_3)_2$$

Insoluble materials within the dolomite include chert, quartz, limonite, haematite, manganese dioxide (wad) and carbon (Brink and Partridge, 1965), which weather to form red dolomitic soils.

The dolomites are traversed by a network of north-south and east-west fractures and lineaments induced by the emplacement of the nearb y 'Halfway House' Granite. Furthermore, it has been shown that the north-south fractures are tensional and the east-west fractures are compressional (Eriksson, 1972).

2.3 Previous Geological and Geomorphological Writing on Sterkfontein and the Surrounding Area

The fossil remains of the Sterkfontein breccias were first reported in palaentological papers (Jones, 1937; Broom, 1937), which did not deal with the geological aspects of the deposits, nor with the cave system as a whole. Broom at that time predicted that the deposits would prove to be Upper Pleistocene in age.

The following year Cooke (1938) published the first report on geological aspects of the upper cave deposits. He showed that they were the filling of a cave formed by solution of the dolomite bedrock. He showed too that erosion hao since removed the roof of the cave, except in two small localities, exposing the cave fillings on the surface of the hill. He did not consider the underground cave system beyond mentioning that it had developed along two sets of joints.

Cooke (1938) interpreted the cave fillings as evidence of three climatic phases. He recognised two distinct breccias underlain by a travertine deposit.[1] Both breccias were cemented in a matrix of red sand, the lower, older breccia containing numerous unweathered dolomite blocks and very few fossils, and the upper breccias containing few dolomite blocks, but a rich content of fossils. The absence of dolomite blocks in the upper breccia led Cooke to believe that the climate had become wetter as the upper breccia was deposited, the blocks dissolving as the rainfall increased.

Interpreting the underlying travertine deposit as an indication of a wet climate, Cooke proposed a wet-dry-wet climatic sequence for the upper cave deposits. He correlated the second wet phase with the 'Third Wet Phase' of the Vaal Basin (Sohnge, Visser and van Riet Lowe, 1937). He dated the deposits correspondingly as upper Pleistocene.

On the basis of new palaeontological evidence, the dating of the deposit was revised from upper Pleistocene to upper Pliocene (Broom, 1945).

Haughton (1947) described the deposits at Sterkfontein, including in his work a description of the deposits in one underground chamber. He claimed, on the basis of variable stratification, that the underground deposits were not related to those on the surface. He did not attempt to date the deposits, beyond saying that they were of Pleistocene age.

The formation of the Sterkfontein Cave System was attributed to control by 'solution along two main fissure directions and secondary joint planes' (King, 1951). King found that Sterkfontein, in common with other caves in the Transvaal, exhibited a phase of older red sand deposits overlain by a travertine, which was in turn overlain by younger red sand deposits.

In contrast to Haughton, King claimed that the underground de-

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[1] 'Travertine' is used in the sense of sheet flowstone deposited underground

posits contained older red sand, and on this basis he connected the surface and the underground deposits. He claimed that the newer red sand extended into the underground cave system as an unconsolidated deposit.

King suggested a Pliocene age for the older red sand deposits.

Robinson (1952) dated the Sterkfontein sequence as Upper Pliocene, from faunal evidence, thus corroborating Broom's conclusion (Broom, 1945).

Oakley (1954), on the other hand, placed the sequence in the Pleistocene, and Sterkfontein in the Kageran-Kamasian interpluvial.

Brain (1958) made a detailed analysis of the breccias at Sterkfontein and other Transvaal caves. His aim was to clarify the sequence of climatic changes during the period of breccia accumulation. Consideration of the angularity of grains in the breccia matrix, of the chert-quartz ratios, and of the particle size gradings led Brain to propose the following climatic sequence: originally, conditions comparable to those of today were followed by a 'fairly intense dry phase', which gave way once again to the original conditions.

Brain (1958) suggested that the Sterkfontein deposits belong to the first Interpluvial and span one of the dry peaks of that Interpluvial.

Brain (1958) envisaged the present-day underground caverns forming immediately beneath a water table. He postulated that a large dolomite block collapsed into the underground cavities thereby opening a cavern above the Fossil Cave[2] - very near the surface of the hill. Many solution pockets, eroded into the exposed breccia mass, were recognised. Most were filled with modern soil (Brain, 1958).

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[2]This name is ascribed throughout to the breccia-filled, de-roofed cavern exposed at the hill surface, from which fossils have been recovered.

Robinson (1962) argued that it was unlikely that the Fossil Cave originated due to the collapse of one very large dolomite block; he proposed that the cave had originated by means of a series of small collapses and regarded the Fossil Cave as an independent high-level cavity separated from the lower caverns by a bedrock floor <u>in situ</u>. He suggested that the floor subsequently collapsed thereby establishing the routeway by which surface-derived debris has entered the low-lying caverns.

Having exposed and excavated a large new area of the Fossil Cave breccias, Robinson (1962) concluded that three unconformable deposits existed rather than a single continuous deposit as envisaged by Brain (1958). Robinson's arguments, discussed later, involved repeated slumping of the Fossil Cave deposit into the underground caverns.

Basing their ideas on those of Davis (1930) and Swinnerton (1932), Brink and Partridge (1965) attributed the lower level chambers of the cave system (i.e. Tourist Cave) to water table levels related to the present cycle of erosion, and correspondingly attributed the upper level cavities (e.g. Fossil Cave) to the previous erosion cycle. Marker and Moon (1969)however, argued that both upper and lower level chambers are best assigned to the earlier (African erosion) cycle, the lower level cavities forming 'during a later phase of that cycle'. These workers invoked deep-lying water tables which are often encountered in the Transvaal dolomites.

Moon (1972) showed that cave passages in the Sterkfontein vicinity of the Blaauwbank valley are aligned preferentially along the east-west fractures of the area - i.e. the compressional fractures (Eriksson, 1971), which Moon argues are more likely to produce shatter zones in the dolomite with the consequent proliferation of microjoints.

Brink and Patridge (1970) reinterpreted the breccia stratigraphy of the Fossil Cave, claiming that the lowest of the three breccias was a collapse deposit rather than a gradual accumulation as Brain (1958) and Robinson (1962) had regarded it. Furthermore, Brink and Partridge (1970) identified a fourth breccia body along the north wall of the Fossil Cave; and also suggested that the fillings of the solution pockets in the breccias are predominantly decalcified breccia.

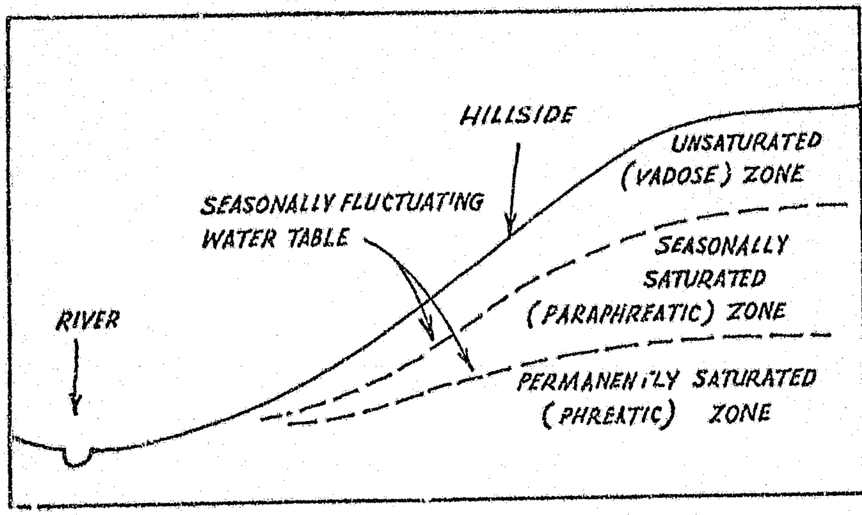

Fig. 3.1 Saturation zones beneath a hillside

CHAPTER 3 - GENERAL THEORIES OF CAVERN DEVELOPMENT

3.0 The salient features of the main theories of cave development are reviewed in this chapter in order to assess their validity for the Sterkfontein Cave System.

3.1 Bretz (1942) has noted that 'conditions of subterranean (water) flow are notably different below and above the water-table', and it is because of this fact that theories of cavern development debate the merits of cave-forming processes above and below the water table. Early American theorists debated the question of cavern development above the water-table in the vadose zone (Fig. 3.1.), or at the water-table itself. Early European theorists however, (e.g. Katzer, 1909 and Bock, 1913) considered that a continuous water-table did not exist, and that cave formation was carried out by flowing water under hydrostatic pressure, thus implying formation in the saturated zone.

In 1930 Davis published an important contribution to cave development theory in which he argued that caves develop in two cycles as opposed to the earlier one-cycle theories (Davis, 1930). Caves were said to be formed by solutional excavation of calcareous rocks beneath the water-table during the first cycle, and then filled with travertine deposits during the second cycle when tectonic uplift and stream rejuvenation have emptied the cave of water. Davis reasoned that caves may form at any depth beneath the water-table, an idea discredited by later writers, but being held once again by the most recent theorists, in modified form.

Swinnerton (1932) also produced a theory of cavern development in the phreatic zone, but qualified Davis' theory to a large degree. Swinnerton argued that caves develop along paths of maximum ground-water flow, which he showed would theoretically exist along the shortest distance between sink and spring - i.e. along the water-table. Ford (1971) points out that most local cave studies in the last 25 years have agreed with the hypothesis of water-table controlled cave formation.

Rhoades and Sinacori (1941) combined aspects of both Davis' and Swinnerton's theories. They postulated deep phreatic weathering early in the karstification process giving way later to shallow phreatic solution at the water-table. Rhoades and Sinacori argued that a master conduit develops headwards from the point of discharge, and in so doing modifies the flowlines of the ground-water circulation and reduces the <u>depth</u> of circulation with time.

This theory introduced the concept of a cave changing the pre-cave water-table, in contrast to a water table determining the position of cave development. The concept has been employed in recent theories of speleogenesis.

Bretz (1942) provided an impressive amount of evidence in support of Davis' deep phreatic zone theory. By careful examination of many cave features he distinguished the vadose-formed from the phreatic formed; moreover he showed that most caves have vadose features superimposed on phreatic features, thus supporting Davis' two-cycle concept of cave development. Bretz further claimed that a stage of clay infilling normally intervenes between the solutional stage and the travertine deposition stage. Bretz's techniques are some of the mainstays of modern speleological investigation.

Other vadose theories appeared after Davis' publication, and that of Gardner (1935) has a bearing on present day thought. Gardner argued that caves form when stream incision drains beds within the limestone mass which are particularly prone to solutional attack. The caves are deemed to develop solely above the water-table as the caves become integrated into the hydrological regimen of the area. Gardner's idea of preferential solution in certain beds is borne out by recent studies on individual caves (Glennie, 1956; Ford, 1964).

3.2 In South Africa Brain (1958) proposed a model of cave development for the Transvaal based substantially on the ideas of Swinnerton (1932). Brain proposed that caverns develop 'immediately below the water-table', and regarded the action of vadose streams in the Transvaal dolomites as 'insignificant', He stressed the importance of percolating meteoric waters in enlarging vertical joints and fissures.

Since Brain was particularly concerned with the fossiliferous cave fillings, the evolution of cave deposits forms an important part of his overall model: externally derived deposits enter the cave voids as soon as surface lowering and even development allow entry of hillslope material. The cavities are partly or entirely filled with travertines and externally derived material (which become cemented by calcium-rich percolating water). Surface lowering continues and ultimately deroofs the upper cavities exposing the solidified deposits at the surface. With time all evidence of the cave and its fillings may be removed. Brain mentions roof collapse as an important feature of some Transvaal caves.

Brink and Partridge (1965) followed Brain substantially in his model for the development and infilling of cave voids in the Transvaal. However, they elaborated on Brain's model by ascribing successive cave-forming water-tables to four cyclic landsurfaces which appear to have bevelled the high lying areas of the Transvaal (King, 1962).

Brink and Partridge (1965) also present a model for the evolution of the notorious sinkholes and the compaction subsidences of the West Rand dolomites, which however, they class as pseudokarst features developed directly above and in concert with voids (not necessarily open to the surface) in the dolomite bedrock.

Some years earlier Sweeting (1950) drew attention to the fact that cave levels in the Ingleborough District of north-west England are related to erosion surfaces in the area. Waltham (1970) however, has since shown that at least some of the caves are controlled by shale bands in the limestones, and cannot, therefore, be attributed solely to water-table control. Marker and Moon (1969) have demonstrated statistically, the coincidence of cave levels and erosion surfaces in the Transvaal, as well as noting that almost all the caves studied (35 caves, some multi-levelled, form the basis of this study) are phreatic in origin with little vadose modification. This study supports that of Brink and Partridge (1965) with evidence from a number of caves in other parts of the Transvaal.

Moon (1972) has since shown that the abovementioned statistical study is not strictly applicable to the Blaauwbank River Valley - in which Sterkfontein is situated - since the amplitude of relief in the valley is the same as the amplitude of the variation in cave levels from one erosion surface. The development of Sterkfontein has in the past been related to both the African and Post-African surfaces (Brink and Partridge, 1965). Although this may be true in fact, the important conclusion of the statistical study does not apply directly to the Sterkfontein cave system.

3.3 Breaking away from the traditional approach to cave development theory, Ford (1971) has argued that:

> there is no one general case of limestone cavern development which can be so precisely defined as older theories would have it. Rather, there are three common cases: the predominantly vadose cave, the deep phreatic cave and the water-table type cave.

In Ford's formulation the controlling factors are the steepness of rock dip, topography, the frequency of permeable bedding planes, joints and faults, and the frequency and geometry of their interconnection.

The type of cave which will develop depends firstly on the number of fissures with 'significant penetration' of ground water - i.e. the ratio of joint length to bedding plane length - and the hydraulic conductivity (Ford, 1971). High conductivity produces a water-table type cave (when rock is highly jointed or when the dip of the rock is shallow (less than 5%), since bedding planes prevent water from descending into the deeper layers of the rock. Low conductivity produces the deep phreatic type cave and is common in steeply dipping limestones, since bedding planes 'guide water to great depths'.

Recently many studies have stressed the importance of lithological and structural factors, recognising with Ford (1971) that various other controls are often dominant in determining the development and morphology of caves.

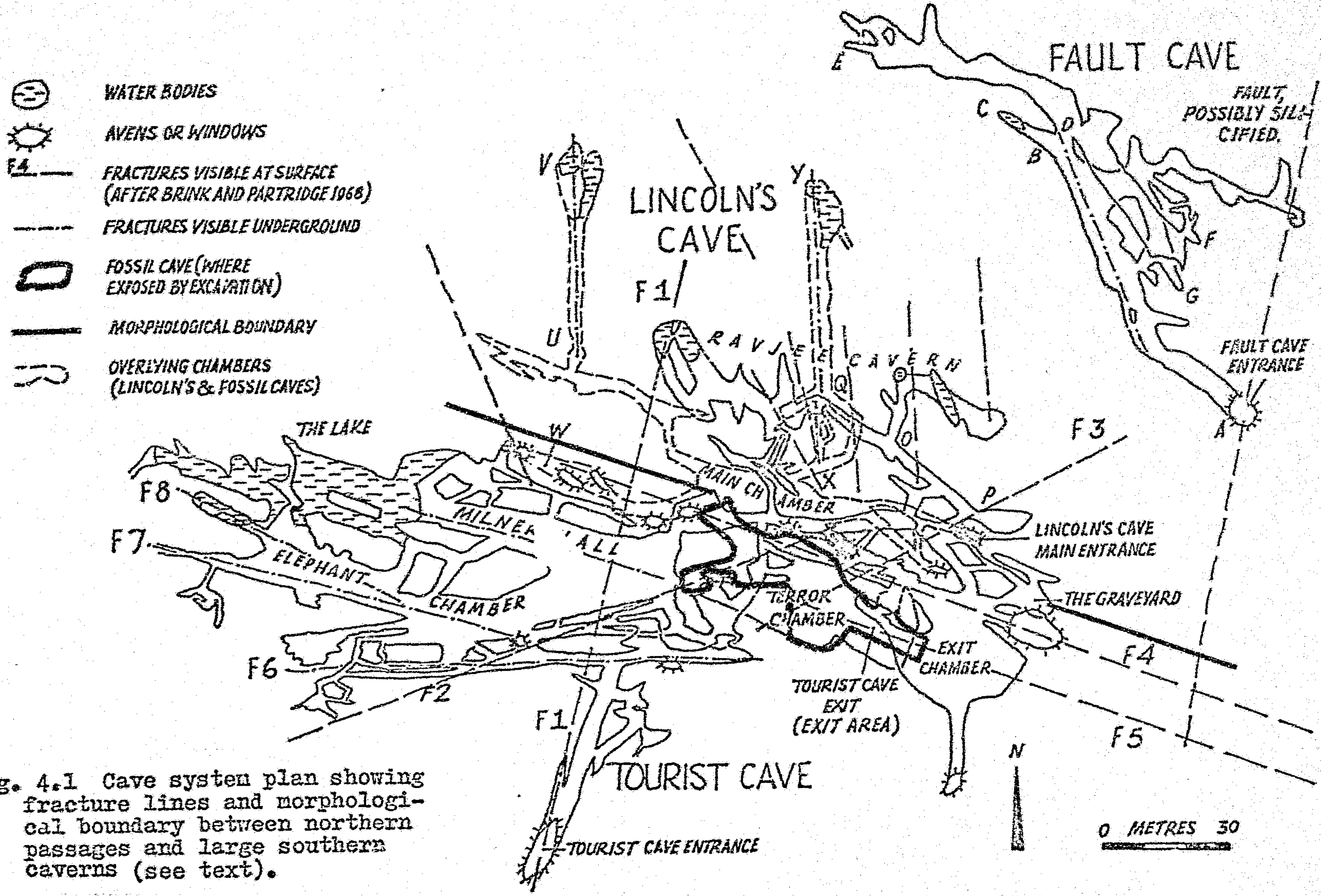

Fig. 4.1 Cave system plan showing fracture lines and morphological boundary between northern passages and large southern caverns (see text).

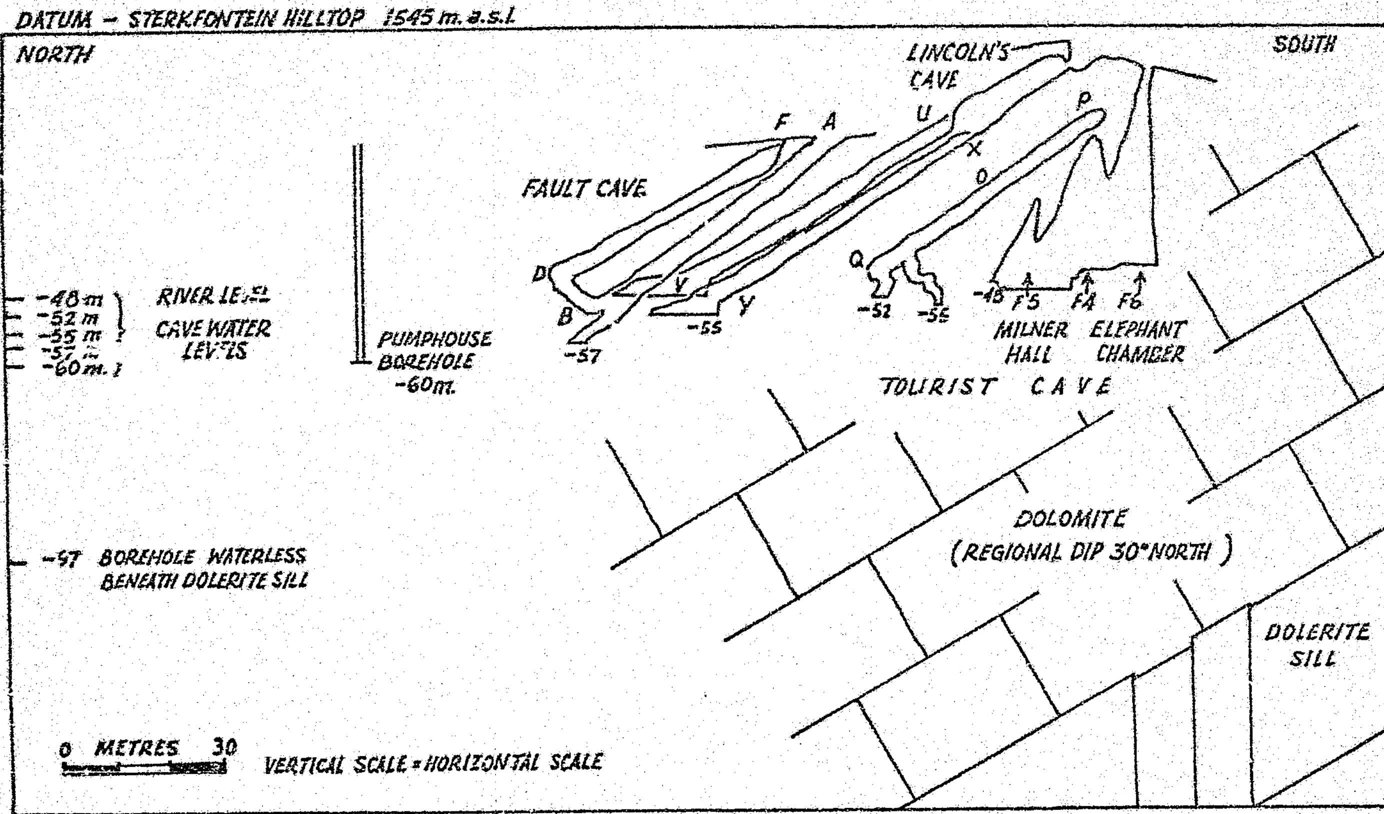

Fig. 4.2 Superimposed cave sections parallel with regional rockdip (see text for explanation)

PART II

THE CAVE SYSTEM

CHAPTER 4 - OVERALL VIEW - PLAN AND SECTION

4.0 This chapter presents a general description of the form and dimensions of the Sterkfontein Cave System. By means of cave plans and sections the system is also related to the surface geology.

The cave system itself was mapped with the degree of accuracy termed 'D5' on the Butcher and Railton Scale (Butcher and Railton, 1966) No attempt was made to map the underwater passages of the system. No large underwater cavities were discovered.

4.1 The Cave Plan and Section - General Description

The Sterkfontein Cave System consists of three large caves - Tourist Cave, Lincoln's Cave and Fault Cave (Fig. 4.1) - in addition to many small cavities in the hillside. Several voids within this system contain breccias some of which are fossiliferous. The Fossil Cave exposed on the hillside contains one of the largest breccia deposits in the System.

The caves lie at a number of different levels: Lincoln's Cave lies a few metres beneath the Sterkfontein hill-summit and descends with the rock dip through more than 50m to the local water level (Fig. 4.2). The main chamber of Lincoln's Cave and the Fossil Cave lie directly above the Tourist Cave, which itself is connected to the surface by means of various shafts and apertures The Fault Cave is situated north-ea`` of the Tourist/Lincoln cave complex.

Although no passages connecting these three caves are known some evidence for connections above and below the piezometric surface exists (Chapter 8).

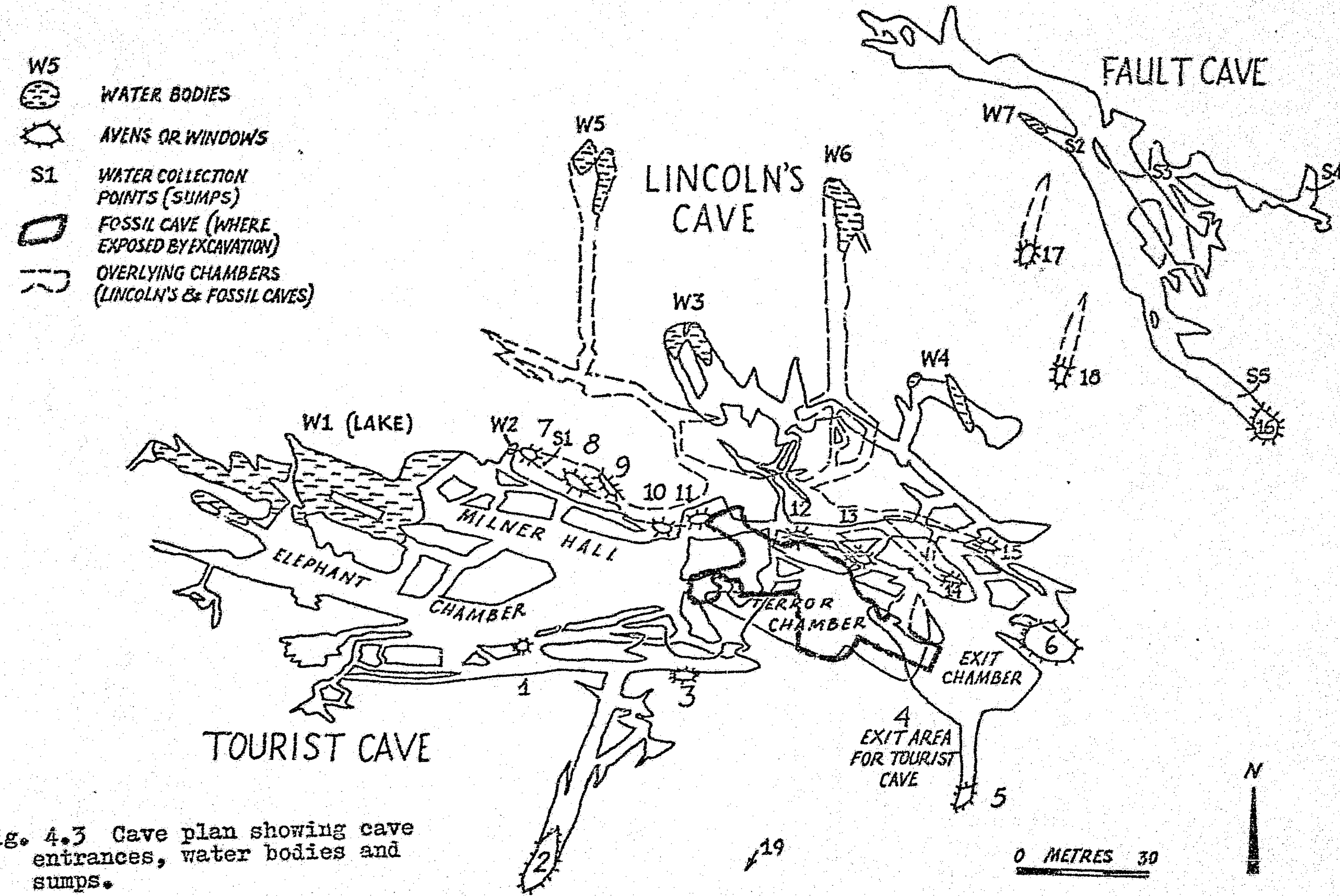

Fig. 4.3 Cave plan showing cave entrances, water bodies and sumps.

The main Fossil Cave and other smaller fossilliferous caves have been deroofed by erosion, exposing the fossil-bearing breccia fill on the hill surface. These breccias have been mined for their deposits of pure secondary limestone. The mining operations have also modified the underground passages in many places, not only by the removal of secondary limestone, but also by the blasting of access routes through the dolomite bedrock, and the blanketing of floors with rubble.

The broad dimensions of the entire cave system are as follows: 350m from east to west and 250m from north to south. The Tourist Cave covers the largest area, 250m from east to west and 130m from north to south. Its largest chambers include the closely connected Elephant Chamber and Milner Hall which together form a void 150m long by 50m wide and about 25m high (Fig. 4.1). The Exit Chamber, Terror Chamber and Ravjee Cavern are the other large cavities in the Tourist Cave. Otherwise the Tourist Cave consists of passages of various dimensions connecting the larger chambers.

Lincoln's Cave is 130m from east to west and 90m from north to south. It comprises a main chamber (30m x 18m and 3m high) with four passages leading away from it; two horizontal low passages leading westwards, and two narrow slot-like passages descending northwards with the dip of the dolomite, to water level.

The Fault Cave is aligned northwest-southeast, being 150m long in this direction, and 120m wide. It consists of several passages trending generally northwest-southeast, which lie at various levels, and which meet at the lowest part of the cave, near the one small water body of this cave.

There are seven water bodies in the whole cave system, consisting of static water with a free surface (W1-W7, Fig. 4.3), in the deepest parts of the cave system. The largest is the Lake in the western end of the Tourist Cave (60m long and 18m wide). Water bodies No. 2 and No. 7 are very small with a surface area of less than $1m^2$. The remainder are water-bodies with a surface area of several square metres. The deepest water-body as far as is known is W5, at 6m deep. The Lake is only 4m deep at its deepest point.

Five mud-filled depressions exist within the cave where water periodically collects before seeping away. One such depression, or sump, lies at a high level in the system, in the south-west branch passage of Lincoln's Cave (S1, Fig. 4.3). The other natural sumps are all to be found in the low lying Fault Cave (S2 - S5, Fig. 4.3).

There are many entrances to the cave system both vertical and horizontal. Entrances 1 - 6 (leading into the Tourist Cave) have all been enlarged by the lime miners and for tourist access paths. Entrances 7 - 15 are mainly natural entrances leading into Lincoln's Cave. Fault Cave has only one entrance (No. 16); entrances 17, 18 and 19 provide access to small, dead-end cavities in the hillside.

4.2 Analysis of the Cave Plan

It can be seen that the Tourist Cave (except Ravjee Passage and its offshoots) and Lincoln's Cave (main chamber) comprise the larger cavities when compared with those passages north of an east-west morphological dividing line (in red, Fig. 4.1). In addition, the larger cavities are aligned generally east-west, whereas the smaller passages to the north have a strong north-south component.

The Fault Cave belongs mainly to the latter category although the passages DE and DF may belong to the former (see Discussion below, Chapter 8).

The Tourist Cave undoubtedly stretched further to both the east and west (from Exit Chamber and Elephant Chamber respectively), as did the Fault Cave passages DE and DF before these extremities were inundated with large influxes of hillslope material. It may be said, therefore, that the east-west component of the larger cavities, south of the dividing line, was

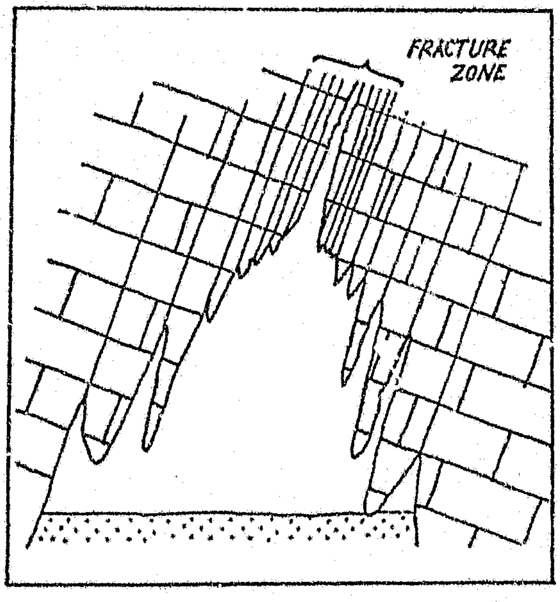

Fig. 4.4 Cavern developed along a zone of fracture

originally even greater than it appears on the cave plan.

The surface geology overlay offers some explanation on the existence of the two morphological divisions mentioned: the longest fracture zones (No. 1 - 5, Fig. 4.1) are concentrated in the portion of the hill underlain by the larger cavities, i.e. the area south of the morphological dividing line. The other, shorter fractures are underlain by the smaller passages north of the dividing line. Fracture zones 2, 3, 4 and 5, or their direct continuation underground, coincide exactly with several of the largest underground cavities. Fracture zone No. 1 determines the area of Elephant Chamber in which the dolomite partitions occur; No. 4 coincides with the Exit Chamber, Terror Chamber and northern part of Milner Hall; No. 4 also coincides with the Exit and Terror Chambers, and the whole length of Milner Hall. On the surface, Nos. 4 and 5 coincide with the Fossil Cave and large Exit Area cavity (centred around entrance No. 4, Fig. 4.3).

In the same way, fractures visible only underground, have determined the position of several of the cave voids (fractures 6, 7 and 8). In several areas in the Elephant Chamber - Milner Hall complex, narrow, slot-like chambers are found closely spaced with dolomite blades and walls acting as partitions between them. These closely-spaced chambers are aligned alon racture zones and indicate that the fracture zones consist of several parallel planes of weakness, rather than a single plane of weakness (Fig. 4.4).

North of the morphological dividing line, however, the coincidence of surface fracture line and cavity is almost non-existent, suggesting that the fractures do not penetrate the dolomite very deeply. Underground it is apparent that single fractures, rather than entire fracture zones, control the development of the passages. The morphology consists of single passages rather than a series of coalesced passages.

The map of surface geology does not supply any information on the Fault Cave; however it is apparent from observation underground that passages ABC and BG are joint-controlled (Fig. 4.3). Any surface expression which controlling fractures may have, is buried beneath the hillslope debris which is more than 1m thick on the lower slopes of the Sterkfontein hill, directly above Fault Cave.

4.3 Analysis of Modified, Superimposed Cave Sections

Cave sections were analysed to ascertain whether the sloping passages in the northern section of the cave system occupy single beds or transgress the dip of the beds. Of the five main passages only two (in Lincoln's Cave) are aligned in the direction of dip (northwards); the slope of these is therefore immediately comparable with the rockdip. The other three passages (POQ, Tourist Cave; AB and DF, Fault Cave - Fig. 4.1) are not aligned in the direction of dip however, and their slope is thus not tooreadily contrasted with the rock dip.

For the sake of comparison, sections of these three passages were drawn <u>in the plane of rock dip</u> thereby reducing the actual passage slopes to slopes in the plane of bedrock dip. These modified passage sections were then superimposed with the two Lincoln's Cave sections (Fig. 4.2) to ascertain the vertical and stratigraphical relationship of the passages to one another. Various correlations are apparent:

4.3.1 The major cavities, such as Milner Hall and Elephant Chamber, and parts of Lincoln's Cave (e.g. point W, Fig. 4.1) occupy fracture zones (Nos. 2, 4 and 5).

4.3.2 The smaller northern passages such as POQ (Tourist Cave), UV (Lincoln's Cave) and AB, DF (Fault Cave) occupy specific strata within the dolomite and do not generally transgress the regional dip. XY (Lincoln's Cave) is intermediate, having substantial vertical development but having developed from a single bedding plane and a single large joint.

4.3.3 Water levels can be seen to drop in !titude towards the north, i.e. towards the Blaauwbank River. (see also Fig. 7.4) The cave water levels lie between 0 and 18m below the river bed however. The resurgence question is discussed in 7.2.3 below.

4.3.4 The diabase sill which underlies the Cave system may have controlled the stratigraphic levels at which the cave has developed (although it has not developed in contact with the dyke). This is evident from the fact that a borehole drilled through the dyke struck no water even at a depth of 97m below datum: i.e. 37m below the lowest water body level within the caves. It is possible, of course, that the borehole simply failed to pierce water filled cavities possibly existing beneath the diabase sill.

4.3.5 The passages almost overlap in places, suggesting that a group of adjacent strata control these passages. Another possible explanation is that a single stratigraphic horizon may control two or more of the passages; e.g. the two Lincoln's Cave passages lie within a single stratigraphic unit. This is a possibility even though the superimposed sections do not show it because mapping errors and small changes in strike direction would result in passage sections occupying apparently different stratigraphic levels.

4.4 Summary

The Sterkfontein Cave System consists of 3 large caves lying at varying levels, and none interconnected by passable passages. Lincoln's Cave overlies the Tourist Cave and the Fault Cave is situated north-east of both. The Tourist and Fault Caves contain breccias as does the deroofed Fossil Cave. The system contains only one relatively large water body - none of the water bodies are deep, and all lie in the lowest parts of the system. Water collection points, or sumps, are found at different levels in the system mainly in Fault Cave. Many cave entrances, vertical and horizontal, pierce the hillside. Some have been artificially enlarged.

Consideration of the cave plan indicates two morphological divisions of cavity type and relationship. Larger cavities in a complex relation with one another and with a general east-west alignment comprise the southern division, whereas smaller passages of a somewhat simpler 3-dimensional pattern, and with a stronger north-south trend, comprise the northern division. A series of major fracture zones traverse the dolomite of the southern chambers, whereas the dolomite hosting the northern passages is almost devoid of major fracture zones.

Superimposed cave sections also indicate the coincidence of the main galleries with various fracture zones. They indicate strong coincidence of bedding plane angle and passage slope. Water body levels descend towards the local stream bed, although they all lie below the level of this stream bed.

The underlying diabase sill may have influenced the level at which the cave has developed.

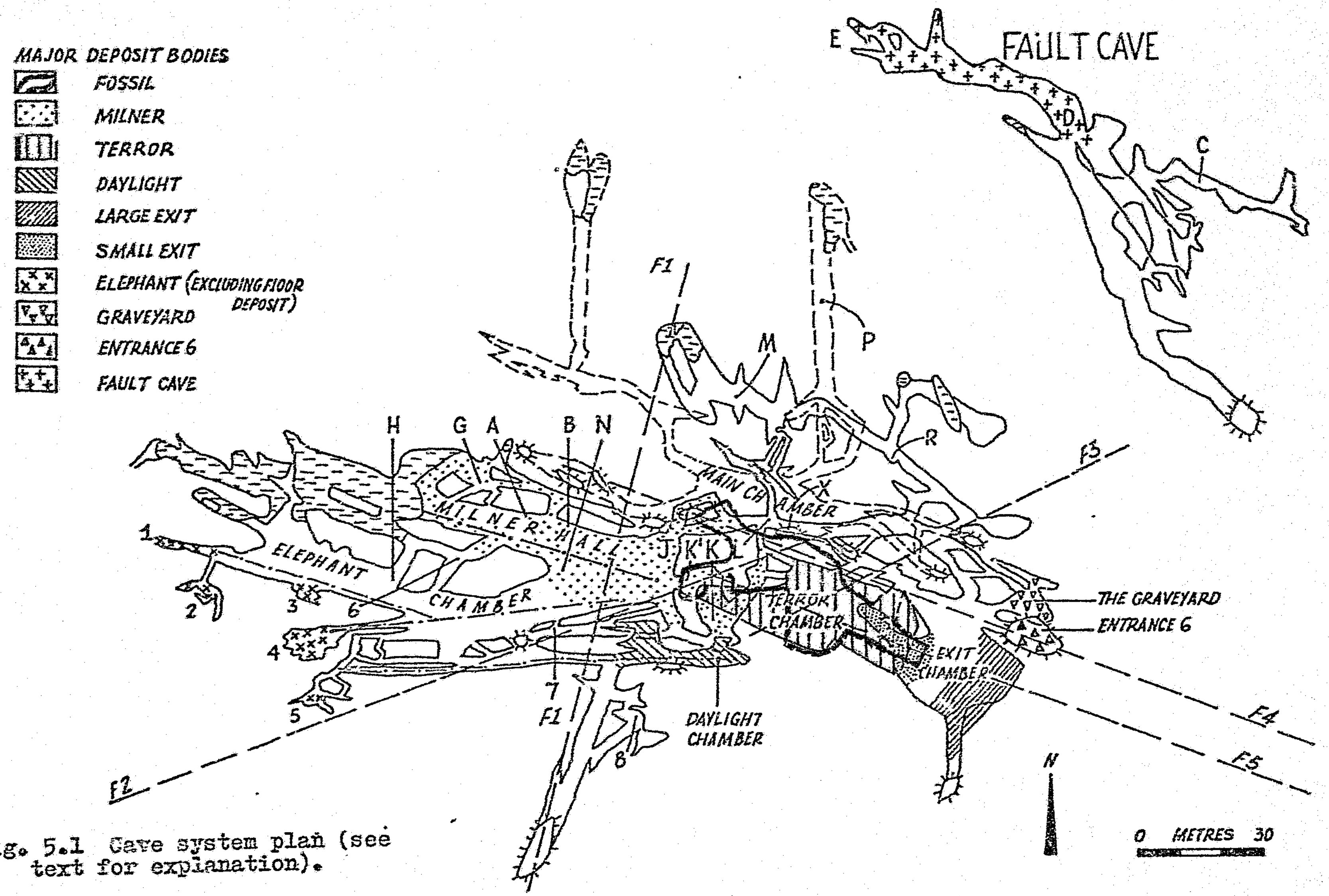

Fig. 5.1 Cave system plan (see text for explanation).

CHAPTER 5 - EROSIONAL FEATURES OF THE CAVE SYSTEM

5.0 Erosional features are classified here according to their origin, which may be by phreatic solution, or vadose erosion. Features of doubtful, and multiple phase origin are classed separately.

Phreatic features are those which form by solution of calcareous rocks under static ground water. Vadose erosion, however, is initiated by moving streams of water which flow underground and which have a free air surface. It is sometimes difficult to differentiate between true vadose and phreatic features caused by sub-water table currents. The passage of percolating water through the interstices of both consolidated and unconsolidated materials can affect the development of both surface and underground features. Percolating water cannot however, be considered as a discrete water body, such as the phreatic and vadose water bodies.

5.1 Phreatic Features[1]

5.1.1 Networks

A room south of Elephant Chamber consists of a series of high (9m), narrow (1m) interconnecting passages formed by the solutional widening of joints in the bedrock (point 2, Fig. 5.1). The passages connecting Elephant Chamber to Milner Hall (point 6, Fig. 5.1) may also be termed a network of somewhat larger dimensions (10m high, 2m wide). The upper parts of this network are encrusted with speleothems, but the lower walls are bare dolomite with protruding chert ledges.

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[1] Phreatic features are identified in this study according to Bretz's classification, using his terminology (Bretz, 1942).

5.1.2 Partitions[2]

These are narrow, wall-like slabs of bedrock in situ which extend from the ceiling to the floor of a chamber. The best examples at Sterkfontein are found east of Entrance 1 (point 7, Fig. 5.1). Partitions may be considered as an advanced form of network developed along close-set fractures. Like networks they owe their origin to phreatic solution along the fracture planes. The partitions near Entrance 1 occur in four parallel rows, 3m apart and 10m high on average. In width they generally become thicker with height. Many become so thin at the lower ends that they taper off before reaching the floor, and thus hang suspended from the roof. Windows occur in some of these partitions due to solutional attack from both sides.

5.1.3 Bedding-Plane Anastomoses

A 2m high room, south of Elephant Chamber, appears to be confined to a single bedding plane - elongated pillars and partitions of dolomite give this room the appearance of an anastomosis. No other bedding-plane anastomoses have been encountered.

5.1.4 Joint-Determined Cavities

Examples of such cavities can be seen in the lower parts of the cave system. At higher levels they are often masked by travertine deposits. However, where travertine deposits are not present, joint-determined cavaties are visible in the higher chambers, such as the Exit Chamber.

One particular joint-determined cavity (point R, Fig. 5.1) appears to have developed as a result of the mixing of karst waters (Bogli, 1971). Although the cavity is partly filled with travertine, the controlling

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[2]When dolomite walls lie at angles of more than 45° to the horizontal Bretz terms them 'partitions' and when lying at less than 45° to the horizontal 'rock spans'. No rock spans have been encountered at Sterkfontein.

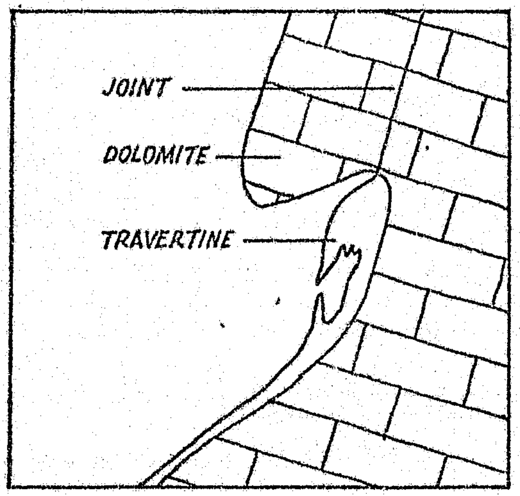

Fig. 5.2 Cavity formed possible by mixing karst water (after Bogli, 1971)

joint is visible. Karst water presumably flowed through this joint during and after the formation of the cavity (Fig. 5.2). Bretz (1942) did not envisage joint-aligned cavities forming due to the mixing of karst waters, but simply as the result of preferential solution along a joint.

5.1.5 Wall Pockets

These features are smaller than joint-determined cavities (up to 0,3m long) and do not appear to be controlled by joints; rather they appear to occupy slightly less resistent strata. They are elongated horizontally but are not asymmetric in section, and are thus not obviously features formed by current flow. Wall pockets occur in great numbers along the lower walls of the Elephant Chamber (point 3, Fig. 5.1) and also in other parts of the cave system.

5.1.6 Boxwork

This is a term to describe relict quartz veins which stand out from the dolomite bedrock giving the impression of cube-shaped boxes. They are found in the lower parts of the caves, near the water bodies, and are poorly developed, and very fragile. Protruding stylolite seams, although not as fragile as the quartz veins appear in the Fault Cave, and like the quartz veins provide evidence of phreatic weathering. Chert ledges can be seen protruding from the dolomite in most parts of the cave system and these too, being less soluble than dolomite, indicate phreatic weathering.

5.1.7 Rock Pendants

In the vicinity of Entrance 10 (Main Chamber of Lincoln's Cave) many, short (5cm) lump-like protusions hang from the ceiling. These appear to be the features which Bretz describes as 'pendants' - i.e. features developed by upward solution of a dolomite roof due to water percolating between an insoluble fill floor and the roof at a time when the cavern was entirely filled with insoluble debris. Features such as spongeworks, ceiling and floor pockets, tubes and half-tubes have not been encountered.

5.2 Vadose Features

The only modern vadose stream in the cave system is that which flows periodically along one of the lowest passages of the Fault Cave (point C, Fig. 5.1). It flows for a short distance only, before disappearing into sump No. S3 (Fig. 4.3). However, there are two erosional features associated with this steam which are worth noting:

5.2.1 Stream Trench

A small trench (1m long, 0,5m deep) is cut into a mud deposit in a small room in the passage mentioned above. A similar trench can be seen in the Tourist Cave (point 8, Fig. 5.1). However, the mud in which this trench has been incised appears to have entered the cave very recently after a dolomite wall had been blasted away by the lime miners.

5.2.2 Meander Scar

Below the trench a small meander scar (0,2m high, 0,7m long) has been cut into the passage wall, where the stream swings around a bend in the passage.

5.3 Other Features

Erosional features of a multiphase type or of doubtful origin are mentioned here - wall-grooves, smoothed surfaces and solution pockets.

5.3.1 Solution Pockets

There are solution cavities which develop downwards through dolomite or breccia by percolating vadose waters. They may be related to the cavities exploited by tree roots, in that water percolating through such cavities will be highly corrosive (due to soil carbon dioxide content).

Solution pockets mentioned by earlier workers, can be seen developed in the breccias of the Fossil Cave where these breccias have been exposed on the hillside. The solution pockets are filled with unconsolidated

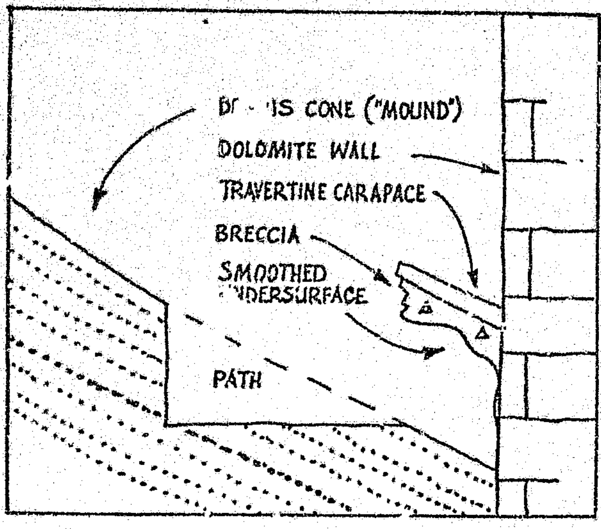

Fig. 5.3 Smoothly-eroded breccia undersu face (Mound breccia, Milner deposit)

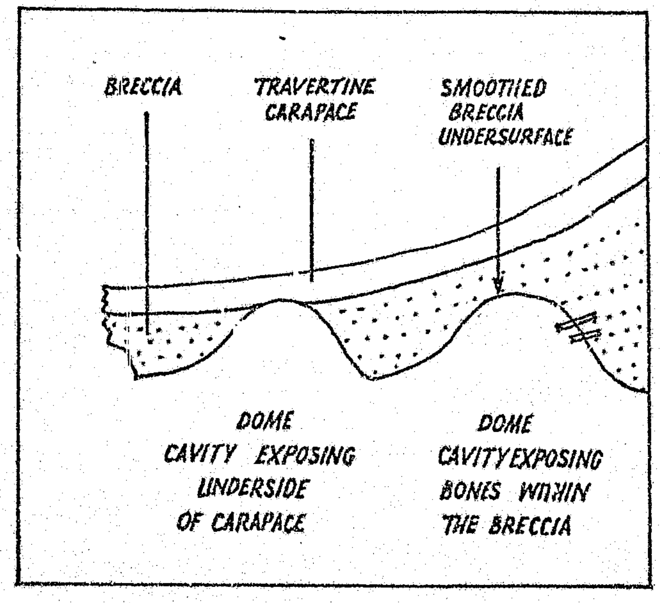

Fig. 5.4 Dome cavities in Mound breccia (Milner deposit)

material, both *in situ* decalcified breccia material and hill wash collected by the solution pockets. Some solution pockets are not soil-filled, but lead directly down to the underground caverns and are therefore better termed avens. A cross section of such a cavity can be seen in the north wall of the Type Site (point X, Fig. 5.1) where it descended into Lincoln's Cave, as Entrance 12, until it was largely destroyed by mining operations.

5.3.2 Smoothed Surfaces

A comparatively small body of pinkish breccia is attached to the wall high in the eastern end of Milner Hall (point J, Fig. 5.1). On its underside this breccia ('Mound breccia') has been eroded and presents a smooth surface. Only a small portion of the breccia remains against the wall overhanging the pathway (Fig. 5.3).

The eroded underside of the breccia passes smoothly onto the dolomite wall, suggesting that a gently flowing current of water fashioned this surface.

Two dome shaped cavities (less than 1m deep) which have developed upwards into the pinkish breccia exposing, in one dome, the carapace travertine which caps the breccia body (Fig. 5.4). These domes seem to have been caused by eddies in flowing water. However, they may also represent the 'enlargements' which Bogli (1971) claims are the result of mixing karst waters. In either case the domes suggest currentflow, even though the flow must have been gentle (fragile bones protrude from the dome walls).

Other smoothed surfaces can be seen near the pendants in Lincoln's Cave. Stalactites have been eroded out leaving hollows (0,2m deep) with smooth surfaces: these surfaces often pass evenly onto the dolomite roof or wall. In a chamber south of Elephant Chamber (point 5, Fig. 5.1), travertines have been eroded flush with the mud and dolomite walls.

5.3.3 Grooves

The Mound breccia is attached to a 13m vertical dolomite wall which is unadorned by travertine deposits. The surface of this wall is slightly grooved horizontally over much of its surface. The grooves are clearly evidence of differential solution which may either result from weaker beds or from current concentration at declining levels since the wall is aligned along the strik. exposing dolomite strata horizontally, or of vadose stream erosion.

This concludes the survey of erosional features encountered in the cave system, and indicates the majority to be phreat.c.

CHAPTER 6 - CAVE DEPOSITS

6.0 Little of the cave system has escaped modification by various deposits. The deposits described in this chapter may be divided into two groups, calcareous and non-calcareous: the modes of deposition of each are entirely different and thus give rise to distinct features. Furthermore, the volume of the calcareous deposits (secondary and tertiary calcium carbonate) is small compared with the large non-calcareous deposits which, often surface derived, have modified the original cave voids dramatically.

A model of debris cone development is presented as a basis for descriptions of the various large debris bodies encountered in the cave system. The location of these bodies within the system is examined but the spatial relationship between them is discussed in Chapter 8.

6.1 Secondary and Tertiary Calcium Carbonate Deposits

6.1.1 Stalactites and Related Formations

Stalactites are best developed in the large caverns and high passages along the structural control line. Few have survived the mining however. Some of the broken remnants have diameters of 0,5m.

Stalagmites are seldom seen, either because they did not form, or because they were easily removed. However, in the low-ceilinged, inaccessible Ravjee Cavern, pillars of travertine can be seen. Pristine calcite straws and helictites are abundant in Ravjee Cavern. Straws and helictites are forming today and a 'younger generation stalactite' has been dated by carbon-fourteen dating (stalactite outer wall: greater than 50 000 years before present, inner wall greater than 47 500 years before present - Vogel, 1971).

FEATURES	RE-SOLUTION LEVELS (METRES ABOVE THE LAKE)
THICK FLOWSTONE WITH TERTIARY GROWTHS	±8m
THICK REDISSOLVED FLOWSTONE WITH WITH TERTIARY GROWTHS	5m
THIN REDISSOLVED FLOWSTONE WITH TERTIARY GRONTHS	2,3m
THIN REDISSOLVED FLOWSTONE	1,5m
BARE DOLOMITE WALL	0 (LAKE)

Fig. 6.1 Re-solution levels on Milner Hall flowstone indicating past lake levels

Stalactites often merge into flowstone deposits, and the two forms generally occur together. Thick (1m) flowstone deposits have been mined at several points in the cave system, especially in the Daylight, Exit and Elephant Chambers, and the Fossil Cave.

A flowstone, too thin to be mined, covers the entire south wall of Milner Hall and has become a tourist attraction. A travertine curtain, high in the roof of Milner Hall and a large stepped flowstone beneath Entrance 1 are some of the only stalactitic formations of any size which remain in the cave.

Re-solution has affected many of the wall deposits, at the lower levels especially. The characteristic honeycombed and pitted surfaces are evidence, and various earlier lake levels can be discerned where subaereal calcite deposition ends, and re-solution begins (Fig. 6.1).

6.1.2 Calcite Floors

These can be seen overlying lake deposits as a crust in various parts of the cave. Notable is that beneath Entrance 1, that at the entrance of Terror Chamber, and that in the recesses of the Graveyard. The calcite floors are less than 3cm thick and little remains of them now (at best $1m^2$ in areal extent). Carapaces merge into floors in places.

6.1.3 $CaCO_3$ Crystals

Aragonite crystals occur on most walls in the cave system, whether dolomite, chert, travertine or cave earth. They can be as much as 2 - 3cm long, mostly of aragonite, and probably some of calcite. Subaqueous aragonite (cauliflower aragonite) occurs on the wall of Milner Hall. Concoidal amorphous calcium carbonate may also coat some walls.

6.2 Non-Calcareous Deposits

These deposits consist of residual wad, internally and externally derived earths, talus and collapse debris. Breccias, formed by the cementing of these deposits, are included here, since the mode of origin is essentially the same.

Although both are found in characteristic cone form, the internally and externally derived non-calcareous deposits are distinguished for the following reasons:

Firstly, the constituent materials are different due to the two distinct sources from which they derive: the externally derived deposits consist predominantly of large quantities of fines (red soil, often layered), whereas the internally derived deposits consist mainly of collapsed chert ledges.

Secondly the externally derived deposits are very large in volume compared with the internally derived.

Thirdly, the presence of externally derived material indicates that a chamber has become connected to the hillside, an important fact when analysing the development of the cave system.

6.2.1 Internally Derived Deposits

(1) Wad is an insoluble residue of manganese oxide which remains as a coating on dolomite walls which have been subjected to solution by karst waters. It is thus found below the present water-table, and in the paraphreatic zone (on walls bounding the Lake and the water bodies 2, 3, 4 and 7, and sump 4 - Fig. 4.3), and in the vadose zone (on dolomite blocks[1] buried in moist, uncompacted gravels e.g. in the Elephant Chamber - point H, Fig. 5.1).

Wad is encountered as a black fine powder, or as a moist, water-retentive, jelly-like substance. Its presence indicates static (or very slowly circulating) water conditions, or it indicates adjacent

[1]Maximum thickness of wad observed on cave walls is 2cm, as opposed to a maximum of 5mm on buried dolomite blocks.

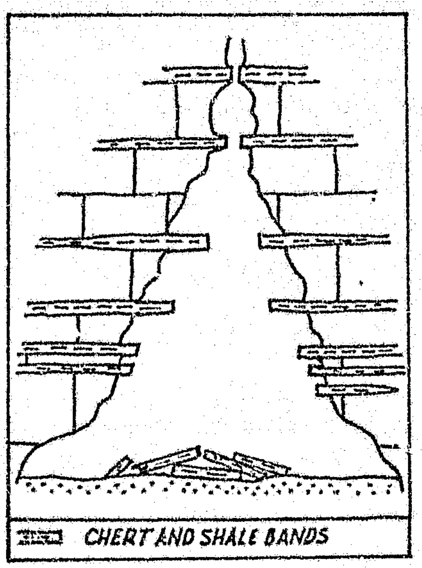

Fig. 6.2 Collapse debris beneath major joint, Ravjee Cavern

moist earth. Wad is found cemented into breccia, with discrete impregnations of crystalline calcite, usually at the base of larger bodies of breccia, e.g. beneath the Fossil Cave breccias and in the Milner Deposit.

(2) Collapse Deposits

These are found mainly in the inner recesses of the system, especially in the northern passages, since the externally derived deposits have obliterated any such features that may have existed near the present-day avens and connections with the surface.

Collapse material can thus be seen near the water bodies of all three caves in the system. They form banks of debris against the walls from which chert and shale ledges have fallen, or they form mounds beneath vertically extending joints (point M, Fig. 5.1 and Fig. 6.2), usually with little fine matrix material.

Of a different order altogether are the very large dolomite blocks which have collapsed from the roof. The largest (7m long, 5m high, 4m broad) is that at the convergence of Milner Hall and Elephant Chamber (point N, Fig. 5.1) which fell a distance of 3m. The Name Chamber is formed by the collapse of a large block which now forms the floor of the Chamber (point K, Fig. 5.1). In Lincoln's Cave, a large collapse block lies in the main chamber, and others lie on top of one another, wedged in the narrow eastern passage (point P, Fig. 5.1).

Blocks of collapsed breccia have fallen from the weakened Terror Chamber roof, and they also occur in the rubble blocking a passage on the south side of Elephant Chamber (point 3, Fig. 5.1).

6.2.2 Externally Derived Deposits

These large deposits, which have affected the interior morphology of the caves so greatly, are considered in several broad groups (6.2.2 (1) - 6.2.2 (10) below). Each group appears to be a continuous

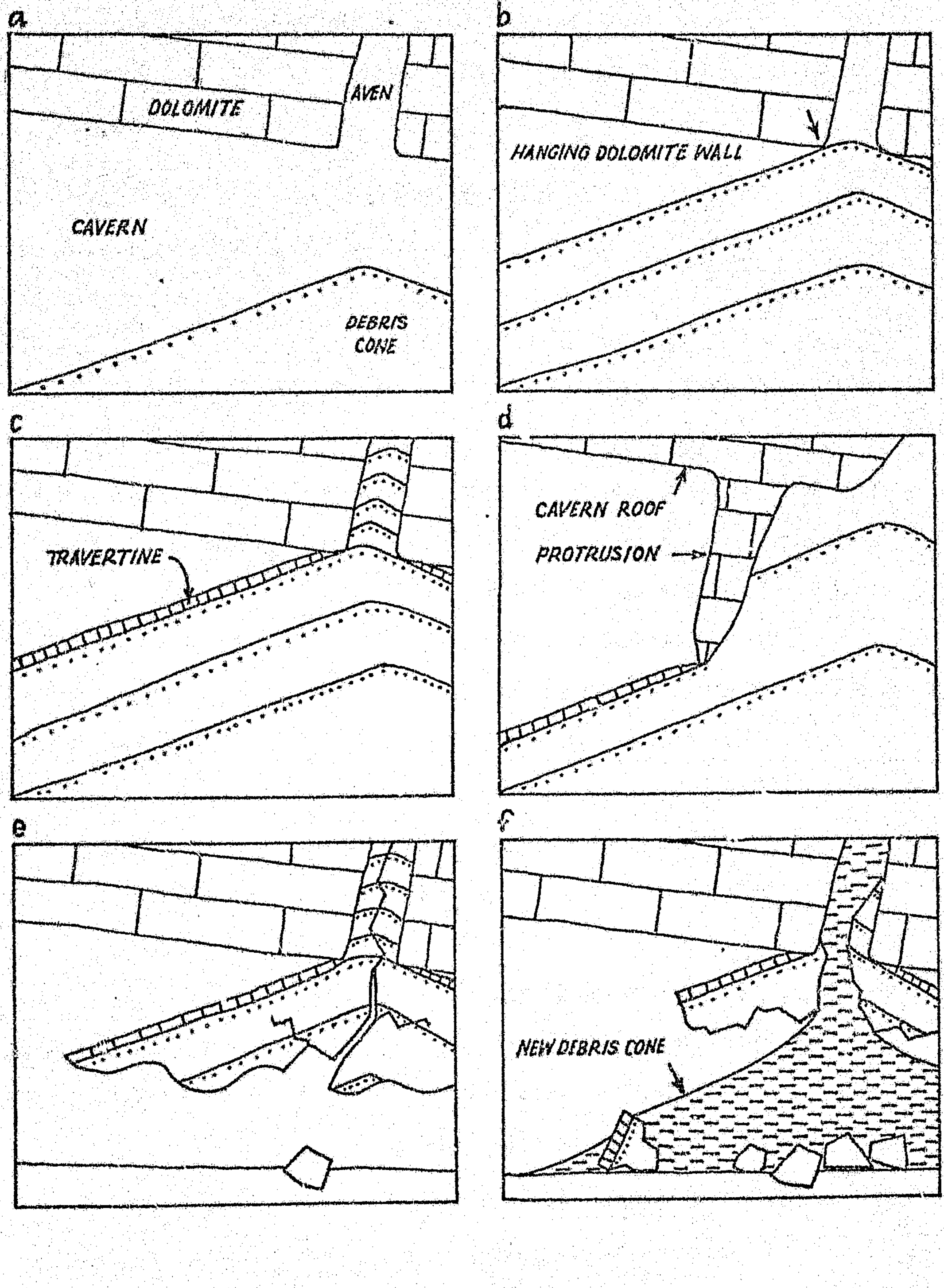

Fig. 6.3 Typical stages in the development of Sterkfontein cave deposits (see text)

mass (except (8)) consisting of various materials, sometimes laid down in a number of phases, but derived nevertheless from the same aperture (or aperture cluster) in the cave roof. The constituents range from mud and soil to gravel, stones and boulders, which have been cemented into breccias of varying hardness. Bone fragments occur, with occasional pockets of high bone concentration.

It is significant that no deposits corresponding to those termed 'clay fill' by Bretz (1942)[2] have been encountered at Sterkfontein.

To aid the description of the ten main debris bodies, a model of debris accumulation in Sterkfontein is presented. Although the model is derived by consideration of these debris bodies, it is nevertheless presented first as an explanation of the particular set of accumulation characteristics encountered, and also as an object against which the individual debris bodies may be compared.

Debris Cone Model

A debris cone grows upwards by the accumulation of debris beneath an aven connected to the hill surface (Fig. 6.3a). When the mound attains the height of a hanging dolomite wall (sometimes the ceiling of the underground chamber), it can grow no higher downslope of this interruption (Fig. 6.3b). Any surface material which enters after this stage has been reached will fill the aven and not the cavern below (Fig. 6.3c).

Any protrusion from the cavern roof will have a similar effect: downslope of the protrusion the cavern will be protected from further infilling; upslope the cavern will fill with debris (Fig. 6.3d).

If debris enters with calcium carbonate-charged water percolating

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[2] Externally derived clay material laid down during the phreatic phase in static water-bodies seldom showing any signs of lamination, current flow or turbulence.

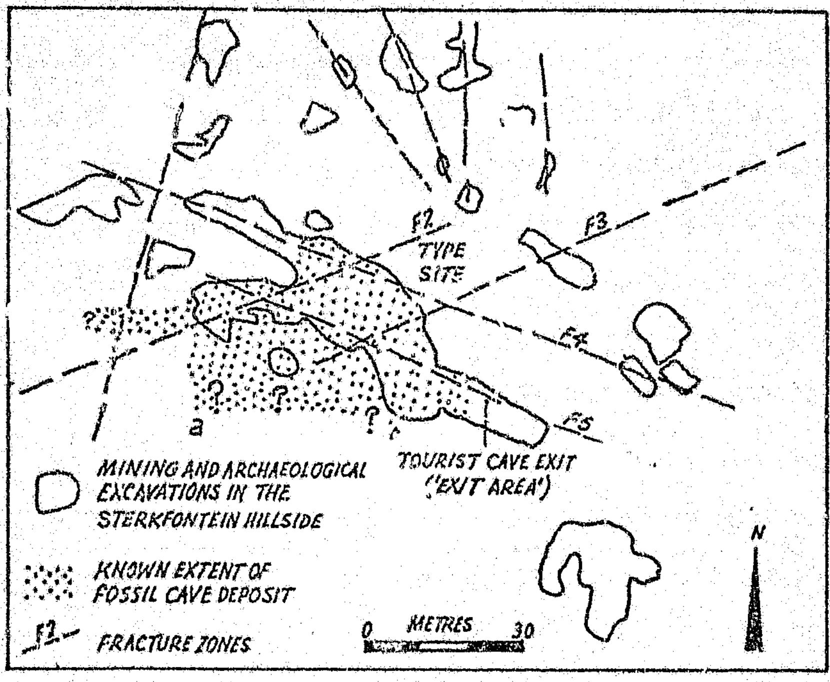

Fig. 6.4 Plan of Fossil Cave Deposit as exposed by excavation

through it, it is cemented into a breccia. However, the supply of percolating water does not cease when the supply of surface debris is halted downslope of a hanging wall. The water thus precipitates a travertine carapace on top of the now static debris-cone talus slope (Fig. 6.3c). Later, the solidified breccia may be disturbed or removed (Fig. 6.3e) - especially by re-solution and consequent collapse (due to both rising ground water and aggressive percolating surface water), to the extent that the cone in the underground chamber is supplied actively once more with surface material or decalcified breccia (Fig. 6.3f).

Of the ten deposits described below all except the Fossil, Terror, Entrance 6 and Fault Deposits (Nos. (1), (3), (8) and (10) below) show these controls and sequences in their development.

(1) Fossil Deposit

The rich bone and artefact content of this deposit exposed at the surface in the Fossil Cave, has long been known and is at present being further investigated. The mode of accumulation of the deposit has been carefully examined (Brain, 1958; Robinson, 1962; Brink and Partridge, 1970), and a general description of it is given here.

The Fossil Deposit has been exposed from the Tourist Cave Exit Area to the Extension Site, and extends 17m further westward (A.R. Hughes, personal communication) (Fig. 6.4). To the north it is bounded by the north wall of the Fossil Cave (a small displacement fault - fracture zone No. 4); to the south its exact extremity is not known, but it outcrops in several places south of the excavations as far as the east-west line a - b (Fig. 6.4).

The deposit consists of four distinct breccias, a thick travertine (which has been mined), and unconsolidated pockets of bone rich soil, possibly a decalcified breccia (Brink and Partridge, 1970). The two main breccias are a collapse breccia and an overlying pink breccia of slow

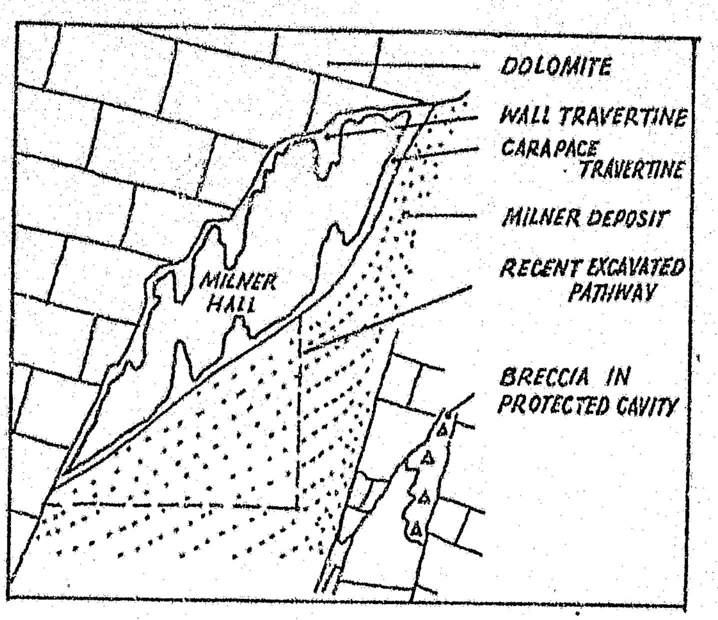

Fig. 6.5 North-south section through Milner Deposit, showing inundation of Milner Hall

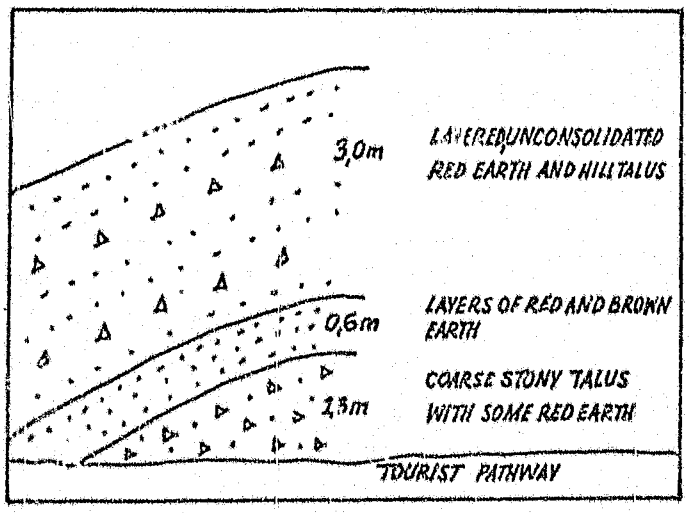

Fig. 6.6 Section exposed by pathway in unconsolidated mound debris cone, Milner breccia

accumulation. The first of the australopithecine skulls was recovered from this contact zone (Fig. 6.4).

The control by four of the major lineaments of the area, on the development of the Fossil Cave, and hence of the extent of the deposit is apparent (Figs. 5.1 and 6.4).

(2) The Milner Deposit

This stretches from the Lake in Milner Hall to point L (Fig. 5.1) a distance of 100m. The western half of the deposit in Milner Hall covers the entire north wall (13m high), reaching the highest parts of the roof (Fig. 5.1, A-B), from where it apparently entered the Hall. This deposit consists mainly of partly consolidated red earth lumps, and small stones, laid down in layers dipping downslope. It appears to be hill talus which has collapsed or slumped down into the Hall. Stalagmites and a thin travertine carapace deck the steeply sloping surface (39^0) of this unconsolidated deposit. A 3m face has been cut into this mass, as a tourist path, and the floor levelled. It is apparent, however, that this deposit originally banked against the opposite wall at a higher level than at present since remnants of the carapace cover can be seen on this wall (Fig. 6.5).

This part of the Milner Deposit contains some masses of breccia. Their relationship to the unconsolidated deposit is not clear as they occur in an adjacent side chamber (Figs. 6.1 and 6.5 - point G).

Towards the eastern end of Milner Hall, the Milner Deposit becomes a very large debris cone (20m high) termed the 'Mound' (point J, Fig. 5.1). This cone can be traced beyond K to L (Fig. 5.1) and forms the eastern half of the Milner Deposit. At J the Mound consists of unconsolidated and partly cemented layers of red earth lumps and hill-talus (as far as it can be ascertained from a 5m section cut into the side of the Mound - Fig. 6.6). One to 2m above this loose debris, a travertine

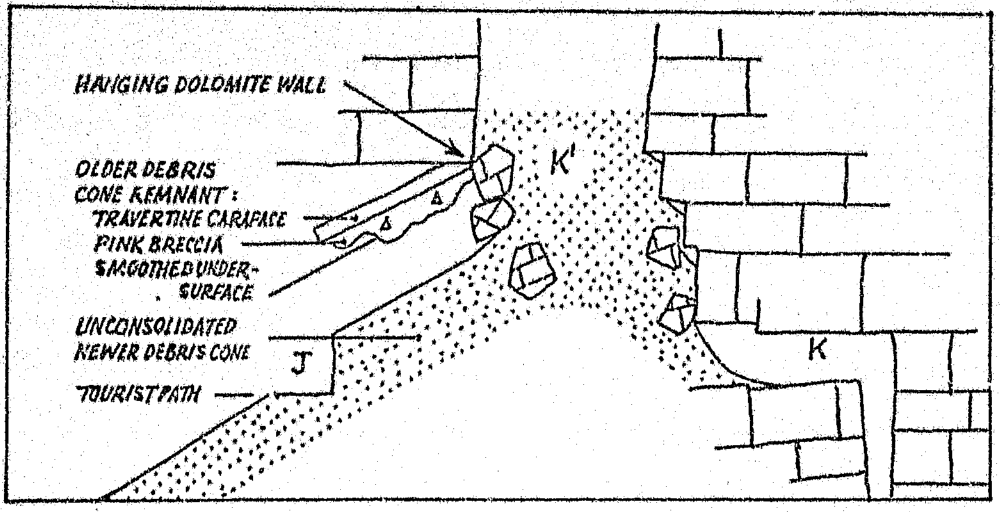

Fig. 6.7 East-west section from points k-j (Fig. 5.1) showing relationship of new deposit to old, and the effect of hanging walls

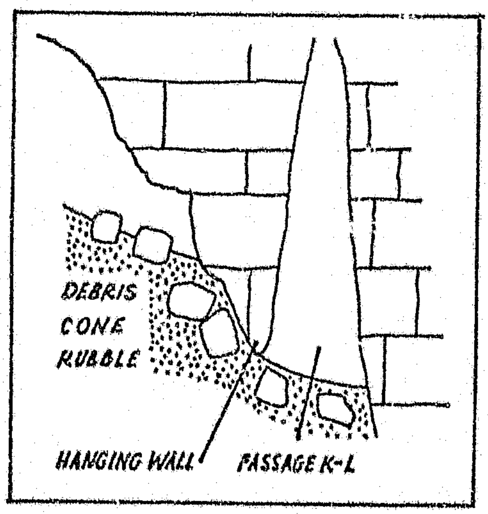

Fig. 6.8 Section showing passage k-l (Fig. 5.1) protected from debris influx by a hanging wall

carapace (13cm thick) overlies a hard pink breccia (the 'Mound breccia'). This carapace and breccia are attached to the dolomite chamber wall (Fig. 5.3) and rise towards the apex of the cone, where cone and carapace meet (Fig. 6.7)[3] The sequence of accumulation and removal evident here appears closely akin to the model proposed.

K' is the highest accessible point on the large Milner Deposit cone. From K' there is a view of Milner Hall and the cutting at Point J. Being on the upslope of a hanging dolomite wall, K' is situated among large collapsed boulders of dolomite and breccia, coated with red soil - of the newer, post-carapace phase of accumulation. It is interesting to note that the hanging dolomite walls have contributed to the size of the blocks permitted to enter into Milner Hall (at J) and the Name Chamber (K). The space between the newer debris and the hanging walls is insufficient to allow the passage of the larger blocks. The result is that comparatively fine debris reaches J and only red soil penetrates into the Name Chamber (K).

From K to L a similar effect can be seen. The passage K-L passes, in effect, along the side of the debris cone. As at K, a low hanging wall prevents boulders from invading this passage (Fig. 6.8).

The coincidence of the Milner Deposit as a whole with the major lineaments of the area is apparent (Fig. 5.1).

(3) Terror Deposit

This deposit, visible in the Terror Chamber, is probably the largest single accumulation in the cave system. Its volume is relatively easily gauged since evidence of both its horizontal and vertical extent exists.

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[3]The capital letters - J, K, K', - in the following paragraph refer to Fig.6.7

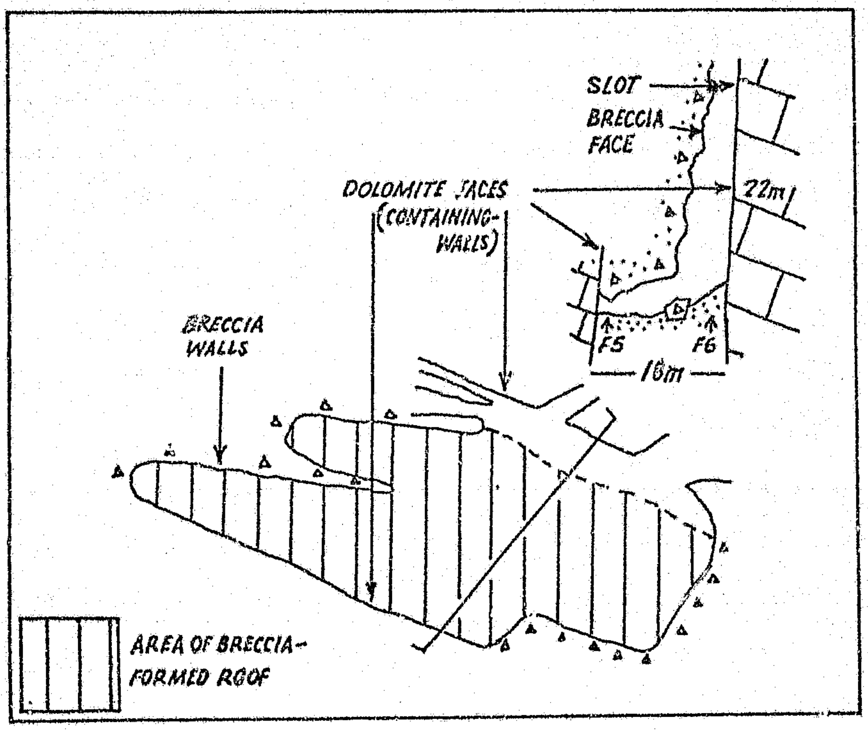

Fig. 6.9 Plan of Terror Chamber showing area of breccia-formed roof and position of vertical dolomite containing walls

The entire Terror Chamber (60m by 18m) has developed as a collapse void within the deposit mass which straddles fracture zones 4 and 5, and the area between. Fracture zones 2 and 3 intersect 4 and 5 in the centre part of the chamber (Fig. 5.1). Since dolomite bedrock is absent in the intersection area, it may be assumed that fracture zone cavities widened by phreatic erosion and finally coalesced to form a large chimney-like cavern. The dolomite walls of this cavern are visible on the north and south sides of the Terror Chamber (Fig. 6.9).

Generally a low (4m) collapse void, the Terror Chamber ascends vertically 22m in the form of a narrow slot in the vicinity of the north wall. The slot gives some indication of the vertical extent of the original chimney-like void. The sheer dolomite face of the north wall forms one side of the slot and the cemented deposit mass forms the other (cross-section, Fig. 6.9). The deposit may be regarded therefore as the filling of a large vertical void centred on the intersection of four fracture zones.

If the Terror Deposit once filled the large vertical void as suggested, then the existence of the abovementioned slot - between the containing bedrock wall (north wall of the Terror Chamber) and the deposit - needs to be explained, since the deposit presumably accummulated against this wall.

The likeliest explanation is that aggressive meteoric water percolated through the deposit mass causing decalcification of the breccia along the bedrock-breccia contact. The breccia was gradually removed leaving a large unsupported breccia wall from which many blocks have collapsed. The decalcified debris was deposited in the Terror Chamber beneath the slot.

A shallow shaft, which connects the top of the dolomite wall to the Exit Area, probably guided the aggressive water from the surface.

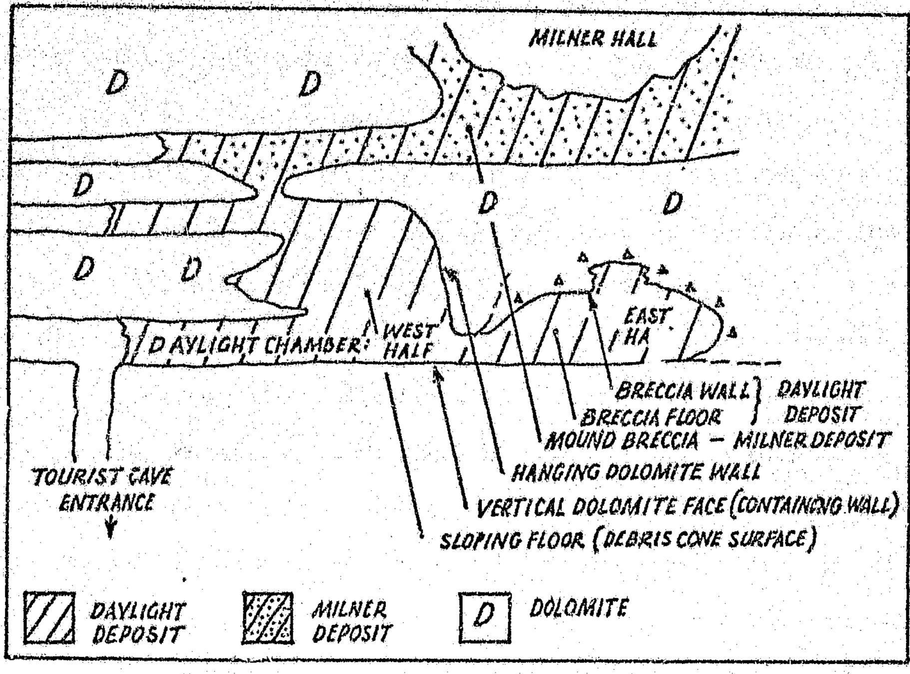

Fig. 6.10 Plan of Daylight Deposit and part of Mound breccia (Milner deposit)

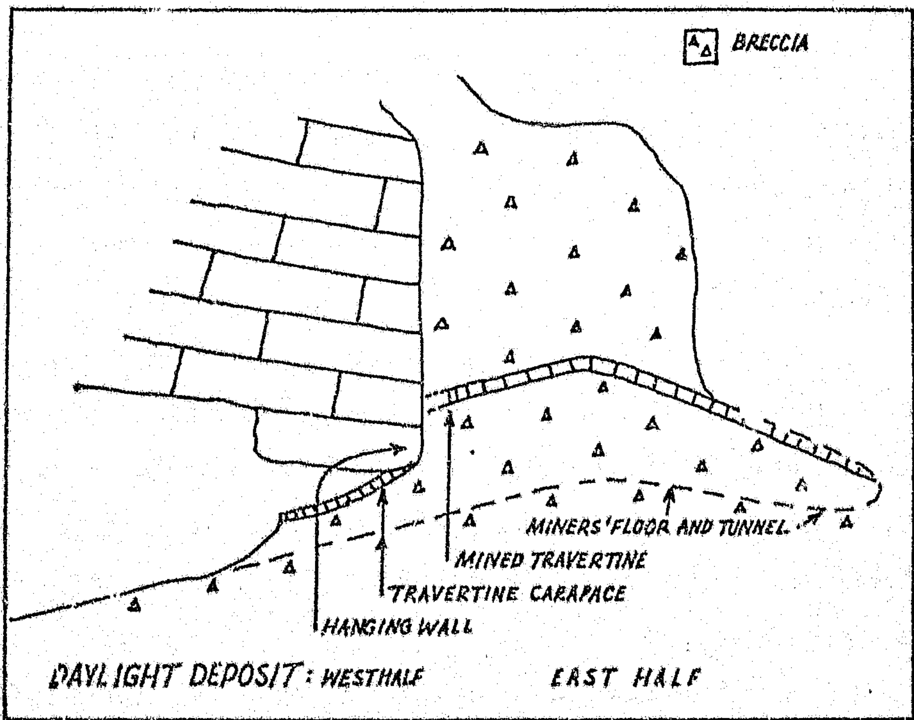

Fig. 6.11 East-west section through Daylight Deposit

A similar situation exists in the Daylight Chamber where the Daylight Deposit beneath Entrance 3 has been eroded away from the vertical dolomite containing wall to form a slot with opposing dolomite and breccia faces.

The influence of hanging walls on this deposit is not evident. This is understandable since the deposit is a slot filling and not a debris cone. Nevertheless an influx of younger material debouches into the west end of the Terror Chamber in the form of a small (2m high) breccia cone capped with a travertine carapace. The breccia roof of the Chamber, acting as the controlling hanging wall, has limited the amount of material entering the Chamber.

It is difficult to ascertain the form and composition of the Terror Deposit since the ceiling of the Terror Chamber is covered by a thin flowstone. However, some small pockets of bone, and a recurring pink sandy matrix have been encountered along the walls and at points on the ceiling. Few large block inclusions occur and the cementing of the deposit appears to be spasmodic: uncemented pockets of red earth are visible in places. The lack of uniform cementing helps explain why the deposit has collapsed over such a large area.

(4) Daylight Deposit

This deposit, mainly a breccia, forms the floor and part of the north wall of the Daylight Chamber (Fig. 6.10). The effect of a hanging dolomite wall is strikingly demonstrated in the formation of this deposit: the west half of the Chamber has a low roof of dolomite, and a sloping floor of travertine overlying a breccia cone (Fig. 6.11). The east half however, is a slot with a high roof (15m); the vertical north wall (a partially mined face) of this half is formed of breccia, and the vertical south wall of weathered dolomite bedrock (Fig. 6.10).

The dolomite buttress separating the west half from the east half has limited the amount of debris flowing into the western half of the Chamber.

The breccia mass in the eastern half may have been even larger than it is today. As in the case of the Terror Deposit, it seems very likely that breccia originally filled the slot (eastern half) completely, resting against the present-day dolomite wall on the south side of the Chamber. It seems that the breccia was removed from the southern side of the Chamber by aggressive rain water entering on this side of the Chamber from the apertures above (Entrance 3).

The morphology of this breccia indicates a stage of development prior to the influx of a younger debris mass (Fig. 6.3e).

The breccias consist of a fine sand with very few stone inclusions. At the back of the excavation, against the dolomite wall, small collapse blocks of dolomite can be seen. A mined flowstone, decalcified pockets and fossiliferous layers can be seen in this breccia. The flowstone and underlying breccias form the apex of a cone, visible in the mined face, which indicates that the debris inlet was in this vicinity during the time of accumulation, that is, near to or at the present-day aperture in the Daylight Chamber roof (Entrance 3).

The Daylight Deposit occupies a lineament (Fig. 5.1) and lies directly above part of the Terror Deposit (see 8.2.1 below).

(5) Large Exit Deposit

In the Exit Chamber a large mass of breccia lies along the eastern wall (Fig. 5.1). In form this deposit is similar to the 'Mound' debris cone (Milner Deposit): a talus slope, consisting of a hard pinkish breccia slopes down from the roof of the Chamber. It is covered by a travertine carapace, mined in places and has been heavily attacked on its underside by phreatic solution. Issuing out from beneath the phreatically eroded undersurface is a newer unconsolidated talus slope which appears

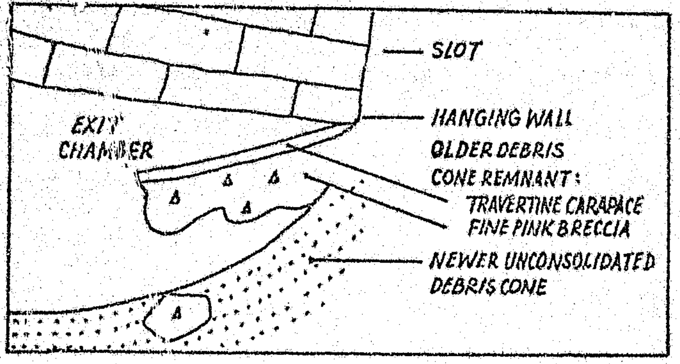

Fig. 6.12 Section through large Exit Deposit

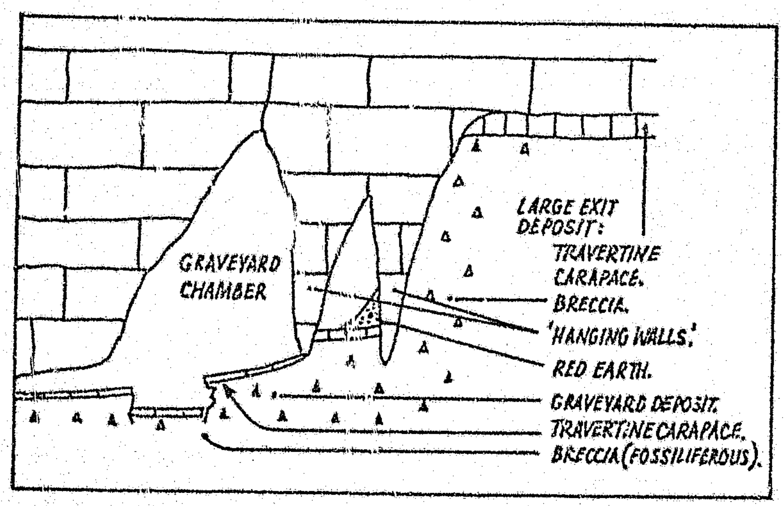

Fig. 6.13 Section through Graveyard Deposit

to have entered the chamber by a similar route to that by which the breccia debris originally entered (Fig. 6.12).

The influence of a hanging dolomite wall is presumed, since the travertine carapace issues from the highest parts of the chamber against the dolomite roof.

(6) Small Exit Deposit

Lying on the south-west side of the Exit Chamber, this deposit is in the form of a debris cone with a very thick (3m) travertine carapace, which has been largely destroyed. Like the large Exit Deposit its upper surface rises to the chamber roof, suggesting that it too entered as an influx from the hillsurface via an aven or slot. As in (5) it is presumed that the lower end of the slot acted as a hanging wall preventing the ingress of further hill talus. However, unlike the large Exit Deposit, the small Exit Deposit appears to be totally unaffected in any way by phreatic attack.

This Deposit consists of numerous small dolomite blocks (5 - 10cm^3) embedded in a red sandy matrix, apparently externally derived. It lies directly beneath the east end of the Exit Area on fracture zone No. 5 (Fig. 5.1).

(7) Graveyard Deposit

Along the southern, western and eastern walls of the Graveyard Chamber, near floor level, lies a relatively small breccia body. Covered with a thin travertine carapace, this breccia body has collapsed downwards a short distance in the middle of the chamber, an example of the kind of breccia cone disintegration envisaged in the model (Fig. 6.3e). The slope of this breccia cone is shallow and lessens across the room (Fig. 6.13) suggesting the deposition of a wet rather than a dry debris. The breccia is pink with a bone-rich layer and few coarse inclusions.

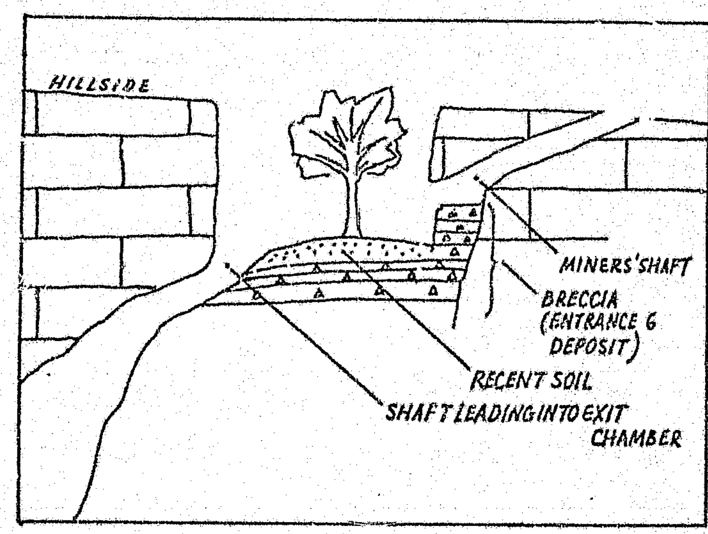

Fig. 6.14 Section through Entrance 6 Deposit

Hanging dolomite walls appear to have prevented the total inundation and filling of this chamber by debris. However, small cones of fine red earth are deposited on the carapace surface in the innermost parts of the Graveyard Chamber, near the apex of the breccia cone (Fig. 6.13). This is the only record of a new unconsolidated deposit overlying a travertine carapace, most newer deposits accumulating beneath a carapaced breccia body. The occurrence of these small cones of red earth presumably indicates that new points of entry for external material have developed since the deposition of the breccia cone.

(8) 'Entrance 6' Deposit

Entrance 6 is a pit 16m in diameter and 9m deep, from the side of which a lime miners' shaft slants down into the cave system (Fig. 6.14) in the vicinity of the Graveyard Chamber entrance (point V, Fig. 5.1). The pit contains partly collapsed breccias overlain by recent soil. The breccia, which consists of a coarse sand matrix with few large fragments, is crudely laminated, suggesting deposition in water.

The Entrance 6 Deposit lies on one of the major fracture zones directly above parts of both the large Exit Deposit and the Graveyard Deposit (Fig. 5.1).

(9) Elephant Deposit

The debris masses grouped in this section do not all have the same source area; they have been grouped together because of their similarity and proximity to one another (Fig. 5.1) in the southern recesses of Elephant Chamber.

The Elephant Deposit consists of small bodies of breccia attached to the walls of the Elephant Chamber, as well as large unconsolidated deposits covering the floor and truncating all the passages leading off south and west from the main Elephant Chamber (Fig. 5.1, points 1 - 5).

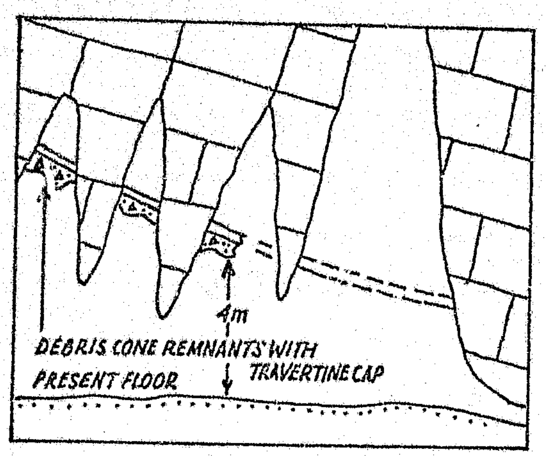

Fig. 6.15 North-south section through Elephant Chamber showing deposit remnants and original debris Mound

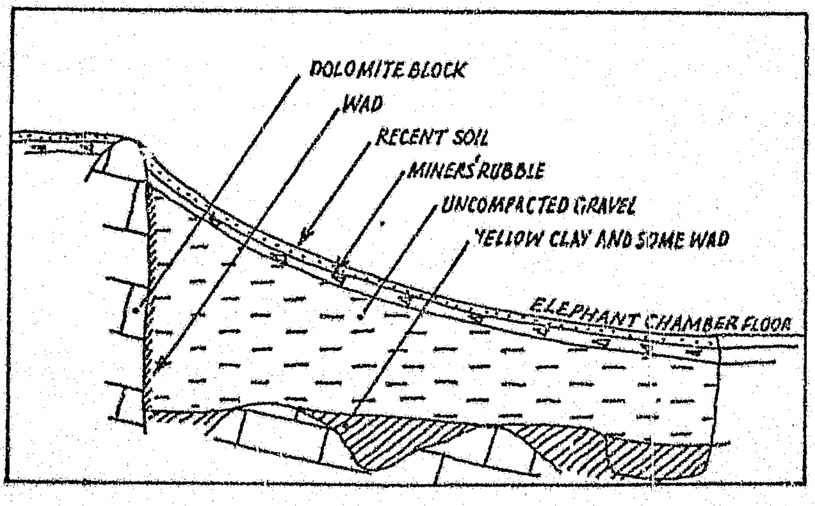

Fig. 6.16 Trench in Elephant Chamber floor deposits

The breccias are small stony agregates, often with a travertine capping, attached in many places to the maze of partitions on the south side of Elephant Chamber. They occur from 4m above the present floor, at increasing heights towards the blocked passages in the south. They seem to be remnants of a large talus slope which must have stretched once to the other side of the chamber (Fig. 6.15). These remnants represent the most extreme example of breccia cone destruction in Sterkfontein.

The unconsolidated material of the Elephant Chamber floor and southern passages is apparently derived mainly from passages 1 and 4 (Fig. 5.1), and also from apertures in the roof of the Chamber (Entrance 1 Cluster - Fig. 5.1). Passages 1 and 4 are truncated by steeply rising slopes of hill talus and red soil. Passages 2, 3 and 5 are truncated by large boulders of dolomite and breccia. Except for those in passages 1 and 4, the deposits are not obviously related to particular lineament zones.

The floor deposit presumably consists partly of the material derived from the now-vanished breccia mound mentioned above. However, such material would be very difficult to recognise in a decalcified and possibly disturbed state. Also, the deposits exposed in an excavation in the floor can all be ascribed to the newer debris phase (derived from the southern passages and roof apertures). The bulk of the deposit appears to be a gravel leached of fines by drip and rain-water which must constantly wash over the present floor.[4]

The fines have been washed to the lower levels and form a yellowish mud (Fig. 6.16) mixed with a black wad residue.

The trench dug in the floor deposits (point H, Fig. 5.1) revealed

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[4]The deposit is reminiscent of leached alluvial fan gravel encountered in a road cutting in the dolomite area of the Hennops River valley 20km north eastwards.

that a surface layer of recent soil overlies calcite chips (miners' rubble). The calcite chips in turn overlie the uncompacted gravel.

(10) Fault Cave Deposit

The innermost passage of the Fault Cave (D-E, Fig. 5.1) is a collapse cavity, usually less than 5m high, developed within a large continuous body of breccia in origin similar to the Terror Chamber. Influxes of newer unconsolidated red sand which have entered through a high, narrow, vertical shaft, have blocked the furthest end of the passage (E, Fig. 5.1). The breccia and the sand together form the Fault Cave Deposit.

The breccia consists of small angular chert and dolomite blocks in a matrix of fine yellow-orange sand. The breccia forming the roof of the passage has been extensively redissolved indicating a rise in ground water levels in this low lying cave (60m below datum).

The morphological characteristics outlined in the cone development model are not fully developed, apparently because the breccia is a slot-filling, much like the Terror Deposit. However, certain characteristics are recognisable: a breccia body has suffered destruction in the lower levels by solutional attack of ground water, and consequent collapse. A certain amount of later unconsolidated hillside debris has subsequently entered.

Since dolomite bedrock is not visible at any point in the passage or on the hillsurface (due to a thick soil cover) fracture zone explanations of the location of the passage and deposits, be they fracture zone or otherwise, are conjectural.

This concludes the description of the cemented and unconsolidated deposits. It should be noted once more that the 'clay fill' which Bretz (1942) found so ubiquitous in American caves is not conspicuous, even if it exists at all in Sterkfontein cave.

The calcareous deposits give evidence for past water level fluctuations, and some information concerning the date of deposition. The non-calcareous deposits are among the main determinants of the internal cave morphology. A model of debris cone development was presented, and the mode of development of each debris body examined in terms of it. Further, the location of each deposit body was related to the cave system revealing that debris influxes (except in Fault Cave) occupy only the large fracture zone chambers, south of the morphological line dividing the northern passages from the large southern chambers. The relationship of the deposits one to another, is discussed later.

PART III

DISCUSSION

CHAPTER 7 - THE CONTROLS OF LOCATION AND FORM OF THE CAVE SYSTEM

7.0 The theories of cave development to be considered with respect to the Sterkfontein Cave system may be summarised as follows: the two-cycle theory of Davis (1930), and its modified version (Bretz, 1942) which includes an intermediate cycle of clay filling; the theories which postulate watertable control of the system (Brain, 1958; Brink and Partridge, 1965; Marker and Moon, 1969) and D.C. Ford's general theory which postulates three common cave-types, the vadose, deep phreatic and water table types (Ford, 1971); Bogli's theory of solution by mixing of karst waters (Bogli, 1971); the theories pertaining to structural control as the dominant and overriding control of the location and form of the system (King, 1950; Moon, 1972; and Waltham, 1971).

7.1 Location of the System

7.1.1 Areal Location

In a valley-wide perspective, Moon (1972) has shown that most of the caves in the Blaauwbank valley are aligned in an east-west direction. Furthermore he has demonstrated that the caves are directly controlled by compressional east-west trending fractures. Sterkfontein itself follows this pattern closely. As has been demonstrated earlier, the system has been controlled dominantly by fracture zones which trend approximately east-west. Cooke (1938) and King (1951) have both claimed this kind of structural control of the cave system, and this detailed study thus supports these earlier theories.

Although tensional fractures also occur in the dolomite of the

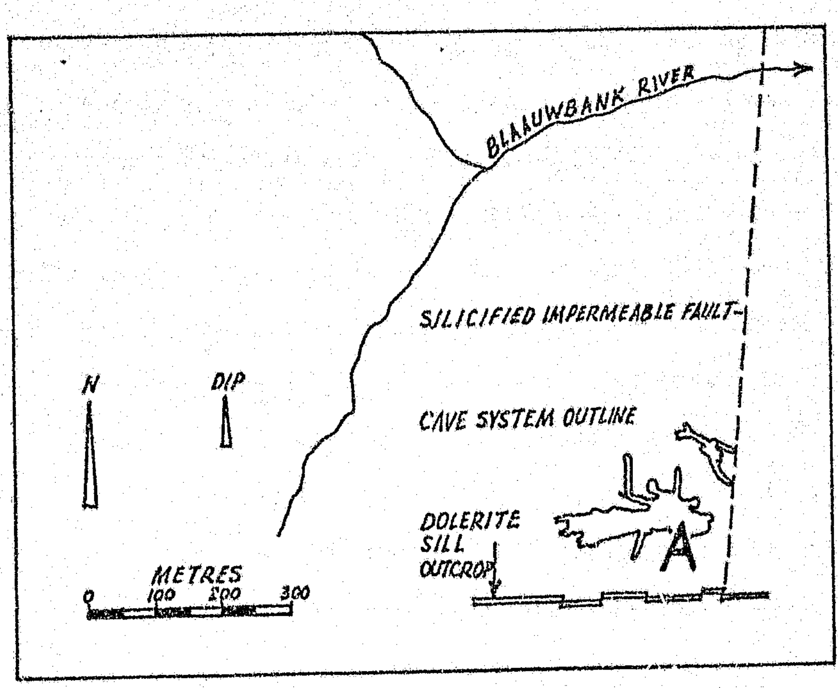

Fig. 7.1 Geological map showing structural determinants of cave system location

Sterkfontein hillock (Moon, 1972), these are aligned north-south and have not exerted any control on the overall position of the system; the reason for this seems due to the fact that there are fewer north-south fractures. From observation underground it is apparent that the north-south fractures are unlike the east-west fractures which consist of zones of fracture rather than single lines of weakness. The north-south fractures have not had an overriding control over any part of the cave system.

The question arises as to why a particular set of intersecting fracture zones favoured the development of this cave system. Two geological factors provide some explanation.

(i) The fault bounding the cave system on the eastward or downstream side. It was mentioned above that 'a possibly silicified fault' (Brink and Partridge, 1968) bounds the system on the east, running north-south and intersecting the river bed to the north. If this fault indeed acts as an impermeable barrier, damming up ground water in the dolomite to the west, it may explain the location of a cave system within this saturated dolomite (A, Fig. 7.1).

(ii) The underlying dolerite sill. The dolerite sill which underlies the cave system outcrops a short distance to the south of it, and it too may have acted to concentrate the ground water in the angle between the sill and the abovementioned fault which it intersects (A, Fig. 7.1). It may be argued that ground water is more likely to collect on the southern side of this sill, since the greater area of dolomite occurs on its southern side (the large area stretching ± 3km southwards to the Witwatersrand hills). However, a borehole sunk into the dolomite on the south side of the sill was dry at a depth of 97m. below datum, i.e. 37m below the lowest water body in the cave system. This suggests that the sill is either not acting as a dam for ground water from the south, or that the ground water to the south is very much lower than that in Sterkfontein, and thus part of a completely disconnected and separate hydrologic system. It is also possible that the borehole simply did not strike any cavities containing water, however.

7.1.2 <u>Altitudinal Location</u>

In the vertical plane, the location of the cave may well be related to the fact that the hilltop dolomite contains numerous bands and layers of chert. It cannot be said conclusively that the <u>greatest</u> concentration of chert occurs in the hilltop dolomite strata, but this appears likely.

The effect of a concentration of chert layers in the dolomite strata of the hilltop is twofold:

(i) Ground water flow would be concentrated on the underside of the chertz strata, leading to cave development (Waltham, 1971; see also 7.2.4 (1) below: Origin of Fossil Cave), and

(ii) The chert bands, being relatively resistant under local conditions would reduce the rate of hill summit lowering by surface weathering.

The first of the abovementioned effects may thus explain the altitudinal location of the cavern voids beneath the hilltop, and the second helps explain why the caves are preserved at the present levels.

The possible effects of water-table control are discussed below (7.2.2).

7.2 <u>Form of the System</u>

7.2.1 <u>Phreatic Origin and Vadose Modification</u>

The morphology of the cave system is a result of phreatic erosion. Features found at all levels in the cave system, and described in detail above, are predominantly of phreatic origin. In that the system has now been largely drained of water, Davis' two-cycle theory applies in a general way (Davis, 1930), although many parts of the system have been submerged deep in the phreas more than once. With the exception of one small passage in the Fault Cave, the system has not suffered any modification by vadose stream action. This contrasts with Bretz's finding that caves in the U.S.A. are usually modified by vadose stream action (only 44 out of 107 caves studied were purely phreatic in origin - Bretz, 1942).

Recent work suggests that caves in the Transvaal are generally purely phreatic in origin (Brain, 1958; Marker, 1971). Although the lack of vadose modification of Sterkfontein may be due to its location beneath a small hill, distant from local drainage lines, this alone is not an adequate explanation.

Bretz (1942) has shown amply that underground drainage patterns can be radically different from surface patterns in terms of direction of flow, watershed positions and volume of flow. Lack of surface water generally, the badly integrated nature of the groundwater system (7.2.3 (1) below), and the steeply dipping attitude of the rocks, have probably all contributed to the lack of vadose modification at Sterkfontein.

7.2.2 Deep Phreatic Development, and Water Table Control

(1) Deep Phreatic Development

In his recent formulation of cave development theories, Ford (1971) postulates that deep phreatic caves, as a common cave type, develop optimally in steeply dipping rocks where the resurgences are downdip. Characteristic of this type are bedding-controlled passages ('dip-tubes') descending through a vertical distance of at least 8m. (Ford, 1971). In Sterkfontein the passages north of the main fracture-zone galleries are controlled by various beds in the dolomite (4.2 above). Many of these descend continuously through large vertical distances (50m in Lincoln's Cave). If these northern passages are regarded as 'dip-tubes', as indeed it seems they must be, then they indicate that Sterkfontein is to be

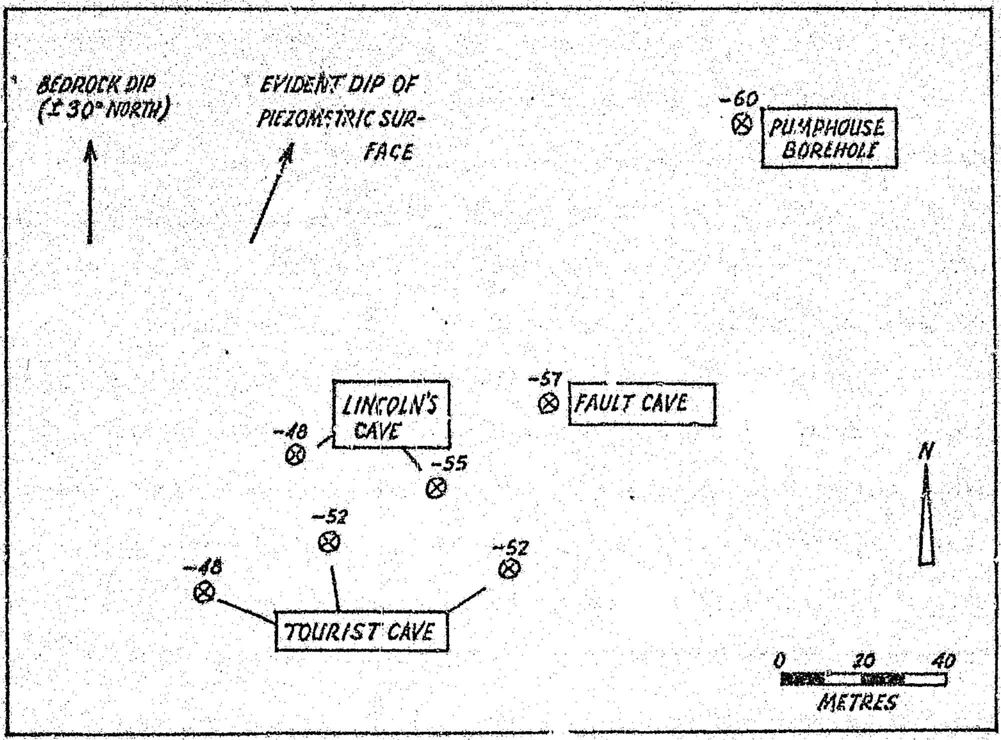

Fig. 7.2 Sterkfontein water [illegible] [illegible]ve positions and surface levels [illegible] [illegible]tum)

classed as a deep phreatic cave.

Another characteristic of the deep phreatic caves is the 'joint-lift tube' (in conditions where the rock dip is steeper than the hydraulic gradient - Ford, 1971). At Sterkfontein the dolomite dips at 30° and the hydraulic gradient averages 6½° downdip (Fig. 7.2). Ground-water must therefore gain stratigraphic height to reach resurgence level (Blaauwbank River streambed). Joint-lift tubes might therefore have been expected in Sterkfontein in terms of Ford's theory.

However, there are no examples of such tubes, probably because so little of the system is wholly bedding controlled; the fracture zones control the major part of the system, and Ford's formulation would obviously not apply under such special local circumstances. Nevertheless, the bedding controlled cavities which do exist suggest the deep phreatic cave pattern of Ford's theory, rather than the water-table cave type.

(2) Water-Table Control

Certain features of the cave system indeed suggest a water-table origin for Sterkfontein. Evidence cited by earlier workers in support of this theory will be discussed.

It has been argued above that the passages north of the large fracture zone galleries do not indicate water table control because they occupy specific strata continuously through a vertical distance of up to 50m. Ford (1971) has said: 'Discussion of a water-table control is irrelevant where the amplitude of the phreatic loop[1] was greater than c.25 ft.'

This opinion is accepted for Sterkfontein where the bedding controlled passages indicate phreatic loops of at least 50m.

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[1] 'Phreatic loop' is Ford's term for a composite feature made up of a joint-lift tube and a dip tube.

However, the question of the morphology of the main galleries remains: the floors of these galleries are approximately horizontal, and those of the two largest galleries are at accordant levels. These two facts, in addition to the size and altitude of the Fossil Cave 50m above the other gallery floors, have persuaded earlier workers that Sterkfontein developed at two distinct water levels, and hence was related to the erosion surfaces in the area (Brink and Partridge, 1965). Although the cave system may be related to regional water levels and the associated erosion surfaces, there is doubt whether the features previously regarded as indicative of water-table control should in fact be regarded as such. For instance, it appears that the Fossil Cave does not in fact have a dolomite bedrock 'floor' separating it from the underground chambers. The existence of such a floor would suggest that water-table controlled cavities had developed above and below it. It is argued below (7.2.4 (2)) that the Fossil Cave simply consists of the upper part of a widened fracture zone of great vertical extent. This widened fracture zone becomes the Tourist Cave at lower levels, and it may well extend far below the present floor level of the Tourist Cave. Similarly it may well have extended above the level of the Fossil Cave. It seems therefore, that discussion of cave development at two distinct levels (Fossil Cave and Tourist Cave levels) cannot be supported.

The present floor levels in the large galleries, as well as gallery-widening near these floors have been taken in the past to represent a level of water-table erosion. However, the present floor levels may not truly represent the lowest parts of the void eroded in the dolomite: the floor material may be many metres thick, especially in view of the opinion that the dominant control of cave development is the erosionally widened fracture. Thus present floor levels may simply reflect the amount of infilling by surface materials of underground cavities.

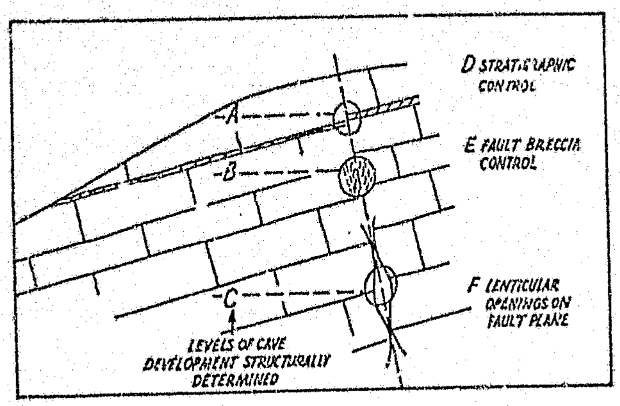

Fig. 7.3 Speleogenesis at any one of several levels (A, B, C) on a fracture zone, controlled by various factors (D,E,F)

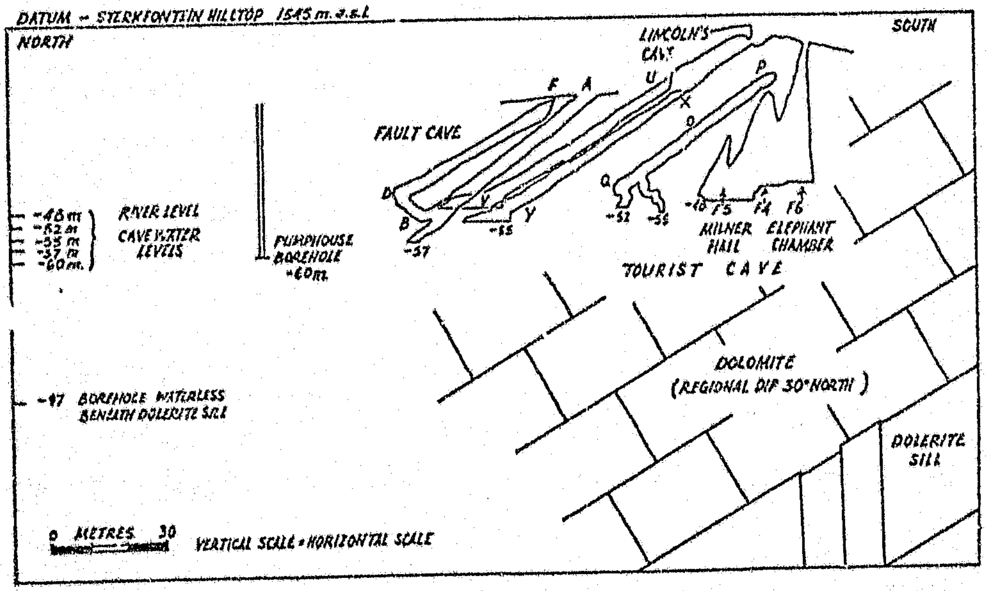

Fig. 7.4 North-south section through Sterkfontein hill showing that water levels descend towards the river (northwards)

This insoluble fill-material may have protected the dolomite beneath it from solutional attack while directing erosion against the cavern walls, thus causing the caverns to widen laterally The insoluble fill-material may well have caused water bodies in the caverns to be perched above the level of the general piezometric surface in the local area.

Overall it appears that the evidence for water-table control in the underground caverns is not convincing. Such possibly indicative features as do occur (floor levels and cavity widening at floor level) can be ascribed as easily to the effect of floor deposits, as to regional water levels.

Waltham (1971) has shown that cave development may be initiated along a fracture line at any level where impermeable bands, fault breccias, or 'lenticular openings on non-planar faults' occur (Fig. 7.3). Such structural factors may also be responsible for the development at a particular level of the main gallery floors and for the lateral widening of galleries at approximately floor level which exist in the Sterkfontein system.

7.2 3 Characteristics of the Water Levels in the Cave System

(1) Gradients

It has been shown that the water levels in the caves vary by as much as 10m (Lincoln's Cave and the Lake: 48m below datum; Fault Cave 58m below datum. See Figs. 7.4 and 7.2). Brink and Partridge (1965) have postulated that water-tables within the Transvaal dolomites are uneven during phases of river incision. The Blaauwbank River is at present incising its valley into the African planation surface (of which the Sterkfontein hillock is believed to be a depressed remnant); the uneveness of the water table within the caves thus appears to support the opinion of Brink and Partridge (1965).

One might even regard the water levels as indicating water-bodies virtually or totally independent on one another, if it were not for the fact that the levels descend approximately in the direction of the nearby Blaauwbank riverbed. This suggests some degree of integration in hydrologic network.

Evidence of current flow within the phreas has been presented: domelike cavities eroded upwards into the breccia of the Milner Deposit suggest a gentle phreatic current. An analysis of hydraulic gradients between the several water bodies in the Sterkfontein Caves supports this evidence of current flow. Assuming some primitive integration between the water bodies, it is evident that the maximum hydraulic gradient in the cave system is that between the two water bodies in Lincoln's Cave (Fig. 7.2). Over a distance of 45m. the gradient is 1:5 (11^{o}), which is steeper than the extreme gradients measured in the Swiss Alps by Bogli (1:10 - Bogli, 1971). It is recognised that such gradients cause strongly flowing sub-watertable currents (Bogli, 1971).

This finding supports the morphological evidence of flow in Sterkfontein, and verifies Bretz's evidence of current flow in the phreas (Bretz, 1942).

(2) That the hydrological regime in the Sterkfontein area is not altogether simple, is illustrated by the fact that the water levels in the system lie at or below the incised bed of the Blaauwbank stream.

It has been shown that the water levels in the cave system descend well below (12m) the level of the incised Blaauwbank river bed. It has also been argued that a primitively integrated system of phreatic connections seems to exist between the water bodies, and that they appear to drain towards the Blaauwbank stream.

The explanation of this situation seems to lie in the thickness of alluvial material beneath the present river bed. The stream has

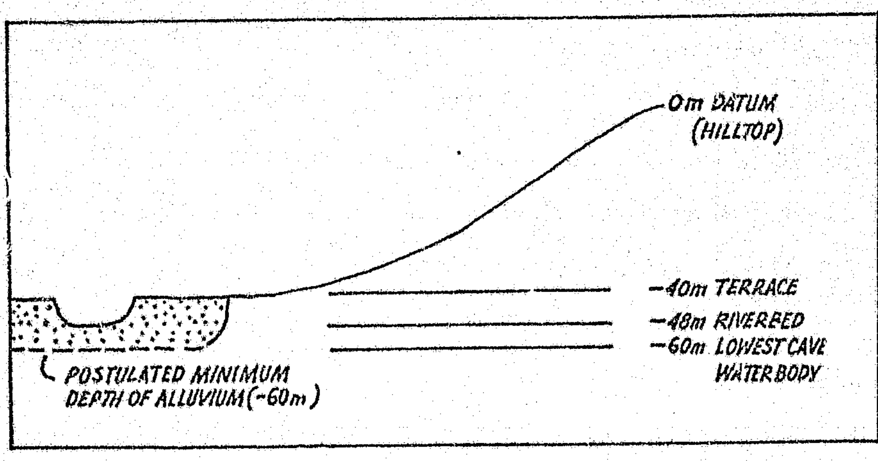

Fig. 7.5 Cave water body levels and the minimum thickness of stream bed alluvium

already incised 8m into the terrace and theoretically it should rest on another 12m at least, in order for the cave water to drain away at the alluvium-dolomite contact level (Fig. 7.5).

7.2.4 Origin of the Fossil Cave

(1) The Fossil Cave Roof

Brain (1958) invoked the collapse of a very large dolomite block to explain the origin of the Fossil Cave, quoting Sterkfontein as an example of the collapse type cavern, as opposed to the solutional type, in his general theory of cavern development in the Transvaal (Brain, 1958). Robinson (1962) agreed that the roof of the Fossil Cave was a collapse feature, but argued against the collapse of a single large block of dolomite. He regarded Brain's explanation as unlikely, and postulated that 'repeated collapses at various heights and of various degrees of magnitude' had caused an irregular roof to develop.

It is apparent from the cave plan (Fig. 5.1) that the Fossil Cave is underlain by slot-like passages. These are developed in dolomite bedrock. With Robinson (1962) therefore, it is difficult to believe that the Fossil Cave was formed by the collapse of one exceedingly large dolomite block, as Brain postulated (Brain, 1958).

As stated, Robinson (1962) attributes the Fossil Cave roof to repeated small collapses. He bases his views on these facts: firstly that the few visible portions of the Fossil Cave roof (especially on the west wall of the Type Site) are planar features dipping with the bedrock dip; secondly that 'numerous examples of collapse unc[illegible] und' exist; and thirdly that the roof of the Fossil Cave is irregular as far as can be seen.

The present writer regards these facts to be inconclusive of small scale collapse; it seems as likely that the Fossil Cave roof was a solutional feature. This opinion is supported by the fact that the

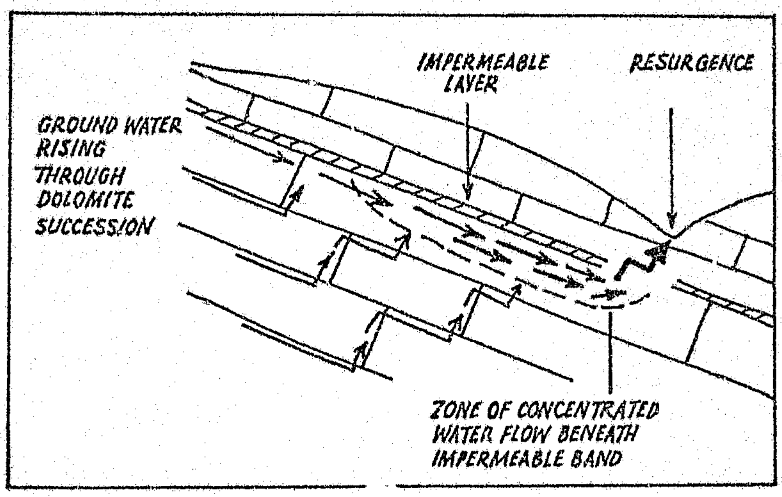

Fig. 7.6 Speleogenesis beneath an impermeable layer (after Waltham, 1971)

largest expanses of cavern ceiling in the cave system are planar features dipping with the bedrock, and developed at bedding planes within the dolomite. These large ceilings (Exit Chamber 600m^2, Lincoln's main chamber 300m^2) appear to be solutional features; they display such phreatic features as joint controlled cavities, deep and shallow, and the ceiling surface is gently undulating, unlike the flat cleavage planes which characterise collapse along bedding planes. Also, as far as can be seen, no collapse blocks lie on the floors beneath these ceilings. The north-west side of the Exit Chamber ceiling is deeply indented (3-4m) by joint-determined cavities which have been carried upwards purely by solution, thus indicating that solutional attack may also produce an 'irregular' ceiling.

It seems justified therefore, to claim that the Fossil Cave roof may also have been a solutional feature.

The mode of formation of such ceilings appears to be due to cavern formation beneath an impermeable bedrock layer due to ground water rising through the stratigraphic succession. Waltham (1971) has suggested speleogenesis of this particular kind, under a set of conditions which are fulfilled in Sterkfontein, namely that the hydraulic gradient should be less than the regional dip, that impermeable strata should exist to concentrate ground water circulation, and that the bedrock should dip towards the resurgence. In Sterkfontein the hydraulic gradient was shown to be less than 11^{o} north towards the local drainage line. The rockdip is 30^{o} north and the hydraulic gradient is therefore less, causing the groundwater to rise through the stratigraphic succession to reach resurgence level (Fig. 7.6). The ceiling of Lincoln's main chamber is a shale band, which appears to have concentrated the rising ground waters beneath it, to form the cavern and the related planar roof feature.

Shale bands are also known in the region of the Fossil Cave roof (Brink and Partridge, 1968). It may be concluded that the Fossil Cave may have developed as a solution feature, i.e. phreatically, just as the other major features of the cave system developed. Very little of the character of the Fossil Cave roof is known, and either the collapse or the solutional theories of development may prove true. It is important to realise however, that planar roofs dipping with the bedrock do not necessarily indicate collapse, as has been claimed in the past.

(2) The Fossil Cave Floor

Brain (1958) considered that the floor of the Fossil Cave would necessarily be the upper side of the collapse block which he hypothesised had collapsed into the underground caves, leaving a large cavity, the Fossil Cave, above it. Robinson (1962) showed that the existence of a collapse block of this size was highly unlikely. Also, it was mentioned above (1) that a series of passages exist underground, developed in bedrock, within the void supposedly occupied by the large collapse block. It is apparent that any floor which may have existed was not the upper side of a large collapse block.

Robinson nevertheless regarded the Fossil Cave as having a floor at approximately the level of the Milner Deposit cone carapace peak i.e. at a level of $\pm$ 30m below datum (Robinson, 1962) (Fig. 8.7). Debris was viewed as having accumulated on this floor, a floor which subsequently collapsed into a lower tier of caverns, at the western end of the Fossil Cave.

It seems very likely, in the light of this study that the Fossil Cave did not have a bedrock floor at all, but that its floor was in effect the floor of the present-day underground caverns, another 16-20m lower. The reasons for this proposal are as follows:

(i) The south wall of the Daylight Chamber is a vertical, almost smooth dolomite face, without ledges or protuberances of more than a few

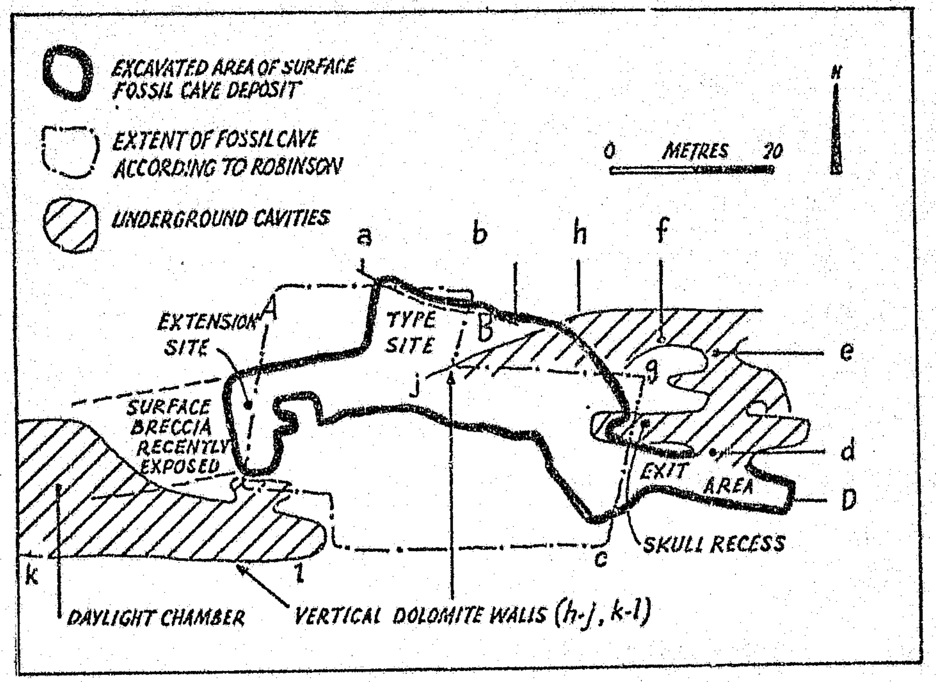

Fig. 7.7 Plan of Fossil Cave excavation with relative positions of underground caverns (see text for explanation)

centimetres. This is true of the entire visible height of the south wall of the Daylight Chamber where it extends westwards down towards the Elephant Chamber, becoming as much as 30m high in parts. With Robinson (1962), the present writer believes that this sheer, cliff-like wall is a good example of the vertical cave development which results from phreatic attack along vertical fractures in dolomite bedrock.

Since this south wall is aligned along a major fracture zone it is reasonable to suppose that it continues eastward, towards point 'C' (Fig. 7.7) as a sheer dolomite face. As no suggestion of a floor can be seen to the west, it seems improbable that a floor exists eastwards of the Daylight Chamber as a support for the Fossil Deposit, (it is argued below (3) that the south wall of the Daylight Chamber is in fact also the south wall of the Fossil Cave) as Robinson's model suggests.

(ii) From the Exit Area a subvertical shaft descends directly (d-e-f, Fig. 7.7) into the low-lying Terror Chamber with no evidence of a bedrock floor at ± 30m below datum, as required by Robinson (1962), to impede the influx of surface debris.

(3) North and South Walls

Bearing in mind that Robinson (1962) envisaged the Fossil Cave with a floor at a comparatively shallow level, his reconstruction of the north and south walls appears true, i.e. a small portion only of the north wall is visible (a-b, Fig. 7.7) because of the existence of much of the original cave roof (areas A and B, Fig. 7.7). At lower levels it is difficult to predict much of the nature of the north wall, although it appears to follow fracture zone No. 4 (Fig. 8.2).

Robinson's surface observations of the position of the south wall tie in closely with the position inferred from the Daylight Chamber (C, Fig. 7.7). Robinson (1962) suspected this connection which the present study verifies. It was argued above that this wall is probably a simple and constant feature for its entire length (Elephant Chamber - Daylight

Chamber - Exit Area), which acted as a sheer, high (up to 30m even at present) containing wall against which the Fossil and Daylight deposits has accumulated.

(4) East and West Walls

Robinson's argument for the existence of these two walls is tenuous. The eastern wall he placed at the eastern extremities of the present-day breccia outcrops (c-g, Fig. 7.7). As argued below (8.5), these breccias probably once filled the Exit Area completely, at least as far as D (Fig. 7.7) at the eastern end of the Exit Area, and at least to the level of the present hillside. Breccia has since been found 17m west of the line regarded by Robinson as the western extremity of the Fossil Cave (Fig. 7.7). Underground breccia bodies, apparently connected with the Fossil Deposit, are found far to the west of Robinson's 'west wall'.

But besides the fact that new breccias have been located and new interpretations of the extent of the eroded breccia bodies have arisen, the concept of sheer north-south aligned walls does not agree with the observed facts of the cave system. The nature of the caves at the east and west ends of the Fossil Deposit is that of closely spaced, east-west trending avens and slots ('partitions' at the base of the Tourist Cave entrance stairway are good examples - they lie directly beneath the 'west wall' area and are probably a close representation of the original morphology near the present surface). The actual extent of the deposit east and west is probably determined mainly by the position of the original debris influx points, and then, by hanging walls (bridges between partition walls) at different levels.

The new interpretations presented above arise from a different, and hopefully a more complete picture of the mode of development of the cave system; the major element in this picture is that of fracture zones causing strong vertical development of cave voids.

(5) Percolating Water and 'Mischungskorrosion'

It has been mentioned above that the main galleries of the cave system have developed on fracture zones, and that they taper upwards becoming mere slots in the dolomite at the highest points. Some avens actually pierce the roof of the gallery and reach the surface; others become encrusted with travertine. Brain (1958) attributed the upward tapering to percolating aggressive meteoric water acting once the water level dropped. It is also possible that the slot-like character of the roofs developed before the water level dropped, i.e. during the phreatic phase, by the action of percolating water mixing with the phreatic water, becoming aggressive thereby (Bogli, 1971), and enlarging the phreatic cavity upwards. Both processes may have been active in the past.

The effect of percolating water on the deposition and erosion of cave fillings is discussed in Chapter 8.

7.3 ssessment

The Sterkfontein cave system appears to have developed in the simplest way, by phreatic erosion of a few dominant fracture zones and bedding planes. Even the evidence of flowing phreatic water is minimal, although present day differences in water level (supporting the idea of a piezometric surface in the Transvaal dolomites) indicate that water bodies are crudely connected and therefore also that current flow probably existed.

In that the caves are now mainly filled with air, the cave system fits Davis' two-cycle theory of cavern development (Davis, 1930). But the caves have not suffered vadose erosion, except in one small passage, and in this respect they do not conform to Davis' or Bretz's theories (Davis, 1930; Bretz, 1942). Sterkfontein conforms best to Ford's recent description of a deep phreatic cave, which he views as different from vadose and water-table caves (Ford, 1971); there is little vadose evidence and none of water-table control in Sterkfontein, although the latter has often been invoked by previous workers. Hence there is no evidence of erosion-surface control.

Water levels in the caves all lie below the external drainage level (Blaauwbank River bed). Since the levels indicate an integrated system of water bodies, it appears that the water outlet must lie beneath a thick layer of alluvium in the river bed, and escape as underflow at the bedrock/alluvium contact. It has been computed that the alluvium must be at least 20m thick, if this explanation of water levels is true. Sweeting (pers. comm.) has called South African karst 'a soil covered karst', and thick allogenic alluvial beds with surface and ground water behaving at least partially independently may prove to be a common characteristic of 'soil-covered karst'.

The formation of cave voids by means of collapse has been strongly advocated for Sterkfontein by Brain (1958) and Robinson (1962). However, little evidence of this kind of cavern formation has been encountered. Strong vertical development of narrow fracture cavities can explain the observed features at Sterkfontein: broad expanses of roof, which are more prone to collapse, are not as common in the caves. Corrosion by the mixing of waters (Mischungskorrosion - Bogli, 1971), may have acted with percolating aggressive water (Brain, 1958), to produce the narrow aven-like galleries of Sterkfontein.

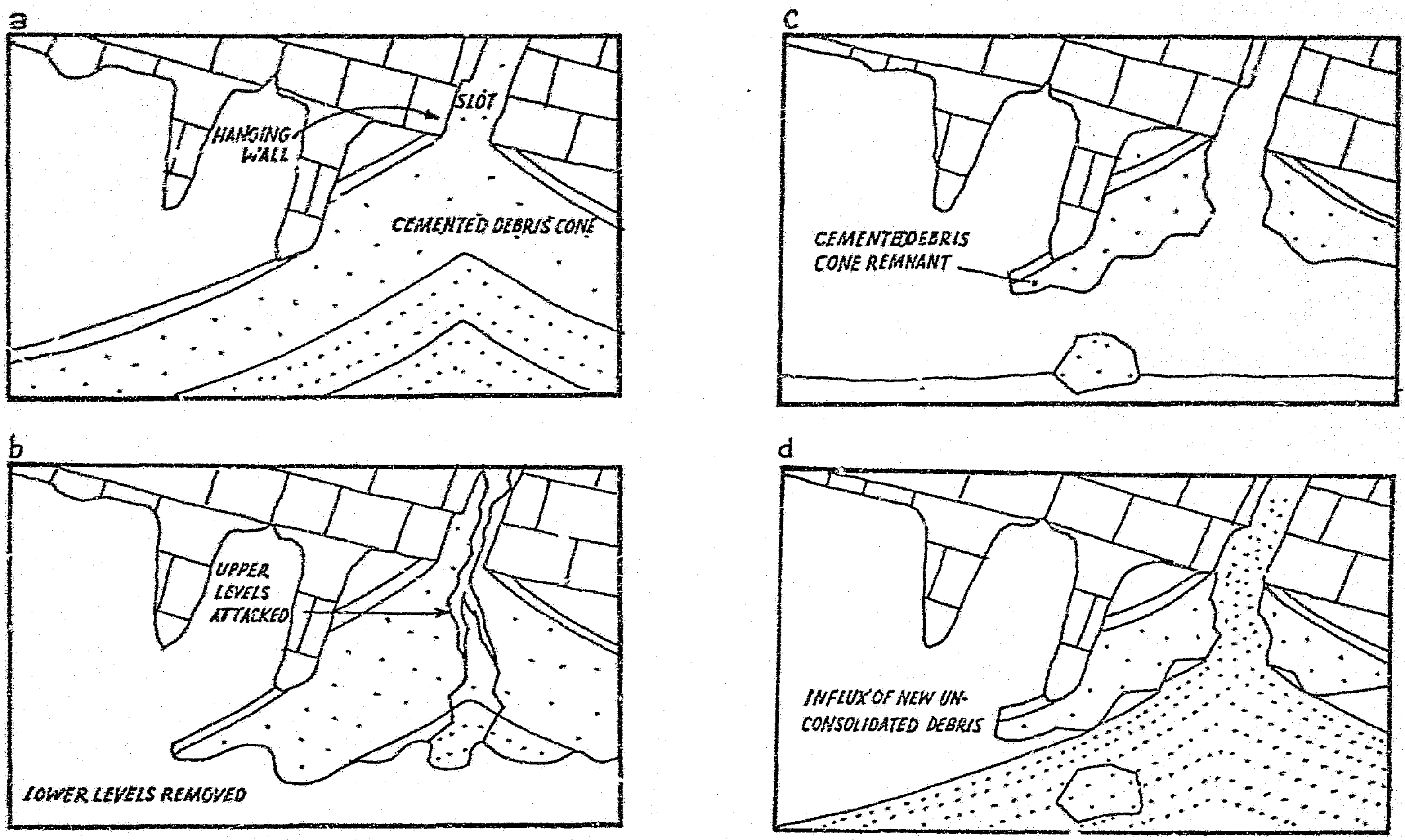

Fig. 8.1 Certain stages in the development of the major Sterkfontein deposits (from the model)

CHAPTER 8

DEVELOPMENT AND IMPLICATIONS OF THE STERKFONTEIN CAVE DEPOSITS

8.0 The deposits of Sterkfontein can be classified as calcareous and non-calcareous. The former are relatively small in volume and are generally found as part of the large non-calcareous deposits. It is these large deposits, their mode of accumulation and subsequent erosion, and a discussion of the thecries pertaining to them which are the subjects of this chapter.

The model of debris cone development presented earlier is briefly stated. Then it is discussed in relation to the various deposits in the cave system. The features of the deposits are then discussed in terms of the theories of other workers who have been concerned with cave deposits in general and the Sterkfontein deposits in particular: Bretz's (1942) theory that an epoch of clay filling intervenes between the phreatic and vadose phases; hypotheses concerning modes of deposit accumulation, past climates, and the ages of hominid and other fossils (Brain, 1958 and Robinson, 1962).

8.1 The Model of Debris Cone Development

The model, presented earlier, attempts to explain how unconsolidated deposits can be found so often at lower levels than cemented breccias in the Sterkfontein debris cones.

It has been proposed that an initial influx of surface debris accumulates in a cavern as a cone-shaped mound which grows upwards until the supply of debris is halted by an interruption such as a hanging wall (partitions which do not reach the floor of a cavern), or a protrusion from the roof of a cavern (Fig. 8.1a).

The cone is cemented by carbonate-charged percolating waters, during or after deposition. A travertine carapace usually covers the debris mound finally. Later, phreatic waters rise and attack the cemented cones by corroding the calcite cement. The waters undermine the cones and carry away or disperse the loosened debris material (Fig. 8.1b). The cone is undermined and subjected to attack by aggressive meteoric water percolating from a now-lowered hill-surface: parts of the cone collapse, eventually causing the original debris inlet route to be re-opened, and new hill-slope debris enters (Fig. 8.1c and d).

The general result is that reworked deposits and newly entered material are found beneath older cemented deposits, an inversion of stratigraphy which should be noted when interpreting cave deposits in Southern Africa where changes in past water levels are suspected.

The deposits in the cave system all follow this model to different degrees: Milner Deposit displays a very large secondary influx ('The Mound'), and Elephant Deposit was almost entirely destroyed, with very little newer material entering to fill the void. Terror and Fault Cave Deposits do not appear as cones but simply as slot fillings - there were apparently no hanging walls to interrupt the inflow of debris and thus prevent these slots from filling completely. Daylight Deposit has been attacked from beneath and above, by phreatic and percolating water. The small Exit Deposit is apparently much younger than the large Exit Deposit, since the latter has been attacked by phreatic water, whereas the former shows no sign of attack, and both lie in the same chamber.

8.2 Debris Penetration of the System

Hillslope debris has penetrated to the lowest parts of the cave system. In this section of the Discussion some attempt is made to give an account of some of the various routes by which the debris has entered; it also attempts to establish the connections between the deposits, since

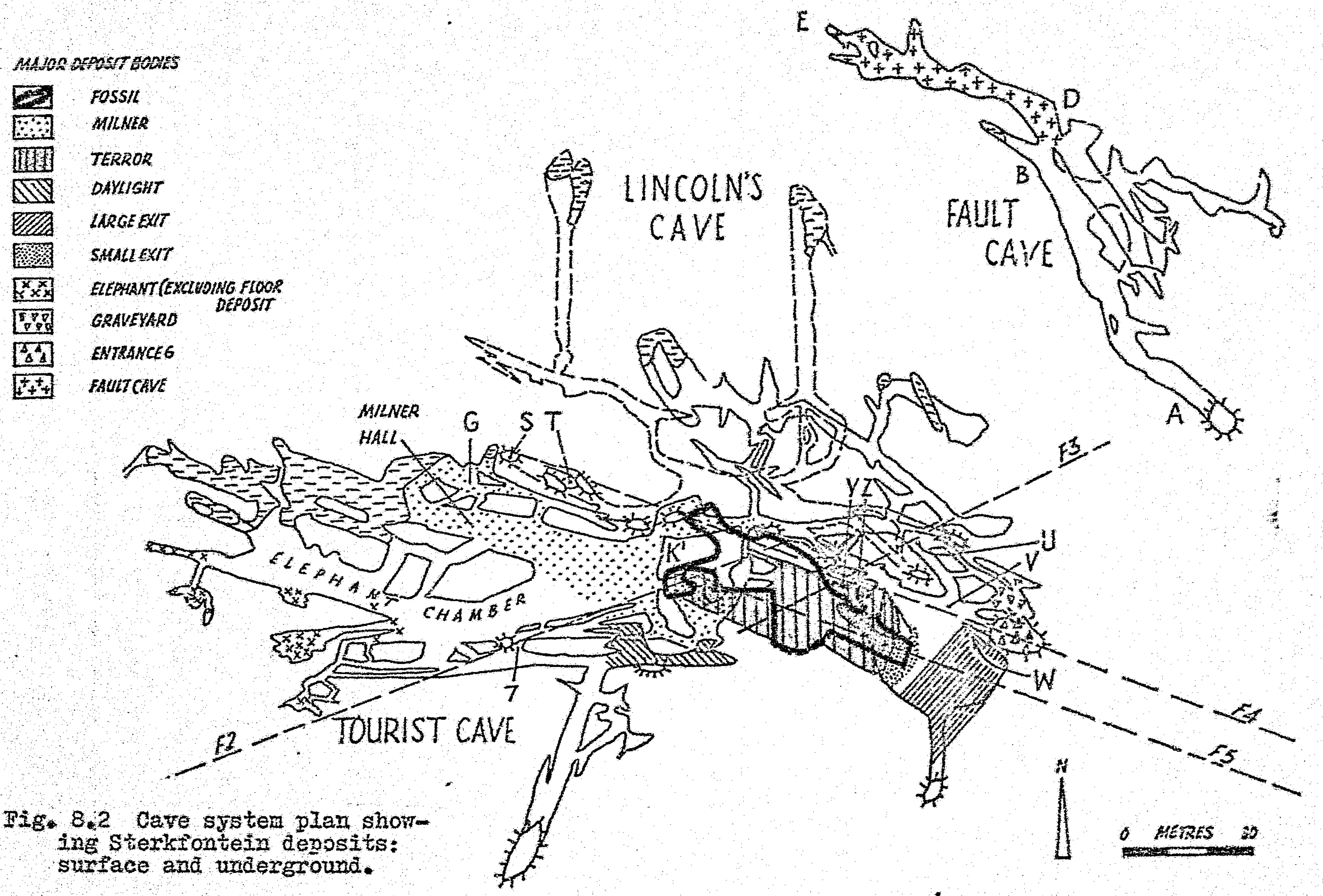

Fig. 8.2 Cave system plan showing Sterkfontein deposits: surface and underground.

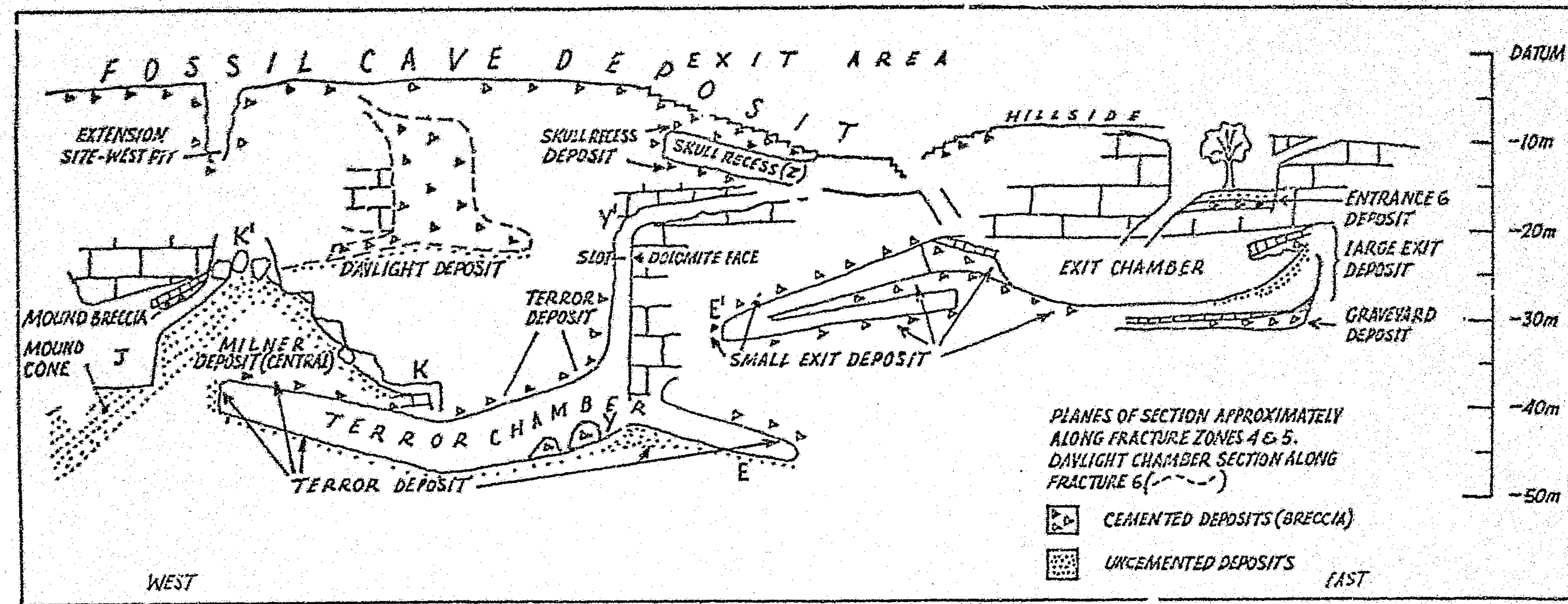

Fig. 8.3 Superimposed east-west sections through the Sterkfontein hill showing the altitudinal relationship of various deposit masses (see text for explanation)

many seem to be related, and thus to make some proposals about the relative ages of the deposits and their effect on the morphology of the cave system. All the main deposits will be discussed except Elephant Deposit and the Fault Cave Deposit since these lie distant from all the other debris bodies.

8.2.1 Fossil Deposit and the Daylight Deposit

The Daylight Chamber lies directly beneath the Extension Site of the Fossil Cave. The south wall of this Chamber, discussed earlier, was regarded by Robinson (1962) as the south wall of the original Fossil Cave. However, Robinson did not suggest that the Daylight Deposit might be connected with the Fossil Deposit, even though the floor, and the north and east sides of the Daylight Chamber consist of breccia.

This connection seems very likely however, since Fossil Deposit overlies the east end of the Daylight Chamber (Fig. 8.2). Also the Extension Site pit has been sunk into the breccias to a depth of 10m below datum, with no sign of the breccia terminating; and since the Daylight breccia rises up to 7m below datum (Fig. 8.3) it seems certain that the two breccia masses are in fact one. Since the Daylight breccia can be traced to a depth of 30m below datum, the Fossil Deposit would descend to this depth (Fig. 8.3).

8.2.2 Fossil Deposit and Milner Deposit

Robinson (1962) calculated that the apex of the 'Mound' debris cone (the large cone at the east end of Milner Hall) should lie directly beneath the Extension Site section of the Fossil Deposit. Hearing the sound of the excavators hammers above him he concluded that the apex of the Mound was not very far beneath the hillside. Robinson was correct about the position (point K', Fig. 8.2), and the apex is known to rise to within 11m of the pit in the Extension Site (Fig. 8.3).

Finding artefacts at the apex of the Mound, Robinson (1962) assumed that he had located the underside of the bone rich breccia (point A, Fig. 8.7e) of the surface Fossil Deposit.

However, several specimens of bone material have been encountered at a lower level in the Mound breccia (pink breccia attached to the wall above the younger Mound material), which Robinson regards as recemented bone-free breccia (point B, Fig. 8.7e). For this and other reasons (8.4.3 below) Robinson's interpretation seems incorrect. The debris mass of the Mound has presumably infiltrated down the avens aligned along the various fracture zones; it seems reasonable to suppose that the Fossil Deposit is thus connected directly to the Mound Deposit, as well as to the Daylight Deposit. As such, the Fossil Deposit would extend downwards as far as 42m below datum, to the floor of Milner Hall (Fig. 8.3).

8.2.3 Fossil Deposit and the Terror Deposit

It will be recalled that Terror Chamber is formed entirely as a collapse void within a cemented deposit. The west end of this chamber lies directly beneath the Mound apex (point K', Fig. 8.2) and at exactly the same level as the tourist pathway cut into the Mound (33m below datum - Fig. 8.3). It seems definite therefore, that the west end of the Terror Chamber has formed within the Mound debris cone.

The Terror Deposit furthermore, stretches to the east in a continuous body forming the roof and walls of almost the entire chamber except for the extreme eastern end. It will be noticed that this deposit lies directly beneath the Fossil Deposit over this distance, both deposits being aligned along fracture zones 4 and 5 (Fig. 8.2).

The east end of the Terror Chamber itself suggests that this connection exists: a vertical dolomite wall, discussed earlier (6.2.2(3)), stretches upwards continuously for at least 22m, which indicates that for most of the vertical distance to the surface there is a sheersided slot, or narrow vertical chamber with no impediments to incoming debris, (points Y' and Y, Fig. 8.3, and point Y, Fig. 8.2).

Furthermore, the breccia deposit in the Skull Recess (point Z, Fig. 8.3) is only 6m above, and south of the dolomite wall (point Y). Since the Skull Recess deposit is connected to the Fossil Deposit, it seems probable that a connection exists at both the eastern end of the elongated Terror Chamber and at the western end.

It is hard to resist the suggestion that the Fossil Deposit descends continuously to the Terror Deposit, forming perhaps the largest mass of breccia in the cave system.

8.2.4 Fossil Deposit and the Exit Deposit

The Skull Recess deposit, which is visibly connected to the Fossil Deposit, lies directly above the small Exit Deposit on fracture zone No. 5 (Fig. 8.2). The shortest distance between the two is about 7m, and thus the connection seems to be fairly certainly established. In turn there may be a connection between the small Exit Deposit and the easternmost part of the Terror Deposit (E - E', Fig. 8.3), in that one lies only 10m vertically above the other on fracture zone No. 4.

8.2.5 Entrance 6 Deposit and Graveyard Deposit

Entrance 6 and its deposit lie directly above and only 10m from the Graveyard Deposit on fracture zone No. 4 (Fig. 8.2). It seems likely that the debris of the latter deposit entered via Entrance 6, although it may also have been supplied from the large Exit Deposit underneath a hanging dolomite wall (point W, Fig. 8.2).

8.3 Implications of the Characteristics of the Deposits

The deposits discussed above have all affected the internal morphology of the cave system profoundly, and it seems, furthermore, that certain features are characteristic of all deposits. These may be summarised as follows:

(i) The deposits all occupy fracture-zone cavities in the system;

(ii) They all consist of surface debris;

(iii) All appear to be connected directly, along the fracture zone, with surface breccias, (Fossil-Daylight connection, Fossil-Mound-Western Terror connection, Fossil-Skull Recess-Small Exit-eastern Terror connection, and Entrance 6-Graveyard and/or large Exit connection) and all descend to the lowest known levels of the cave system.

With this pattern of characteristics now discerned, it is possible to hypothesise with more assurance about the nature of other important deposits in the system, namely the Elephant, large Exit and Fault Cave Deposits, all of which have affected the morphology of the system to the degree of truncating and entirely blocking several sections of the sys. It seems likely, for instance, that the low-level Elephant Deposit, which straddles several fractures, extends up to the surface of the hill, and that the original Elephant Chamber void extended southwards many metres at least. Similarly the low-lying Milner breccia (point G, Fig. 8.2), which occupies fracture zone No. 4, may extend upwards to Lincoln's Cave, which also occupies this fracture zone (points S and T, Fig. 8.2). Two mud-filled sumps, at points S and T, at present collect modern soil in Lincoln's Cave, and these sumps may have been source-points [illegible] the Milner Deposit. The very large, low-level (+31m below hill surface) Fault Cave Deposit (points D and E, Fig. 8.2) may also adhere to the pattern discerned for the Fossil and related deposits: the fact that it lies so deep underground, consists of externally derived material (as far as can be seen), is large in volume and occupies an approximately linear passage, suggests that it is in reality a fracture-zone slot-filling which therefore extends, in all probability, to the surface. The thick talus cover on the lower slopes of the Sterkfontein hillock masks the dolomite fractures in the vicinity, however.

In contrast, the highlying (18-27m below datum) large Exit

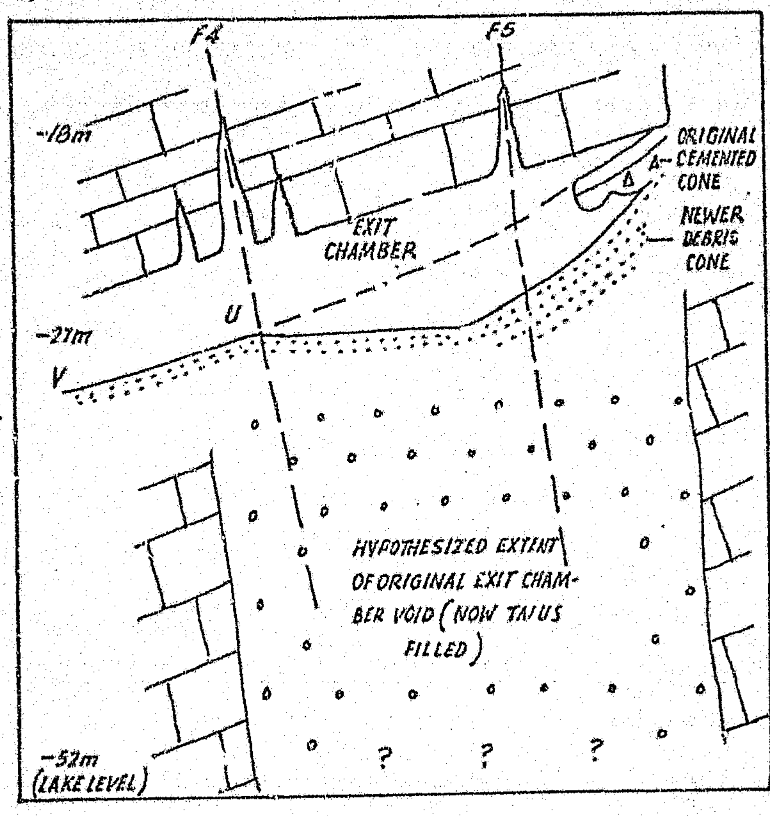

Fig. 8.4 North-south section through Exit Chamber showing possible development of original void and subsequent fillings

Deposit is probably only the topmost visible section of a very large deposit which extends downwards to the lowest levels of the system (45m below datum). (The visible part of the Exit Chamber void is determined by two fracture zones (Nos. 4 and 5, Fig. 8.2), and also occupies the area between these two fracture zones. It is likely therefore that it descends as far as other fracture zone voids in the system). The sloping floor of passage U-V leading off northwards from the Exit Chamber, is probably a modified debris cone slope (Fig. 8.4).

Future research will determine whether or not these hypotheses are correct.

Besides morphological implications, this study of cave deposits also has archaeological implications, especially with respect to dating. As argued above, it is expected that the Fossil Deposit extends continuously downwards in the cave system almost to the level of standing water, a distance of almost 50m. It is therefore reasonable to expect that lowest parts of the deposit are older than the highest parts. Excavation has reached a depth of 7m (Extension Site), a thickness which Robinson (1962) very roughly gauged might represent a time span of up to 10 000 years. Brain (1958) attributed the 11m thickness of the Limework's deposit (Makapan Caves, N. Transvaal) to the dry peak of the first Interpluvial of the Pleistocene. It seems, therefore, that the lowest parts of the large Sterkfontein deposits may contain significantly older archaeological material than has yet been found, especially since it is known that all the cemented deposits contain bone material and that the Mound breccia contains artefacts (Robinson, 1962).

No bone or artefact material has as yet been encountered in the unconsolidated portions of the various deposits, whether these unconsolidated deposits are simply collapsed and subsided parts of the breccia bodies, as Robinson (1962) suggests, or whether they are newer deposits incorporating reworked material altogether, as has been argued below (8.4.3).

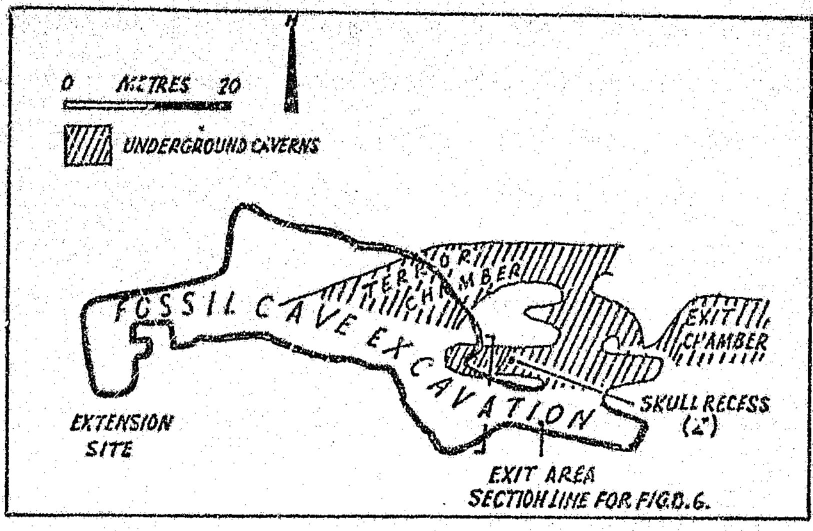

Fig. 8.5 Plan of Fossil Cave excavation and part of the underground caverns

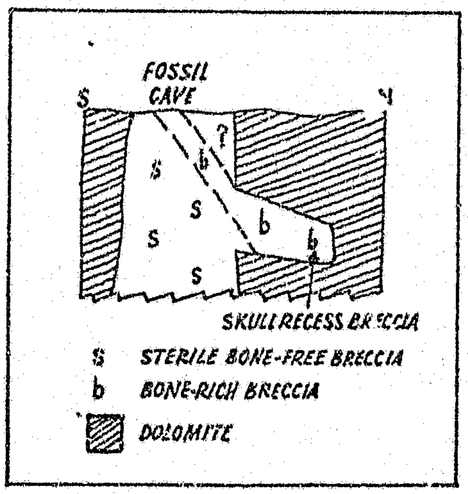

Fig. 8.6 Relationship of Skull Recess Deposit to bone-rich and bone-free breccias of the Fossil Cave (after Brain, 1958)

The implications of an understanding of the large Sterkfontein deposits, both for cave morphology and for archaeology, should stimulate further study of these deposits, in the same way that the Fossil Cave deposits have been closely analysed.

8.4 Examination of the Theories of the Fossil Deposit Development

Several workers in the past have examined the Fossil Cave deposits, and various interpretations have ensued. Because archaeological and especially climatic discussion is based on the stratigraphy of the deposit, an attempt is made here to reconcile the main interpretations which have arisen, (especially those of Brain, 1958; Robinson, 1962 and Brink and Partridge, 1970), in the light of new information.

Brain (1958) interpreted the deposit as one conformable mass of breccia with different properties at different levels. Robinson (1962) however, regarded them as three unconformable deposits, which allowed him to reinterpret climatic and archaeological evidence quite differently (see Chapter 2). Brink and Partridge (1970) reinterpreted the bone-poor breccia and identified a new breccia lying along the north wall of the Fossil Cave. Only Brain has mentioned the Skull Recess breccia (Fig. 8.5), a breccia lying just inside the mouth of the Tourist Cave, off the Exit Area (point Z, Fig. 8.2). By means of breccia matrix analysis, Brain found that this breccia was 'comparable' to the bone-rich breccia of the Fossil Deposit; he therefore concluded that it was connected to this breccia, overlying conformably the bone-free breccia (Fig. 8.6, after Brain, 1958). The present writer finds no such connection, and hence regards the Skull Recess breccia as another separate body of breccia within the Fossil Deposit. Its relationship to the other breccias is discussed below.

8.4.1 Origin of the Bone-Poor Breccia (Robinson's (1962) Lower Breccia; Brink and Partridge's (1970) 'Class II' Breccia)

Brink and Partridge (1970) regard the bone-poor breccia as a collapse deposit, because of the sharp-edged, unweathered appearance of the constituent dolomite blocks, the abundance of these blocks, the proximity of the blocks to one another, the existence of air filled interstices in parts, and the lack of a sandy matrix in many places, the blocks being cemented purely by travertine.

This interpretation conflicts with that of the earlier workers who considered the bone-free breccia to be a gradual accumulation. The solution to this problem seems particularly difficult since the breccia matrix particles show definite changes from one level to another, changes which have been interpreted as indicating a climatic fluctuation (Brain, 1958); i.e. matrix accumulation lasted long enough to overlap changes in climate. It is difficult therefore, to see how the deposit could have accumulated suddently as evisaged by Brink and Partridge.

The solution to this problem has been indicated by Brink and Partridge (1970). They point out that the bone-poor breccia contains pockets of sand within it which have probably 'subsided' from the sandy overlying bone-rich breccia (Brink and Partridge suggested that the entire mass was cemented after the sand had subsided, but this is unlikely since Brain has shown that it everywhere contains more than 60% calcium carbonate cement by weight, indicating simultaneous cementing, not subsequent cementing - Brain, 1958).

The mode of accumulation of the sandy pockets envisaged by the present writer is less one of subsidence prior to cementing and more one of infiltration into the interstices of the collapse blocks, simultaneously and perhaps with the aid of percolating water.

It is felt that this mode of accumulation, if correct, has implications which may invalidate Brain's climatic inferences, though there can be no doubt that he has ascertained conclusively that the breccia matrix has a differing character from level to level.

8.4.2 Implications of the Collapse Theory of Origin of the Bone-Poor Breccia

The main implication of the finding that the bone-poor breccia is a collapse deposit, is that Brain's (1958) matrix analysis (of this breccia) does not necessarily have climatic significance: it seems likely that the infiltration process referred to above, to explain the presence of sand pockets in the rapidly accumulated collapse deposit, is an extremely complex one, if not a chaotic one.

(i) The infiltration process may involve preferred pathways of infiltration which would lead sand to lower levels. Interstices set apart from such pathways would only be filled after the pathway cavities had been - i.e. sand pockets would not have accumulated chronologically with height, as Brain assumed they had, an assumption basic to his and to Robinson's climatic interpretations (Brain, 1958; Robinson, 1962). Percolating water is likely to have aided the process substantially since it is improbable that it flowed through the collapse deposit uniformly. Sand penetration thus relates most probably to preferred pathways leading through the deposit, pathways determined locally by larger voids in the deposit and/or by the routes of percolating water.

(ii) There may also have been sand particle sorting during the infiltration process: the rounded particles and the quartz grains (the concentrations of which are Brain's (1958) evidence for climatic fluctuation) may be transported differently to the angular and the chert grains. Brain (1958) himself shows that the particle <u>size</u> increases on average from the top to the bottom of the breccia matrix, but he offers no explanation for this (Brain, 1958, p.49). Coarser particles may in fact penetrate further the interstices of a collapse-block mound. And this size sorting with depth may affect angularity and quartz ratio measurements if there are varying proportions of these particles in different size

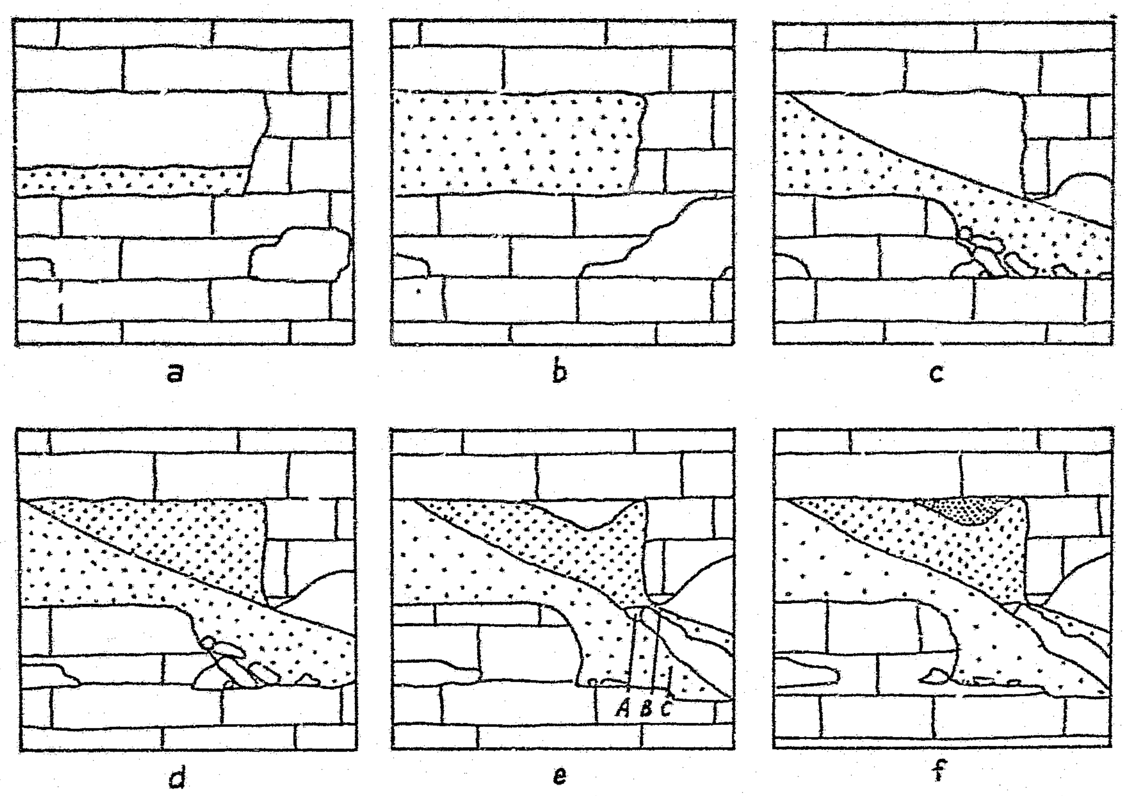

Fig. 8.7 Stages in the development of three unconformable breccias in the Fossil Cave (after Robinson, 1962) Diagrams a and d illustrate additional sections at right angles to the others. a and b show the accumulation of lower breccia and the growth of a lower cavern system. Some time after the fossil cavern filled to the roof, the floor collapsed at the western end (c) opening a new cavity. This filled up (d) wich middle breccia. Then a smaller-scale collapse occurred again (e) opening a smaller cavern, which filled with upper breccia (f).

fractions (Brain only examines the 35-60 mesh particles) in dolomite soils.

For these reasons it does not seem valid to ascribe climatic interpretations to variations which undoubtedly do exist in the breccia matrix, because of all the complex influences which can reasonably be expected to have controlled the infiltration of earth into a collapse deposit of dolomite blocks.

Brain's subsequent analysis of the uppermost chocolate breccia (Robinson's 'Upper Breccia') however, certainly seems to have meaning especially when compared with the analysis of the bone-rich breccia, since both of these deposits are gradual accumulations (see Chapter 9, Climatic Evidence).

8.4.3 Robinson's Theory of Origin of the Fossil Deposit

Because Robinson (1962) regarded the bone-poor breccia as a 'gradual' accumulation, there had to be a reason for the change to a bone-rich breccia overlying this. Robinson proposed that the bone-poor breccia had filled the original Fossil Cave to its roof, (Fig. 8.7b) and that the subsequent bone-rich breccia was deposited only once a void had been created again within the cave. The mechanism he advocated for this was collapse of the Fossil Cave 'floor' with consequent subsidence of the bone-poor breccia into the underground caverns (Fig. 8.7c). The bone-rich breccia then accumulated in the space previously occupied by the bone-poor breccia (Fig. 8.7d).

To explain the abrupt change in deposits from the bone-rich breccia to the small overlying chocolate brown breccia, Robinson used the same argument - namely, subsidence of the bone-rich breccia creates a space which can be filled by the chocolate brown breccia (Figs. 8.7e and f). In this way it was possible to explain the existence of three separate, unconformable breccias in the Fossil Cave. However, there are various objections in this formulation:

(i) There is no need to advocate large-scale subsidence of the bone-free breccia into the underground caverns to explain the existence of the overlying bone-rich breccia, if the former is regarded as a collapse deposit: a collapse deposit necessarily cannot fill the original cave to the roof, and hence there must be space above it in which the bone-rich breccia might collect.

It seems unnecessary to advocate a second slumping of the bone-free breccia to explain the existence of the chocolate brown breccia. The chocolate brown breccia is at present a small body, and there is no evidence of it having been large or widespread. Minor slumping and compaction of the very large bone-rich breccia seems a far more likely explanation of the way the chocolate breccia void was formed. Since Robinson regarded the bone-rich breccia as 'a maximum of 20 feet thick', compaction would not have been considered. However, it has been argued at length that this breccia descends even now 33m below the surface, a mass in which compaction very probably did occur.

It seems more likely that the bone-rich breccia grew upwards from the Milner floor, until at the level of the Skull Recess, accumulation was interrupted by the collapse of the bone-poor deposit, and then continued, sandwiching the latter. This explanation accounts for the fact that the Skull breccia accumulated under climatic circumstances similar to those of the lower bone-bearing breccia in the Fossil Cave (Brain, 1958).

(ii) Robinson claims to have found blocks of bone-poor breccia cemented in the Milner breccia (B, Fig. 8.7e), and quotes these as evidence of the initial collapse of the former into Milner Hall. The present writer has encountered no such blocks of the distinctive bone-free breccia either in the Milner breccia or anywhere else in the cave system.

(iii) Robinson interprets the Mound (Milner Deposit) as the subsided portion of the bone-free breccia (point C, Fig. 8.7e). This seems unlikely for various reasons: firstly, it contains no cemented breccia blocks; it is entirely unconsolidated, as far as can be seen from the 3m excavation i' the side of the deposit, and from the other parts. It seems impossible that this supposed collapse section of a deposit should be so completely and uniformly decalcified that there would be no trace of the original cemented mass. Secondly, this unconsolidated deposit contains no dolomite blocks even of a small size, the largest material being a coarse gravel. Both the bone-free breccia and the bone-rich breccia contain dolomite blocks, especially the former, and one would therefore expect to find such blocks in a deposit derived from either of these. Thirdly, it seems improbable that a collapsed deposit would retain any semblance of layering. Yet the unconsolidated Mound cone is distinctly layered with no evidence of disturbance due to collapse or subsidence (Fig. 6.6).

In short, this unconsolidated mass appears not to be derived as a subsidence feature of an earlier breccia cone, but to be a younger, as yet uncemented deposit, altogether different from the breccia material.

The alternative to Robinson's model may be summ ed as the following:

A bone-rich material enters the cave system, along well-developed vertical avens, and comes to rest in the lowest parts It becomes cemented by percolating $CaCO_3$-rich water. As it is filling a cavity in the upper levels (present Fossil Cave), a roof collapse occurs depositing a heap of closely packed dolomite blocks. The bone-rich material continues to accumulate slowly (now on top of the collapse cone), as some matrix-forming soil penetrates the collapse deposit beneath. The dolomite collapse blocks and pockets of sand, by means of percolating water are cemented into a hard bone-free breccia. The lower parts of the bone-rich material, also cemented by this stage, are attacked by rising phreatic water, undermined, and removed, allowing the influx of new hillslope debris. The roof of the upper cavity (Fossil Cave) is slowly removed, exposing the fillings to attack and decalcification by meteoric water. The effect of attack becomes very pronounced in parts, such as the Exit area (8.5 below).

8.5 Decalcification of the Fossil Deposit Breccias

One of the final stages in the evolution of the Fossil Cave breccias involves the major modifications of the breccias by decalcification and erosion, and the corresponding recent underground deposition. Brain (1958), Robinson (1962) and Brink and Partridge (1970) all refer to the pockets of earth which occupy hollows in the surface breccias, and attribute them to decalcified bone-bearing breccia because of the rich accumulations of bone and artefact material in them. Brink and Partridge (1970) also refer to solution pockets which have pierced the cave system in various places. Decalcification thus appears to be commonplace in the Fossil Cave breccias. However, previous writers have not invoked this process to explain any large features: it seems to the present writer that the development of the entire Exit Area, and the Daylight Chamber, can only be attributed to decalcification. It was postulated earlier that the Exit Area fissure was probably ultimately completely filled with breccia at least to the level of the present hill surface. It is now postulated further, that once this breccia body was exposed directly to aggressive meteoric water, that large-scale decalcification ensued, the water percolating into the voids beneath, transporting the loosened breccia material with it once routeways had been established.

It seems quite possible that given sufficient time, an aperture as large as the present Exit Area (Fig. 8.5) could have been fashioned, an aperture leading not only into the shallow-lying Exit Chamber, but also into the lowest part of the Cave (eastern Terror Chamber, Fig. 8.5).

The same decalcification and erosion process is believed to have

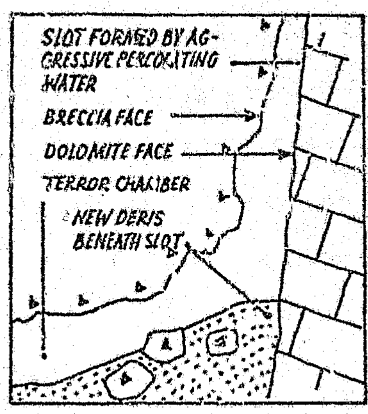

Fig. 8.8 High vertical slot, Terror Chamber, showing opposing breccia and dolomite faces

eroded the aperture in the Daylight Chamber roof, and thereafter to have removed those parts of the Daylight Deposit breccia which lay against the dolomite south wall of the chamber.

This theory seems the only tenable one in that there is no evidence that the apertures and shafts originated by collapse into the underground caves. Also it seems to be the only theory which can explain the existence of bare, vertical dolomite walls in close proximity to walls of breccia, a situation which occurs in both Daylight and Terror Chambers. It appears that the breccia bodies in both cases once lay up against the dolomite walls which contained the early uncemented debris. However, once the debris mass had hardened, the cave above was deroofed, aggressive water percolated downwards, and the breccias were removed from these walls, which are situated beneath the source of the percolating water. The main breccia mass was rigid enough not to collapse once the support of a containing wall had been removed (Fig. 8.8).

If the above process has indeed operated, then the large volumes of breccia removed have been deposited in the caves. The Terror Chamber, lying at the bottom of the re-established shaft, contains a cone of fine material directly beneath this shaft. Daylight Chamber, however, is purely an erosional feature, and the breccia removed during its formation probably contributes to the rise in floor level in Elephant Chamber beneath Entrance 1 (point 7, Fig. 8.2). Unconsolidated floor material in other parts of the cave system may also contain decalcified surface breccia materia

Except for small breccia solution pockets on the hill surface (Robinson, 1962; Brink and Partridge, 1970), features in the cave system arising from the erosion of the cave fillings and deposition of the eroded material - by the agency of percolating water - have not been mentioned before for Sterkfontein.

8.6 Assessment

Externally derived debris bodies have modified all the largest caverns markedly, usually forming the floor, certain walls and even the ceiling (the small northern deepset caverns have only been affected by internal collapse of minor proportions); because of the vast size of these deposits, and the fact that climatic and archaeological interpretations are inferred from them, they have been closely scrutinised.

The debris cone model was presented firstly to elucidate the apparent stages in the development of the debris cones in the cave system, and secondly to amplify Bretz's (1942) discussion of cave deposits which treats the 'clay-fill' deposits almost exclusively. No 'clay-fill' deposits such as those described by Bretz have been encountered at Sterkfontein. Sterkfontein appears to be unique even in the Transvaal on this particular score. The reason appears to be that phreatically widened fracture zones allowed coarse debris in large quantities to enter the cave system, as opposed to the fine clay particles which filtered into the American Caves (Bretz, 1942).

The importance of the fracture zones on deposit accumulation was stressed since fracture zone control explains the depth of debris penetration, the connection of surface and underground debris bodies as continuous masses, and the fact that these bodies appear entirely to consist of externally derived material.

Three partially concealed deposits (Elephant, large Exit and Fault Cave Deposits) have been discussed in the light of the proposed pattern of debris mass development. Fossil Deposit was also examined on this basis: Robinson's argument that the deposit contains three unconformable breccias (Robinson, 1962) was contested, and Brain's earlier view of a conformable breccia mass (Brain, 1958) supported. However, it was concluded that Brain's (1958) climatic interpretations are untenable in the light of Brink and Partridge's (1970) reinterpretation of the bone-free breccia. Large-scale decalcification and erosion of the Fossil Deposit was postulated to explain the present configuration of this exposed deposit (excluding small features like solution pockets). Corresponding deposition of the decalcified deposit material was recognised at two points in the Cave system.

CHAPTER 9 - CLIMATIC EVIDENCE

9.0 The evidence for large scale water level fluctuations underground has been presented. This consists of variable thicknesses of flowstone on the south wall of Milner Hall, different degrees of re-solution on this flowstone, and phreatic attack on the underside of hardened breccia masses in Milner Hall, Elephant Chamber, Terror Chamber, Exit Chamber and Fault Cave.

In addition there is evidence that the rate and type of calcium carbonate deposition has been variable in the past and is now virtually nil.

These phenomena will be discussed with particular reference to a climatic oscillation explanation.

9.1 Water Level Fluctuations

Re-solution features on the Milner Hall wall flowstones, and also on breccias at different levels within the cave system have been described. Various explanations are considered.

9.1.1 Climatic Change

It has been postulated that longterm climatic oscillations cause water-level changes in a cave: Marker and Brook (1970) made tentative climatic interpretations from the abundant evidence for water level fluctuations in Echo Cave, 320km east of Sterkfontein, since theoretically it is reasonable to suppose that a wet climatic phase would raise the level of the surface of the saturated zone in a rockmass. It has been shown that the water bodies in Sterkfontein are probably connected, and that the connections must be poorly developed in order to preserve water body levels at different heights (-40m to -60m).

An increase in the supply of water during a wet climatic phase might thus be expected to cause a rise in water levels. Similarly there is undoubtedly a direct relationship between dry climatic phases and low water levels in cave systems.

9.1.2 Weather

Short-term, large magnitude water level changes can result from long return floods. Such high water levels are of short duration and appear to cause minimal, if any re-solution. The chance of such random events raising cave waters to the same level on more than one occasion is remote and visible stillstand levels would not therefore be imprinted on wall travertines. Furthermore seasonal and long return underground water level fluctuations are of small vertical magnitude in areas of low relief amplitude. They reach major proportions only in areas of great dissection and high seasonal rainfall.

9.1.3 Blocking of Primitive Water Routes

Another factor which may come into play is the effect of blocking. The narrow, primitively developed connecting passages between the water bodies (and between the water bodies and the resurgence) may become blocked by insoluble residues. Such blockage would be random and independent of climatic oscillations, but would nevertheless affect water levels within the cave.

9.1.4 Cut and Fill

It is generally accepted that episodes of cut and fill in river valley alluvia are causally related to climatic oscillations. Such episodes may influence the resurgence levels for ground water. The precise relationship of cut and fill phases to changing climatic conditions is not yet fully elucidated, although it is generally believed that cutting results from arid phase flash floods. Nevertheless, it remains difficult to equate episodes of cut and fill in the drainage line with water level

FEATURES	RE-SOLUTION LEVELS (METRES ABOVE THE LAKE)	FIRST INTERPRE-TATION	SECOND INTERPRE-TATION
THICK FLOWSTONE WITH TERTIARY GROWTHS	±8m	2	3
THICK REDISSOLVED FLOWSTONE WITH TERTIARY GROWTHS	5m	3	1
THIN REDISSOLVED FLOWSTONE WITH TERTIARY GROWTHS	2,3 m	4	4
THIN REDISSOLVED FLOWSTONE	1,5 m	5	2
BARE DOLOMITE WALL		1	
	0	6	5

Fig. 9.1 Re-solution levels on Milner Hall flowstone indicating past lake levels

changes underground caused by changes in rainfall.

9.1.5 The Amplitude of Water Level Fluctuation

The evidence for large amplitude water level changes underground in Sterkfontein is established. The causes of these changes are more difficult to ascertain. However, it seems as though climatic oscillations, whether directly or indirectly, must have caused at least some of the underground water level changes.

9.1.6 Climatic Interpretations

The climatic interpretations which can be made from the Milner Hall flowstone, and other localities where water level fluctuations have occurred, are discussed below. It is assumed that the levels of still-stand identified earlier (6.1) for the Milner Hall flowstone, are climatically determined.

(1) Milner Hall Flowstone

Two interpretations of the sequence of travertine deposition and re-solution are possible, one implying a single climatic oscillation, the other a multiple climatic oscillation.

Single Oscillation. The sequence of water levels is most simply interpreted as follows: firstly, an original high water level during the phreatic excavation of Milner Hall; thereafter a low water level, (level 1, Fig. 9.1)[1], allowing the deposition of flowstone over the entire south wall of Milner Hall down to the lowest existing level of travertine, (level 5). Then the water rises more than 6,5m (level 2), to dissolve the flowstone. The next four levels (3-6) occur at successively lower positions on the wall, as is evident by progressively more eroded flow-

[1] Ensuing water level numbers refer to Fig. 9.1

stone, until between levels 5 and 6 the flowstone is entirely removed (if it ever developed at this level).

The tertiary growths developed on the travertine above the dropping water level, and apparently have not had time to develop below level No. 4. These tertiary growths may indicate a change in cave environment ending active flowstone deposition.

This interpretation raises certain questions: for example, it is not clear why there should have been a sudden large rise in water level (of 6,5m) and then several small lowerings. This appears inconsistent and suggests that the water may have risen in stages as well, the evidence of which has been destroyed or rendered unrecognisable.

Another possibility is that the small lowering stages represent fewer periods of actual still stand: the present-day lake fluctuations are as large as 1,5m, and therefore the distance between levels 4 and 5 may also represent the fluctuations during one stillstand rather than two. This argument may also apply to the fluctuations between levels 3 and 4, and 5 and 6 although fluctuations of 2,7m and 2,25m[2] seem somewhat extreme during one climatic regime; it seems possible that the phase of dropping water levels in this sequence represents as few as two still stands, not four, a conclusion which fits better with the initial single large rise of water level. The degree of speculation in this interpretation, and the next render these conclusions very tentative as yet.

Multiple Oscillation. This interpretation arises because the upper, thick portion of the travertine can be regarded as the older Deposit, and the lower, thinner portion as the younger, with a time-gap separating the two. Level 3 divides the two, and if it is regarded as the first

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[2]Present-day lake level as indicated on Fig. 9.1 is a mean lake level: the 1,5m distance between levels No. 5 and 6 increases to 2,25m during very dry seasons.

level of this sequence, then the chronological order of the levels is 3 - 5 - 2 - 4 - 6:- when the water level drops from the first position (level 3) to level 5, the thinner travertine is deposited, with the thick travertine all the while becoming thicker. Then the water rises to level 2 dissolving both thick and thin travertines. The water thereafter drops to level 4 and then to level 6.

If the first level (3) is taken as a high level, the sequence indicates two wet climatic phases (levels 3 and 2) and two dry phases (4 and 5). The high water level which seems required in a regular sequence such as this between level 5 and 6, may indeed have occurred without leaving any recognisable trace on the travertines. If this is accepted then the sequence represents three high levels alternating with three low levels - i.e. three wetter climatic phases separated by three drier. This interpretation is in marked contrast with the first which involves only one climatic fluctuation.

In this interpretation it seems unlikely that fluctuations during one climatic phase could explain any two of the observed water levels, as was possible above. However, the effect of river bed incision is likely to be more pronounced during the period of 3 oscillations. Marker and Brook (1970) argue conclusively that the water level fluctuations in Echo Cave are best explained by relatively small changes (due to climatic oscillation) superimposed or a general lowering of ground water (due to river incision). The levels in Sterkfontein suggest an opposite trend however: the second high-low fluctuation (levels 3 and 4) is at a higher level than the first (levels 1 and 2). This may indicate that the second oscillation was far more intense than the first (intense enough to offset the lowering due to incision); or it may indicate that the effective resurgence level in the Blaauwbank River alluvium had risen slightly, as it seems possible that during a wet phase the lower levels of the alluvium

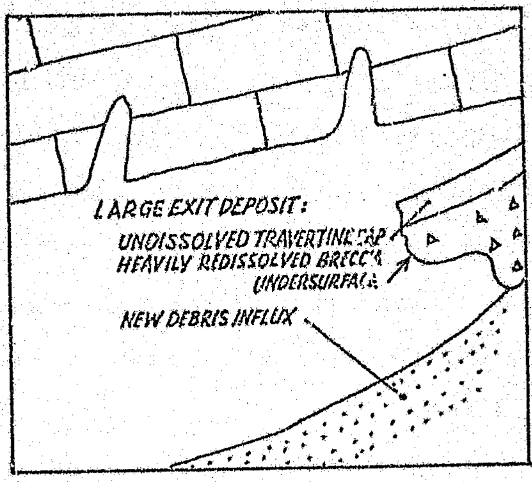

Fig. 9.2 Re-solution of the Large Exit Deposit breccia

would become saturated, thereby raising the effective level of the underflow from the alluvium/bedrock contact to some slightly higher position.[3]

(2) Mound Breccia

It has been argued that the Mound breccia was deposited and cemented simultaneously in an air filled chamber, and that the resolution of this breccia must therefore indicate a rise in water level. This rise is best explained as a response to a wetter climatic phase. The magnitude of the rise, as far as can be ascertained, was approximately the same as that on the wall flowstone (9m).

(3) Exit Chamber

There is evidence of a re-solution phase in the Exit Chamber on the underside of the large Exit Deposit breccia. This breccia hangs from the cave wall, its base removed by re-solution. Its evolution is similar to that of the Mound breccia in that it is a hard breccia which must have accumulated in an air-filled chamber. The ground water then rose and attacked the base of the breccia cone, removing and dispensing the material, and leaving the upper part of the cone suspended from the wall (Fig. 9.2). The water subsided (it now lies 26m below the large Exit breccia) thereafter.

The implication is that a wetter climatic phase caused a long-term rise in water level.

9.2 Changes in Travertine Deposition

9.2.1 Calcite Straws

Vogel and Partridge dated an inner and an outer wall of a calcite straw 4,5m above the water level in Ravjee Cavern. These walls

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[3] It has been argued above (7.2.3(2)) that since water levels in the caves are generally lower than the riverbed, the cave water resurgence is probably at the dolomite/alluvium contact 12m lower than the riverbed.

appear to have been deposited at different times, the earlier at some date before 47 000 years before present, and the older at some date before 50 000 years before present (Vogel, 1970). It is presumed that a change in cave environment must account for the cessation in calcite deposition represented by the unconformity between the inner and outer walls of the straws.

A dry climatic phase could explain the cessation and a wetter phase the resumption of calcite deposition. However, both immersion during a period of high water levels, and also the possible blocking of the percolation routes, could account for the break in $CaCO_3$ deposition on the straw. The last explanation is unlikely, however, since several of the straws in Ravjee Cavern are composed of two separate layers of deposited calcite. Immersion in cave water seems unlikely as no obvious re-solution evidence can be detected on the .traws, although it is possible that the period of immersion, and consequent hiatus in calcium carbonate deposition, was short, neither destroying the calcite straws nor re-dissolving them noticeably. Changes in the supply of $CaCO_3$-charged percolating water thus seems the most plausible explanation. And this factor is best attributed to climatic oscillation.

9.2.2 Thick and Thin Travertines

Ravjee Cavern contains a great thickness of travertine near the present water level. The travertine has been severely attacked by re-solution.

The small calcite straws mentioned above are clearly younger than the phase of thick travertine deposition, since they occur at the same level, but display no trace of re-solution. The difference in quantity of $CaCo_3$ deposited before and after re-solution is so marked that it is pertinent to ask why this has come about. The two walls of the calcite straw dated by Vogel (1970) yielded ages of greater than 47 000 years before present and greater than 50 000 years before present, which suggest that enough time has elapsed for the deposition of large speleothems if conditions suitable for such deposition have existed. Two explanations arise for this marked change in speleothem development, before and after the period of re-solution: firstly that the percolation routes have been blocked in some way, limiting the supply of charged ground water into Ravjee Cavern; and secondly that the concentration and supply of charged ground water has been climatically controlled, such that a thick mass of travertine developed, succeeded by a period of calcite straw formation. Both explanations appear plausible in the setting of Ravjee Cavern.

9.2.3 Aragonite Crystals

These crystals develop on various surfaces within the cave system, and appear to grow best on travertine deposits, in badly ventilated, humid recesses. These younger crystals protruding from travertine surfaces are relevant to this discussion because they indicate a change in the conditions of $CaCO_3$ deposition. They are younger than the underlying travertine and far smaller in dimension.

Aragonite crystals are preferentially precipitated in the presence of a foreign ion (magnesium in the case of the Transvaal system dolomites). Marker (1973) has shown that the magnesium/calcium ratio increases when the rate of solution decreases, and that crystal formation can therefore be attributed to a period of diminishing karst solution.

9.3 Dating the Water Level Fluctuations and $CaCO_3$ Changes in Deposition

Since evidence of climatic change becomes more meaningful once it is dated, dating information will be discussed.

9.3.1 Dating the Ravjee and Milner Deposits

It has been mentioned that the inner and outer walls of a calcite straw in the Ravjee cavern have been dated as greater than 47 000 years before present, and greater than 50 000 years before present, which gives a partial indication of the age of the straw. The thick travertine in Ravjee Cavern, the Milner Hall flowstone and re-solution features imprinted on them can only be dated relative to the straw. Both deposits must be older than the straw because both have been heavily redisolved whereas the straw has not, even though they lie at similar levels.[4]

Another approximate indication of the age of the Ravjee Cavern and Milner Hall speleothems, and their associated phases of re-solution, exists in the relation of these speleothems to the Mound breccia. Above the highest re-solution level (level 2, Fig. 9.1), the Milner Hall flowstone has not been attacked by phreatic water, whereas the Mound breccia has suffered phreatic attack. Since the Mound breccia is 13m higher than level 2 it becomes apparent that the travertine and the flowstone were deposited and redissolved after deposition and re-solution of the breccia had occurred. It has been suggested that the bone-rich breccia in the Fossil Cave may be as old as 1,75 - 2,50 million years old (Cooke, 1970). It was postulated earlier that the Mound breccia is connected to the bone-rich breccia. If this is true, the Mound breccia would be of similar age, i.e. 1,75 - 2,50 million years old. The phases of re-solution which have affected the Ravjee Cavern travertine, the Milner Hall flowstone and the Mound breccia would therefore have occurred after the deposition of the Mound breccia.

9.3.2 Aragonite Crystal Growth

Dating of the phase of aragonite crystal growth may be possible by the C^{14} method since it appears to be among the youngest phases of

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[4] It is assumed that the relationship between water levels and fluctuations of the water bodies have remained approximately the same.

deposition. In relative terms, however, the crystal growth has occurred since the re-solution of the Milner Hall flowstone: crystals have developed on all the redissolved surfaces except at the lowest levels (between levels 4 and 5, Fig. 9.1), where presumably re-solution has been more recent than the phase of crystal growth.

9.3.3 Exit Deposit

Dating of the Exit Deposit sequence of deposition and re-solution is also very approximate. It relies on Brain's finding that the hardest breccias are those which have been cemented during the process of accumulation (Brain, 1958). From this it is apparent that the Mound breccia was deposited and cemented simultaneously: it could not, for example, have been deposited in water and then been cemented once the cave water had subsided to lower levels.

Since the Exit Deposit re-solution features lie 20-24m below datum, it is apparent that the Mound breccia, at 30m below datum, was deposited after the phase of high water levels which attacked the Exit Deposit. Therefore the water and fluctuations which caused the re-solution of the Exit Deposit are older than the postulated dates for the deposition of the Mound breccia, namely 1,75 - 2,5 million years before present.

9.4 Assessment

It was argued that water level fluctuations and changes in $CaCO_3$ deposition in Sterkfontein may well be evidence for climatic change, especially the larger fluctuations and $CaCo_3$ deposition changes. All the evidence quoted suggests two climatic oscillations (from arid to humid, and back to arid) except for the Milner Hall flowstone which was susceptible to two interpretations, one suggesting two and the other suggesting more than two climatic oscillations.

The dating of the fluctuations is at present far sketchier than that deduced by Marker and Brook (1970). Whereas these workers were able to ascribe the water level fluctuations in Echo Cave tentatively to the major climatic oscillations of the Pleistocene, it is only known that the oscillations at Sterkfontein occurred after the deposition of the bone-rich breccia (approximately 2 million years before present) and prior to 50 000 years before present. The oscillations represented at Sterkfontein thus overlap those at Echo Cave.

CHAPTER 10 : SUMMARY AND CONCLUSIONS

10.0 Summary

A summary of the results from the detailed analysis of the cave system are presented. Thereafter evidence of climatic oscillation is summarised. The relation of the results to various existing theories of cavern development and climatic change in Southern Africa is evaluated.

10.1 Morphology and Location of the System

10.1.1 The cavities comprising the system may be divided into two morphological categories:- the large main galleries, and the smaller passages to the north of these.

10.1.2 Main galleries are relatively narrow, sheer-sided, slot-like, elongated cavities with strong vertical development (up to 30m), and with earth floors which conceal the total original depth of the voids.

10.1.3 There is an approximate boundary between the large galleries and the smaller passages lying to the north of these. The smaller galleries dip variably to the north, are relatively wider than the main galleries and are often oval in cross-section.

10.1.4 The large galleries are aligned along major east-west compressional, fractures and fracture zones; they occupy the area of the hill in which the fracture zones are concentrated.

10.1.5 The smaller galleries to the north occupy an area largely devoid of major fracture zones, and are aligned along joints and occupy specific stratigraphic layers, often with small bands controlling the roof.

10.1.6 The smaller galleries have developed to the north of the fracture zones in response to water-flow from the fracture zone voids towards the local drainage line.

10.1.7 The position of the cave system is thus determined by the location of fracture zones which have developed according to a specific pattern in the Blaauwbank River Valley. A 'possibly silicified fault' which bounds the cave system on its eastern or down-stream side, may have encouraged cave development by concentrating groundwater in the dolomite on its western or upstream side.

10.2 Erosional Detail

10.2.1 Erosional detail such as networks, partitions, rock-spans, flutes, joint-determined cavities, boxwork, stylolites, and protruding chert bands, points to an origin almost entirely phreatic.

10.2.2 A few features indicate flowing phreatic water, and one seasonal vadose stream flows in a phreatically formed passage.

10.2.3 Much evidence of percolating water action exists in the form of solution pits in the cemented breccias of the Fossil Cave and also in an underground chamber (Daylight Chamber). Large scale attack by percolating water appears to have caused the Exit Area which has been linked by solution of the breccias to the lowest parts of the cave system.

The slot-like form of the main galleries suggests upward elongation due to percolating water.

10.2.4 Small collapse-formed cavities were encountered centered on various joints, mostly in the inner parts of the cave system.

10.2.5 The cave system corresponds to Davis' (1930) formulation of cave development in that it underwent deep phreatic erosion and is now air-filled. It also corresponds to Ford's formulation (1970) that deep phreatic caves develop in steeply dipping rocks. The small northern passages show control by specific layers within the bedrock, the importance of such controls being advocated by Gardner (1935), Glennie (1956) and Waltham (1971).

10.2.6 The Main galleries of the cave system do not correspond to any specific theories of cave development in that they have developed entirely according to the particular geological structure, the fracture-zone pattern of the Sterkfontein area. Within the confines of the area with the same geological structures, it may be possible to detect some systematic development of caves.

10.3 Water Levels in the Cave System

10.3.1 Cave sections indicate that the seven water bodies occupying the lowest parts of the cave system, all lie below the Blaauwbank River bed level by 5 - 18m, and that they decline in height towards the north-east, suggesting that they are crudely connected to one another (hydraulic gradient of the order of 6^0 north-eastwards).

10.3.2 Resurgence of the cave water is probably at the bedrock/alluvium contact in the Blaauwbank River, in the form of underflow.

10.4 $CaCO_3$ and Non-Calcareous Deposits

10.4.1 Speleothems of Primary and Secondary Growths

(1) The accumulations of $CaCO_3$ (in economically exploitable quantities) occur in the cave system in a variety of forms: calcite in the form of stalactites, stalagmites, flowstone, calcite straws, rafts and helictites. Other forms are aragonite crystals (subaqueous and subaerial) which occur on all kinds of surface, and concoidal amorphous $CaCO_3$ in one locality.

(2) At least two distinct phases of $CaCO_3$ deposition are evident.

(3) The largest volumes of $CaCO_3$ have accumulated along the roofs of the fracture controlled caverns.

10.4.2 Non-Calcareous Deposits

(1) The non-calcareous deposits are of three types; Wad , the insoluble dolomite residue, collapse material derived internally, and coarse earthy deposits.

(2) Wad collects underwater: it is found extensively in the lower parts of the cave system as a wall coating, and is another pointer to the phreatic origin of the cave system. Normally it is found as a black powder or jelly-like substance, but it is also found cemented into breccia.

(3) Collapse material is found in the inner recesses of the system in comparatively small quantities. Any such material in the main chambers is buried beneath the large influxes of hillslope debris.

(4) Coarse earthy deposits are ubiquitous in the caves, especially in the large galleries. They consist of red earth with subangular stones and some collapsed boulders. Though usually roughly stratified these deposits do not display sorting within individual strata. They contain some bone and artefact material and may be cemented to different degrees of hardness.

(5) These deposits cover most floors and many cavern walls. They occupy the major fracture-zone chambers as large continuous bodies of debris. It is apparent that these deposits are externally-derived hillslope materials.

(6) The coarse earthy deposits often occur as two distinct entities, viz. a cemented and carapaced deposit situated above an uncemented, uncarapaced deposit: the upper cemented deposit often shows evidence of phreatic attack on its underside.

(7) The large unconsolidated debris cone of the Milner Deposit has different constituents from the overlying cemented deposit, and is therefore not a decalcified, subsided portion of the cemented deposit, as suggested by Robinson (1962).

(8) A model has been proposed to explain stages of development of the deposit masses.

(9) No epoch of clay fill, as proposed by Bretz (1942), ever affected Sterkfontein as a specific stage in the development of the cave system. Well developed fracture zone avens allowed coarse external debris to enter in very large quantities, unlike the very fine soil filling recognised by Bretz.

(10) Surface breccias are connected with underground breccias through distances of at least 35m. The breccia material enters by, and accumulates in widened, near-vertical fracture zones.

(11) Archaeologically in particular it is important to note that the lower parts of the thick deposits will be older than the upper parts.

(12) It is accepted that the coarse fraction of the bone-poor breccia of the Fossil Cave is of collapse derivation. The fine matrix material of this breccia, however, is believed to be infiltrated into the coarse fraction dolomite blocks with the aid of percolating water. Therefore this deposit cannot be accepted as a climatic indicator, as proposed by Brain (1958).

(13) Unconformities between the three contiguous surface breccias in the Fossil Cave do not necessarily represent time hiatuses; they represent changes to different modes of deposition. The collapsed bone-poor breccia is simply an interruption in the continuous, gradual accumulation

of the bone-rich deposits, i.e. the deposit mass is conformable, as Brain (1958) originally suggested, and not unconformable as Robinson (1962) viewed it.

(14) The upper chocolate brown breccia, of the Fossil Deposit, probably accumulated in a void caused by the compaction of the underlying deposits, rather than in a void caused by collapse of the underlying deposits into the underground system as proposed by Robinson (1962).

10.5 Evidence of Climatic Oscillations

It has been mentioned that breccia matrix analyses have been used to make various climatic influences. As doubt has recently been thrown on these interpretations they will not be discussed.

10.5.1 Re-solution features on many travertine masses in the cave system indicate that water levels in the caves have fluctuated in the past.

10.5.2 Such fluctuating water levels are best explained by climatic oscillations which affected the hydrological regime of the Sterkfontein area.

10.5.3 Water level fluctuations have occurred at three detectable levels in the cave system. The two upper-level examples indicate two climatic changes each; the low level fluctuations indicate only one definite climatic oscillation.

10.5.4 All three sets of water level fluctuations occurred prior to 50 000 years before present. The upper level fluctuations probably occurred before the bone-bearing breccia accumulated, whereas the lower two sets occurred after this breccia had accumulated (bone-bearing breccia dated variably between 1,75 and 2,5 million years before present).

10.5.5 The climatic fluctuations evident from the past lake levels cannot at present be equated with the other evidence of climatic change from the Transvaal.

10.5.6 Variations in the thickness of successive travertine deposits, indicating variation in either the rate of deposition or the duration of deposition, also indicate climatic fluctuations.

10.6 Conclusion

The two hypotheses being tested in this thesis can now be evaluated in the light of the conclusions listed above. The two hypotheses are

1. That the Sterkfontein cave system fits the models of cave development established elsewhere in the world.

2. That the Sterkfontein cave system, like other cave systems in the Transvaal, preserves evidence of climatic oscillations.

It is apparent from the conclusions that the first hypothesis may be only partially accepted, since the major cavities of the system are unique, having developed along a series of fracture zones. The minor cavities, however, fit most closely the theory of cavern development in dipping rocks as proposed by Ford (1971). Also, Sterkfontein fits Davis' very general 'two-phase' theory of cavern development (Davis, 1930), since it is almost entirely a phreatically formed cave.

In relation to the second hypothesis the conclusions indicate that it can be accepted. Distinct changes both in the volume of calcium carbonate deposition, and in the cave water levels have undoubtedly occurred. Such changes can best be explained in terms of changes in surface climatic conditions.

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