THE GEOLOGY OF THE TRANSVAAL APE-MAN-BEARING CAVE DEPOSITS

With 81 Figures, 129 Photographs, 4 Charts
and a geological map

All photography is by the writer
unless otherwise stated.

C. K. BRAIN

Department of Vertebrate
Palaeontology and Physical
Anthropology,
Transvaal Museum,
PRETORIA

One of the specimens that has provided the Transvaal sites with their particular interest and value : a *Paranthropus* skull from Swartkrans.

Photograph by Dr. J. T. Robinson.

PART 1 : PRINCIPLES AND METHODS.

Contents

Part I

Residual cave earth . . .

Introduction.

The object of the investigation

The remains of the South African fossil ape-men, found in ancient limestone caves of the Transvaal, have stimulated an immense amount of world-wide interest and have added greatly to man's knowledge of his primitive beginnings. But while various aspects of the fossils themselves were being intensively studied, the geological aspects of the caves, from which they came, were being badly neglected. This was not, by any means, because geological information was not required; on the contrary it was most important to know how old the fossils were, and to establish what the climate and environment was like when the animals were alive. Realising that this sort of information could only be obtained by systematic enquiry, Dr. J.T. Robinson invited the writer to do research on the project that forms the basis of this thesis.

As a result of generous financial assistance from the Wenner-Gren Foundation in New York, a laboratory was equipped at the Transvaal Museum in Pretoria and work was started in February 1954.

Scope of the enquiry.

It was previously intended to include an evaluation of the Taung deposit in the monograph to be published on the Transvaal sites. When work was started however it was found that since the Taung cave was not in dolomite, the geological problems involved there were quite different from those of the Transvaal sites. The results of the Taung investigation will therefore be published separately; the present work is concerned only with the Transvaal caves.

The Transvaal sites in question are Sterkfontein, Swartkrans and Kromdraai, all three being in the Krugersdorp area, and the Makapan Limeworks in the Potgietersrust district. The relative positions of the Makapan and Krugersdorp areas are shown in Figure A .

This thesis is in two parts: the first [illegible] concerned with principles and methods, the second with the site descriptions and correlational conclusions. It was found necessary to include so extensive a section on principles and methods because no systematic work had previously been done on South African caves and their contents. New techniques had to be developed for the climatic evaluation of

the cave deposits . . .

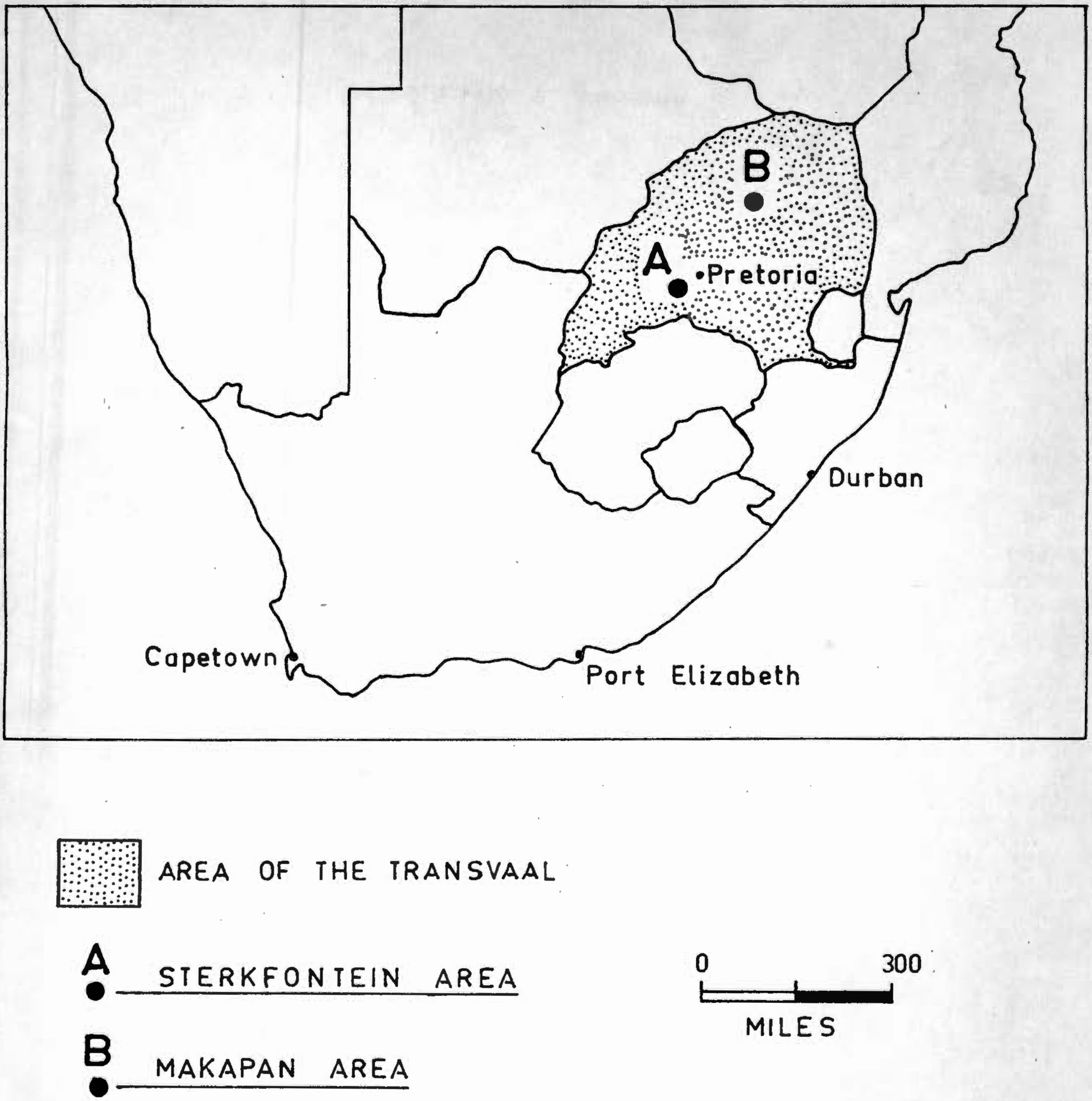


FIGURE **A**

MAP SHOWING THE LOCATIONS OF THE STERKFONTEIN (Krugersdorp) AND MAKAPAN (Potgietersrus) AREAS the cave deposits; these are fully described in Part I of the work. Investigations on modern caves had to be carried out so that the original forms of the fossil caves could be visualised. Bone accumulations in contemporary caverns had to be studied in order that the origin of the fossilised collections might be better understood.

Part II is concerned with systematic descriptions of the various cave sites. Results are presented of the analyses that were designed to throw light on the nature of the climate that prevailed when the deposits accumulated.

In the final chapter, the evidence of the fossil fauna, the past climate and the cultural material from the deposits is combined. Conclusions are then drawn on the correlation of the deposits and the age of the entire sequence.

The use of certain terms.

In this work the following terms have been used in particular senses :

1. "Dolomite" should be taken throughout to imply "impure dolomitic limestone".

2. "Cave breccia" is used to describe any sediment or debris that has been calcified inside a cave.

3. "Water table". It may be argued that a true water table cannot be said to exist in a limestone formation. At the same time, although limestone may not have a primary porosity, it has, in cavernous areas, a well developed secondary porosity. In all speleological literature the term "water table" is thus used to denote the contact between the vadose and phreatic zones, where this exists in a cavern. A similar usage of the term is employed here.

4. Kageran and Kamasian. In literature on South African quaternary chronology it is customary to use these East African terms to denote stages in the Pleistocene timescale. Where East and South African climatic episodes appear to correspond in time, then it is reasonable to apply the East African terms to the Transvaal in their strictest, or climatic, senses.

5 "Aven". Throughout this thesis the term "aven" is used to denote an enlarged vertical joint in the limestone. It is therefore applied in its English sense and should not be confused with the French term "aven" meaning a pothole.

Special Note

The discovery, by the writer, in May 1956 of unquestionable stone artefacts in the australopithecine breccia at Sterkfontein, has necessitated the revision of a number of theories previously held. In Chapter 4 consideration is given to the origin of bone accumulations in the ape-man bearing cave deposits. It was suggested that some of the accumulations may have been built up by *Australopithecus*. In view of the Sterkfontein discovery, however, it now appears that the caves may well have been primitive human occupation sites and that the ape-men formed part of the human diet.

Acknowledgements

Grateful acknowledgement for financial assistance is made to the Wenner-Gren Foundation for Anthropological Research, New York, and to the South African Council for Scientific and Industrial Research. Without this assistance the investigation could not have been undertaken.

The writer would like to express his thanks to Dr. J.T. Robinson who made the necessary arrangements for the work to be started; also to the authorities of the Transvaal Museum for the laboratory space in their building.

Thanks are due to Professor R.A. Dart for his permission to work at Makapan; to Dr. R.F. Ewer and my wife for their constant assistance; to Mr. Jack Scott for his generous gift of a power drill and to all of the following people for the assistance they have given in various ways: Professor G.B. Barbour, Dr. K.P. Oakley, Dr. V.F. FitzSimons, Mrs. Hemens, R.J. Mason, Dr. H.B.S. Cooke, Dr. J.D. Clark, A.R. Hughes, B.J. Grobbelaar, Dr. G. Bond, Dr. Len Freedman, L.E. Collins, Dr. D. Dodds, Miss Jean Humphries, A.B.A. Brink and Daniel Mosehle.

1.

MODERN CAVE FORM IN THE TRANSVAAL DOLOMITE

The object of the enquiry.

The fossilised remains of the Transvaal ape-men have all been found in the consolidated fillings of very ancient limestone caves. Due to their great age, these caves have suffered seriously from the effects of the weather: in every instance erosion has removed the greater part of the original cave roof, leaving the cave filling exposed on the surface. At such sites as Kromdraai A, the only indication one has that a roof ever existed is that the walls enclose deposits that could only have been produced in a closed chamber.

If one is to understand the contents of such relic-caves, then it is essential to be able to reconstruct the sites as they were when accumulation was proceeding. Reconstructions are only possible when one has some knowledge of modern cave form. Consequently, the writer has examined as many contemporary caves as possible. Conclusions concerning them are now presented.

Characteristic cave form . . .

Characteristic cave form

Due to the complexity of the factors that influence the development of solution chambers in the Transvaal dolomite, it is not easy to generalise on characteristic cave form. The angle of dip of the dolomite, the distribution of major chert bands within it, and the incidence of both joint and fault planes, all combine to determine the structure of any caverns that may happen to be developed. Nevertheless, so far as this investigation is concerned, only two dolomite regions - in the Krugersdorp and Potgietersrust districts, need to be considered in detail. In both these areas the dolomite is of similar character, in so much that its bedding planes are clearly demarcated by numerous but generally thin bands of chert, while the entire formation is found to dip at a fairly shallow angle. Under these conditions, the solution chambers developed appear to take the characteristic forms that will now be discussed.

Consider the case of a typical irregularly-shaped cavern below the surface of the dolomite. From the point of view of this enquiry, such a cavern only becomes significant when it acquires an opening to the surface, serving to allow surface derived material to enter the main chamber. The way in which the initial cave entrance develops is found to be very largely determined by the surface topography of the area. Where the country is relatively flat or undulating, as in the Sterkfontein area today, it is the roof of the cavern that approaches closest to the ground surface. This is shown in Fig. 1. Thus the cavern opens via its roof. In more rugged terrain, however, as is encountered to the north of Sterkfontein and in the vicinity of Makapan, the valleys themselves have been very deeply incised, with the result that a side wall of the cave frequently comes closer to the surface than does the roof. Such a state of affairs is shown in Fig. 2. In this case then, the most usual opening is a lateral rather than a vertical one. Typical views of the two types of countryside responsible for the different cave forms are shown in Photographs 1 and 2. The writer feels that the majority of South African dolomitic caves can be divided into ~~the~~ two groups depending on the nature of the topography in which they are developed. These two groups will now be discussed separately.

Caves occuring . . . .

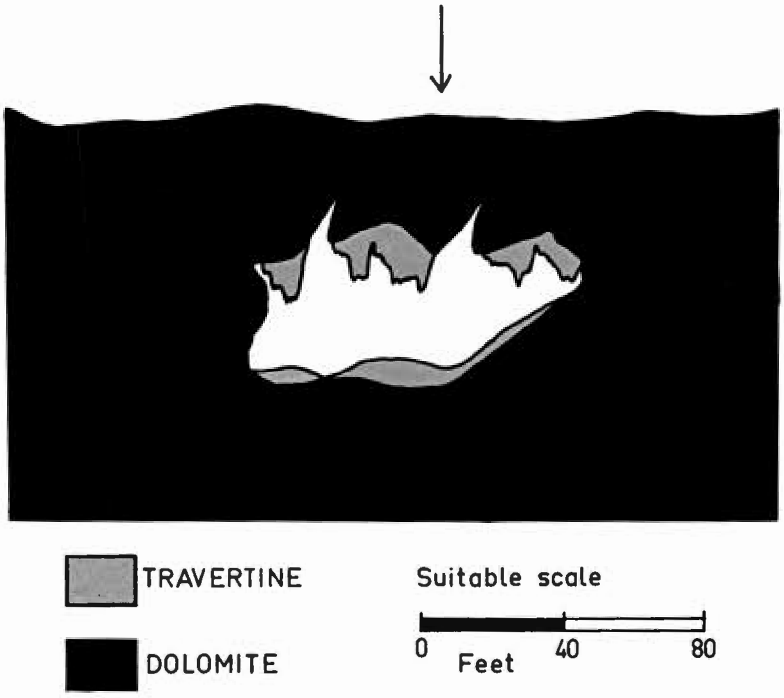


Figure 1.

A vertical section through a cavern developed beneath flat country, showing how the roof approaches closest to the surface.

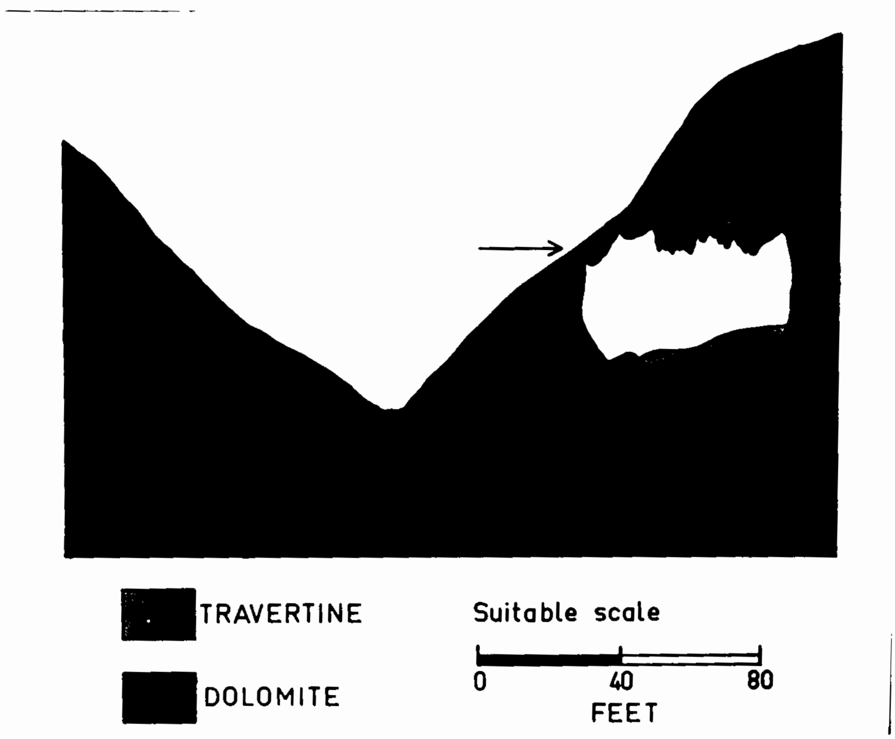


Figure 2.

A vertical section through a cavern developed in mountainous country, showing how an opening may be formed by way of a sidewall.

Photograph 1.

A general view of the undulating dolomite countryside in the Sterkfontein area.

Photograph 2. Rugged dolomite country north of Sterkfontein.

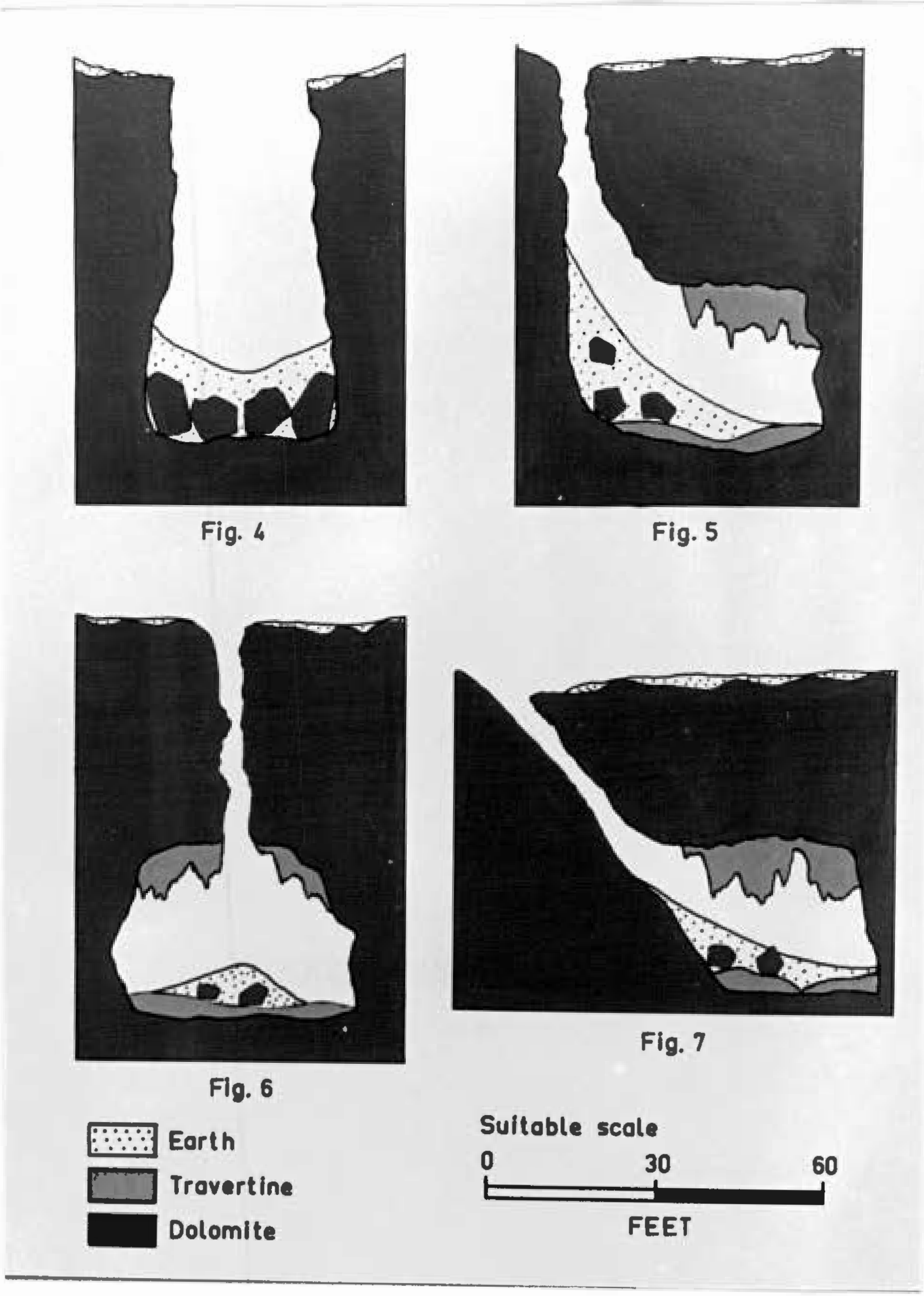


Figure 3.

Simplified vertical sections through the various cave types characteristic of flat dolomite country.

Fig. 4 : the open sinkhole. Fig. 5 : the vertical shaft.

Fig. 6 : the bottleneck. Fig. 7 : the inclined passage.

<u>Caves occuring in relatively flat country</u>

Caves developed where the surface relief is slight may be classified as follows:

(a) caverns opening more or less directly to the surface.

(b) caverns connected to the surface by passages or gallery systems.

(a) In the case of those caverns that are found to have a very direct connection with the surface, it is usual to find that the greater part of the cavern roof has disappeared through the combined effects of dissolution and collapse. This results in a more or less vertical-sided crater whose diameter has been determined by the size of the original cavern. Such "sink-holes" are common in the dolomite south of Pretoria, but perhaps one of the most spectacular examples is the chasm near Kalkheuwel, known as Klinkgat which descends vertically for 220 feet.

Vertical sink-holes, as shown in Fig. 4, appear to have developed practically wherever the dolomites occur and may be seen even in the most arid regions such as at

Annisfontein . . .

Annisfontein in the Richtersveld. On the Otavi Plateau, very fine examples were observed, particularly those at Harasib, Otjikoto and Guinas. The particularly large Guinas sink-hole is shown in Photograph 3.

Open caverns of this type vary considerably in depth. Although seldom less than 30 feet, some like the Guinas crater descend to over 600 feet and then ramify considerably. A common feature of the deeper sink-holes is that they are filled with water, while the bottoms of shallower ones are generally littered with roof collapse debris and abundant surface derived material.

(b) The opening of a cavern upwards to the surface does not necessarily mean that the entire roof will invariably collapse. Quite frequently, the link is effected by means of a passage or gallery system either vertical or inclined and leading downwards from the surface.

The case of the vertical, or shaft type of opening, is shown diagramatically in Fig.5. Such shafts are particularly common in the Sterkfontein area and are frequently found to connect with the main chamber at one side of the roof, thus making it easy for the speleologist to enter. In some cases however, such considerate foresight is decidedly lacking, and the shaft opens centrally into

Photograph 3.

The Guinas Sinkhole near Tsumeb, South West Africa.

An example of a large and exceptionally deep water filled sinkhole.

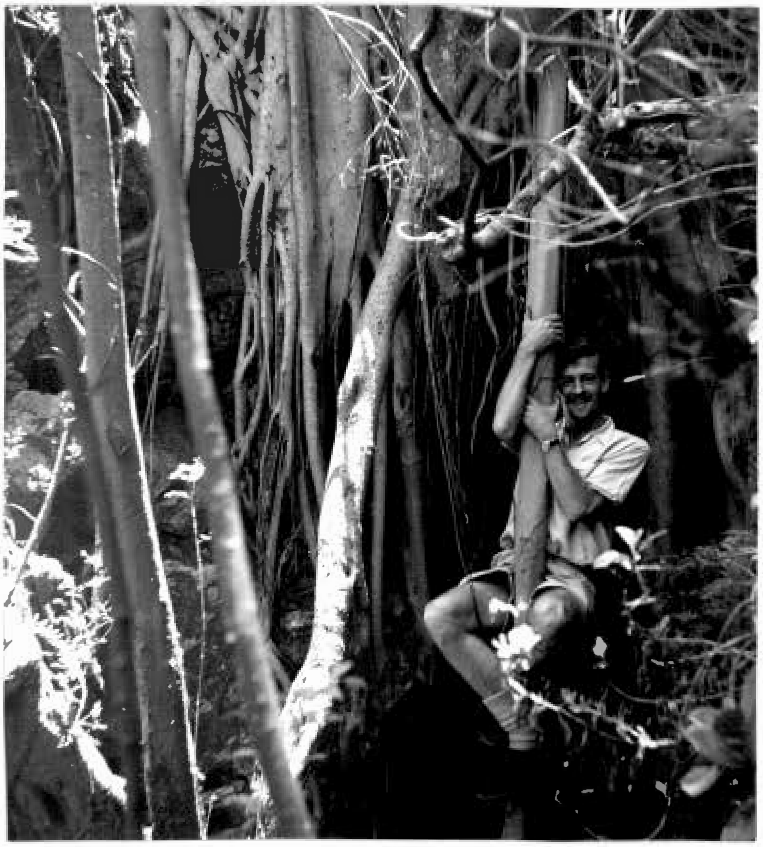
the main chamber forming a perfect bottleneck. This cave form is shown in Fig.6, while actual examples are admirably provided by van Wyk's Main Cave and the Uitkomst Bottleneck, both of these being in the Krugersdorp area. In some cases shafts and bottlenecks may be regarded as transitional stages in the formation of sink-holes. Usually however, their form is maintained until the lower cavern has been practically filled with loose material.

The shafts are found to vary considerably in cross section from a few feet as at Swartkrans, to about 30 feet as in Uitkomst D. The latter example, shown in Photograph 4, is interesting because of the great profusion of tree-roots that make their way down the shaft, and provide easy access to the cavern.

Photograph 5 shows the entrance to a typically vertical shaft in the Sterkfontein area. Such entrances often occur in slight depressions on the surface and are usually surrounded with trees which provide shelter for animals in an otherwise rather treeless area.

The shafts are variable in depth from about 30 feet in numerous examples about Krugersdorp, to the alarming figure of over 500 feet in the West Driefontein Cave recently explored by the South African Speleological Association.

An alternative . . .



Photograph 4.

The vertical shaft of the Uitkomst D Cave, showing an abundance of free-hanging tree roots.

Photograph 5.

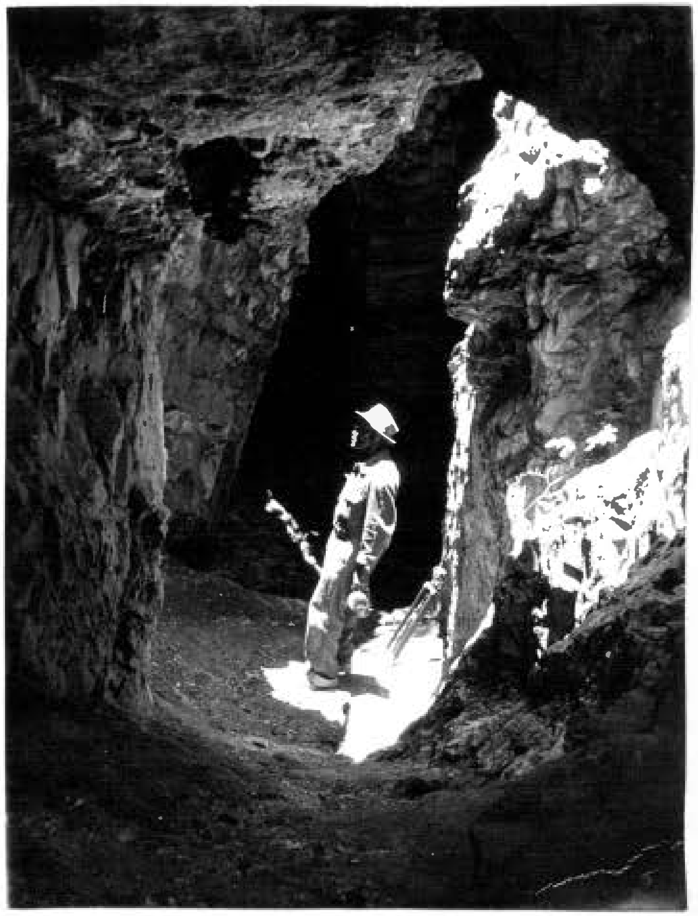
A characteristic surface opening to a vertical shaft in the Sterkfontein area.

An alternative type of surface opening which, although developed in fairly flat country does not appear to be very common, is the inclined passage or gallery system as is found at Sterkfontein itself. Diagrematically, this cave form is shown in Figure 7. It appears that the floor slope of this type of passage is generally determined by the angle of dip of the chert bands enclosed in the dolomite itself. The direction of the passages is likewise determined by the orientation of the master joints in the country rock. Since these joints are commonly aligned at right angles to one another, a gallery system whose passages form a rectangular pattern is a not infrequent occurrence.

Photographs 6 and 7 show one of the entrances to the modern Sterkfontein cave. It should be realised that the final break-through of this passage to the surface did not occur naturally, but was brought about by lime-mining operations some years ago. It is very probable nevertheless that the lime miners only accelerated a process that would have ultimately taken place in any case.

At Sterkfontein and elsewhere, the passages leading down from the surface open into extensive caverns at depths occasionally exceeding 100 feet. The form of these caverns is much influenced by the structure of the dolomite, particularly the incidence of the more massive

chert bands . . .



Photographs 6 and 7.
The surface opening to
the underground cavern
system at Sterkfontein.

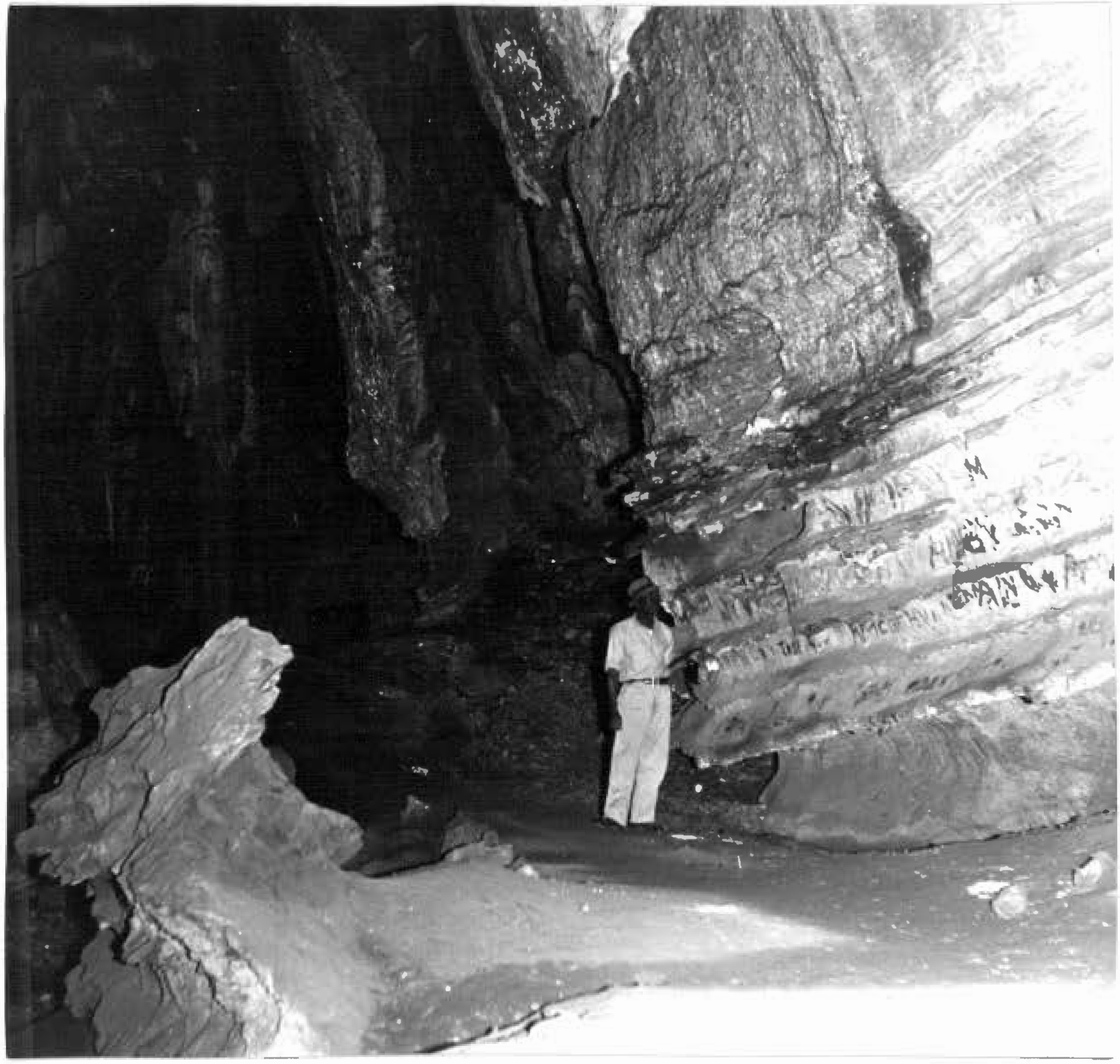
chert bands. Photograph 8 shows the interior of the modern Sterkfontein cave. This is an example of a cavern where travertine deposition has not been abundant. Others in the same area, such as the van Wyk's Main Cave, shown in Photograph 9, contain travertine ornamentations in a most spectacular profusion.

The deeper caverns like West Driefontein and the modern Sterkfontein descend to below the level of the water table, and open underground lakes occur, as shown in Photograph 10. As a result of an investigation carried out by members of the Speleological Association, it has been established that the surface of this water is at almost exactly the same level as is the main spring in the Blaaubank River nearly a mile away.

Caves occuring in rugged or mountainous country.

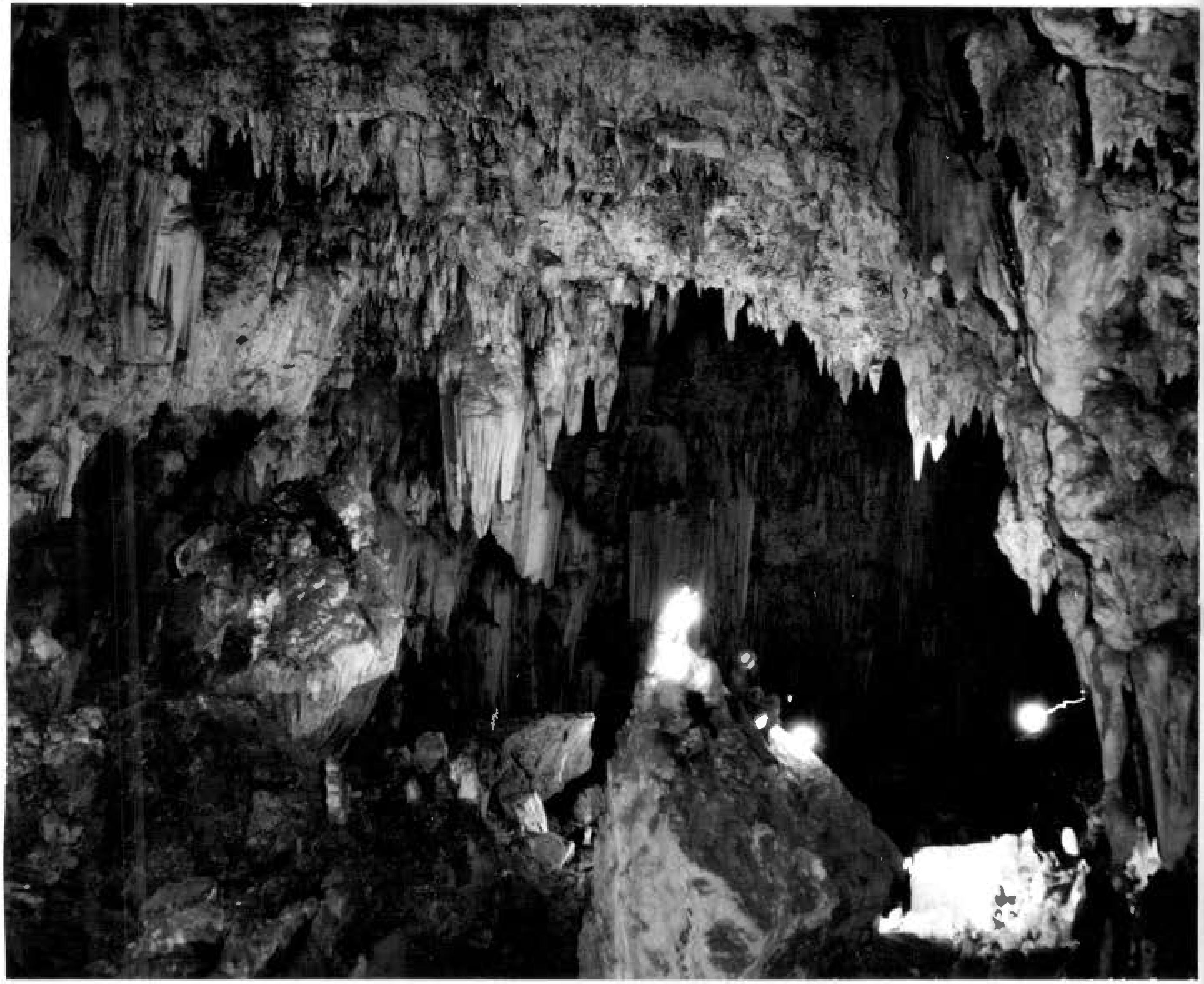
As opposed to the undulating country in the vicinity of Sterkfontein, the upper levels of the dolomite horizon, where the "giant chert band" is developed to the north, give rise to very mountainous and broken topography. Similar relief is to be found at Makapan and in the Eastern Transvaal wherever the dolomite is exposed. As has been

mentioned . . .



Photograph 8.

A general view inside an underground cavern at Sterkfontein. This is an example of a cave largely free of travertine.



Photograph 9.

A general view inside the main chamber in van Wyk's Main Cave in the Sterkfontein area. This is an example of a cavern rich in travertine.

Photograph by J. C. Viljoen.

Photograph 10.

Open phreatic water standing in the main chamber at Sterkfontein.

mentioned previously, this type of country, with deeply incised valleys, often causes a cavern present below the surface to open sideways rather than vertically. The experience of the writer indicates that the cavern often opens very directly to the surface by means of a break-through of one of its side walls: a state of affairs shown diagramatically in Figure 8. Good actual examples are provided by the Uitkomst A, C and G caves and by the "Wet" and "Dry" caves near Pilgrim's Rest.

With this type of surface opening a fairly large entrance, as shown in Photograph 11, is a characteristic feature. Immediately inside such an entrance, an inclined scree slope is usually developed leading down to the floor of the main chamber at a lower level.

Although this appears to be the most characteristic cave form in the sides of steep valleys, openings more typical of flat country are not entirely absent.

Subsidence caves . . .

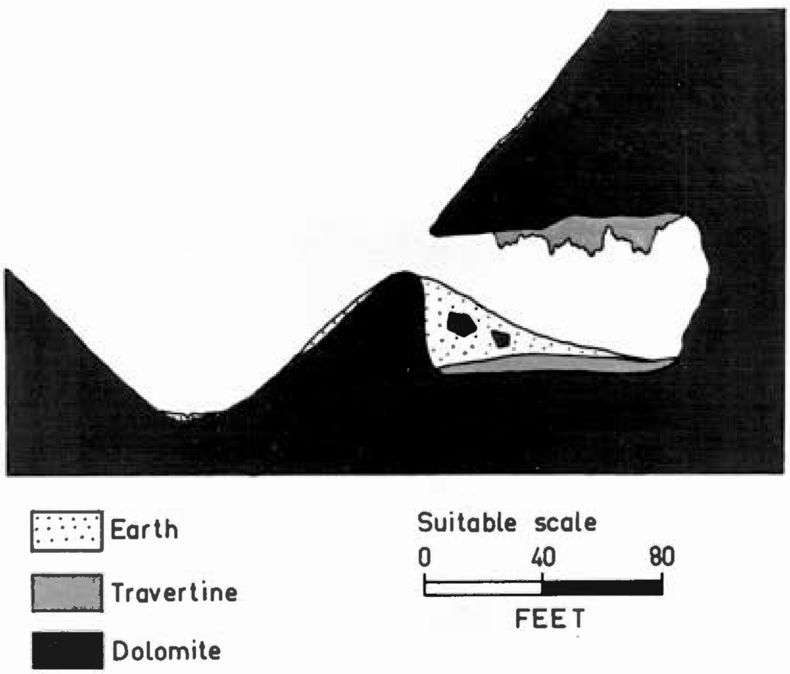
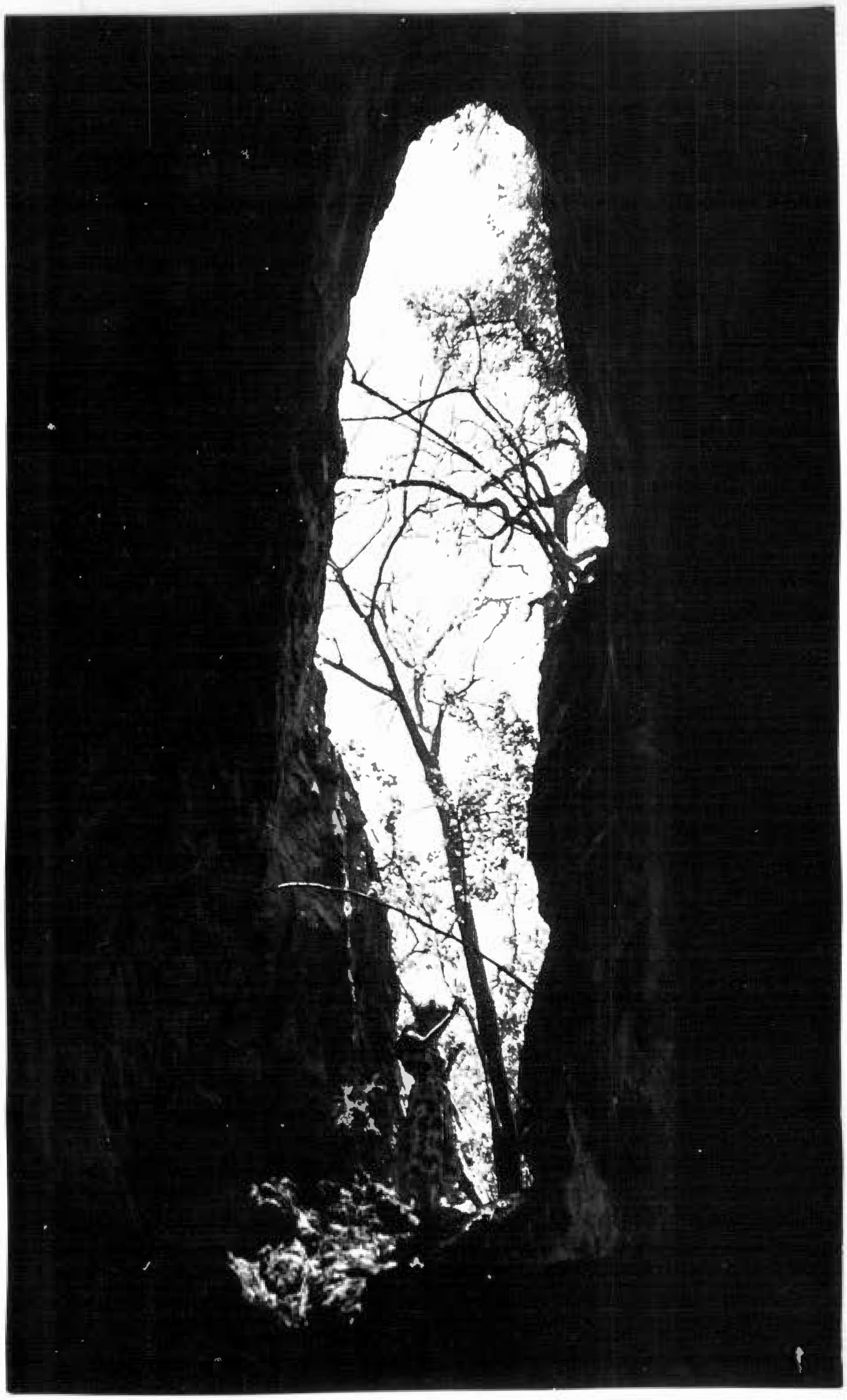


Figure 8.

A simplified vertical section through a cavern opening on a steep slope showing the characteristic scree-slope developed inside the entrance.



Photograph 11.

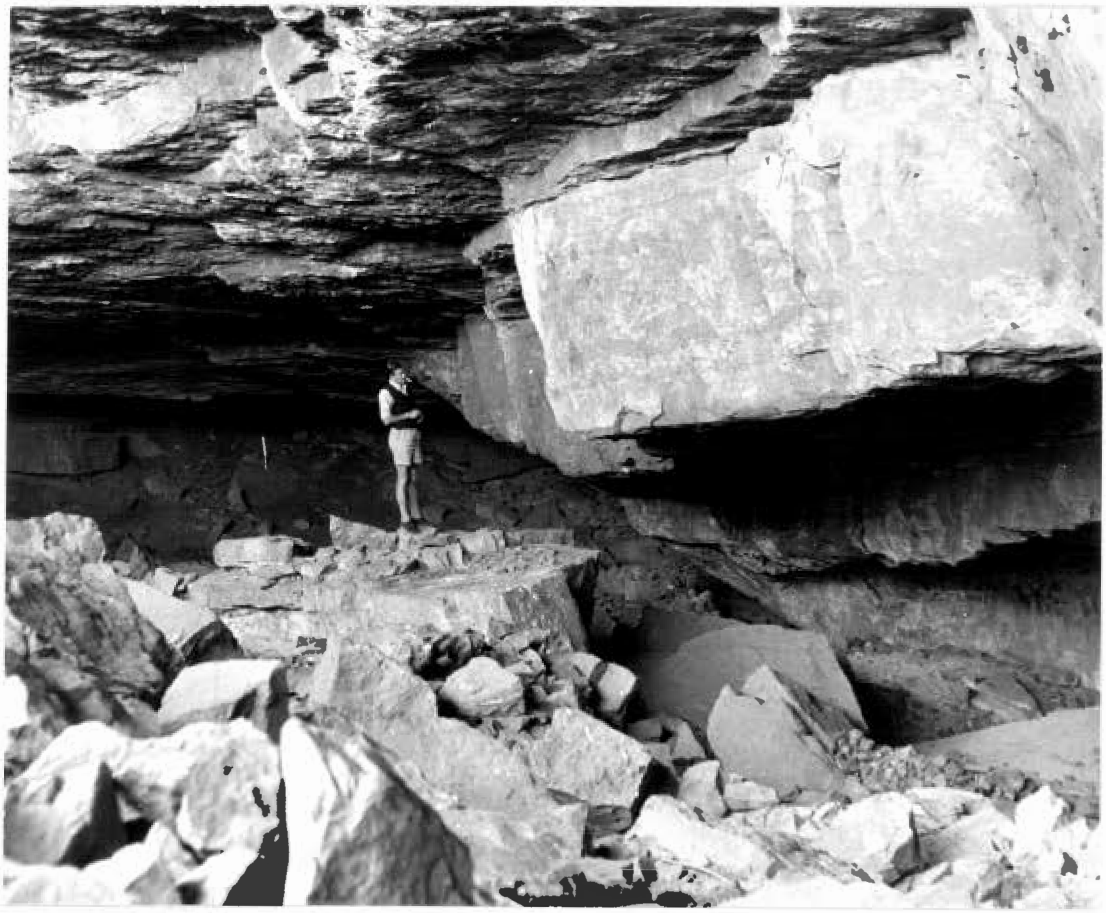
An example of a doorway type of opening developed in the side of a steep valley. Uitkomst C Cave, Transvaal.

Subsidence Caves

Occasionally, caverns are encountered in the dolomite that are clearly not solution chambers. They have come about by collapse, since irregularities in their roofs can be matched by similar contours in the floors. These collapse chambers can only originate when a solution chamber has developed at a greater depth and its roof has become unstable. Although they may form irrespective of topography, they are more likely to develop close to the edge of a steep valley, which leaves one side of the dolomite unsupported.

The most important single feature of a subsidence chamber is the structure of the roof. In evenly-bedded dolomite the falling block is likely to part from the hanging roof along a bedding plane. Thus the contour of the roof is likely to be determined by the bedding planes of the country rock. This is not true for solution chambers, except where the bedding planes are demarcated by substantial chert bands, representing insoluble barriers.

In actual fact, a subsidence roof is frequently stepped, as the fracture plane changed from one bedding plane to another. This is shown in Photograph 12, taken inside the Makapan Historic subsidence cave.



Photograph 12.

A characteristic subsidence chamber with abundant roof-fall blocks. Historic Cave, Makapan.

Other good examples of collapses are visible in Peppercorn's Cave and in the fossil caves of Sterkfontein, Limeworks, Swartkrans and Coopers B.

A brief summary of Characteristic modern cave forms.

A : Caves in flat or undulating country:

(a) Caverns opening directly to the surface: open sink-holes.

(b) Caverns opening indirectly to the surface:

1. Vertical shafts.
2. Inclined passage and gallery systems.

B.: Caves in hilly or mountainous country :

Lateral openings by means of the "doorway" type of entrance.

C : Caves developed independently of topography :

Subsidence chambers.

2.

ORIGIN AND DEVELOPMENT OF DOLOMITE CAVES

Some previous literature on the origin of limestone caves.

In 1930, W.M. Davis published the first comprehensive paper to deal with the origin and development of limestone caves. He recognised that caverns came about through the dissolution of the limestone by subsurface water. This water, however, acted in two distinct zones: the vadose and the phreatic. In the former zone, which is close to the surface, the water is transient, passing downwards through the rock whose cracks are normally filled with air. Lower down however the phreatic zone is encountered, which may be described as the zone of saturation. The contact between the vadose and phreatic zones is normally referred to as the water table, or the level at which the free water stands in caverns and fissures in the country rock.

Davis (1930) concluded that cavern development proceeded in two distinct cycles. The first occurred in the phreatic zone where the form of the cave was determined and where the various chambers and passages were excavated to their maximum size. The cavern system was then raised

above the . . .

above the level of the water table by regional uplift and the second cycle commenced. In the vadose zone, this second cycle was characterised by the deposition of cave travertines, and by the modification of passages by subterranean streams and rock falls. Davis considered that the entire development of limestone caverns could be associated with what he termed the "peneplain cycle" in the following way:

1. A network of fissures and passages develops in the phreatic zone below the surface of a peneplain.

2. The various openings are enlarged to their maximum proportions, while they are still below the water table.

3. Regional uplift raises the caverns above the water table, into the vadose zone.

4. Deposition of travertines occurs in the caverns.

5. The cave system is finally destroyed by surface erosion.

The sequence of events proposed by Davis was modified by J.H. Bretz, (1942). He suggested that an extra stage should be introduced into the cavern cycle, to explain the deposition of clay beds that he found almost completely filling cavern passages. This clay was considered to be partly residual and partly surface-derived, and was thought to have settled in the quiet water of the phreatic reservoir. Once the clay filled passages were raised into the vadose zone, streams would start to excavate the clay, and possibly even remove it.

Malott (1937) supported Davis' theory but suggested that vadose streams could develop underground courses along selected passages originally developed in the phreatic zone. In this way the passages would become greatly enlarged and more properly interconnected.

In opposition to the two cycle development of limestone caves various authors have put forward their views. Cvijic (see Sanders 1921) suggested that three ground-water zones would be present in limestones: the dry vadose zone, the zone of fluctuation and the zone of saturation. He considered that water in the vadose zone would mainly percolate downward, while horizontal movement would take place at, or just under the water table. So it would be at the level of the water table that the greatest development of cave passages would occur. A rather similar conclusion was subsequently reached by Swinnerton (1932, 1942).

Gardner (1935), on the other hand, considered that large caves were more likely to be formed above the water table, since he believed that phreatic waters were most commonly static. In fact he favoured a one cycle theory for cavern development and recognised that dripstones could be deposited in a cavern at the same time as it was being enlarged by vadose waters.

It will be appreciated that there is a certain amount of disagreement between authors on the subject of cave origin. The writer feels that much of this disagreement has been occasioned by the tendency of several authors to generalise too widely in an extremely complex subject. Limestone cavern form is often so diversified that examples can doubtless be found to fit any of the theories postulated. Thus the specific description of caves in a particular type of limestone seems to be of greater value than the generalisations on universal cavern form.

Suggestions on the origin and development of the Transvaal dolomitic caves.

The observations which follow on the origin

and development . . .

and development of Transvaal caves will be largely restricted to the examples available in the Krugersdorp and Makapan areas. In both these regions the dolomite is of a similar nature, in so far that chert bands are thin and numerous, while the bedding planes are inclined at a shallow angle.

At the outset, it is necessary to decide whether the large, irregularly shaped caverns, so commonly developed in the dolomite, are the result of solution above or below the water table. In order to decide this a knowledge of phreatic and vadose criteria is essential.

(a) Phreatic Origin Criteria

Cavern features which owe their origin to solution below the water table have been considered recently by Stone (1949) and Warwick (1953). In both these papers reference has been made to the criteria described by Bretz, (1942). These may be summarised as follows:

Bedding plane anastomoses
Joint plane anastomoses
Continuous rock spans
Pockets
Joint determined cavities

Tubes and . . .

Tubes and half tubes

Horizontal chambers in vertical beds

Spongeworks and Networks.

Such structures serve to make the internal contours of the cavern exceedingly complicated while features like anastomoses and networks are often unbelievably fragile. Delicate remnants of this sort were very probably developed by solution in quiet water, as is likely to be found in the phreatic zone.

(b) Vadose Origin Criteria.

According to Bretz, vadose features are commonly superimposed upon phreatic ones. Since vadose water is normally in transit, its erosive results are very different from the effects of solution in the phreatic reservoir. The delicate structures so characteristic of phreatic solution are most unlikely to occur in cavities of vadose origin. The reason for this is that vadose water enlarges a cavity not only by corrosion, but also by corrasion. Thus beds of clay previously deposited in passages may be deeply eroded, rock floors may be smoothed and 'rock mill' action developed, while the deposition of gravel beds is characteristic. The direction in which the water has flowed through a vadose passage can sometimes be established by examining structures known as 'scallops' or 'flutes' often developed on the walls and floors. These ripple-like structures are the result of the turbulent flow of water, and according to Coleman (1949) and Glennie (1950) they are asymmetric in cross-section with the steeper slope on the upstream side of the scallop.

According to Warwick (1953), it is possible in smooth tubular passages, where scallops are developed, to calculate the minimum velocity required for turbulent flow, and thus to gain some idea of past water velocities.

It appears, therefore, that a cavity which has been enlarged by vadose agencies is likely to have internal contours reflecting corrasion as well as solution. These contours are likely to be smooth and water-worn.

The Transvaal caverns

In considering the origin and development of the Transvaal caves, examples will be discussed separately from the relatively flat Sterkfontein area and from the more mountainous region at Makapan.

(a) Caves in the undulating Sterkfontein Area.

One of the most noticeable features of the larger caverns developed in the Sterkfontein area is the extreme complexity of their internal contours. In shape, these caverns are most irregular, and commonly have dead-end passages radiating from them in different directions. The main chambers themselves are often incompletely partitioned off by thin and very fragile 'curtains' of dolomite, as shown in Photograph 13. Fine grained earth is usually deposited evenly over the floor, while joint- and bedding-plane anastomoses are not uncommon. All these various features are best shown in those caverns that are today still at a considerable depth below the surface and close to the water table. The modern Sterkfontein cave itself is an excellent example. There can be no doubt that caverns of this sort are the result of solution in quiet water in the phreatic zone. The main Sterkfontein underground cave is still partly filled with water, and this water has been established by members of the Speleological Association to be at the same level as the main spring in the Blaaubank River, about a mile away. When this river has lowered its course by another

ten feet . . .

Photograph 13.
Fragile dolomite curtains or partitions rising from the phreatic reservoir in the Sterkfontein caverns.

ten feet the main cave at Sterkfontein will be almost completely drained of water and the phreatic zone will presumably have migrated into new chambers at a lower level. The present caverns will then be left largely dry.

When caverns are dissolved in the phreatic zone they do not necessarily have any connection with the surface. Evidence of unopened caves below water-level has been gained by mining operations in North Wales and Derbyshire as described by Warwick, (1953). Similar occurrences in Tennessee and Mexico have been reported by Moneymaker, (1941 and 1949).

Davis (1930) and Bretz (1942) seem to consider the most likely way that caverns become raised from the phreatic into the vadose zones is by regional uplift. This does not appear to be a likely possibility in the Sterkfontein area, and the writer feels that it is much easier to explain the drying out of caves by the lowering of the water table itself, than by the raising of the entire terrain. Such a lowering will inevitably be effected by the denudation of the ground surface in general and the incision of the river valleys in particular.

Once out of the phreatic zone, the internal contours of a cavern appear to be modified by vadose

action . . .

action of a rather particular kind. The writer contends that subsurface vadose erosion should be divided into two categories: that brought about by true underground streams running in graded channels, and that caused by meteoric water percolating downward from the surface, to replenish the phreatic reservoir. It appears that the effects of true underground streams are practically negligible in the Sterkfontein area but this is not the case for the vadose action of water seeping down from above. In limestone rocks generally water is found to percolate downwards by means of the joint and bedding planes. This is because most limestones have a high secondary porosity, but a low primary, or intergranular, one. Nevertheless, recent work by Hohlt (1948) has shown that the pore spaces themselves of certain dolomite rocks tend to become enlarged by solution, providing the rock with a high primary porosity. In any event surface water will tend to seep down into the dolomite. This will naturally occur all over the dolomite area, but the seepage will be greatly facilitated by the presence of a cavern below the surface. This is because the water is able to drip out at the bottom of the seepage passage almost as fast as it comes in at the top. Thus relatively free movement of water through the dolomite immediately above a cavern will undoubtedly result in the rapid enlargement of the seepage

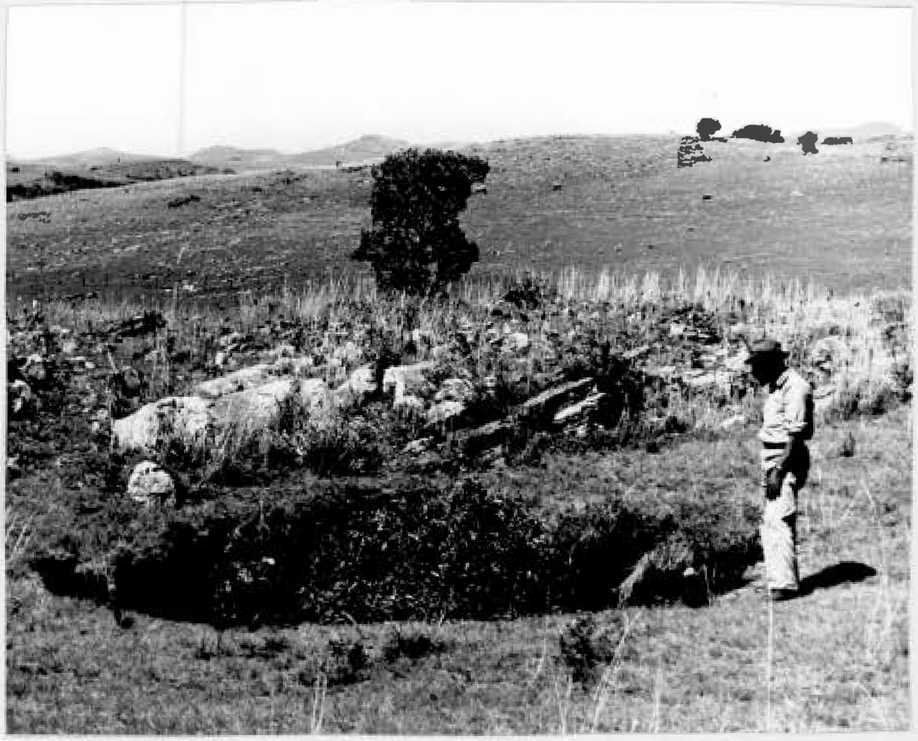
channels . . .

channels themselves, especially since meteoric water is capable of its maximum solvent action immediately after it has passed through the surface soil. It is found that pure water can only dissolve between 14 and 74 parts per million of calcium carbonate. Dissolved carbon dioxide, however, makes the water capable of taking much larger quantities into solution. Adams and Swinnerton (1937) demonstrated that the most important source of carbon dioxide in ground water was soil air, where the concentration of the gas is from 25 - 90 times that normally found in the atmosphere. Thus, as the water passes through the soil it becomes super-saturated with carbon dioxide, and is thus capable of dissolving very considerable quantities of calcium and magnesium carbonate. Adams and Swinnerton reported that ground waters normally dissolved about 400 parts per million of calcium carbonate, while the highest figure, obtained from Kentucky was 1,931 p.p.m.

In the Sterkfontein area, the most obvious result from the solvent action of the downward seeping vadose water is the development of the shafts or passages linking the main cavern with the surface. Such passages are occasionally inclined and determined by the bedding planes, or they are vertical and independent of such structures. English equivalents of these shafts and passages, known as "avens" have been described by Warwick (1953), while similar structures in Kentucky have been discussed by Pohl (1955).

The other important effect of moving vadose water, especially once the connection with the surface has been somewhat enlarged, is that it tends to destroy the very delicate structures in the cavern that have resulted from solution in the phreatic zone. The joint and bedding plane anastomoses become widened and enlarged, the fragile dolomite curtains become broken down, and the internal contours of the cavern generally are somewhat smoothed. The effects of this degradation process are very noticeable in caverns with a fairly direct connection with the surface that has existed for some time. In deep caverns, like the modern Sterkfontein one, the process is only beginning. At the same time cave travertines may be deposited in great profusion.

In the Sterkfontein area caverns usually appear to develop their first openings to the surface by means of the shafts and passages already discussed. An example of a very newly acquired opening is shown in Photograph 14. Such small openings are then commonly enlarged by further dissolution and collapse. Occasionally before a shaft or



Photograph 14.

A newly developed shaft opening in undulating dolomite country. Cooper's Sinkhole near Sterkfontein.

passage opens to the surface, part or all of the cavern roof collapses. If a slab of rock, not extending to the surface, falls into the lower solution chamber, then a subsidence cave will be produced higher up. If however, the entire roof subsides, then an open sink-hole will result. The form and occurrence of sink-holes South of Pretoria has been discussed by Enslin (1955) who was mainly concerned with the embarrasment that such collapses occasion when they take place underneath a building. Roof collapse is a very important feature of dolomite cavern development and many of the structural principles involved are well known as a result of investigations carried out in mines. A useful early work on the subject was published by Lane and Roberts (1929) while two papers by Davies (1949, 1951) deal exclusively with the structural principles involved in American caves. These were briefly summarised as follows:

"1. The rock strata over the cavern act as uniformly loaded beams either fixed or cantilever.

2. The beams sag under their own weight to a point where failure takes place.

3. The critical time in the development of breakdown is the point at which a fixed beam sags and separates into cantilevers. If the cantilevers are developed in nearly equal proportions across the passage it will generally stand; if it is unequally developed, collapse will take place

along . . .

along the longer segment of the cantilever.

4. The relation of beam thickness to length, as well as the sag causing failure, can be approximated by applying the engineering formulae developed for ordinary structural beams."

Once open to the air, a cavern begins to fill up with material derived from the surface and from the cave roof. This will continue until the available space is completely occupied. Then, with the passage of time, surface denudation slowly removes the overlying dolomite and exposes the cave filling on the surface. Eventually this too disappears and the cavern with its contents ceases to exist.

A summary of events in the development of caves in the Sterkfontein area.

In this summary reference should be made to the vertical sections shown in Fig.9.

Stage 1. A large and very irregularly-shaped cavern develops in the phreatic zone beneath the water table, as shown in Section A. Residual earth is deposited on the floor.

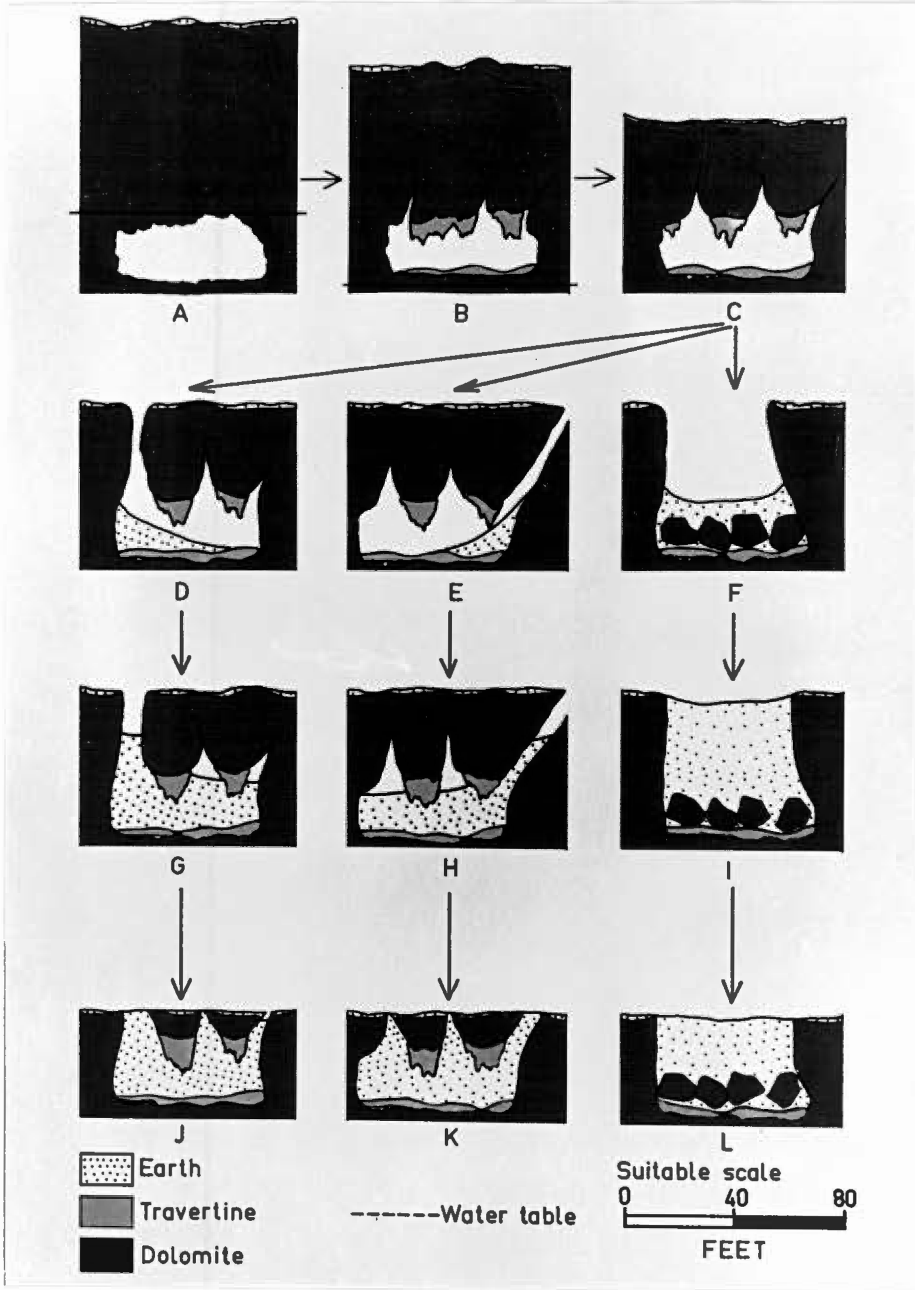


Figure 9.

Suggested stages in the development of the three principal cave types characteristic of flat or undulating dolomite country: the vertical shaft, the inclined passage, and the open sinkhole. The sections are vertical.

Stage 2. Surface denudation lowers the level of the water table and brings the ground surface closer to the cavern. The cavern is then in the vadose zone as shown in Section B. Cave travertine form.

Stage 3. Selected passages above the cavern are opened and enlarged by percolating vadose water. Surface denudation continues to lower the general ground surface. Section C.

Stage 4. The cavern opens to the surface in one of several possible ways: by a vertical shaft (Sect. D.), by an inclined passage (Sect. E.) or by a total roof collapse (Sect.F.)

Stage 5. Surface derived material gradually fills the cavern. Sections G., H. and I.

Stage 6. The lowering of the ground surface by erosion starts to destroy the cave and its filling. Sections J., K. and L.

. . . .

(b) Caves in mountainous areas

As far as the early stages of cavern development are concerned the writer considers that there is no significant difference between the examples developed in mountainous and flat areas. The difference comes in at the stage that the caverns open to the surface. In gently undulating sountryside caverns must of necessity open from above. In more mountainous country however the valleys have been so deeply incised that their bases are often at a lower level than are the caverns themselves. Thus it is possible for a cavern to open sideways instead of upwards.

In mountainous country the internal contours of the caverns have definitely been smoothed by vadese action, as in the Sterkfontein area, but the development of vertical shafts and inclined passages appears to have been somewhat restricted. This is doubtless due to the fact that, in mountainous country, surface run off is much greater than on flatter ground, which results in very much less water percolating dowmward into the dolomite at the level of the caves than is the case in a flat area.

Normally, the large caverns open more or less directly to the surface on steep hillsides. Immediately inside the rather large entrances scree-slopes are developed, built up of surface soil and roof rock fall material.

According to King (1951) surface erosion in the Makapan area is effected by parallel scarp retreat. As this occurs, the caves are gradually destroyed by the progressive breaking back of their entrances, until only remnants are left as at the Limeworks today. The removal of caves in this way was described from Tennessee by Barr, (1954).

A summary of the development of caves in mountainous country.

Reference should be made to the vertical sections shown in Figure 10.

Stage 1. A large and irregularly shaped cavern develops in a phreatic zone beneath the water table as shown in Section A. Residual earth may be deposited on the floor.

Stage 2. Valley deepening lowers the water table and

brings the ground . . .

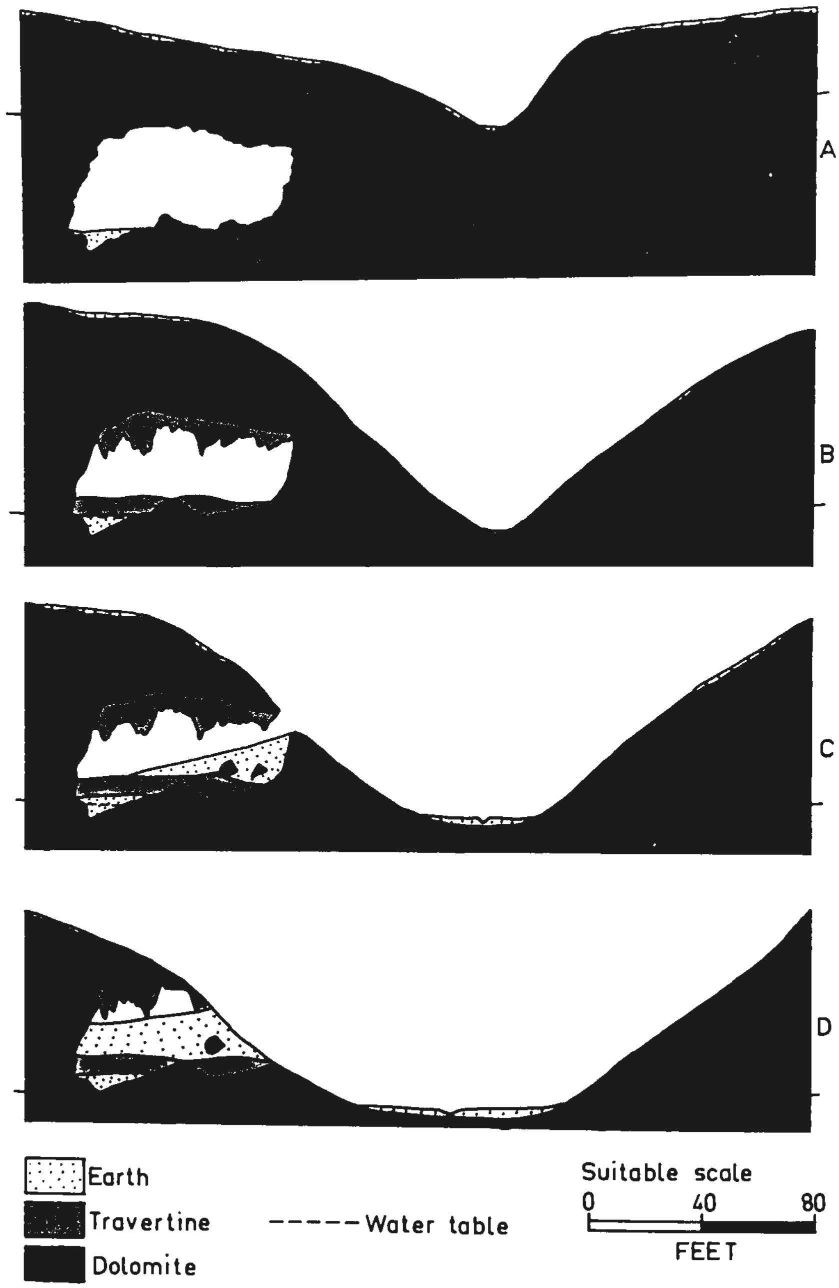


Figure 10.

Vertical sections showing the suggested stages for the development of a cavern in mountainous country.

brings the ground surface closer to the cavern, which is then in the vadose zone as shown in Section B. Cave travertine form.

<u>Stage 3</u>. The widening of the valley causes a lateral opening to develop into the cavern, which begins to fill up with material from the surface and the roof. Section C.

<u>Stage 4</u>. Continued valley widening slowly destroys the cavern and its contents. Section D.

<u>Cave development in relation to Pleistocene erosion levels.</u>

Investigations in Europe and America have shown that major caverns are often developed at levels determined by erosion surfaces. Sweeting (1950) concluded that large caverns in North-west Yorkshire occur at well defined levels, which are probably connected with stages in the deepening of the Dales. From America, Davies (1953) stated that "The caverns of the Appalachians are developed at uniform levels that are closely related to Pleistocene river terraces." It seems very probable that a similar

state of . . .

state of affairs may well exist in the Transvaal, although there is not nearly sufficient information to make any conclusions possible. Nevertheless it is interesting to notice how, in the Sterkfontein area, there is such a wealth of fossil caves, exposed on the surface today, whose fillings are all of approximately the same basal Pleistocene age.

3.

The Origin of Bone Accumulations in Caves.

Bone accumulations are commonly found in caves all over the world, but the ways in which they have been introduced vary considerably from one site to another. In deciding how a bone accumulation was formed, it appears that the most important single factor is the structure of the cave itself. Some caves, such as fissures and sink-holes, open to the surface in such a way that animals are unable to gain access to them. Others, however, are capable of providing efficient shelter for wild animals and men. Nevertheless, both types of cave are commonly found to contain bone accumulations, although the ways in which the bones have collected may be very different in each case. In fissures and sink-holes, the larger bones are usually concentrated by natural agencies, while in those caves that are normally used by animals, bone accumulations may be artificially built up. Thus, in the following account of bone accumulations, fissures and sink-holes will be considered separately from the shelter caves.

(a) Caves unsuitable for shelter or habitation.

Bone accumulations in fissures and sink-holes are usually built up in one of two ways: either animals accidentally fall down the shafts, or bones lying on the surface are washed in by water.

(1) Natural Death Traps

As has been mentioned previously, vertical shafts are a very common feature in the dolomite areas of the Transvaal. The writer has investigated the contents of a large number of such shafts and has established that animal bones are very commonly concentrated immediately below the entrance. These bones, which usually make up complete skeletons, are doubtless derived from animals that have been so unfortunate as to fall into the chasm.

On one occasion the writer was approaching the entrance to the Uitkomst Bottleneck Cave, when a brown hyeana was suddenly and most unexpectedly encountered. In the confusion that followed the hyeana made a desperate effort to jump across the entrance of the shaft, which at that point was about ten feet wide. Underestimating the distance, the hyaena missed its footing and fell seventy feet into the abyss beneath. On descending the shaft by means of a rope, it was found that the hyaena had not been the first animal to have so unfortunate and experience. The floor of the cavern was littered with the bones of

antelopes . . .

antelopes, rock rabbits and hares.

Bone accumulations of this type are not by any means restricted to the Transvaal. The remarkable cave discovered in the centre of St. Louis, Missouri, and described by Simpson (1946) yielded abundant Peccary remains which are presumed to have entered through a vertical fissure. The extremely rich accumulation in the Cumberland Bone Cave, discussed by Nicholas (1954), is thought to have been made up by carcasses caught in surface crevices, and slowly working their way downwards to the main cave.

Buckland (1823) discussed the remains of rhinoceros, horse, reindeer and urus found in the Dream Cave, Derbyshire. He concluded that the animals had fallen in through a vertical shaft.

A very much richer accumulation, presumed to have a similar origin was described by Dawkins (1874) from Hutton Cave, Somerset. The animals included mammoth, rhinoceros, reindeer, giant deer, bison, horse, cave lion, hyaena, wolf, foxes, bears, wild cats, leopards and numerous rodents.

(2) <u>Bones transported into caves by water</u>.

It appears that water can be responsible for

transporting . . .

transporting bones into underground caverns. If an animal is killed in a surface streambed that leads underground, the bones are likely to be washed into the cave. Such an occurrence has not been personally observed by the writer, but it has been described in the case of several caves in America and England. Bones collected by water are likely to be broken and associated with waterworn stones, as have been described by Parker (1953) from the Port Kennedy Cave in Pennsylvania.

From Yorkshire, Miall (1880) described bones of large animals that had been washed into a pothole known as Raygill Fissure, 120 feet deep. Jackson (1953) mentioned a similar occurrence in the Great Rocks Dale fissure ~~in~~ of Derbyshire, while Dawkins (1874) described a large bone accumulation from Banwell Cave, Somerset, thought to have been introduced by water through vertical fissures.

(b) Caves suitable for shelter and habitation.

Caves that are suitable for shelter and habitation are those that are roofed over and are easily accessible to man and animals. Such caves are most likely to be developed in the sides of steep valleys, although it is not

impossible . . .

impossible for them to occur in relatively flat ground.

Suitable caves in the Transvaal are found to be used not only by carnivores but also by certain herbivorous animals. The commonest of these are rock rabbits, hares and porcupines, and from time to time they may die in the caves. Thus bone accumulations built up of complete and relatively undisturbed skeletons may develop.

By far the most important bone accumulations, however, are those composed of the fragmentary food remains of carnivores, who find it more convenient to partake of their meat inside a cave than outside.

Primitive man appears to have been by far the most important collector of bones in caves, although several other animals, which will be discussed shortly, were responsible for fair numbers.

Bone accumulations by primitive man.

Throughout the world there are very numerous caves that have been inhabited by primitive peoples. In almost every instance, a bone accumulation is an important by-product of human occupation. The bones are normally associated with hearths and artifacts: moreover they are frequently charred and cracked open.

Of the 83 . . .

Of the 83 British bone-bearing cave deposits reviewed by Jackson (1953), sixty nine were shown to contain accumulations introduced by primitive men.

The writer considers that so far as South African Pleistocene bone accumulations are concerned, primitive man has also been an important collecting agent. In the case of those accumulations that were formed during basal Pleistocene times, when true man was evolving from a prehominid ancestor, there is evidence to suggest that carnivorous australopithecines were responsible for at least some of the bones collected. This evidence will shortly be dealt with in detail.

Bone accumulations by various carnivorous animals

There are doubtless numerous different sorts of carnivores that, from time to time, will carry bones back to the caves where they live, so that they can feed on them in peace. Unfortunately this is an aspect of animal behaviour which has not been fully investigated.

From America it has been reported that the red fox sometimes makes a habit of collecting bones in caves.

In the Centerport . . .

In the Centreport Cave of Pennsylvania Parker (1953) reported a collection of hog jaws that had been made by this animal. Parker also mentions that in the Pennsylvania Guthsville Cave, a very large collection of chicken bones were found to have been brought in by skunks. An accumulation of large bones, presumed to have been assembled by wolves, was described from Wavering Downs, Somerset, by Balch (1948). The assemblage was said to be late Pleistocene in age, and to consist of horse, brown bear, deer and wolf remains.

Ever since early in the last century it has been supposed that hyaenas have been responsible for large bone deposits in caves. Buckland (1823) described the very abundant bones found at the Kirkdale Cave in Yorkshire. Apart from the remains of 200 - 300 hyaena individuals there were the broken and gnawed bones of hippotomus, elephant, rhinoceros, mammoth, reindeer, cave lion, cave bear, bison, horse, deer, boar, hare and birds. There was apparently no evidence of human occupation in the cave.

A rather similar bone accumulation which was likewise attributed to hyaenas was discussed by Dawkins (1903). This was found in the Victoria Quarry near Buxton, and was presumed to be of Upper Pliocene age.

From Castlepook Cave, Scharff and others (1918)

described . . .

described the only known hyaena den in Ireland. No human evidence was present but hyaena remains were extremely common.

Four caves have been reported in England, which although presumed to be hyaena lairs, have also yielded traces of human occupation.

One of these, known as Tor Bryan Cave in Devon was described by Lee (1880) and was regarded as a Late Pleistocene hyaena den. From it were recovered 20,000 hyaena teeth representing at least 800 individuals, together with bones of cave lion, cave bear, wolf, fox, deer, vole, elephant, rhinoceros and hippopotomus. The cultural material included flint implements, a sandstone spindle-wherl, a polished stone axe and a bone pendant.

The other three caves said to show evidence of hyaena and human occupation are:- Wookey Hole and Uphill Cave in Somerset, both described by Dawkins (1852, 1874), and King Arthurs Cave in Herefordshire discussed by Symonds (1871).

Although the hyaenas appear to have gnawed the bones in the caves mentioned above, it has not been indisputably established whether these carnivores actually brought the bones back to the caves or not. It is possible

that there . . .

that there was alternate occupation by primitive man and hyaenas, and that the hyaenas gnawed what the men left.

The concept of hyaenas as habitual collectors of bones in caves has been challenged by Hughes (1954) and Dart (1955). Hughes published a number of opinions expressed by well known wild life authorities in Africa on the question of hyaena habits. The object of the investigation was to decide whether bone deposits, such as have been found at the Makapan Limeworks, could be attributed to hyaenas or to carnivorous australopithecines. Hughes concluded that hyaenas do not make a habit of collecting large quantities of bones in caves, but rather eat where they find their food. Thus he was inclined to discredit hyaenas as important collectors at Limeworks.

Some observations based on South African caves

During the past few years the writer has had the opportunity of examining a large number of modern dolomite caves in South Africa. In many of these, bones have been found lying on the surface of the floor debris. By far the most important point about these bone accumulations is that they can clearly not be attributed to any single agency. Some have been introduced during periods of

intermittent . . .

intermittent human occupation. Other much damaged bones are associated with hyaena droppings in parts of the cave where the hyaenas have had their young. Still other bones have been derived from the skeletons of animals, such as baboons, hares, rock rabbits, porcupines and bats, that have died naturally in the cave. Such originally complete skeletons have often become disarticulated as a result of the slumping of the cave earth down a slope, or due to the bone-gnawing activities of porcupines.

Dolomite caves are constantly being filled with earth, so that bones lying on the surface at any one time will afterwards become covered and preserved. Observations on the surface floor debris of modern caves thus provide one with information about a very restricted period of cave life. Nevertheless, in this restricted period, it is possible to see various bone collecting agencies at work. For this reason, if one tries to attribute all the bones in a thick deposit, as at Sterkfontein or Makapan, to a single collecting agency, one is unquestionably over-simplifying a rather complex problem.

In caves where the rate of accumulation of earth is slow, due to smallness of the entrance or the seclusion of the site, it is possible for rich bone accumulations to be built up over a long period of time. As several thousand

years . . .

years may only result in a foot or two of deposit being formed, it is obvious that bones do not have to be collected very fast. Thus although hyaenas, for instance, may not make a habit of collecting large quantities of bones at any one time, they would only have to bring back one or two bones every few years to build up an impressive collection with the passage of time.

Another important periodic collecting agency is probably the leopard. In bush country, leopards make a habit of hiding the remains of kills in trees so that they can return to finish them later on. Where caves occur, leopards are known to make use of them as hiding places during the day. Observation is thus required on the question of whether leopards are liable to leave occasional bones in cave lairs. If they are, the bones would probably be largely undamaged, as the leopard dentition is not suitable for the crushing of bones.

Again it must be stressed that leopards do not have to be habitual bone collectors in order to contribute to important bone accumulations. A very slow forming cave deposit is a far more important requirement.

It has been stated that bones in a modern cave show signs of having been introduced by a variety of

agencies . . .

agencies. An example of a modern bone-bearing cave will now be described, in order that this point may be clarified.

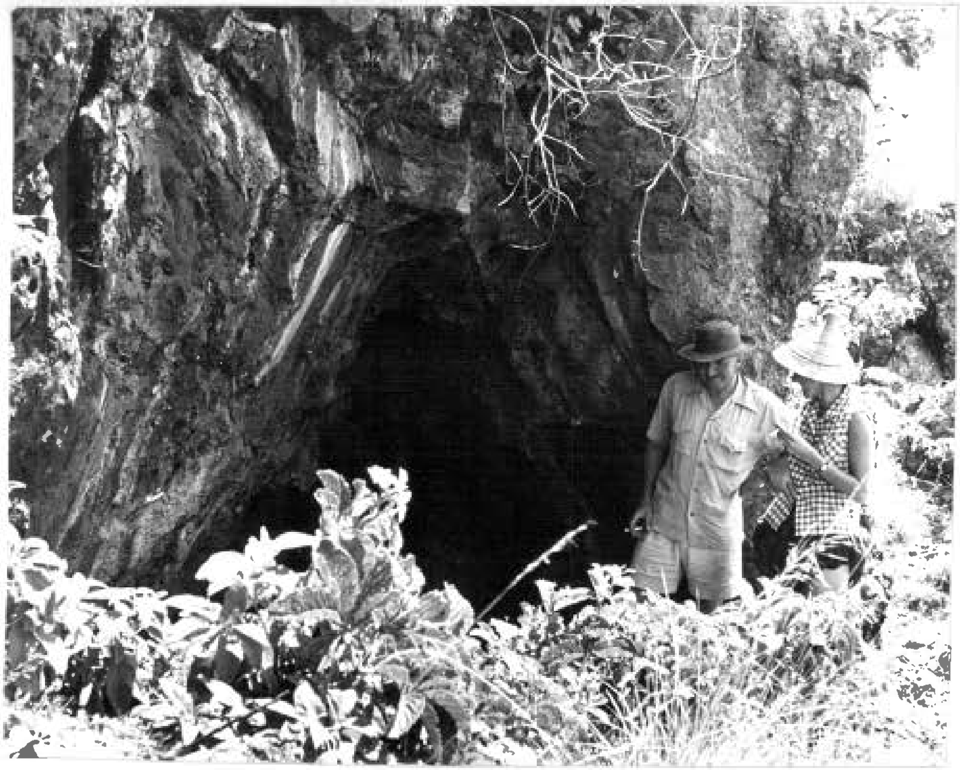
The Uitkomst Hyaena Lair Cave.

This cave, situated on the farm Uitkomst, 45 miles west of Pretoria, is known to be a favourite haunt of brown hyaenas (Hyaena brunnea). The cave is situated in the side of one of the very steep-sided dolomite valleys running down to the Scheerpoort River, and it opens at the base of a precipitous rock krans about 20 feet high. The entrance itself is shown in Photographs 15 and 16.

A simplified and diagrammatic cross section through the cave system is shown in Figure 11. It will be seen that the cave opens horizontally into a steep-sided valley, and that ramifying passages then connect with chambers at different levels. At the time of the investigation, the cave was being occupied by hares and rock rabbits, while it was clear that the hyaenas had not been away for very long.

Scattered in all parts of the cave, except in the deepest cavern, were numerous whitened hyaena droppings together with a number of damaged bones. These were all collected and a full list of the finds will be given shortly. An undisturbed part of the cave floor with bones and hyaena

droppings . . .



Photographs 15 and 16.

The entrance to the hyaena lair cave on the farm Uitkomst near Scheerpoort, Transvaal.

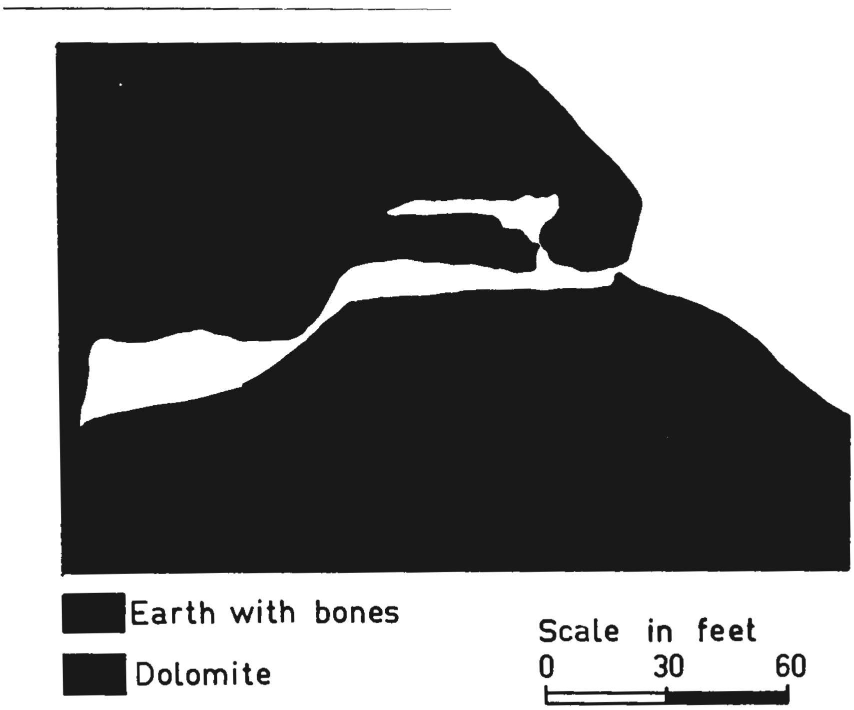


Figure 11.

A diagrammatic vertical section through the Uitkomst hyaena lair.

droppings is shown in Photograph 17. The cave has probably not been open for very long and the floor deposit is consequently thin and patchy.

Articles taken from the cave may be classified as follows:

A. BONES

Human

1 metacarpal bone.

1 fibula.

Large antelope (wildebeest)

1 palate

1 mandibular fragment

1 radius and ulna

3 tibiae

2 tarsal bones

3 pelvis fragments

2 humeri

8 fragmentary limb bones

1 scapula

Small antelope

2 mandibular fragments

3 tarsal and carpal bones

Baboon . . .

Photograph 17.

A view of the undisturbed floor of the Uitkomst hyaena lair, showing bones and hyaena droppings.

<u>Baboon</u>

1 palate

1 rib

<u>Rock rabbits</u>

2 complete skulls

1 damaged skull

palatal fragments of 2 skulls

<u>Hares</u>

8 mandibular fragments

13 vertebrae

<u>Hare or rock rabbit</u>

1 pelvis

7 ribs

4 scapulae

9 humeri

4 radii and ulnae

6 femora

4 tibii and fibulae

<u>Unidentifiable bone fragments</u>

3 - 8 inches long : 28

$<$ 3 inches long : 100

B. MISCELLANEOUS

<u>Hyaena droppings</u>

395

Clay pot fragments

5

Owl pellets ----

2

It should be noticed that the clay pot fragments were associated with numerous flakes of bone and were restricted to the chamber closest to the entrance. The dassie and hare remains were found in the deepest recesses of the cave, while the hyaena droppings and other bones were collected from all parts except the deepest chamber. It is suggested that the bones listed had been introduced into the cave by different agencies. These agencies will be considered separately.

A. Human

Numerous bone flakes were associated with the clay pot fragments and with ash in the entrance chamber. It is very probable that these bone flakes represented food remains of natives who sheltered in the cave. It is doubtful whether the human bones indicate human occupation or not.

B. Hyaenas

In the dark upper chamber particularly, badly damaged bones were associated with numerous whitened hyaena

droppings... The ...

droppings. The damage on bones, such as the antelope pelvic fragments shown in Photograph 18, has clearly been caused by the crunching of carnivores. It cannot be established definitely whether these bones were originally brought to the cave by hyaenas. A feasible argument is that they were carried in by people and then chewed by hyaenas.

Several bones collected, such as those shown in photograph 19, displayed gnawing marks characteristic of porcupine activity. It is doubtful however, whether porcupines would carry bones into a cave, when perfectly satisfactory bones to gnaw are already present there. Most probably the porcupines simply gnawed what they found.

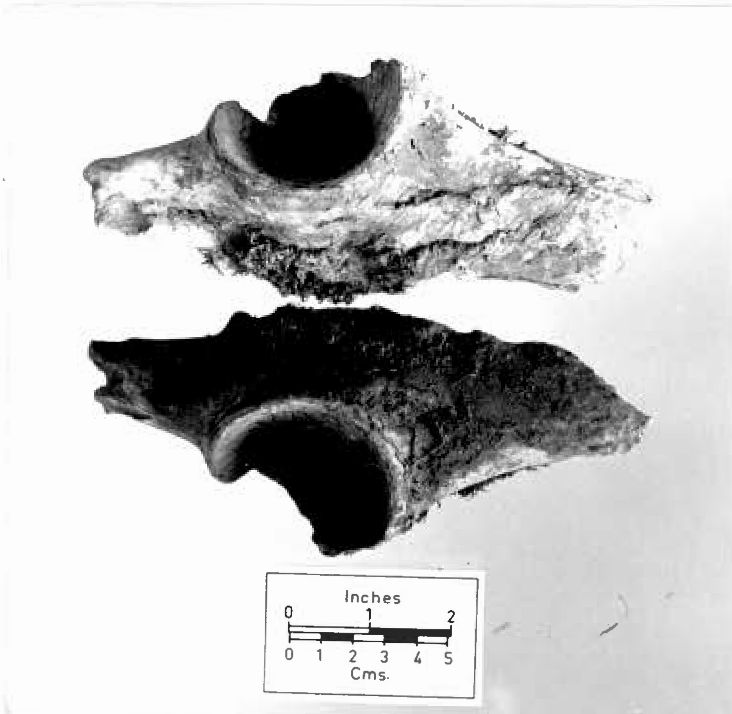
C. Natural deaths

The skeletal parts of the hares and rock rabbits were relatively undisturbed and were clearly the remains of animals that had gone into furthest recesses of the cave to die.

D. Owls

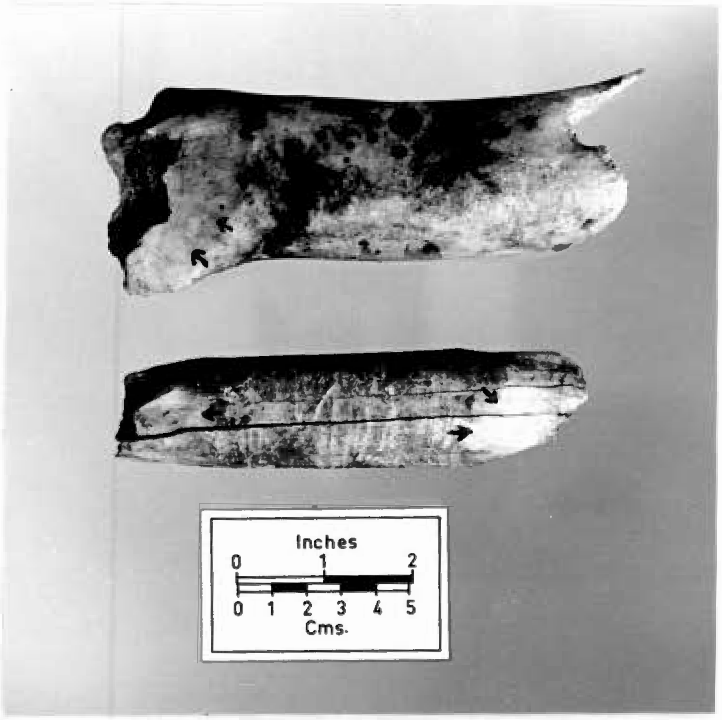
Two owl pellets were found immediately underneath a perch used by an owl during the day. Each contained the complete skeleton of a rat, neatly rolled in fur.

Conclusion . . .



Photograph 18.

Two antelope pelvic fragments from the Uitkomst hyaena lair showing extensive damage caused by the hyaenas.



Photograph 19.

Bones from the Uitkomst hyaena lair showing characteristic gnawing marks caused by porcupines.

Conclusion

One point is clear : that a variety of agencies have been responsible for the bone accumulation in the Uitkomst cave. Moreover, the cave has not been open for any great length of time, and since the entrance is still small, the bones are not mixed with much surface derived debris.

Rodent Bone Accumulations in Caves

In modern dolomite caves it is not unusual to find large concentrations of rodent bones mixed with the floor debris. Such concentrations are also features of the fossil caves, such as Swartkrans where there is a deposit five feet thick containing over 20 % by weight of bone.

The origin of these rodent bone concentrations is somewhat different from that of the normal bone accumulations. It appears that owls represent the sole collectors of the rodent bones.

Many of the large varieties of South African owls habitually perch in dark caves during the day and feed

exclusively . . .

exclusively during the evening and night. From personal observations on different owls from time to time the writer has established that the rodents, on which the owls subsist, are usually eaten fur and all in a very short space of time. Within twelve hours, in the case of the Spotted Eagle Owl, the acceptable parts of the rodent have been digested, while the indigestible fractions, consisting of skeleton and fur, have been rolled into a neat pellet and ejected by reversed peristalysis. It appears that this regurgitation process normally occurs during the day when the owl is resting, and since owls roost daily on the same perch for long periods at a time, they tend to build up quite a collection of owl-pellets on the cave floor beneath. When this sort of activity is continued by succeeding generations of owls over many centuries, a very considerable accumulation can result. The beginning of such an accumulation, on the floor of a modern dolomite cave, is shown in Photograph 20.

In the normal course of events, owls tend to select perches at some height above the cave floor. These usually take the form of recesses in the cave roof or walls. Where suitable perches are lacking however, owls certainly do resort to roosting on the floor, amongst their numerous pellets. The writer has observed this personally in a cave on the Otavi Plateau not very far from Tsumeb in South

Photograph 20.

A rodent bone accumulation being built up from owl pellets dropped from a perch in a modern cave.

Historic Cave Makapan.

West Africa. This cave consisted of a large cavern connected to the surface by means of a vertical shaft 40 feet in depth. On the flat floor of this cavern a pair of Spotted Eagle Owls were nesting, and had already built up a large collection of rodent bones about them.

General Conclusions.

It is suggested that the most important single factor affecting the type of bone accumulation formed in a cave, is the structure of the cave itself. Vertical sink holes and fissures will contain the bones of animals that fell in, or remains that were washed in from the surface.

On the other hand, caves that are suitable for shelter and habitation will contain bones introduced by a variety of agencies. Large bone concentrations are likely to be built up in caves where the rate of accumulation of surface-derived debris is slow. Since long periods of time are involved, bones do not have to be collected fast. Thus occasional bones left by various carnivores and primitive men, or resulting from natural deaths in caves, may contribute towards a major accumulation. It must be stressed that carnivores do not have to be habitual collectors of large quantities of bones to contribute materially to extensive bone deposits, built up with the passage of time.

4.

THE BONE ACCUMULATIONS IN THE SOUTH AFRICAN APE-MAN BEARING CAVE DEPOSITS

The bone accumulations that will be considered here are those from the sites of Taung, Makapan Limeworks, Sterkfontein, Swartkrans and Kromdraai. To start with, the sites will be considered separately and some previously expressed opinions on the origin of the accumulations will be reviewed.

Taung

Thirty years ago Dart (1925) described the first australopithecine specimen ever to be discovered. With it were obtained a number of baboon skulls showing interesting depressed fractures which Dart (1934) regarded as resulting from intentionally delivered blows.

Dart believed that the faunal remains associated with *Australopithecus* from Taung represented the food remains of the ape-men. He referred to the deposit as an ape-man kitchen-midden (1926), while in 1953 he enlarged on the carnivorous habits of the ape-men in the following way (Dart 1953) :

"In the breccia accompanying *Australopithecus* eggshells,

crabshells . . .

crabshells and turtle shells, and the bones of birds, small insectivores, bats, rodents, baboons and buck revealed evidence of the carnivorous diet of these creatures which appeared to be little if at all advanced beyond that of the baboons, which live today in the same locality. So I claimed from the outset and in 1929 that they were flesh-eating, shell-cracking and bone breaking, cave-dwelling apes; and that in the carnivorous habits of South African baboons (which, under stress of drought, as in that year, attack flocks of sheep and goats and carry off not only the young but adults for food and in coastal areas go down to the sea and eat shellfish) had already become stereotyped."

As far as the writer is aware, no serious challenge has been published to Dart's concept of the Taung *Australopithecus* as the principal collector of the associated bones. In fact Broom (1946) shared Dart's views on the subject.

Makapan Limeworks

When Dart first drew attention to the rich bone deposits at Limeworks (Dart 1925), he considered that the nature of the accumulation indicated that the site had been used for human occupation. In 1947 however, remains of *Australopithecus* were recovered from the consolidated

bone-rich . . .

bone-rich deposit, and their appearance caused Dart to alter his opinion on the origin of the bone accumulation. Instead of regarding the cave as a site of human occupation he thought it more likely to have been the living quarters of Australopithecus. He summarised the similarity between this bone deposit and those resulting from human activities in the following way (Dart 1953) :

"Other principal features in which the Makapansgat deposit resembles those left by mankind are that these large bones are not gnawed but split and crushed to extract the marrow; and the double-ridged extremities of the arm bones (humeri) of antelopes are cracked and fractured through having been used as bludgeons. The broken ridges of these humeri correspond with double furrowed fractures found in baboon (and even in australopithecine) skulls found at all three main man-ape sites: Taungs, Sterkfontein and Makapansgat."

At the Third Pan-African Congress on Prehistory held during July 1955, Dart (in press) presented a statistical analysis of the bones already extracted from Limeworks. He stated that of the 7,159 bones so far examined, 4,560 had been fully identified.

Of the total bones 91.7% were found to belong to antelopes, while as a result of careful study of the

whole . . .

whole collection, Dart has been able to list the minimum number of individuals of each animal type to be represented in the deposit. This list may be summarised as follows.

Animal type	Minimum number of individuals
Large antelope (kudu, roan etc.)	39
Medium antelope (wildebeest etc.)	126
Small antelope (gazelle)	100
Very small antelope (duiker)	28
Horses	4
Chalicotheres	6
Rhinoceroses	5
Pigs	20
Giraffes	6
Hippopotami	1
Baboons	45
Australopithecines	5
Hyaenas	17
Small carnivores	7
Medium carnivores	2
Leopard	1
Sabre-tooth cat	1
Jackal	1
Wild dog	1

Hares . . .

Animal type	Minimum number of individuals
Hares	2
Porcupines	8
Birds	5
Tortoises and turtles	3

Dart showed that the non-antelope remains were very largely made up of skull fragments. In fact 82.5% of them represented cranial parts. The antelope remains however took the form of many different skeletal parts and only 34.5% of the total were found to be cranial fragments.

Dart was of the opinion that all the bones at Limeworks had been collected by _Australopithecus_. Moreover the ape-man was selective in what he brought back to the cave, concentrating on those bones that would be of use to him as tools. In fact _Australopithecus_ was thought to have made use of an "osteodontokeratic culture".

Sterkfontein

One of the few published statements on the origin of the Sterkfontein bone deposit appeared when Broom (1950) stated:

"There seems to be little doubt that the quarry which has yielded our best _Plesianthropus_ specimens is the

upper part . . .

upper part of a large cave which for many years had been the lair or lairs of sabre tooths, and that the bones had been introduced by them".

This opinion was not shared by Dart (1953) who stated that he thought that the Sterkfontein bones had been collected by Australopithecus (= Plesianthropus) in the same way as they had been at Limeworks.

Swartkrans and Kromdraai

No statements appear to have been made in the literature on the origin of the bone accumulations at Swartkrans and Kromdraai.

Australopithecines as possible bone collectors

If the various Transvaal caves represented occupational sites of the ape men, then evidence should be forthcoming on the question of whether australopithecines were active bone collectors or not. Dart has produced evidence to suggest that the Limeworks cave was actually inhabited by Australopithecus. Unfortunately, however, with this and with the other caves, it is practically impossible to prove whether they were occupational sites or not.

Supposing for the moment that they were, some suggestions can be made that provide interesting scope for future research.

As far as the australopithecines are concerned, it is clear that feeding habits are most important in determining what sort of occupational debris will accumulate in their living quarters. According to Robinson (1954 a), the South African australopithecines may be divided into two genera : _Australopithecus_ and _Paranthropus_.

The _Australopithecus_ group was made up of small pigmy individuals, whose remains have been obtained from Taung, Sterkfontein and Makapan Limeworks. The _Paranthropus_ group was composed of much larger animals known from Swartkrans and Kromdraai.

As a result of a study of australopithecine dentition, Robinson (1954 b) concluded that _Australopithecus_ was much more partial to meat than was _Paranthropus_. He stated :

"The diet of _Paranthropus_ appears to have been primarily vegetarian, while that of _Australopithecus_ seems to have been omnivorous and to have included a fair proportion of flesh. The resulting differences in strength and nature of the masticatory forces has affected the shape and structure of the face and braincase."

Thus if the two types of ape men differed in their feeding habits to the extent that one was carnivorous while the other was vegetarian, one would expect to find a marked difference in the sort of occupational debris accumulating in the living quarters of each type. Therefore it would be of value to compare the nature of the articles found in caves that have probably been used by the two types of ape-man. When such a comparison is made it is necessary to consider every single article and piece of bone if a true picture of the animal habits is to be obtained.

In investigating occupational debris, the sites that could be used for the different ape man are these :

<u>Australopithecus</u> : Taung, Sterkfontein and Limeworks.

<u>Paranthropus</u> : Kromdraai B.

The Swartkrans site can probably not be considered, as Robinson thinks it likely that this was a <u>Telanthropus</u> living site rather than a <u>Paranthropus</u> one.

Unfortunately all the available bones have not been kept and cleaned in the case of Taung and Sterkfontein. Thus the only two sites that are useful for comparisons are Limeworks and Kromdraai B.

A complete analysis of the Limeworks material

has already . . .

has already been made by Dart (1955), and was discussed earlier in this work.

The writer has been directing the excavation of Kromdraai B during the greater part of 1955, and great care has been taken to preserve every article of interest from the deposit. The work is still in progress and new material is constantly being obtained. For this reason the list of articles provided here only includes those obtained up to the end of November, 1955. As rather less than half the deposit has been excavated so far, one can confidently expect that the total number of specimens finally unearthed will be much greater than that given in the present list.

Kromdraai B..Bones . . .

Kromdraai B. Bones up to December, 1955.

Australopithecines : (Paranthropus robustus) :

Half adult skull (Photograph 21) :
Half adult mandible :
Child mandible :
Fragmentary adult palate :
11 Isolated permanent teeth :
1 Isolated milk tooth :

Distal end of humerus
Os magnum
Metatarsal
Calcaneum
Phalanx.

Baboon

Cranium (1) : Parapapio coronatus

Mandibular fragments : 5

Isolated teeth : Erupted : 65

Unerupted: 40

Small antelope

Mandibular fragment : 1

Isolated teeth : 6

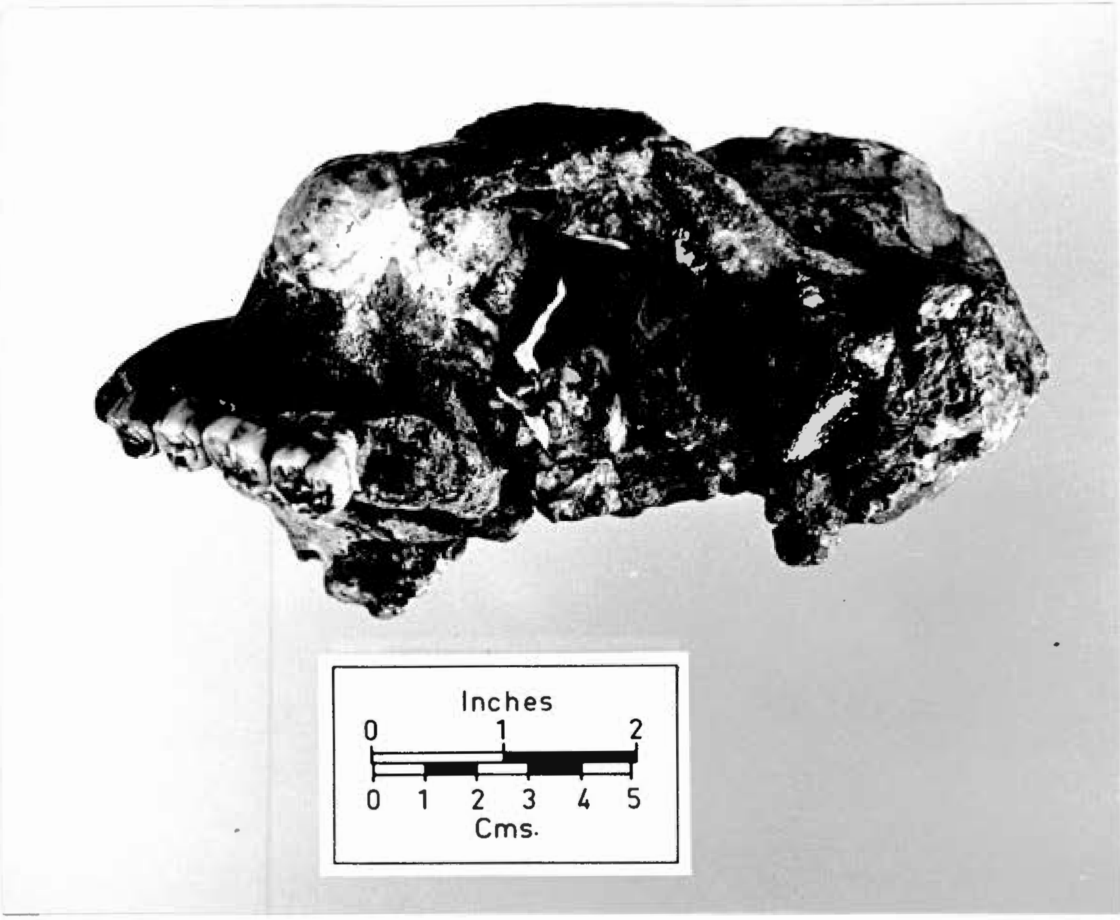
Carnivores

Hyaena molar : 1

Jackal molars : 2

Small carnivore claws : 8

Bones of baboon, . . .



Photograph 21.

The original *Paranthropus* skull obtained from Kromdraai B.

Kromdraai B. Bones up to Dec. 1955 (continued)

Bones of baboon, antelopes, carnivores, etc :

Horn cores	10
Ribs	15
Scapulae	2
Humeri	6
Tibiae and fibulae	2
Femora	8
Ulnae	7
Radii	9
Tarsal and carpal bones	102
Post-sacral vertebrae	33
Pre-sacral vertebrae	33

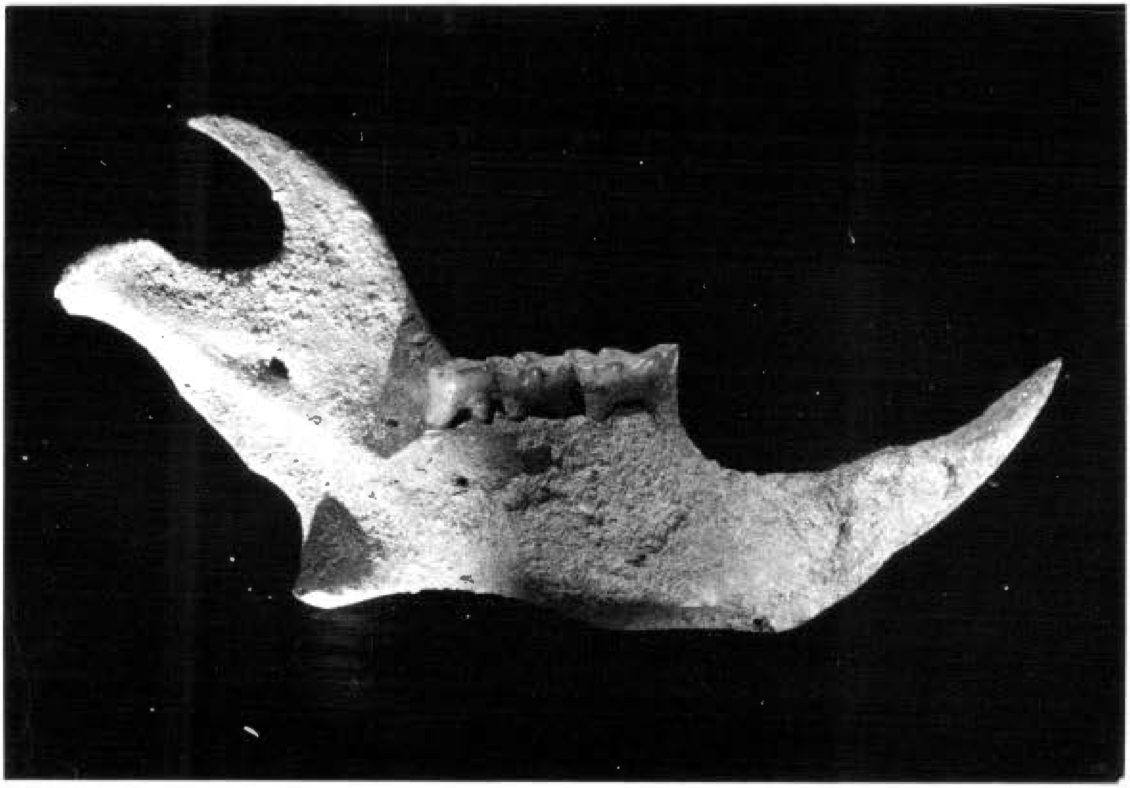
Reptiles

Lizard jaws :	7
Lizard scales:	6
Chamelion jaws :	11

Rodents

Half-mandibles :	left side	: 394	(Photograph 22)
	right side	: 406	

Skull fragments . . .



Photograph 22.

One of the very numerous rodent half-mandibles that have been obtained from Kromdraai B.

Magnified 6 times.

Kromdraai B. Bones up to December 1955 (continued)

Rodents (continued)

Skull fragments	:	599
Limb bones, etc.	:	9,435
Vertebra~~t~~e	:	50

Shrews

Half-mandibles	:	5

Elephant-shrews

Half-mandibles	:	120	(Photograph ~~24~~ 23)
Skull fragments	:	10	

Unidentifiable bone flakes : 3 - 8 inches long : 7

Less than 3 inches long : 2,111

(Photograph 24)

Carnivore coprolites : 4

Waterworn stones

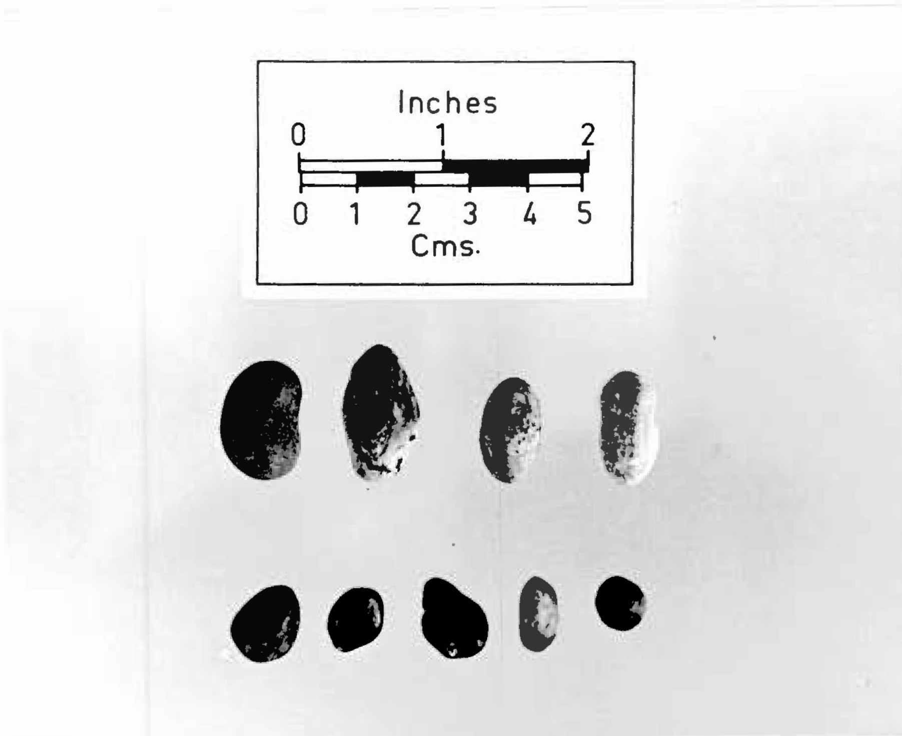
More then 2 inch diameter	:	2 of quartzite
Less than 2 inch diameter	:	72 of quartzite, chert and jasper. (Photograph 25)

From the list of animal remains just given it is possible to determine the minimum probable number of animal individuals that have gone to make up the deposit:-

Animal table . . .

Photograph 23.

Half an elephant-shrew mandible from the Kromdraai B excavation. Magnified 6 times.



Photograph 25.

Some examples of small waterworn stones found associated with *Paranthropus* at Kromdraai B.

Animal	Probable number of individuals
Australopithecines	5
Baboons	8
Small antelopes	5
Hyaena	1
Jackal	1
Lizards and chamelions	10
Rodents	406
Shrews	3
Elephant shrews	60

The unidentified bone fragments doubtless represent the broken skeletons of the larger animals in this list, while the four carnivore coprolites are from animals of about jackal size. The waterworn stones are interesting in so far that several of them are foreign to the immediate area. It was previously thought that these stones must have been introduced by Paranthropus, as the deposit as a whole is certainly not alluvial. Subsequent excavation, however, has shown that the smaller of these stones represented the nuclei of weathered cave pearls. The presence of foreign stones, and of the large waterworn ones, probably indicates that the Kromdraai B cave was quite close to river level originally, although its contents were not essentially alluvial in origin.

In considering . . .

In considering the Kromdraai bone accumulation, the lizard and chamelion remains were perhaps derived from reptiles that died naturally in the cave. The bones of rodents, shrews and elephant shrews were almost certainly brought in by owls. Thus, from the point of view of this enquiry, only the larger animal remains need be used in the comparison with the Limeworks material. The comparison is set out in table form below :-

Animal type	Probable number of individuals represented	
	Limeworks	Kromdraai B.
Australopithecus	5	0
Paranthropus	0	5
Baboons	45	8
Large antelopes	39	0
Medium antelopes	126	0
Small antelopes	100	5
Very small antelopes	28	0
Horses	4	0
Chalicotheres	6	0
Rhinoceri	5	0
Pigs	20	0
Giraffe	6	0
Hippopotami	1	0
Hyaenas	17	1
Small and medium carnivores	9	0
Leopards	1	0
Sabre tooth cats	1	0
Jackals	1	1
Wild dogs	1	0
Hares, porcupines, birds and chelonians	18	0

It will be seen . . .

It will be seen that there are remains of five individuals of Australopithecus at Limeworks and five of Paranthropus at Kromdraai. In spite of this, the composition of the associated faunal remains is very different in the two bone deposits. Limeworks has provided remains of 428 animal individuals other than the ape men. Kromdraai B, on the other hand, has so far yielded remains of only 15 animals other than the ape men.

Conclusion

The most obvious conclusion is that Australopithecus was probably more partial to meat than was Paranthropus : a conclusion that was reached by Robinson on completely different grounds in 1954. The few animal remains found at Kromdraai could even have been collected by the jackals that produced the droppings and used the cave at times when the ape men were absent. They may have been responsible for breaking up bones into the now identifiable flakes recovered from the cave.

Necessary precautions

1. The evidence of the bone accumulations from the different sites can only be used to elucidate ape-man habits, if it ~~can~~ be definitely established that the caves were ape-man living quarters. As this will probably never be established

with complete . . .

with complete certainty, the conclusion about ape-man feeding habits must be accepted with caution.

2. It must be appreciated that the Limeworks bone accumulation is large, and must have been built up over a long period of time. In view of this, it is most improbable that Australopithecus was the only collecting agent involved, although he may have been the most important. Bones inevitably introduced by other means will have complicated the issue. Their presence throws doubt on any sweeping conclusions that one may be tempted to draw.

General conclusions . . .

General Conclusions

It has been suggested by previous writers that the extensive bone accumulations at the sites of Taung, Sterkfontein and Limeworks are the result of the carnivorous feeding habits of *Australopithecus*.

The euhominid, *Telanthropus* may well have contributed to the bone collection at Swartkrans.

For the sake of discussion it is assumed that Limeworks and Kromdraai B were the living sites of *Australopithecus* and *Paranthropus* respectively. The nature of the bone accumulation from the two caves is then compared.

The very rich bone accumulation at Limeworks might be taken as indicating that *Australopithecus* was carnivorous, while the paucity of bones from Kromdraai B suggests a vegetarian diet for *Paranthropus*. The necessity for caution in accepting these conclusions is stressed.

THE NORMAL DEPOSITION CYCLE IN TRANSVAAL DOLOMITE CAVES.

A study of the materials that have accumulated both in modern caves, and in their fossil counterparts, has served to elucidate the normal deposition cycle in Transvaal dolomite caves. Firstly, a brief description of this cycle will be given, while in the next chapter the nature of the various deposits themselves will be considered in detail.

In the following account, reference should be made to the vertical sections shown in Figures 12 and 13. The continuous deposition cycle can be divided into several stages which will now be discussed.

STAGE 1

The cavern has already formed and is being enlarged beneath the water-table in the phreatic zone.

The most important deposits to form at this stage in development consist of the insoluble fractions of the dolomite, left when the cavern itself is dissolved out. These may conveniently be grouped into manganous muds and

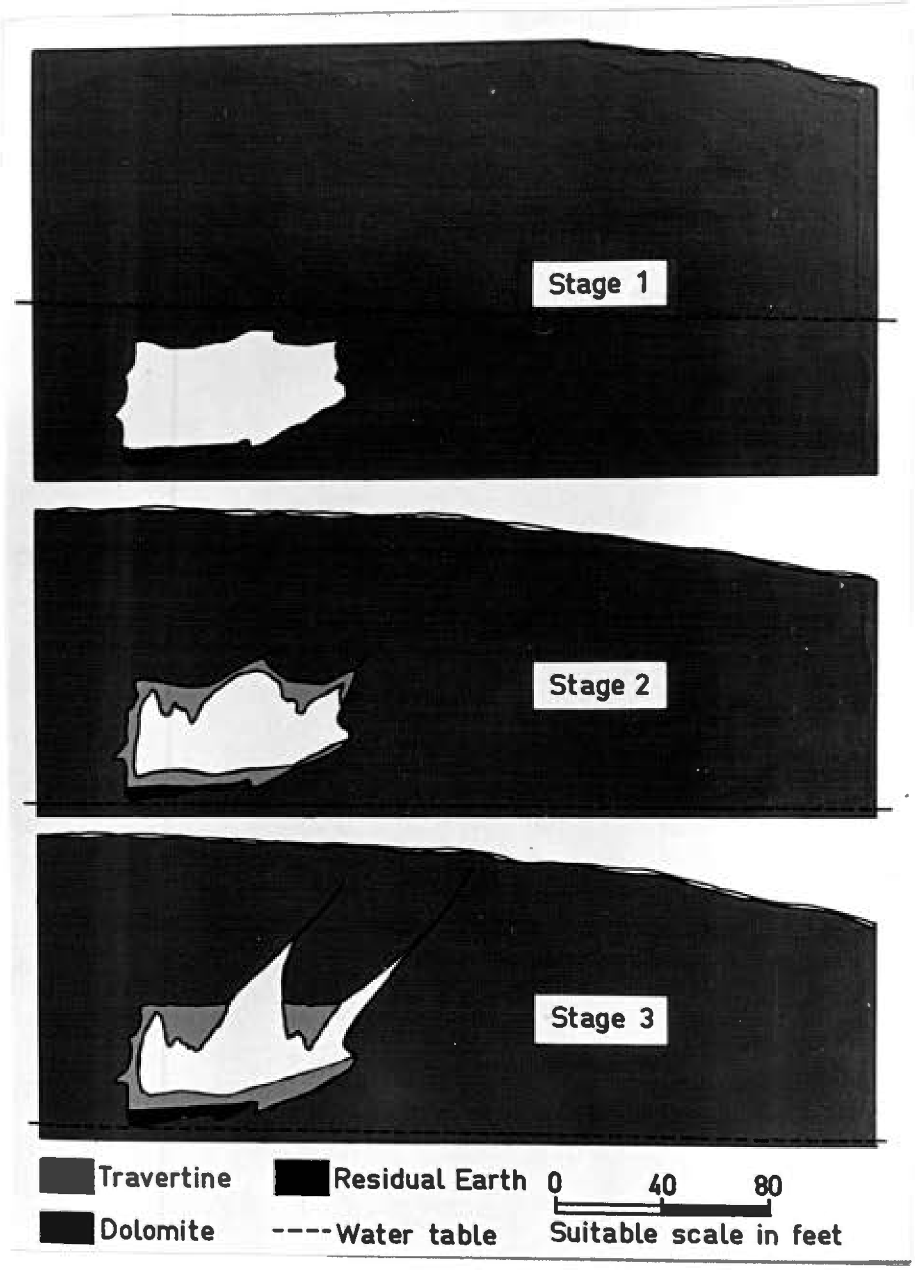


Figure 12.

Vertical sections through a hillside containing a cavern, to show the stages of the normal deposition cycle in Transvaal dolomite caves. Further stages are given in Fig. 13.

normal fine-grained sediments. Their characteristics will be discussed in the next section.

The residual sediments are normally deposited in horizontal layers which have settled slowly in the quiet waters of the phreatic reservoir. Another type of deposit, which although much less common, may form at this stage, is a coating of crystals ~~of~~ on the walls and roof of the cavern. This is found to consist of either calcite or aragonite and has undoubtedly been precipitated from the phreatic water itself. When a crystal-lined cavern has been recently drained of water it presents a sight of great brilliance and beauty.

STAGE ~~II~~ 2.

A drop in the level of the water table has brought the cavern into the vadose zone and it is now air-filled.

The deposits most characteristic of this developmental stage are the cave travertines, which may be divided into:

Roof and wall travertines or stalactites
Floor travertines or stalagmites.

These travertines are normally composed of carbonates of

exceptional . . .

exceptional purity, precipitated from transient vadose solutions making their way down to the phreatic reservoir. Nevertheless, occasional contamination with residual cave earth derived from cavern enlargement, may be observed.

In addition to the travertines, other interesting but comparatively insignificant formations may develop. These take the form of helictites and gypsum flowers.

STAGE 3

This stage is characterised by the vadose enlargment of selected passages and shafts above the main cavern itself. As discussed earlier, the shafts, known as "avens" are the result of active solution by meteoric water passing downward through joint and bedding planes. The presence of the cavern beneath such planes greatly facilitates the downward water movement, and solutional enlargement of the passages is thus much accelerated.

The process of dissolving the dolomite again produces a quantity of insoluble residue which will collect on the cave floor as fine sand grained manganous sediment. Layers of this sediment are frequently interbedded with the floor travertines which will be forming at rates dependent on such factors as ventilation and temperature.

Stage 4. . . .

STAGE 4

The continued enlargement of the joint and bedding planes above the cavern results in a small opening being produced linking the cavern with the surface. The advent of this opening has the effect of admitting the first small quantities of surface derived material to the cavern. This material becomes mixed with the residual earth, produced by the enlargement of the cavern, and is commonly deposited either interbedded with, or just above the floor travertine, which continues to form at various points on the cave floor. When calcified, the mixture of surface-derived and residual materials is termed a PHASE I breccia.

It must be appreciated that Phase 1 breccias do not represent true samples of surface-derived material, since they have often been liberally contaminated with residual cave earth. These deposits are consequently of little value as indicators of surface conditions. They are, however, often of great palaeontological value, since being slow accumulations, their bone content may be very high.

STAGE 5

At this stage, the cave entrance has enlarged considerably, and is now constantly admitting large quantities of material from the surface. Once a cave

entrance . . .

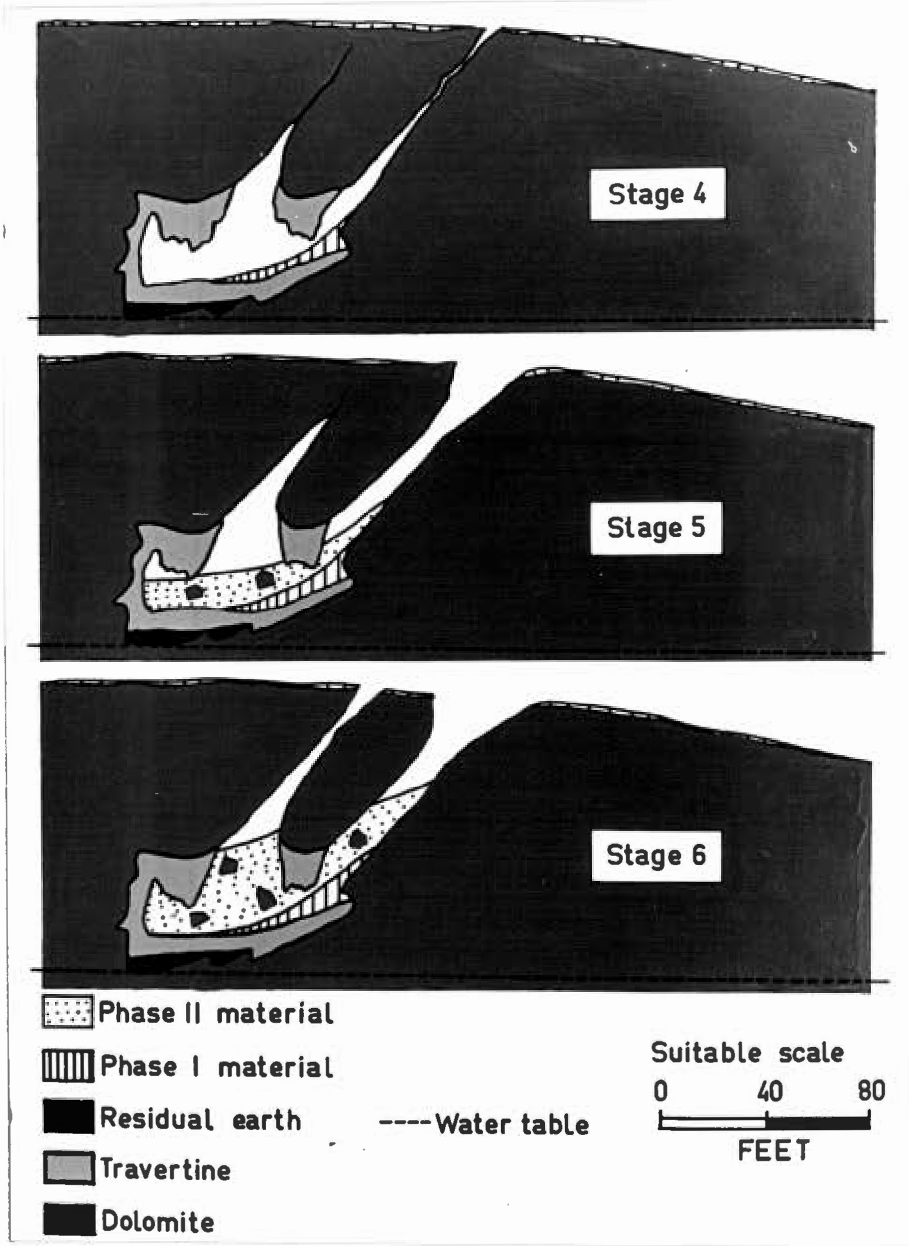


Figure 13.

Vertical sections through a hillside containing a cavern, to show the stages of the normal deposition cycle in Transvaal dolomite caves.

entrance has formed it normally appears to enlarge fairly fast as a result of continued solution and roof collapse. This is more particularly the case in caves opening from above than from the side.

Stage 5 represents a time when material from the surface is coming through the entrance so fast, that the quantity of residual cave earth, still slowly accumulating, becomes quite insignificant by comparison. Thus the material coming to rest on the cave floor can, for all practical purposes, be regarded as a representative sample of that on the surface. Such material, when it has been calcified is termed a Phase II breccia by the present writer. These breccias are of great value as indicators of surface conditions during the period of cave filling.

The nature of Phase II breccias is, of course, dependent on the character of the material on the surface.

In the . . .

In the dolomite country, where the caves are developed, surface materials may usually be classified into the three following types:

Normal dolomite soil

Alluvial debris

Wind-borne sand or loess.

The distinguishing features of these three types will be discussed in the next chapter.

In addition to the Phase II materials that accumulate in the cave at this stage of the cycle, others such as roof fall blocks and travertines are also found.

The travertines are most likely to be roof and wall varieties. Floor travertines are liable to be much contaminated by the fast accumulating earth.

Bone contents in Phase II breccias are usually much lower than those in the Phase I equivalents. This is because the matrix of a Phase II breccia represents a relatively rapid accumulation, and the bones are consequently more widely scattered through its bulk.

Stage 6 . . .

STAGE 6

At this stage the deposition of the Phase II material has progressed further and the available space in the cavern is now almost completely filled. Continued roof collapses have again enlarged the area of the surface opening, with the result that the filling process of the cave has been accelerated. In previous descriptions the writer has referred to this final, rapidly accumulating material as a PHASE III breccia. This term is now considered to be artificial and unnecessary, and will not be used in this work.

Roof travertines may contimue to form till all the available space has been taken up.

In this way the deposition cycle in the cavern comes to an end. Then follows a very protracted period of denudation, in the course of which the cave and its contents will be totally destroyed.

Brief summary of events . . .

A brief summary of events in the normal deposition cycle.

Stage 1

The cavern is being enlarged in the phreatic zone beneath the water table.

Deposits : Residual cave earth
Linings of carbonate crystals.

Stage 2.

A lowering in the level of the water table brings the cavern into the vadose zone.

Deposits : Cave travertines
Helictites and gypsum flowers
Residual cave earth.

Stage 3

Selected passages and shafts above the cavern are produced and enlarged by active vadose solution.

Deposits : Same as in Stage 2.

Stage 4

The first small opening to the surface is acquired and small quantities of surface derived material mix with the residual cave earth.

Deposits : Phase I breccias
Cave travertines.

Stage 5 . . .

Stage 5

The cave opening is much enlarged by solution and collapse. Large quantities of material from the surface enter the cavern.

Deposits : Phase II breccias
Cave travertines
Roof fall debris

Stage 6

The cave entrance has been further enlarged and is now admitting very large quantities of material from the surface to the cavern. Roof falls are frequent.

Deposits : Phase II breccia
Cave travertines
Roof fall debris.

. . . .

The Nature of the Cave Fillings

Cave Travertines.

Cave travertine is a general term applied to the variety of forms of calcium and magnesium carbonate that may be developed in caves. Of the two carbonates, analysis has shown that calcium is far more important than magnesium, and many of the Transvaal cave travertines consist of calcite of exceptional purity.

As has been previously mentioned, pure water represents a rather feeble solvent for the carbonates in question. The presence of dissolved carbon dioxide, however, increases the solvent action very considerably. Adams and Swinnerton (1937) have shown that the main source of carbon dioxide in ground water is soil air, where the concentration of the gas is often between 25 and 90 times that found in the normal atmosphere. Water seeping downwards through the soil may thus dissolve considerable quantities of carbon dioxide. When this carbonic acid solution comes into contact with dolomite, the dolomite is dissolved and a solution of calcium and magnesium bicarbonate results. This solution will then pass downwards through the vadose zone. If an opening or cavern in the dolomite is encountered on the way, the solution may drip from the roof or seep over the walls or floor. In the course of this, some of the carbonate held in solution may be deposited. This may be effected in well ventilated caves by normal evaporation. Frequently, however, the cavern atmosphere will be humid, so that precipitation is more likely to result from the loss of carbon dioxide than from the normal evaporation of the solution.

Loss of carbon dioxide from the solution will occur until the partial pressure of that held in solution is the same as the partial pressure of the gas in the cave atmosphere. This loss of carbon dioxide will inevitably result in the precipitation of some of the carbonate as travertine. Obviously, where the two carbonates of calcium and magnesium are concerned, the less soluble one will be precipitated first, while the more soluble one will be carried down with the water until the phreatic reservoir is reached. Since magnesium carbonate is approximately ten times as soluble as the calcium equivalent, it can frequently escape precipitation, a fact that results in its general absence in the travertines of the Transvaal caves.

It appears that temperature is important in determining how much carbon dioxide will be lost to the cave atmosphere. An increase in temperature will accelerate the loss of gas, consequently resulting in an increased precipitation of carbonate.

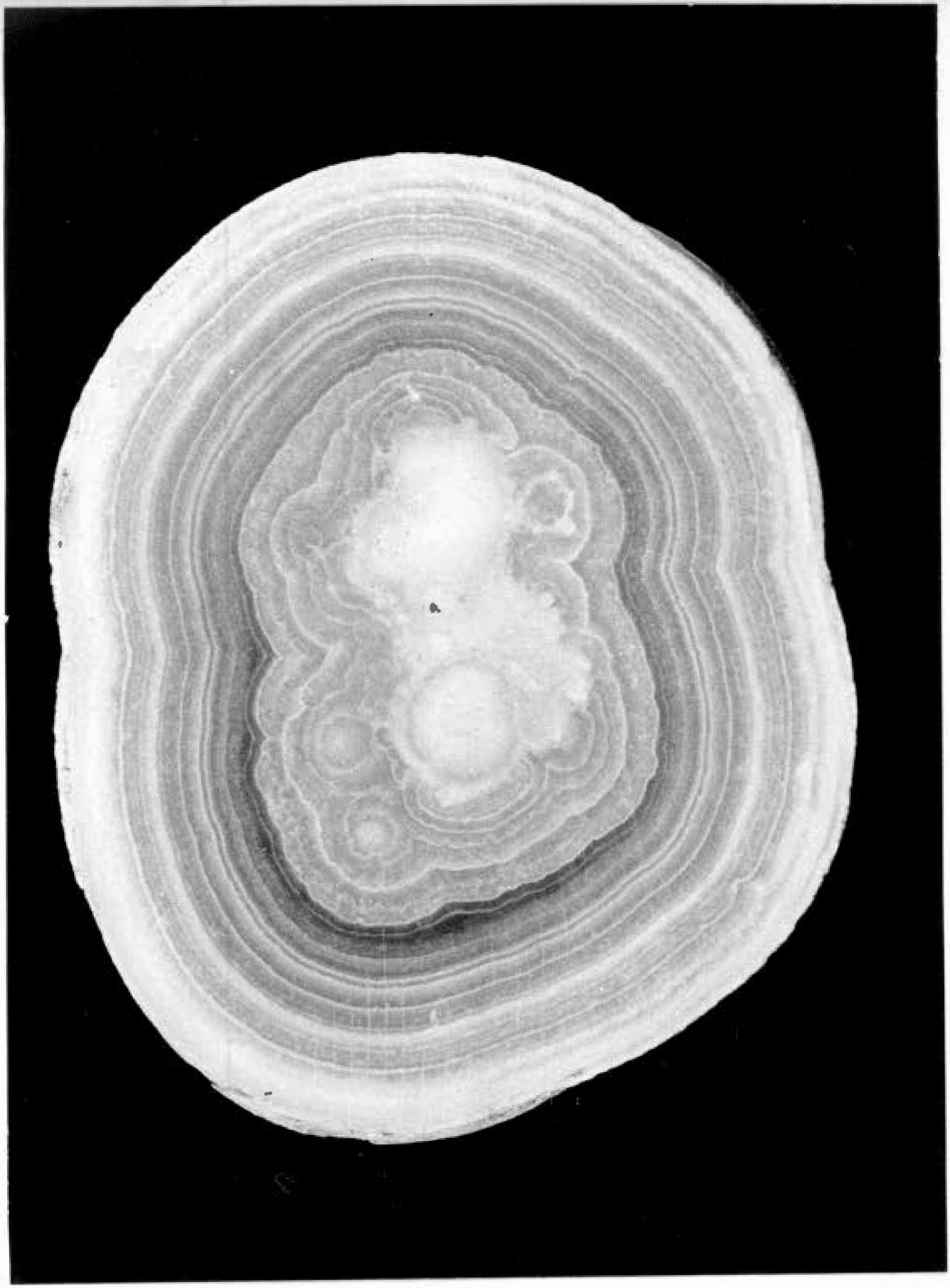
The more important forms shown by travertines in the Transvaal caves will now be discussed.

Stalactites

Stalactites, which consist of travertines hanging from the cave roof, can only form where evaporation or loss of carbon dioxide from the solutions is sufficient to cause carbonate precipitation before the drop leaves the roof. The formation of stalactites has been carefully discussed by Allison (1923), who distinguishes between the thin straw-like type which results from fast growth, and the thicker type which has been built up more slowly.

Characteristic slow-growing stalactites hanging from the roof of van Wyk's Main Cave are shown in Photograph 9 (page 25). Such stalactites are found to be made up of concentric rings of carbonate, and to have one or more channels down the middle through which the solutions pass. A horizontal section through a slow-growing stalactite from the Makapan Limeworks is shown in Photograph 26.

Fast-growing, straw-like stalactites are generally thought to be made up of a single crystal. It occasionally happens that the temporary failure of the incoming solution



Photograph 26.

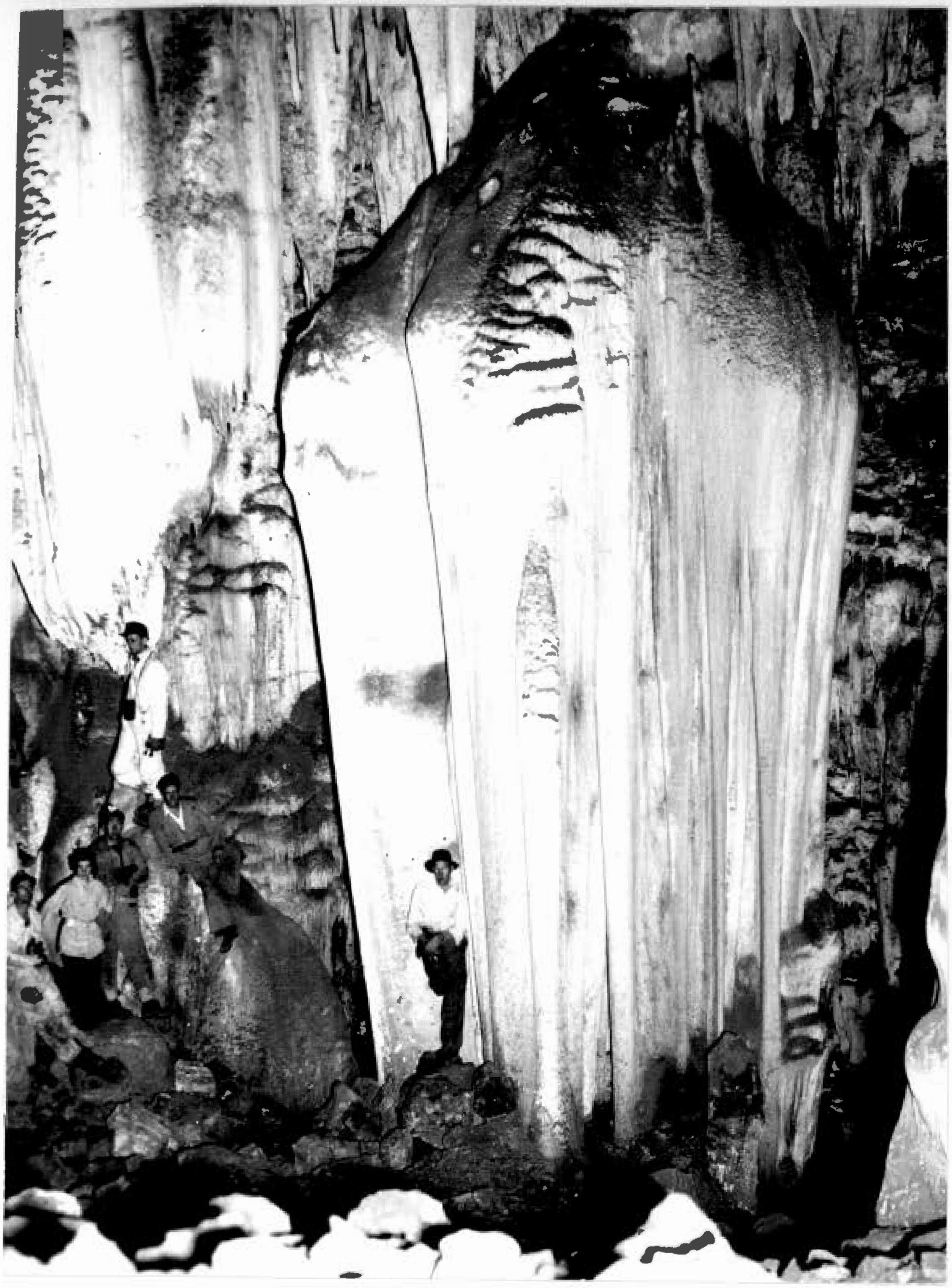
Horizontal section through a slow-growing stalactite from the Makapan Limeworks. Natural size.

causes the end of a straw-like stalactite to become blocked. If the solution is subsequently resupplied, it may penetrate the wall of the tube higher up and make the straw irregular in form. Irregular straws of this sort are shown in Photograph 27. Also visible are true <u>erratic stalactites</u> or <u>helictites</u> which have a rather different origin. Helictites are characteristically thin filaments of calcite which seem to have a complete disregard for gravity and are capable of growing both horizontally and upwards. Their origin has been discussed in a comprehensive and convincing paper by Moore (1954). In this paper, Moore reviewed the remarkable previously published opinions on the origin of helictites, some of which will now be quoted:

> "Condensation of vapour containing lime.
> Deposition along horizontal spider webs.
> Deflection by air currents.
> Deposition as lateral outgrowths having fungi as starting points.
> The twining tendency in the crystallisation of calcite.
> Alternate deposition of calcite and aragonite."

As a result of a careful enquiry, Moore was able to show what the true origin of helictites was. His conclusions were briefly stated as follows:-

"Growth . . .



Photograph 28.

Curtain stalactites in the van Wyks Main Cave near Sterkfontein. Photograph by J C. Viljoen.

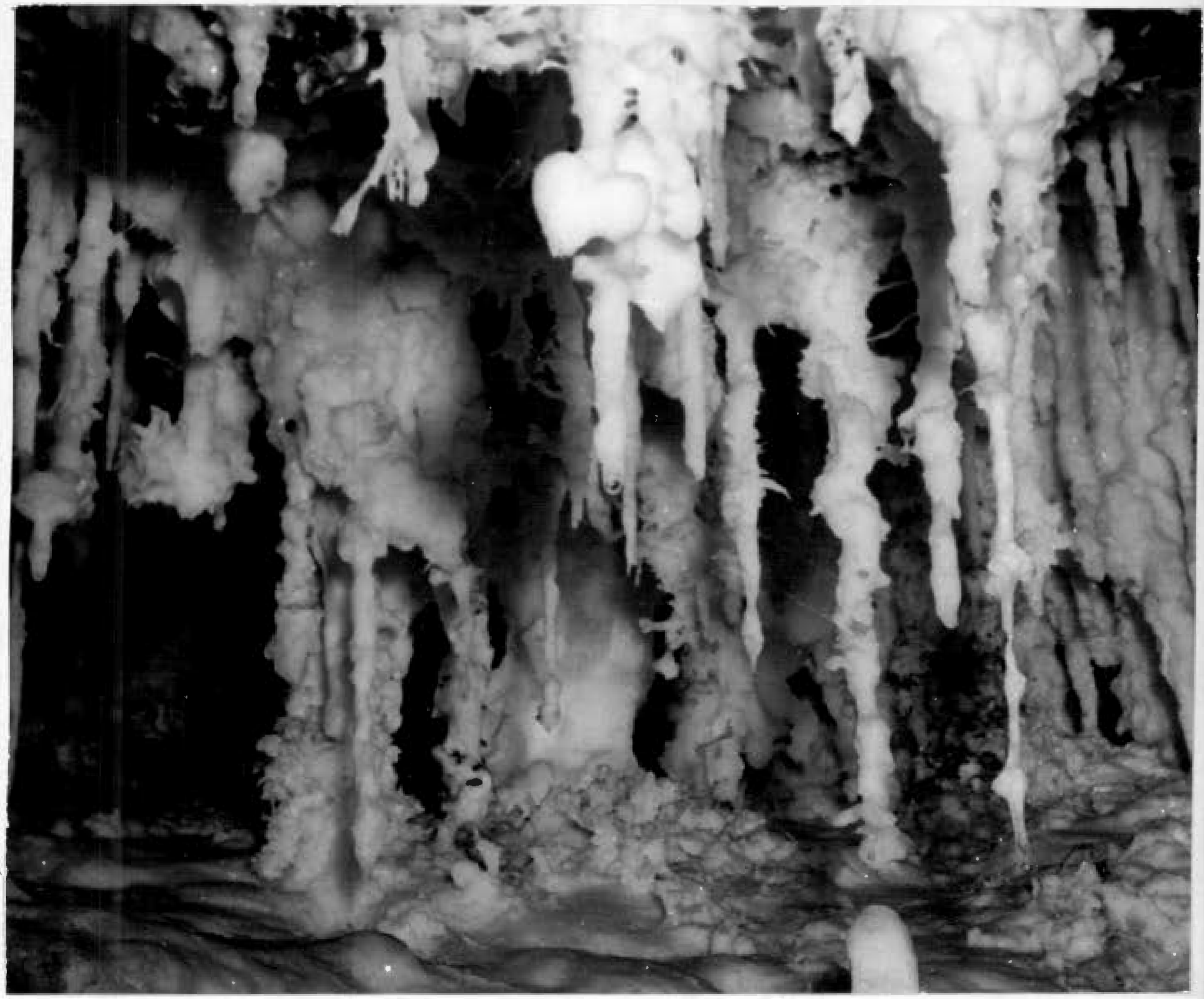
"Growth is accomplished by deposition around the orifice of a narrow canal which follows the center of the helictite. Helictites are composed of an aggregate of crystal units each with a slightly different crystallographic orientation than the next. Wedge-shaped increments of deposition cause rotation of the c-axis of successive crystal units which result in the curvature of helictites. Opposed to this curvature and tending to create deflection in the opposite direction is the crystal habit which favours a greater rate of growth in the direction of the long axis of the crystal units. The physical variables which control the relative importance of these two factors, and therefore the direction of growth, are believed to be the rate and periodicity of flow through the tube."

It occasionally happens that stalactites do not hang completely free from the cave roof, but become joined either to one another or to the wall of the cave. When this occurs they are known as <u>curtain stalactites</u>, and when suitably lit can present a sight of great beauty. Curtain stalactites developed in van Wyk's Main Cave are shown in Photograph 28.

<u>Stalagmites</u>

Cave floor deposits equivalent to the hanging

stalactites . . .



Photograph 27.

Irregular straw-like stalactites and true helictites from the Sterkfontein chambers. Quarter natural size

Photograph by J. C. Viljoen.

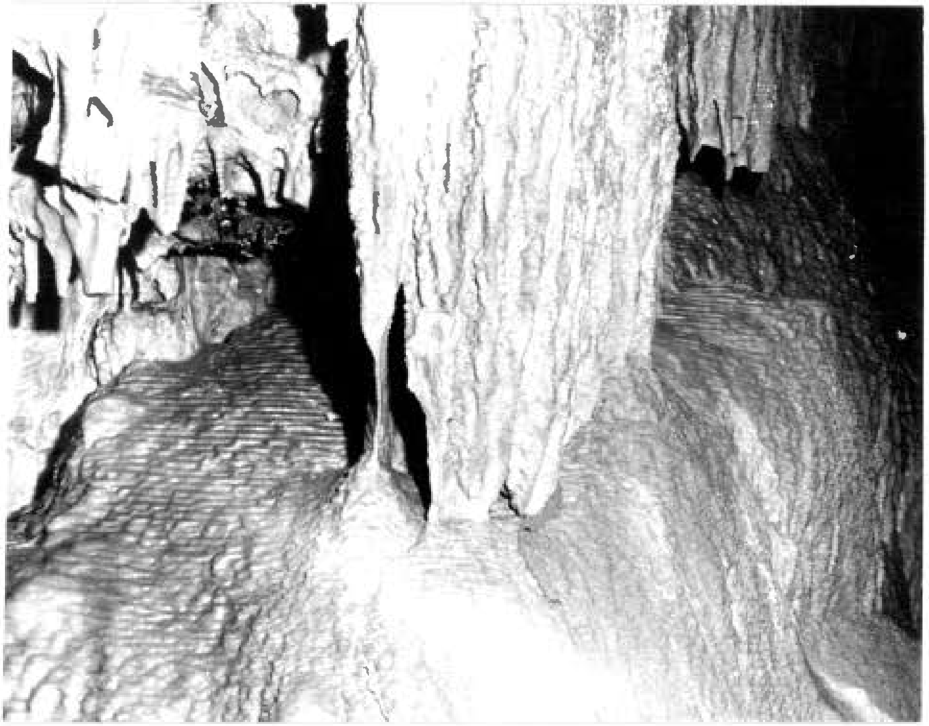
stalactites are known as <u>stalagmites</u> and are deposited from drops of solution that have fallen from the stalactites themselves. Ultimately the two may join and the combined pillar is then termed a <u>stalactostalagmite</u>. Although true stalagmites do occur in the Transvaal dolomite caves, floor deposits that are much more common are the bedded layers and low bosses which can more accurately be called <u>flowstone</u>. These accumulations are deposited from thin films of saturated carbonate solution that seep over the surface of the floor. Photograph 29 shows a flowstone boss in a modern dolomite cave. In section, flowstone frequently shows a layered structure caused by the irregularly superimposed laminations. This structure is shown in Photograph 30.

In thin section, flowstone, like the majority of cave travertine forms, is found to be made up of a mosaic of interlocking calcite crystals. Superimposed layers often display differences in texture and crystal size. A typical cave travertine in thin section is shown in Photograph 31. A contact between two distinct layers is clearly shown.

<u>Cave Pearls</u>

An interesting, though unimportant, calcite

formation . . .



Photograph 29

A flowstone boss with stalactites hanging down into it.

Gaub Cave

Photograph 30. Vertical section through a block of flowstone to show the laminated structure. Two-thirds natural size. Makapan Limeworks.

Photograph 31.

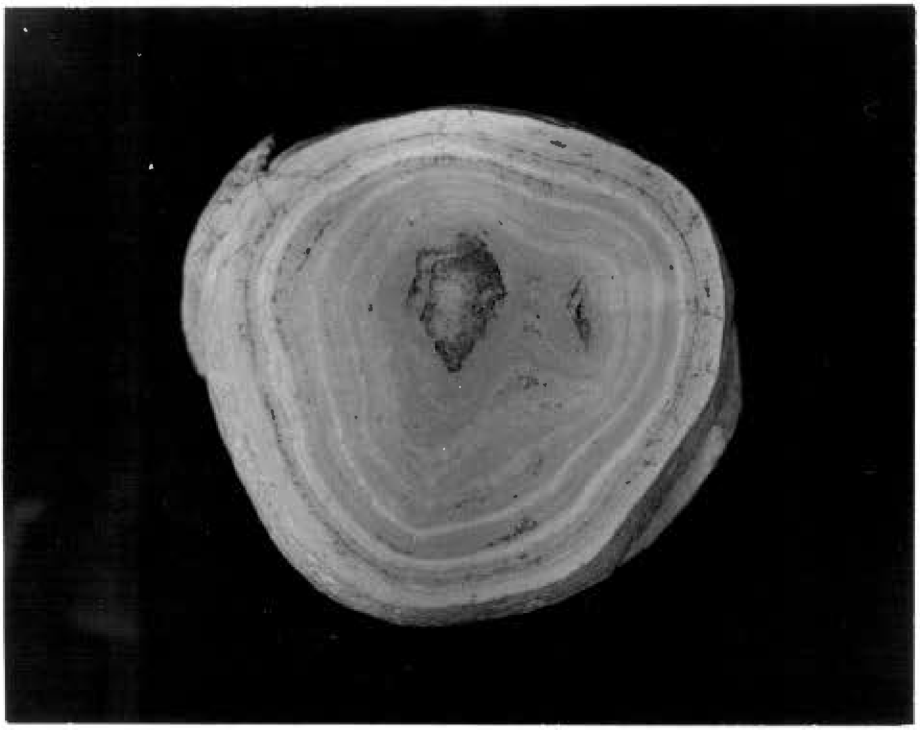
A thin section of flowstone to show the mosaic of interlocking calcite crystals. X~~40~~22. Ordinary light.

formation found occasionally in the Transvaal caves is the cave pearl. This consists of an approximately spherical mass of calcite deposited in concentric layers round a small stony nucleus. The pearls may vary in diameter from a quarter inch to several inches. They are typically found in small basin-like pools of water which are constantly agitated, either by drip, or by water flow. The agitation of the water causes any small stones at the bottom of the pool to be repeatedly turned over. If the water of the pool is saturated with calcium bicarbonate, calcite is likely to be precipitated round the stone nuclei. In this way concentric layers may be deposited to build up the growing pearl. Photograph 32 shows a section through an example from the Makapan Limeworks. Notice the chert nucleus and concentric calcite layers.

Aragonite Formations

Although aragonite deposits in caves are much less common than calcite ones they certainly do occur. ~~certainly do occur.~~ Warwick (1953) has described a thick flowstone accumulation of aragonite from the Lamb Lair Cave of Somerset. In addition to this, English helictites and normal stalactites have been described as being composed of aragonite.

Clusters . . .



Photograph 32.

Diametric section through a cave pearl from the Makapan Limeworks, to show the chert nucleus and concentric calcite layers. Twice enlarged.

Clusters of aragonite crystals are a fairly common feature of some of the Transvaal dolomite caves. Examples from the van Wyk's Main Cave near Sterkfontein are shown in Photograph 33. These crystal clusters are frequently found on the vertical cave walls, and are a common feature of a number of the Uitkomst caverns. The way in which the crystals develop is still very imperfectly understood. It seems as if some may grow under the water of the phreatic reservoir, while the cavern is still beneath the water table. Before any reliable conclusion can be reached however, a great deal of observation and research is required.

Gypsum

According to Warwick (1953), gypsum formations in caves are usually formed close to shale horizons containing pyrite. Upon decomposition of the pyrite, sulphuric acid is liberated. This reacts with the calcite in the country rock to produce the gypsum which is then presumably deposited by evaporation. Although reports of gypsum crystals in caves have been received, the writer has not observed any formations personally.

The Cave Breccias . . .

Photograph 33.

Clusters of aragonite crystals from the wall of van Wyk's Main Cave, near Sterkfontein. Approx. half size.

Photograph by J. C. Viljoen.

The Cave Breccias

As discussed in the last chapter, the general term cave breccia is applied to the varieties of forms of earth, soil and sand that have been calcified subsequent to their deposition in a cave. Thus a cave breccia comes to consist of two parts: the residue and the carbonate cement. The writer finds that, treating the breccias as rocks, it is often difficult to deduce much of interest from them. They usually consist of muddy limestones of which thin sections are not particularly instructive. A far more profitable approach, however, is through carefully dissolving away the carbonate cement, either in dilute acetic or hydrochloric acid, and then investigating the properties of the residue in the loose state as it was originally deposited in the cave. At the same time it is important to determine how much carbonate cement is present in each sample, while routine thin section examination is certainly very desirable.

In the following account, the properties of the various types of cave filling will first be considered in their decalcified forms. In each case the breccia samples have been dissolved in dilute acid, and the residue has been quantitatively collected by filtration, using a Buchner funnel and suction pump. After washing, the residue is dried in a low temperature oven. It can then be treated and analysed as a normal incoherent sediment or aggregate.

The technique for carbonate analysis will be dealt with in Chapter 9.

Residual Cave Earth

In the previous chapter it was stated that pure residual cave earth, uncontaminated with outside material, is only formed before the cavern acquires a direct opening to the surface. Once the cavern is open to the air, surface derived debris is likely to become mixed with the residual cave earth, in quantities dependent on the size of the cave entrance and the proximity of this entrance to the site of deposition.

ORIGIN

Since residual cave earth, like residual dolomite soil, is composed of the insoluble fractions of the dolomite itself, its nature is dependent on that of the country rock. The most obvious insoluble parts of dolomite are the chert bands so commonly found throughout the horizon. A study of insoluble residues in caverns, however, has shown that the chert bands, more than a

centimetre . . .

centimetre or so thick, do not break down into fine-grained sediment, but make up the blocks and stones of the residue. Thinner chert bands may disintegrate into sands and gravels, but the fine-grained constituents of the residue are definitely derived from impurities more sparsely scattered throughout the dolomite.

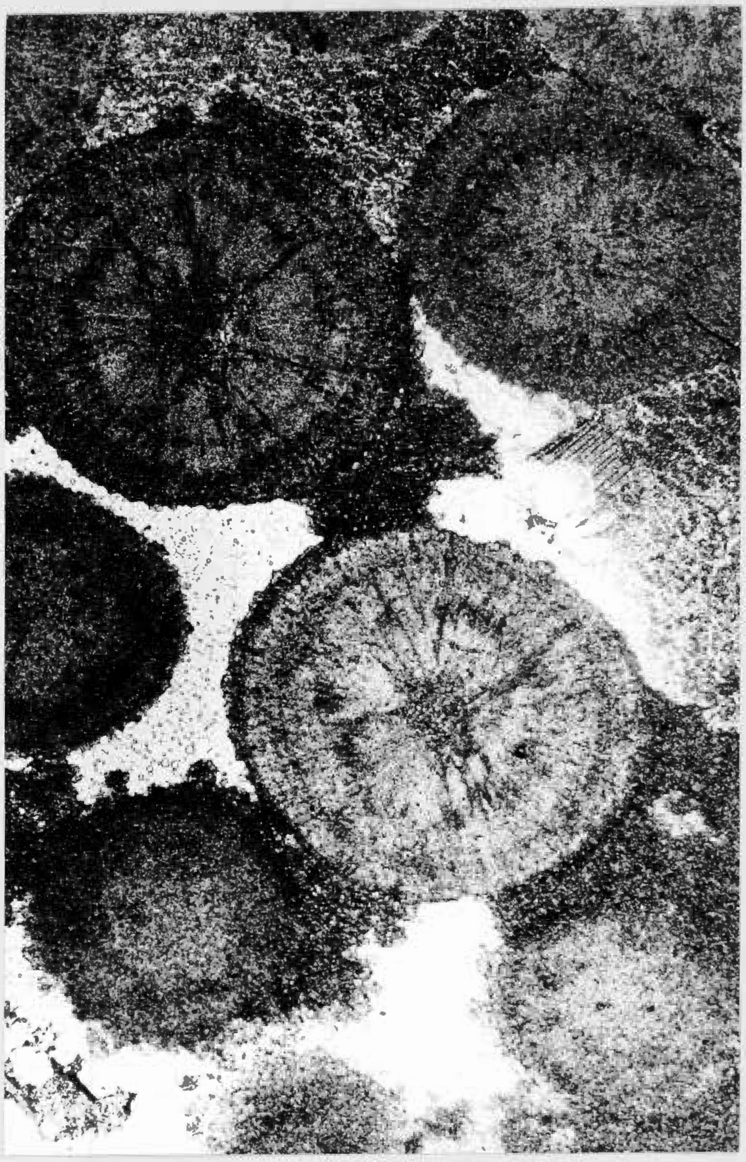
In this description, particular attention is given to those residues whose particles are smaller than fine gravel size. By far the most important single constituent of these residues is silica in the form of chert and quartz. The remainder of the bulk is made up of oxides of iron and manganese, together with shale particles, clay and heavy minerals. If weathered blocks of dolomite are carefully examined, or if samples are artificially dissolved in dilute acid, it is usually found that irregular grains of silica are scattered throughout the rock. Such grains, together with solid chert bands weathering out of a block of dolomite are shown in Photograph 34. Besides scattered grains of silica, numerous samples of pisolithic dolomite from the Sterkfontein area were found to contain a silica framework whose spaces have been filled with dolomite and calcite. A typical framework in thin section is shown in Photograph 35.

Whether the silica is as scattered grains, or is

Photograph 34.

A block of naturally weathered dolomite showing chert bands and scattered silica grains.

Approximately half natural size.



Photograph 35.

A thin section of pisolithic dolomite from Sterkfontein, showing the silica framework with spaces filled with dolomite and calcite. Ordinary light. X22.

in the form of a continuous, but fragile framework, it produces, when the dolomite is dissolved, the silicious sediment so characteristic of residual cave earths.

Characteristic features.

Since residual cave earth results from the solution of dolomite in the same way as does normal surface soil, it is obvious that many of the properties of the two products will be similar. Fortunately there is one most distinctive feature of residual earth which is invaluable in its diagnosis. This is the shape of the silicious sand grains that may be isolated from the residue.

A large number of residual earths, both natural and artificially prepared from the dolomite, has now been investigated. In every case the sand grains of chert and quartz present in the samples have had the same rather remarkable appearance. They are invariably very ragged grains of extreme fragility, resembling the skeletons of normal grains that have been severely corroded. The very irregular form of the grains is doubtless due to the fact that they have ~~been~~ crystallised in the uneven pore-spaces of the dolomite itself.

Silica ~~and~~ sand grains produced by artificially

dissolving . . .

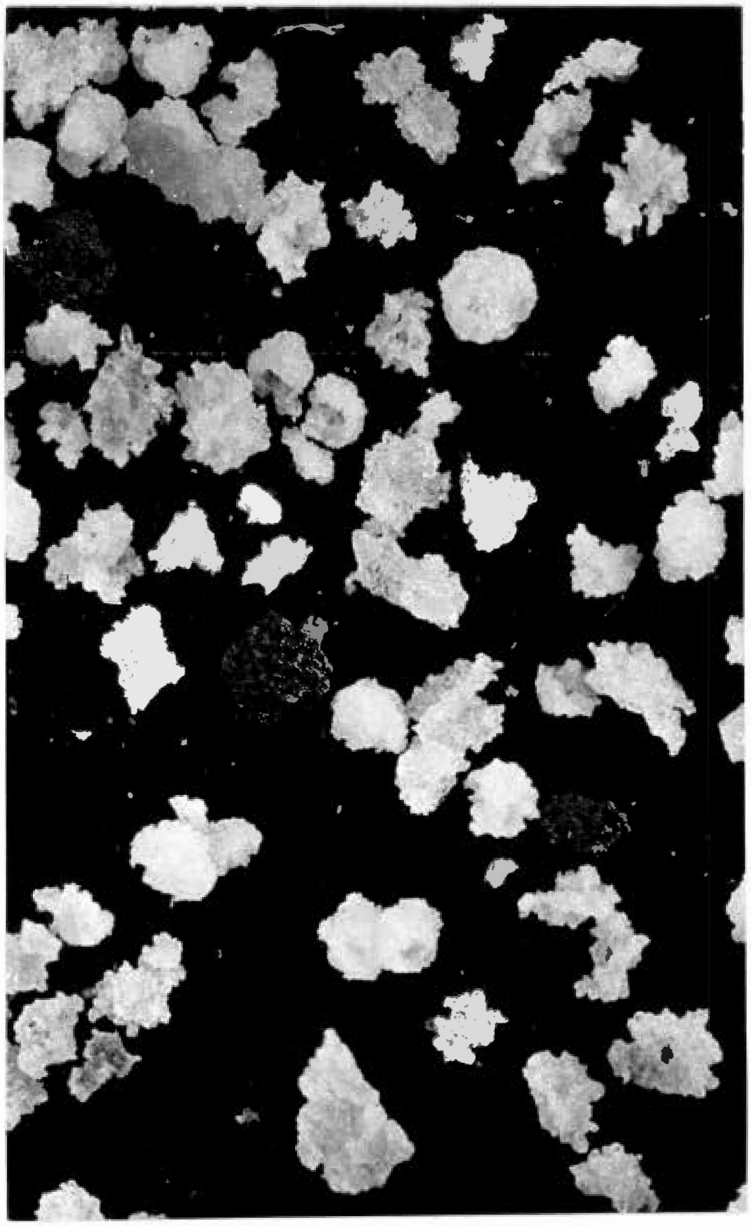
dissolving Transvaal dolomite are shown in Photograph 36. Their very ragged appearance is clearly visible.

It is of course not usually possible to obtain samples of earth from caverns that have no opening to the surface. Nevertheless, largely uncontaminated residual earth samples can usually be collected in dead-end gallery systems far removed from the surface openings of the caves. Such samples have been collected from a number of Transvaal dolomite caves both in the Sterkfontein and Makapan areas. In every case the sand grains contained in the samples were identical in appearance to those shown in Photograph 36.

The oldest deposit in the Swartkrans fossil cave is found to be heavily calcified residual cave earth in the form of a grey breccia. Sandgrains isolated from this deposit are shown in Photograph 37. They are found to be similar in form to those from the other artificial and natural residues already discussed.

It is clear that these extremely fragile sand grains are only preserved undamaged in the residual cave earths because of the fact that they have not suffered abrasion resulting from transportation or weathering. This represents the essential difference between a

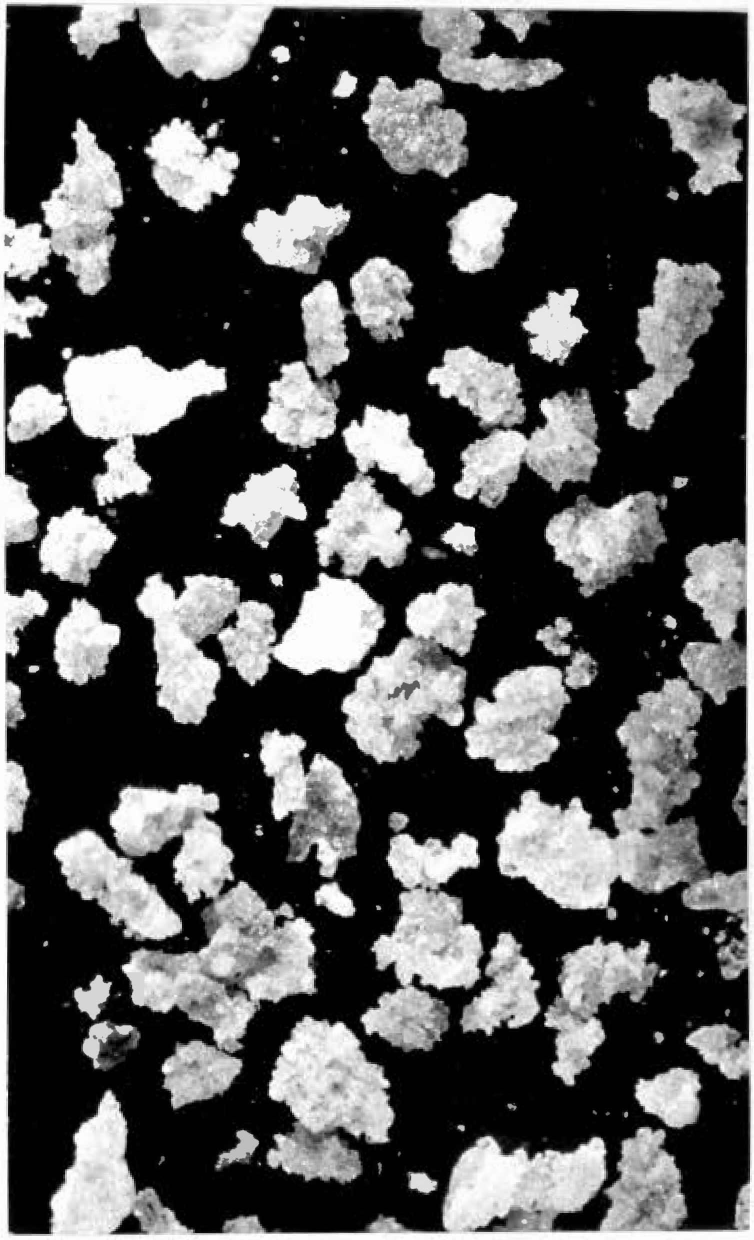
residual . . .



Photograph 36.

Silica sand grains artificially dissolved from Transvaal dolomite. Notice their very ragged appearance.

Magnified 40 times.



Photograph 37.

Sand grains characteristic of residual cave earth isolated from the grey breccia at Swatrkrans. These should be compared with the grains shown in Photograph 36.

Magnified 40 times.

residual cave earth and a residual surface soil. Sand grains of such fragility cannot survive when they are exposed to the elements on the surface.

Grains from the surface invariably show the effects of the weather and can be very readily distinguished from those that have been carefully protected in a closed cavern.

It should be appreciated that all the residual earths discussed here have resulted from solution of dolomite in the quiet water of the phreatic reservoir. Occasionally however, a cave may be encountered, such as the "Wet Cave" near Pilgrims Rest where a true underground river runs through the cavern system. When this occurs, residual sand grains derived from within the cavern may be abraded by transport without ever having been on the surface. True underground river courses fortunately appear to be very rare in the Transvaal dolomites generally. The technique used in the examination of the shape of individual sand grains is discussed in Chapter 9.

GRADING

It is to be expected that the grading of residual cave earths will vary from site to site in accordance with the nature of the parent dolomite. Horizons rich in chert bands are likely to produce a coarser grained residue than those composed of purer limestone. The technique

employed . . .

employed in the quantitative estimation of sediment grading is discussed in Chapter 9. Actual results for analyses done ion residual earths from the Sterkfontein caverns and the Swartkrans grey breccia, as well as on an artificially prepared residue of Transvaal dolomite are now provided:

RESIDUAL EARTHS:		Sterkfontein caverns	Swartkrans	Artificial
Clay	:	22.1	21.8	11.4
Silt	:	38.9	30.4	27.0
Fine sand	:	12.7	9.4	9.5
Sand	:	15.9	18.4	9.9
Coarse sand	:	8.3	11.2	22.0
Fine gravel	:	2.5	8.8	20.2
		100.4	100.0	100.0

It will be noticed that the two natural residues are predominantly fine grained sediments with the greater part of their bulk falling in the silt and clay grades. The artificially prepared residue, on the other hand, contains a large proportion of coarser aggregate of fine gravel and coarse sand dimensions. This is doubtless due to the fact that, in this case, the dolomite has been rapidly dissolved and insufficient time has been provided for the

coarser . . .

coarser chert particles to be disaggregated and digested.

Calcified residual earths

In all but the very modern caves, deposits of residual earth have characteristically been heavily calcified. They then form typical grey cave breccias. The colour results from the fact that manganese dioxide is a major constituent, while the additional iron is normally incompletely oxidised. In fact iron carbonate or siderite is a common component.

In thin sections the grey breccias show up as muddy limestones often containing well developed crystals of calcite and siderite. A thin section of grey breccia from Swartkrans is shown in Photograph 38. As mentioned previously the identification of a calcified residual earth cannot be made successfully in this section. It can only be done on examination of the sand grains in the sediment.

As grey breccias are normally formed in caverns before they acquire openings to the surface, they are likely to be completely sterile from the palaeontological point of view.

Phase I Breccias

ORIGIN

In the previous chapter the essential nature of

Photograph 38.

A thin section of calcified residual earth from Swartkrans. It consists of muddy limestone with occasional crystals of calcite and siderite. Ordinary light. X22.

In the previous chapter the essential nature of Phase I materials was considered. It was pointed out that these sediments have a dual origin: being composed partly of residual cave earth and partly of surface derived material. Mixed material of this sort is normally deposited in a cave at a time when the cave entrance is small, and the quantity of surface material entering the cavern is not excessive.

CHARACTERISTIC FEATURES

As is the case with residual cave earth, the identification of a Phase I breccia can not easily be made by the examination of thin sections. Investigation of the properties of the decalcified sediment is found to be much more profitable.

The residual cave earth component in a Phase I breccia can be recognised by means of the extremely irregular and fragile sand grains already discussed. The surface-derived component may obviously consist of any of the variety of materials likely to be found on the surface. The most important of these are eluvial dolomite soils or transported materials either alluvium or wind-borne sediment.

If the surface-derived component in the Phase I sediment is small it may be difficult to decide precisely

what its . . .

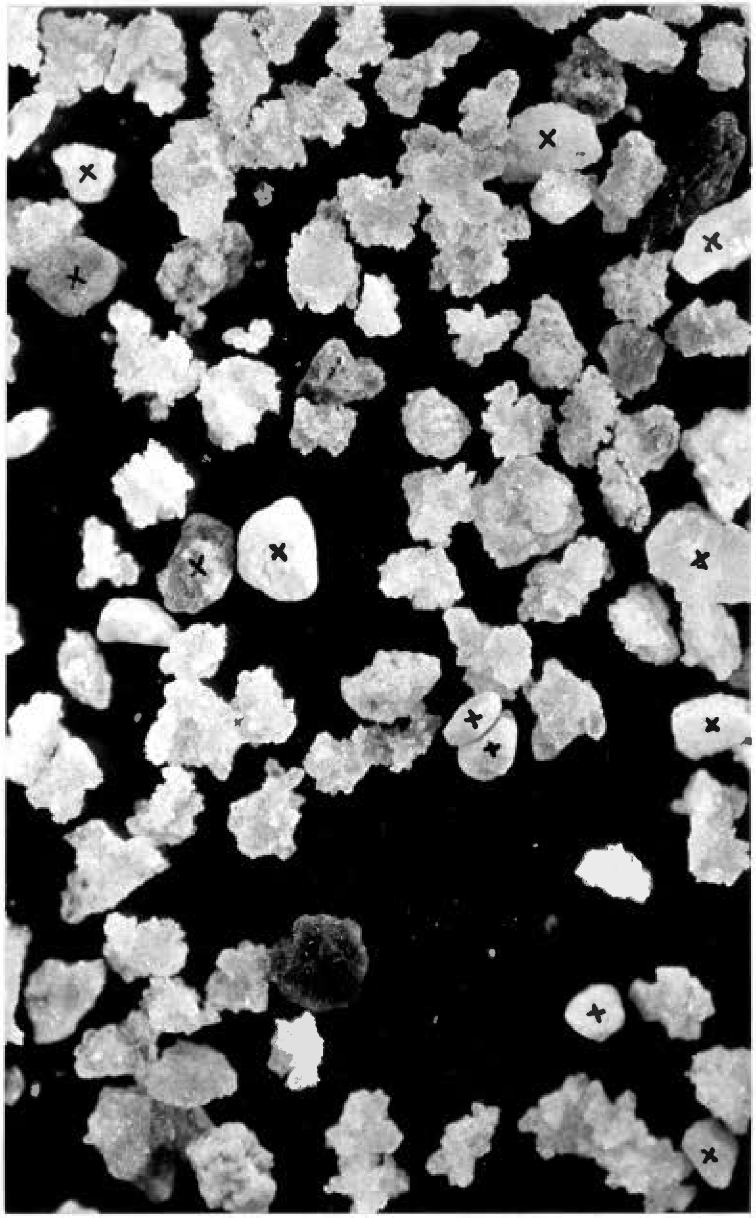
what its nature is. The criteria used in distinguishing between dolomite soils, alluvia and wind-borne deposits are dealt with in the succeeding section on Phase II breccias.

Examination of the shape and form of sand grains is again the most useful means of identifying a Phase I sediment. Grains of two strongly contrasted types are invariably present: the excessively angular residual earth grains, and the obviously worn grains derived from the surface. It is found that the grains will show unmistakable signs of wear whether they come from surface dolomite soil, from alluvium or from a wind-borne deposit.

Grains from the Phase I deposit on the floor of the Modern Sterkfontein chamber are shown in Photograph 39. Worn grains from the surface are marked so that they can be recognised easily. Photograph 40 shows sand grains from the Phase I deposit in the Swartkrans fossil cave. Again, the two strongly contrasted forms are present.

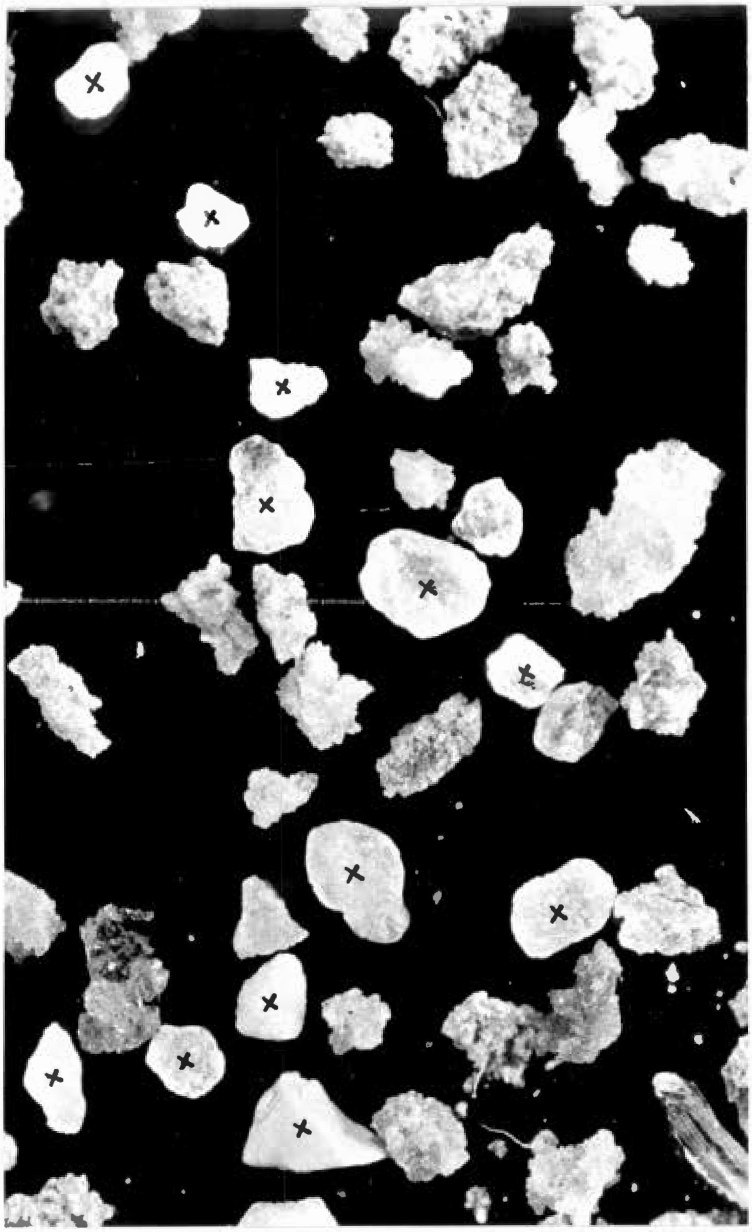
Grading

It is not possible to generalise on the characteristic grading of all Phase I sediments. This is because the grading will obviously depend both on that of the residual earth and of the surface derived material. Since surface derived materials vary very much in particle size distribution, the influence that they exert on the



Photograph 39.

Sand grains from the Phase 1 deposit in the modern Sterkfontein caverns. Worn, surface-derived grains are marked with crosses. The remainder are grains typical of residual cave earth. Magnified 40 times.



Photograph 40.

Sand grains isolated from the Phase 1 breccia at Swartkrans. Worn, surface-derived grains are marked with crosses. The remainder are grains typical of residual cave earth. Magnified 40 times.

grading of the Phase I sediment can vary considerably. In actual fact the grading of the majority of Phase I sediments examined did not vary very much from that of a normal dolomite soil. As an example an analysis of a Phase I sediment from the Sterkfontein underground chamber is provided:

Clay........:	7.4
Silt........:	35.4
Fine sand...:	17.5
Sand........:	15.6
Coarse sand.:	12.4
Fine gravel.:	11.6
	99.9

Calcified Phase I sediments

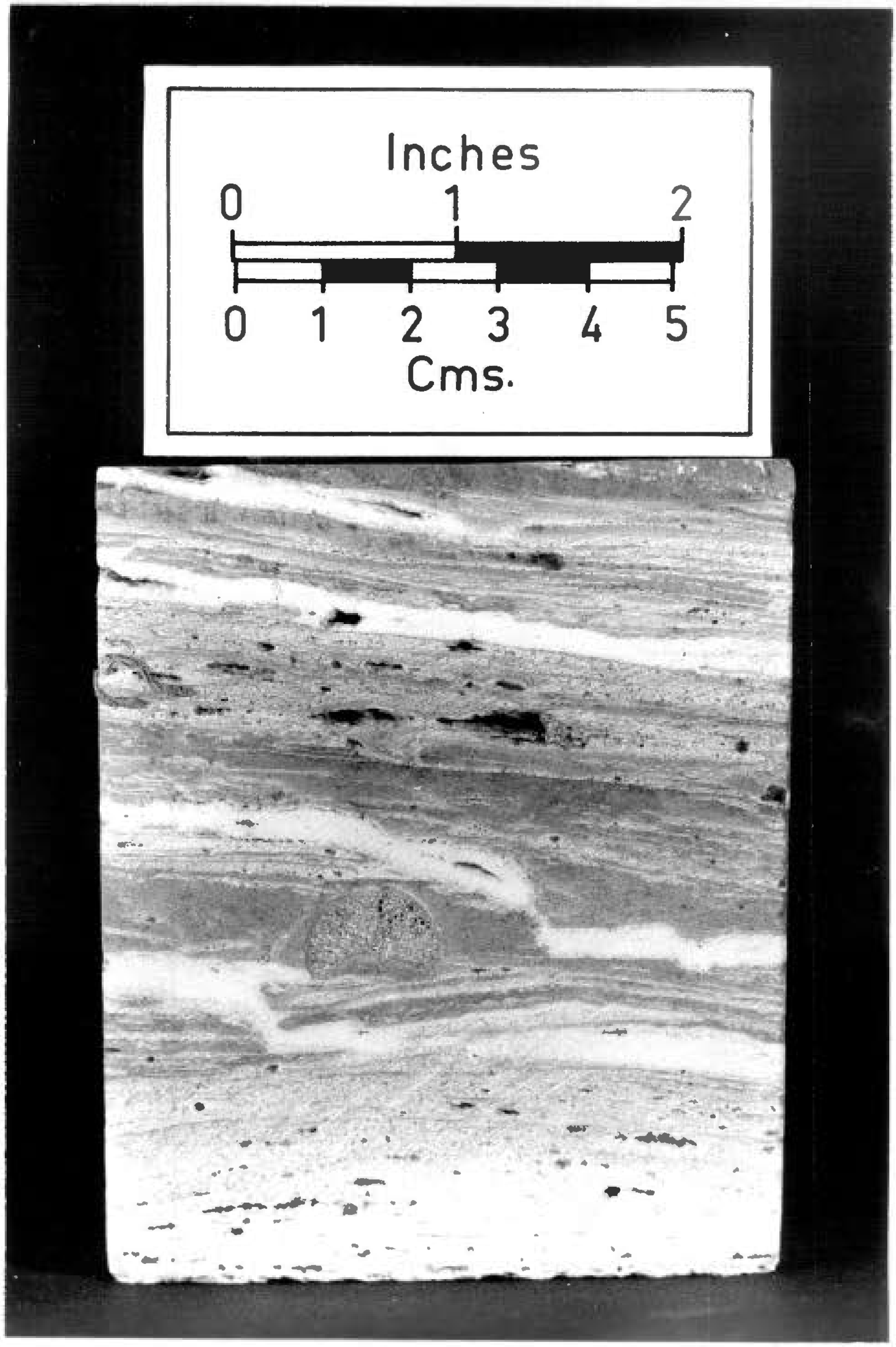
It should be realised that Phase I deposits are normally very slow-forming accumulations. This is because residual cave earth is produced slowly from the parent dolomite, while the surface-derived material is only admitted in small quantities to the cavern. The stage in cavern development at which Phase I sediments accumulate is also characterised by the abundant deposition of cave travertine. The usual result is that the floor travertine becomes contaminated with the sediment particularly over the lowest areas of the cave floor. Thus in all but the very modern caves, Phase I sediment is to be found in the form of contaminated or banded travertines with carbonate contents frequently over 90% by weight. Colours vary from

bright red . . .

bright red to grey or buff, depending on the nature and quantity of the contaminating sediment. A section through a block of Phase I banded travertine from the Makapan Limeworks is shown in Photograph 41. It will be noticed that this sample contains a sectioned bone. This is perhaps to be expected since Phase I breccias are usually extremely rich in bone, and are therefore of considerable palaeontological value. The reason for this is that the cave is open to the air and odd bones will be introduced through the entrance from time to time. These will finally become concentrated and preserved in the extremely slowly forming Phase I deposit.

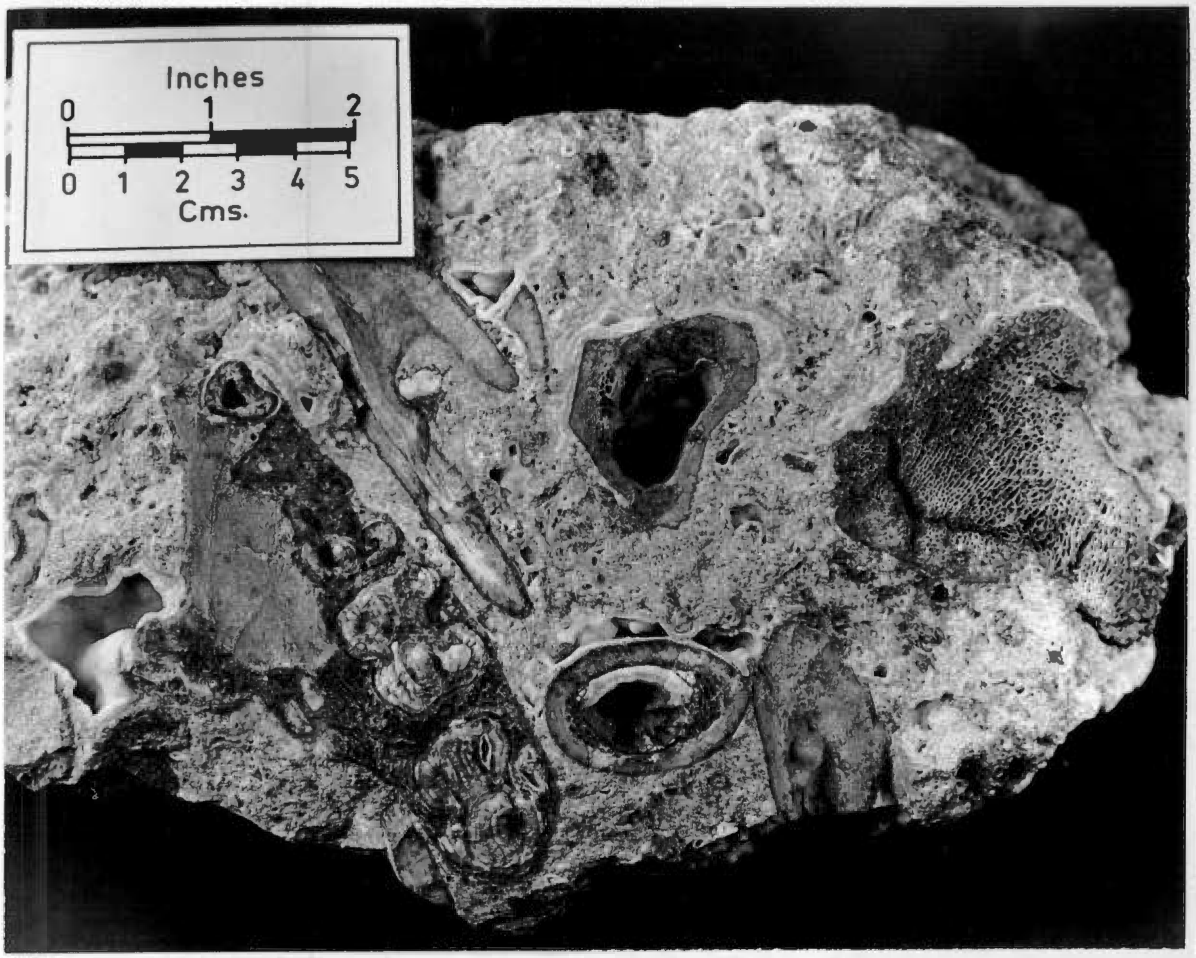
Practically all the very numerous bones from the Makapan Limeworks have been derived from the Phase I breccias. Photograph 42 shows a block of grey, Phase I contaminated travertine from Limeworks. Notice the included bones in characteristic abundance.

The greater part of the Phase I deposit at Swartkrans consists of an extraordinarily rich deposit of rodent bones. A hand specimen of this accumulation is shown in Photograph 43. Six samples of the deposit have been analysed and the average weight percentage of bone present is found to be 23.3. The actual results will now be given:-



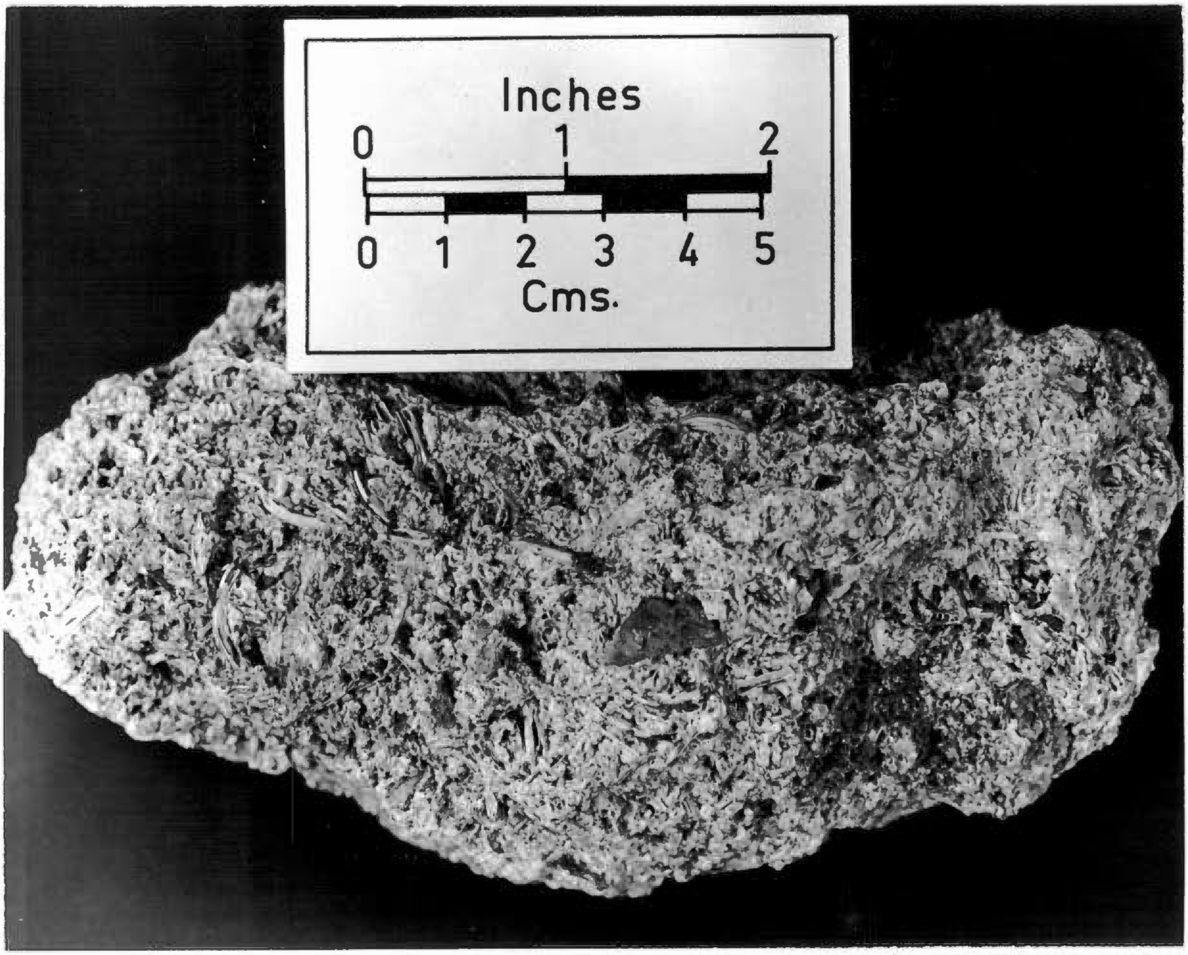
Photograph 41.

A vertical section through a block of Phase 1 banded travertine from Makapan Limeworks. Notice the piece of included bone.



Photograph 42.

A block of Phase 1 contaminated travertine from the Makapan Limeworks, showing the abundant included bones.



Photograph 43.

A block of Phase 1 breccia from Swartkrans, showing the very abundant rodent bones characteristic of the deposit.

Swartkrans rodent bone layer samples:

	1	2	3	4	5	6
Weight % bone	25.5	19.8	17.3	22.6	25.7	28.7
Weight % earth	4.9	6.1	4.8	6.9	3.3	7.2
Weight % carbonate cement	69.6	74.1	77.9	70.5	71.0	64.1
	100.0	100.0	100.0	100.0	100.0	100.0

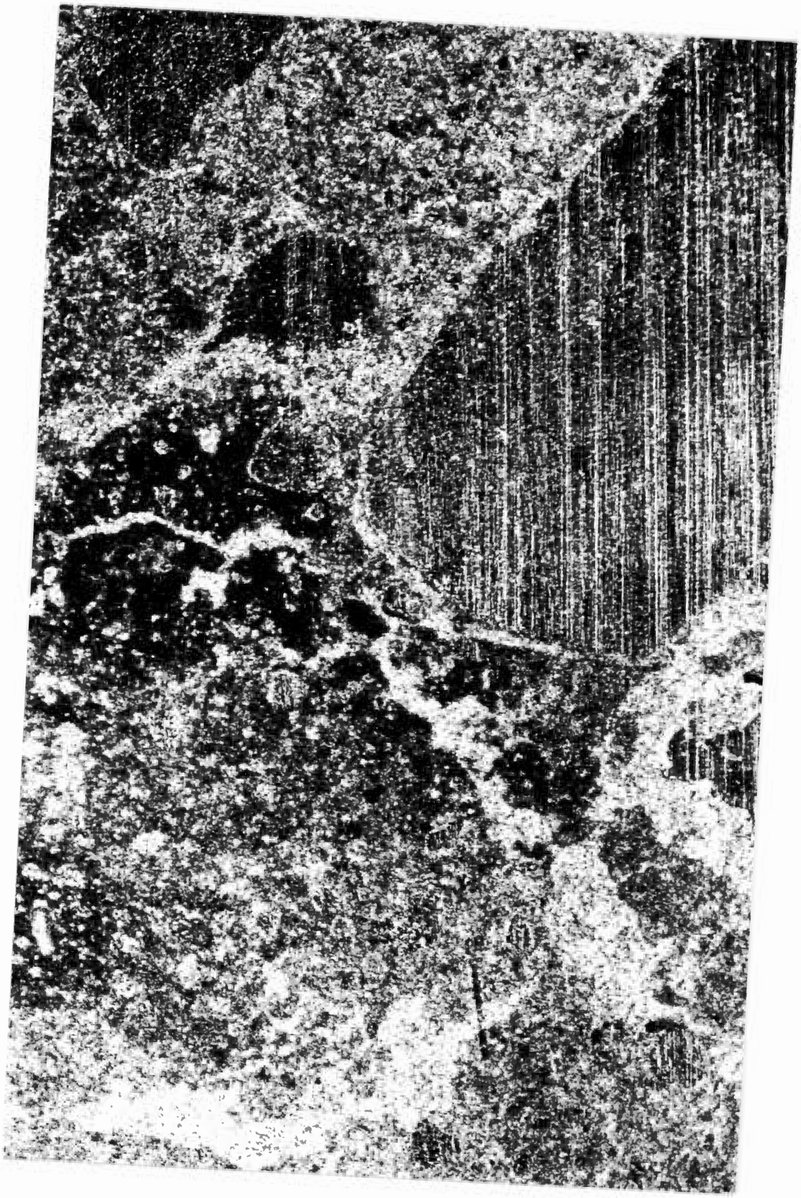
In thin section, Phase I breccias vary from dirty limestones to practically pure travertines. Photograph 44 shows a grey Phase I breccia from Limeworks in thin section. Note the large well developed calcite crystals.

PHASE II MATERIALS

Uncalcified Phase II sediments deposited in caves consist of practically uncontaminated surface derived materials. They are characteristic of a stage in cavern development when the cave entrance is large, and is admitting outside material in such quantities, that the small proportion of residual cave earth still accumulating becomes altogether insignificant. Thus Phase II aggregates in caves can be regarded as truly representative samples of the surface materials, in the vicinity of the cave entrances, at the time of accumulation.

Phase II deposits in the Transvaal dolomite caves are likely to be composed of either normal dolomite soil or

transported . . .



Photograph 44.

A thin section of the Phase 1 breccia from Makapan Limeworks. Large calcite crystals are developed in this contaminated travertine. Ordinary light. X22.

transported material in the form of alluvium or wind-borne sand. These various materials will now be considered separately.

Normal dolomite soils.

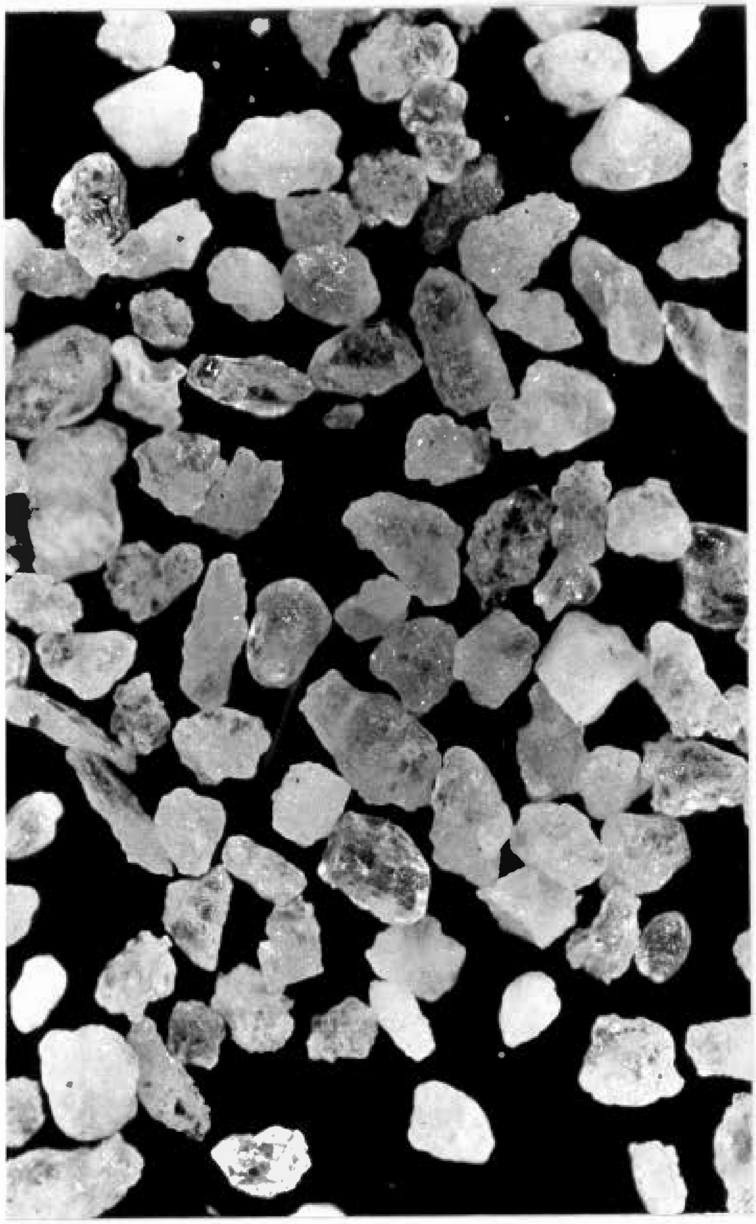
As is the case with residual cave earths, the surface dolomite soils are composed of the insoluble residues of the dolomite left when the rock is weathered by solution. Unlike the residual cave earths however the soils, being on the surface, are subjected to the agencies of weathering lacking in closed caverns. Thus one finds that although the silica sand grains emerge from the dolomite in the same ragged and fragile form as already discussed, they do not survive thus, but quickly have their outgrowths knocked off them and then become more normal in appearance. Photograph 45 shows sand grains altogether typical of a normal dolomite soil or a Phase II breccia.

The modifying effects of various climatic environments on normal dolomite soils are discussed in the chapter on climatic deductions from soils.

GRADING

In grading, modern dolomite soils vary to some extent, but all show a fairly even particle size distribution

from fine . . .



Photograph 45.

Sand grains from a typical modern dolomite soil. The grains are of quartz and chert, and without exception, show some signs of wear. They may thus be distinguished from residual cave earth sand grains. Magnified 40 times.

from fine gravel to clay. Results of grading analyses done on 18 samples of modern dolomite soils from the Transvaal are now provided.

MODERN DOLOMITE SOILS

GRADING ANALYSIS RESULTS

	PERCENTAGES						
LOCALITY	Fine Gravel	Coarse Sand	Sand	Fine Sand	Silt	Clay	Totals
SWARTKRANS	6.0	13.6	20.9	23.6	28.3	7.7	100.1
"	0.2	1.0	4.0	38.6	48.5	7.9	100.2
"	25.3	18.7	10.0	19.6	23.0	3.4	100.0
"	2.0	14.6	18.3	22.5	35.0	7.5	99.9
"	14.9	18.5	14.7	19.7	26.2	6.0	100.0
"	15.1	18.3	12.0	20.7	27.3	6.6	100.0
STERKFONTEIN	10.7	13.6	20.4	20.6	29.5	5.2	100.0
KROMDRAAI	16.3	16.3	17.4	18.1	26.3	5.7	100.1
UITKOMST	19.1	30.1	20.7	7.6	18.7	3.5	100.0
HENNOPS-RIVER	6.0	18.1	29.3	21.7	19.0	5.9	100.0
TAFELKOP	4.8	17.2	16.8	22.0	33.5	5.8	100.1
SCHURVEBERG	21.2	19.5	26.8	10.7	17.8	4.2	100.2
MOOIPLAAS	4.0	24.9	27.2	14.8	24.2	5.0	100.1
FOUNTAINS	16.4	30.9	20.2	11.8	14.3	6.2	99.8
MAKAPAN LIMEWORKS	20.2	19.6	30.9	7.6	18.5	3.1	99.9
"	9.6	18.4	19.5	16.4	31.6	4.5	100.0
"	8.2	16.8	24.0	12.0	32.1	6.9	100.0
"	9.6	21.3	27.8	6.8	30.3	4.3	100.1

In deciding whether a Phase II cave deposit

represents . . .

represents a normal dolomite soil or not, it is useful to know what range of variation may be expected in the various size groups of normal dolomite soils. The variation in the six size fractions deduced from the 18 soil samples analysed are now given.

		Weight percentages		
Fine Gravel	:	0.2	-	25.3
Coarse sand	:	1.0	-	30.9
Sand	:	4.0	-	30.9
Fine sand	:	6.8	-	38.6
Silt	:	14.3	-	48.5
Clay	:	3.1	-	7.9

In addition to the particle sizes reflected in the grading analyses, normal dolomite soils almost invariably contain an abundance of stones and boulders, derived from the insoluble chert bands of the parent rock. Typical dolomite soil profiles are dealt with in the section on climatic deduction.

Transported materials: Alluvium and wind-borne deposits

The characteristic features of alluvial and aeolean deposits are generally ~~[illegible]~~ well known and are

discussed . . .

discussed in the majority of text books dealing with sedimentary rocks. In this work, therefore, some particular features only will be considered.

GRADING

One of the most obvious results of transport in alluvial and aeolean deposits is the sorting of the sediment into various particle size groups. With both water and wind transport the finer grades are carried much further than are the coarser and the various size fractions are commonly laid down separately as distinct deposits.

The grading of alluvial deposits is found to vary from accumulations of gravel and boulders to beds of clay All intermediate stages and mixtures can be found. With aeolean deposits, stones and pebbles too heavy to be carried by the wind are left behind on the stone-littered, wind-swept flats known as gibber plains. An example of a gibber plain from the Northern Namib desert in Angola is shown in Photograph 46. A closer view of the surface of the plain is shown in Photograph 47. Notice the example of a wind abraded pebble typical of this sort of environment.

The most characteristic of all aeolean deposits

are the . . .

Photograph 46.

A gibber plain in the Northern Namib desert, Southern Angola. In the background are wind-fretted cliffs of soft sandstone.

are the desert sands frequently in the form of dunes. In grading these sands are found to be very well sorted and usually consist of sand to the practical exclusion of other size fractions. In the following table a number of grading analyses is provided for aeolean sands from the Kalahari and Namib deserts. Notice particularly how the material has been sorted into the sand grades.

WIND BORNE SANDS OF DESERT TYPE

GRADING ANALYSIS RESULTS

	PERCENTAGES						
LOCALITY	Fine Gravel	Coarse Sand	Sand	Fine Sand	Silt	Clay	Totals
Kalahari-type sands							
Inkruip S. Kalahari	0.2	43.7	35.1	17.4	0.9	2.7	100.0
Witsand S. Kalahari	1.5	27.4	41.2	23.2	4.3	2.3	99.9
Niekerkshoop S. Kalahari	1.8	9.8	66.0	16.2	0.9	5.5	100.2
Livingstone S.R.	0.0	29.8	58.0	8.6	0.7	2.9	100.0
Lupani S.R.	0.2	16.0	49.4	29.2	2.2	3.2	100.0
Rietfontein S. Kalahari	0.0	0.2	89.0	10.1	0.7	0.0	100.0
Namib Desert sands							
Porto Alexandre. S. Angola	1.1	34.9	60.9	1.5	0.0	2.3	99.8
Alexander Bay	0.5	27.6	60.4	8.5	1.1	1.9	100.0
Springbok Namaqualand	0.0	67.1	29.3	2.2	0.0	1.4	100.0

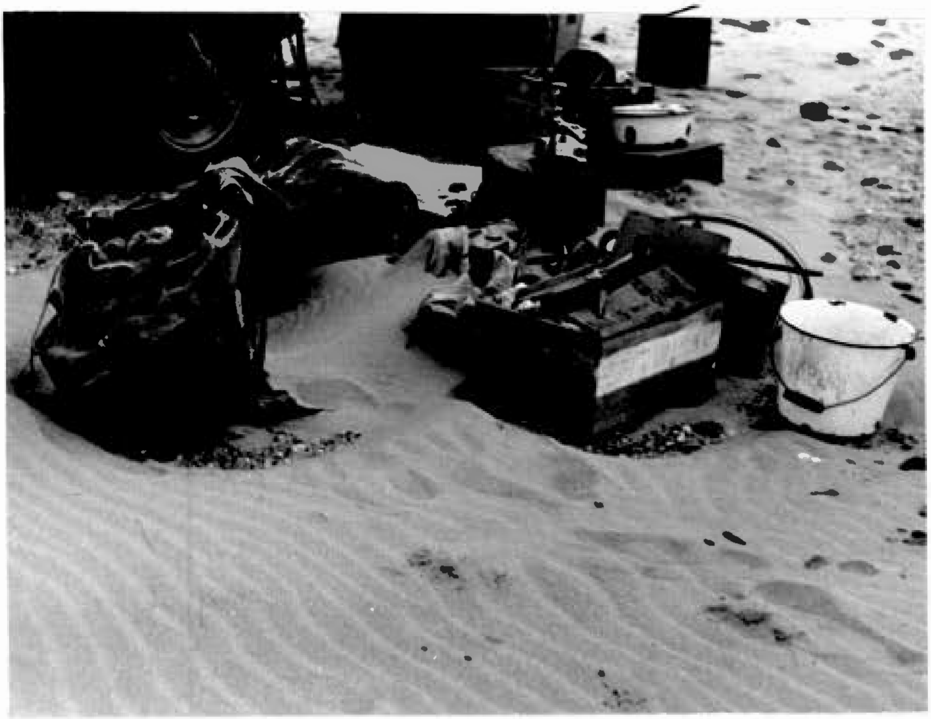
The way . . .

The way in which sand is concentrated to the exclusion of the other particle sizes can be conveniently observed in any active desert region. Unfortunately the greater part of the Kalahari represents a dormant desert, where aeolean activity cannot be observed at its full intensity. From this point of view the Namib is very much more satisfactory. Here, strong winds are a regular feature for the greater part of the year and the mechanism of wind sorting can be easily observed.

Whenever a strong wind blows the sand grains are picked up and moved in a series of hops over the surface. Very considerable quantities of sand can thus be transported in a short space of time . Photograph 48 shows sand that was deposited on a stony flat by the wind during a single night in the Namib desert.

While the sand grains are being transported close to the surface of the ground, the finer silty sediment is usually swept high into the air and may be carried for a great distance. A ~~desert~~ dust storm obscuring mountains in the coastal Namib desert is shown in Photograph 49.

As was observed by King (1942) thick deposits of wind-laid silt or loess are very uncommon in the present day arid regions of South Africa. This is



Photograph 48.

Sand deposited on a stony flat during a single night by the wind in the Namib desert. Southern Angola.

Photograph 49.

A severe dust storm in the mountains of the coastal Namib desert, near Alexander Bay. The fine grained silty sediment is thus sorted from the sand by the wind certainly because the loess becomes so widely dispersed by the wind. The closest that the writer has seen to an extensive and recent loess deposit was found in the Orange River valley between the Richtersveld and the sea. Here minature barchan dunes, as shown in Photograph 50 were found to be composed of very fine grained sand. The grading of this material may be expressed as follows:

	Percentage by weight
Clay :	4.6
Silt :	0.0
Fine sand :	77.8
Sand :	17.6
Coarse sand :	0.0
Fine gravel :	0.0
	100.0

Distinguishing features between alluvial and aeolean deposits.

As has been discussed, it is possible for two deposits of equivalent grading to be produced through transportation by either water or wind. Thus when such deposits are preserved in a cave and it is required to decide what their depositional history has been, the grading analysis technique is not of much assistance. Other means

therefore . . .

Photograph 50.
Minature barchan dunes in the bed of the Orange River between the Richtersveld and the sea. These dunes are composed of extremely fine grained sediment.

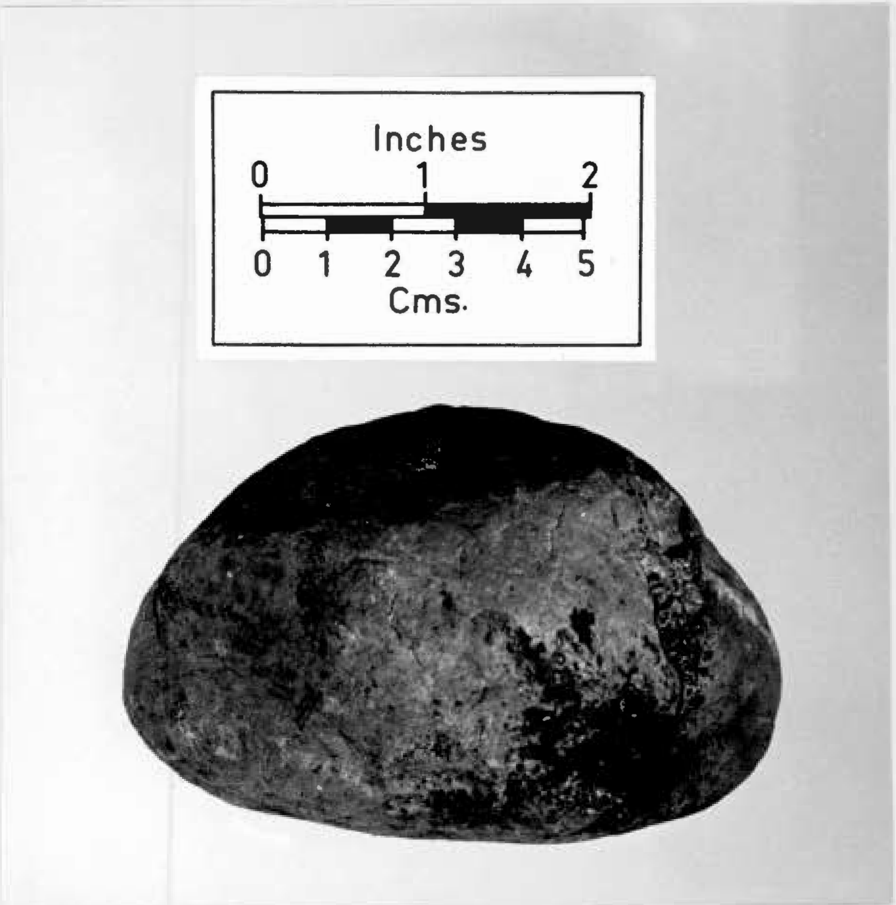
therefore have to be employed.

Fortunately, it is found that very distinctive differences are present in both the gravel and the sand grades of the two deposits involved. The differences in each grade will now be discussed separately.

Gravels

The properties of waterworn alluvial gravels are well known. Their most distinctive feature is that the individual pebbles have been rounded in accordance with the distance that they have travelled. Even in the small Transvaal stream courses the pebbles and boulders have been characteristically well rounded, while it appears that a few miles of travel have a profound effect on pebble shape. An example of a waterworn pebble typical of the Transvaal stream courses is given in Photograph 51.

Particles of gravel size associated with deposits of aeolean sand show very different features. Such particles have not been transported themselves by the wind but have been abraded by the sand passing over them. In this way facets become cut on the sides of the pebbles and the resulting, frequently pyramidal, stones are known as ventifacts. Another characteristic result of wind abrasion is the etching or fretting out of any soft portions of pebbles so that ultimately a mere skeleton remains.



Photograph 51.

A typical waterworn pebble from a Transvaal stream course. This should be compared with the windworn pebbles shown in Photograph 52.

Etched stones are perhaps a more reliable indicator of aeolean activity than are facetted ones. This is because various authors have reported that facetted stones may be produced by stream action. (See Taljaard, (1939)). True ventifacts and etched stones from the Namib desert in Southern Angola are shown in Photograph 52.

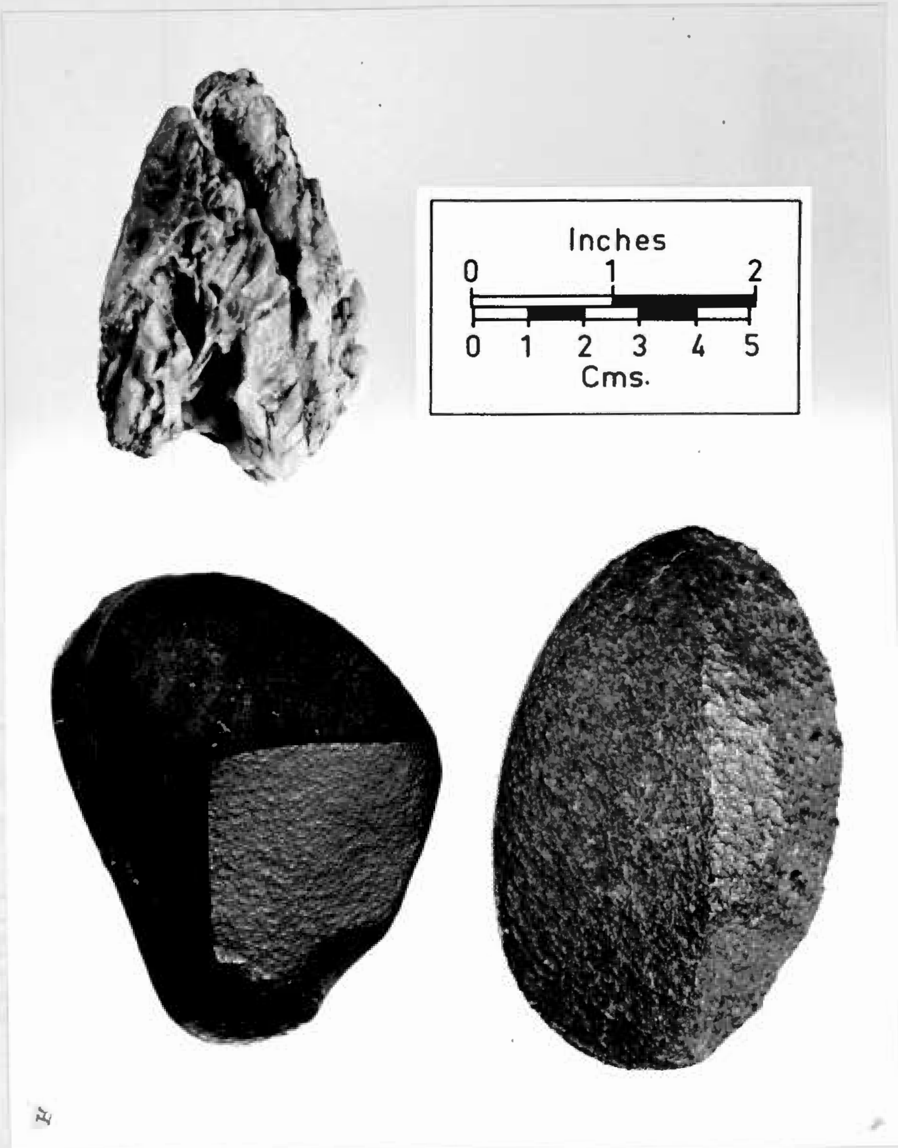
<u>Sands</u>

It is a well known fact that sand grains may become rounded as a result of transportation by either water or wind. It is also well known that the rounding process is very much slower in the case of water than wind. (See Pettijohn 1949, Krumbein 1941 and Russel and Taylor 1937).

Although sand grains may be equally well rounded by either agency, Bond (1954 and 1955) has shown that it is an easy matter to distinguish between the two products. The distinction is made not on shape, but on <u>surface texture</u>.

Bond has shown that wind-borne sand grains characteristically have a matt or frosted surface texture, and although they may be composed of transparent quartz, they appear "milky and opaque". He states: "This texture is made up of a meshwork of minute scratches and small pits. The milky opacity of the dry grains is caused by the scattering of light by the surface markings. It is only

possible . . .



Photograph 52.

Wind-abraded pebbles from the Namib desert. Note how some have had facets cut on their sides, while others have been etched and fretted by the blown sand.

possible to see through the surface in a very small proportion of the grains."

Bond has shown that such grains, when transported for as little as 40 miles in the Zambesi River, undergo a very dramatic change in surface texture. Of them he says:-

"The grains are brilliantly smooth and polished. They are transparent and glossy and their interiors can be examined with ease even in dry mounts. Occasional pits remain on the surface, but even these depressed parts of the surface are highly polished."

Thus the examination of surface texture can be extremely useful in deciding how a sand was transported and deposited. The writer has examined the surface texture of a very large number of samples of aeolean and river sand from South Africa. It is found that Bond's conclusions on surface textures do almost invariably apply. In a few cases, however, river sands were found to still show frosted surfaces doubtless due to the fact that they had not been carried far by the water. Another complication was that in a number of samples examined, quite a high proportion of the sand grains were composed of milky quartz. In these, surface polish was not as easy to see as in the transparent grains, although it could be detected with careful examination.

Photograph 53 . . .

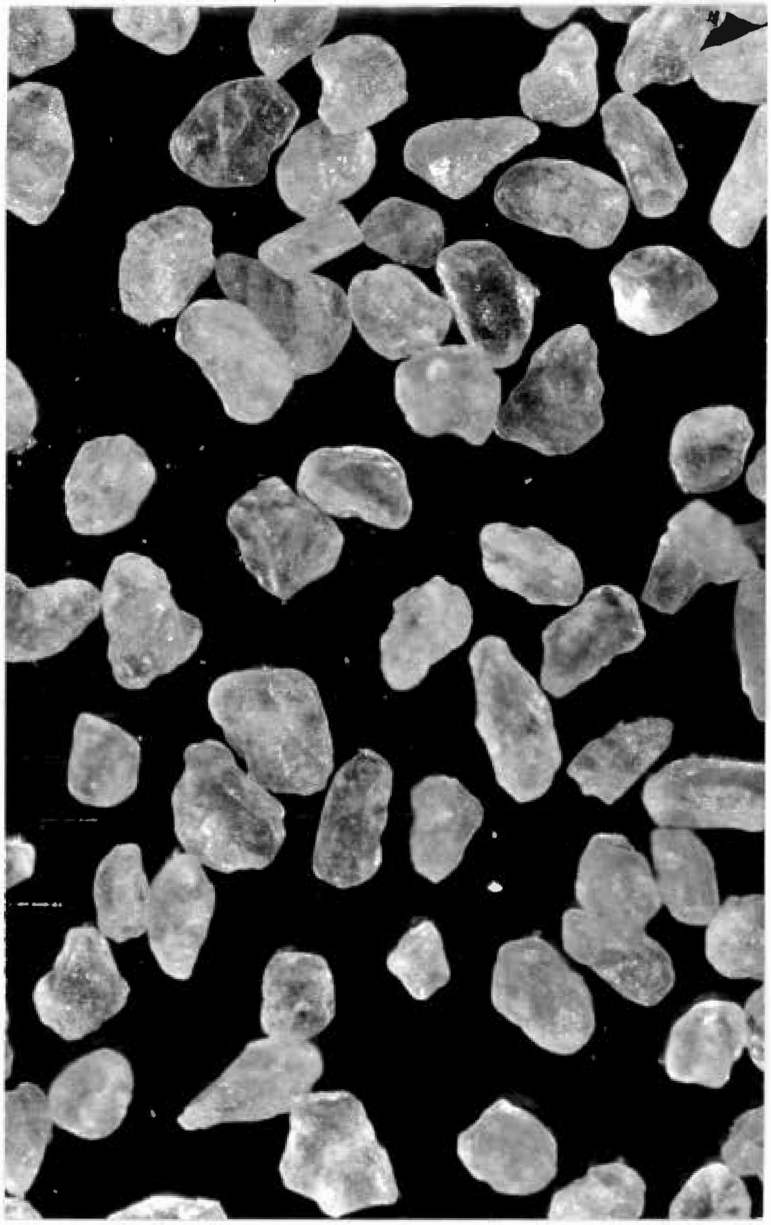
Photograph 53 shows typical frosted sand grains from a desert dune sand. These should be compared to the highly polished grains shown in Photograph 54 which form an example of a river sand.

CALCIFIED PHASE II DEPOSITS

Phase II materials are by far the commonest fillings found in the Transvaal dolomite caves. They have very frequently been heavily calcified and are then termed Phase II breccias. In thin sections, these breccias are found to consist of muddy or sandy limestones devoid of special features. Photograph 55 shows a thin section of a typical Phase II breccia from Swartkrans. This example represents a calcified dolomite soil. The calcite content of breccias varies very much from one site to another. In the section on inter-site correlation, comprehensive carbonate analyses are provided for all the main sites.

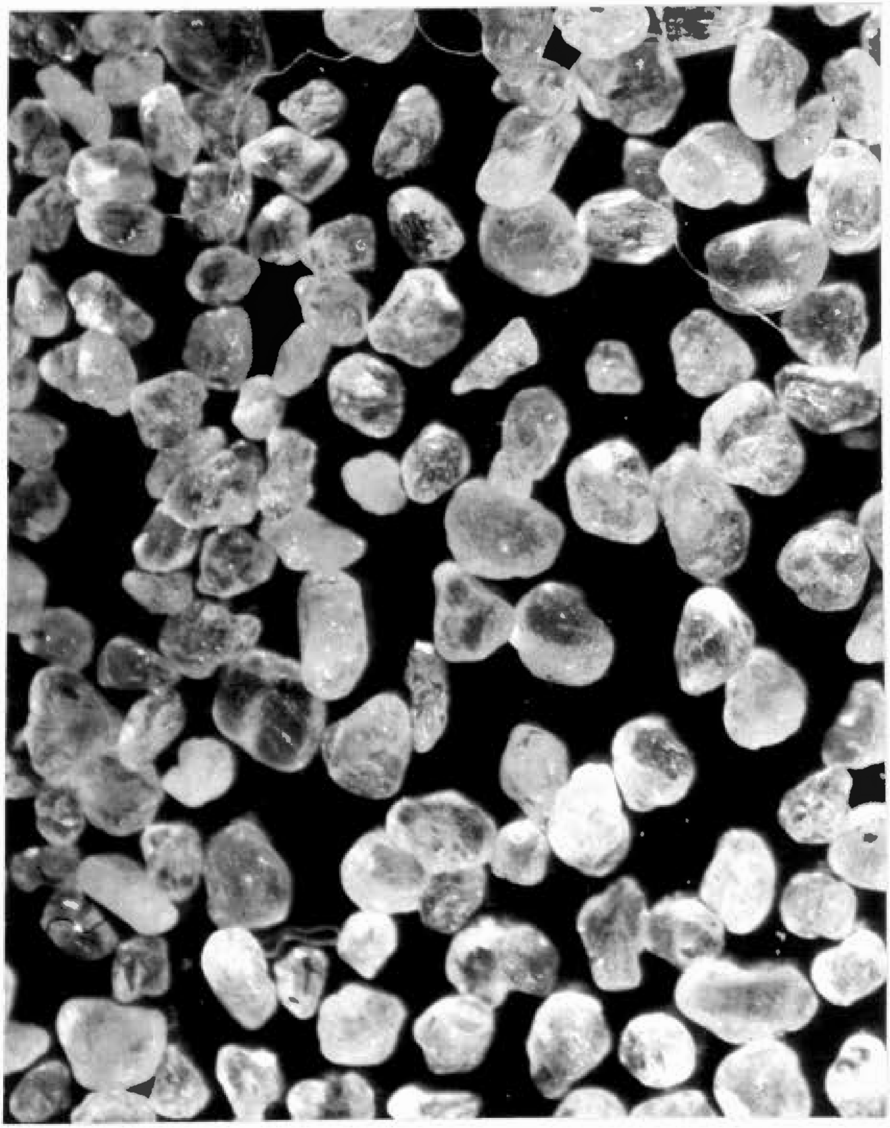
Of the various Phase II materials that may be deposited in caves, by far the most common in the Transvaal sites is normal dolomite soil. The calcified product then outcrops as brown or pink limestone with numerous blocks of chert and dolomite set in a fine-grained matrix. Photograph 56 shows a typical outcrop of Phase II dolomite soil breccia.

The only . . .



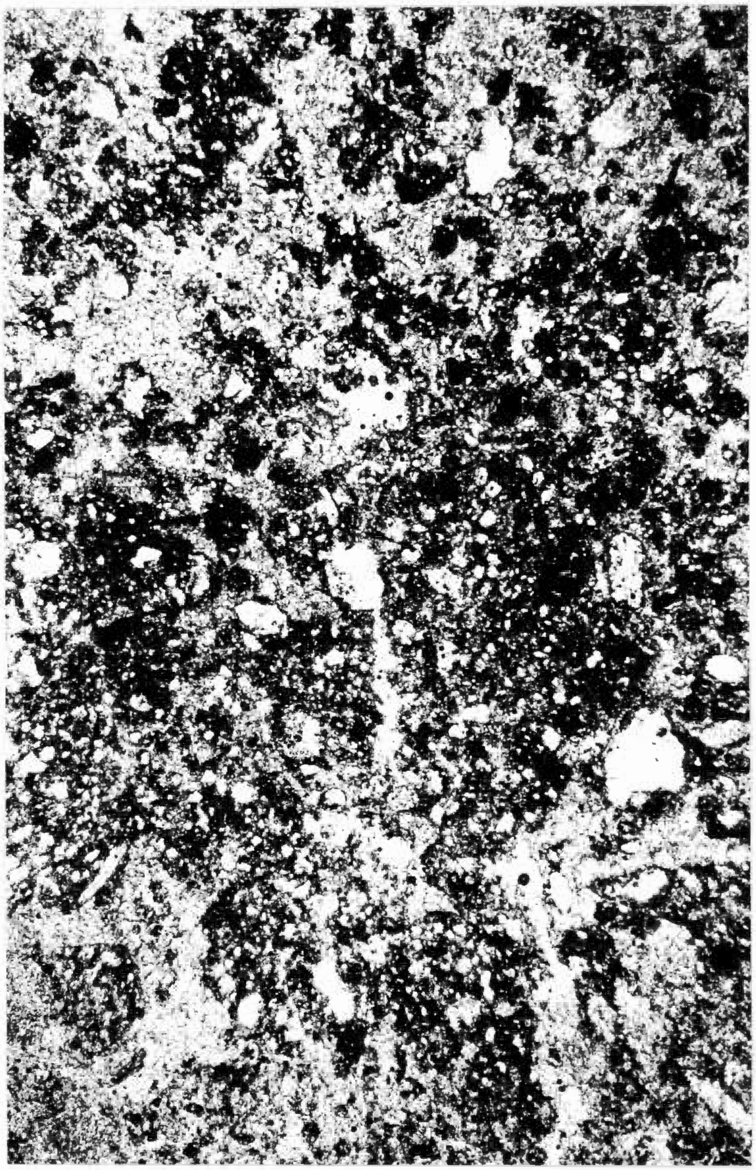
Photograph 53.

Wind abraded sand grains showing frosted or matt surface texture. These should be compared with the grains shown in Photograph 54. x 40



Photograph 54

River sand grains showing polished surface texture. This texture is characteristic of water-transported sand grains magnified 40 times.



Photograph 55.

Thin section of a typical Phase 11 cave breccia. The pink breccia from Swartkrans. It consists of a fine grained muddy limestone. Ordinary light. X22.

Photograph 56.

A typical outcrop of Phase 11 breccia. This material is composed of calcified dolomite soil. Kromdraai B.

The only occurrence of calcified alluvium in a cave that has so far been investigated was found at Makapan Limeworks. This rather lightly calcified deposit, over 40 feet thick, contains very abundant waterworn pebbles of dolomite, chert and quartzite. Its exposure in the side of a vertical wall at Limeworks is visible in Photograph 57.

The writer has not so far encountered any Phase II cave deposit in the Transvaal that can be regarded as primarily aeolean. Although various breccias have been described by different authors as consisting of calcified wind-borne sand or loess, analysis has shown, in every case, that these materials are more typical of residual dolomite soils.

<u>The bone content of Phase II breccias</u>.

Since the matrix of a Phase II breccia normally accumulates fairly fast in a cave, it is unusual for large concentrations of bones to be built up in it. Normally, what bones are present are fairly sparsely scattered through the bulk of the deposit. All the fossil specimens that have come from Sterkfontein and Kromdraai have been derived from Phase II material. This is also true for Swartkrans if the Phase I rodent bone accumulation is excluded.

Photograph 57.

A section through the deposit of calcified Phase 11 alluvium at the Makapan Limeworks. The matrix contains numerous waterworn pebbles of dolomite, chert, and quartzite.
Photograph by J.T. Robinson

Weathering of cave breccias.

So far as weathering is concerned, cave breccias show the same characteristics as do more normal limestones. They weather predominantly by solution. When exposed naturally on the surface, they often become honeycombed with solution channels. A block of naturally weathered cave breccia is shown in Photograph 58. It can be seen how certain selected areas have been dissolved in preference to others.

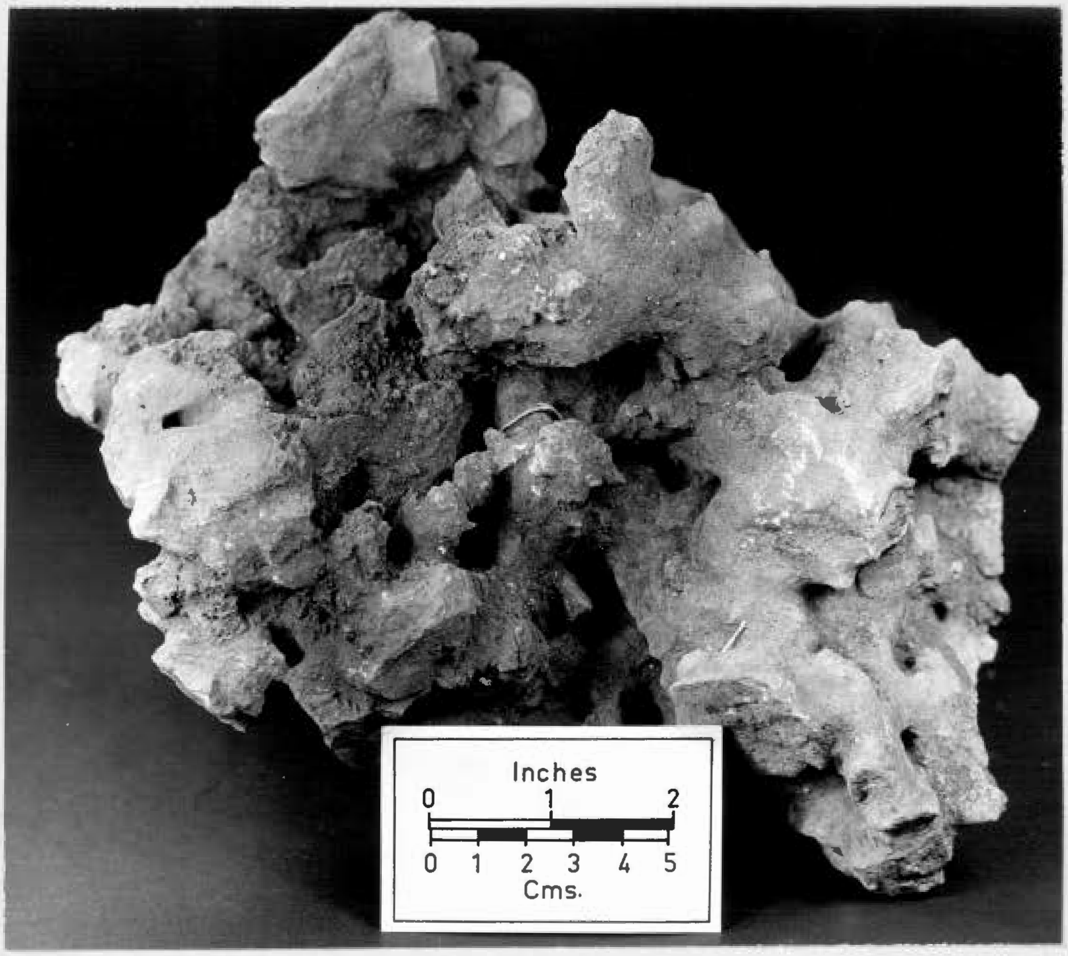
In low lying areas, where cave breccias are kept constantly moist, as on the northern side of the Kromdraai B deposit, their whole bulk is found to decompose and revert to the decalcified forms. At Kromdraai, where the breccia represents a calcified dolomite soil, the weathered product can hardly be distinguished from the modern dolomite soil on the surface.

GENERAL CONCLUSIONS

Cave travertines

The variety of forms of calcium and magnesium carbonate developed in caves may be collectively termed cave travertine.

Travertine . . .



Photograph 58.

A block of naturally weathered cave breccia, showing how the material is selectively dissolved away by rain water.

Travertine is precipitated from solutions passing down through the vadose zone. Precipitation is effected either by evaporation or by loss of carbon dioxide.

Of the carbonates, calcium is much more important than magnesium. Magnesium carbonate, being the more soluble of the two salts frequently escapes precipitation.

The forms of travertine important in the Transvaal caves are: Stalactites, helictites, curtain stalactites, stalagmites, flowstone and aragonite crystals.

Cave Breccias

In the study of cave breccias it appears more profitable to investigate the properties of the decalcified residues, than to examine the breccias in thin section.

The cave breccias may be classified as:

Residual Cave earth.

Phase I material

Phase II material.

Residual cave earth represents the insoluble fractions of the dolomite derived from inside the cavern. It can be recognised by the characteristic shape of its included sandgrains. From the fossil point of view it is sterile.

Phase I material is deposited when the cavern has only a small opening to the surface. It is a mixture of residual cave earth and surface-derived material. The identification of a Phase I sediment is based on the shape of the two sharply contrasted sand grain types characteristic of it.

Being very slow accumulations, Phase I deposits are often very rich in bone.

Phase II deposits represent true samples of surface-derived material laid down in a cave when its entrance is large. They make up the bulk of the Transvaal occurrences.

In the Transvaal, Phase II deposits may consist of normal dolomite soil or of transported material in the form of alluvium or aeolean sediment. Dolomite soil is the commonest cave filling and this may be distinguished from aeolean sand or loess on grading and composition. Fig. 14 shows the difference in grading between a normal dolomite soil and an aeolean sand of desert type. Grading cannot be used successfully to distinguish between alluvial and aeolean deposits. The distinction can be made on particle shape differences in the gravel grade and surface texture differences in the sand grade.

The Phase II sediments in Transvaal caves are

usually . . .

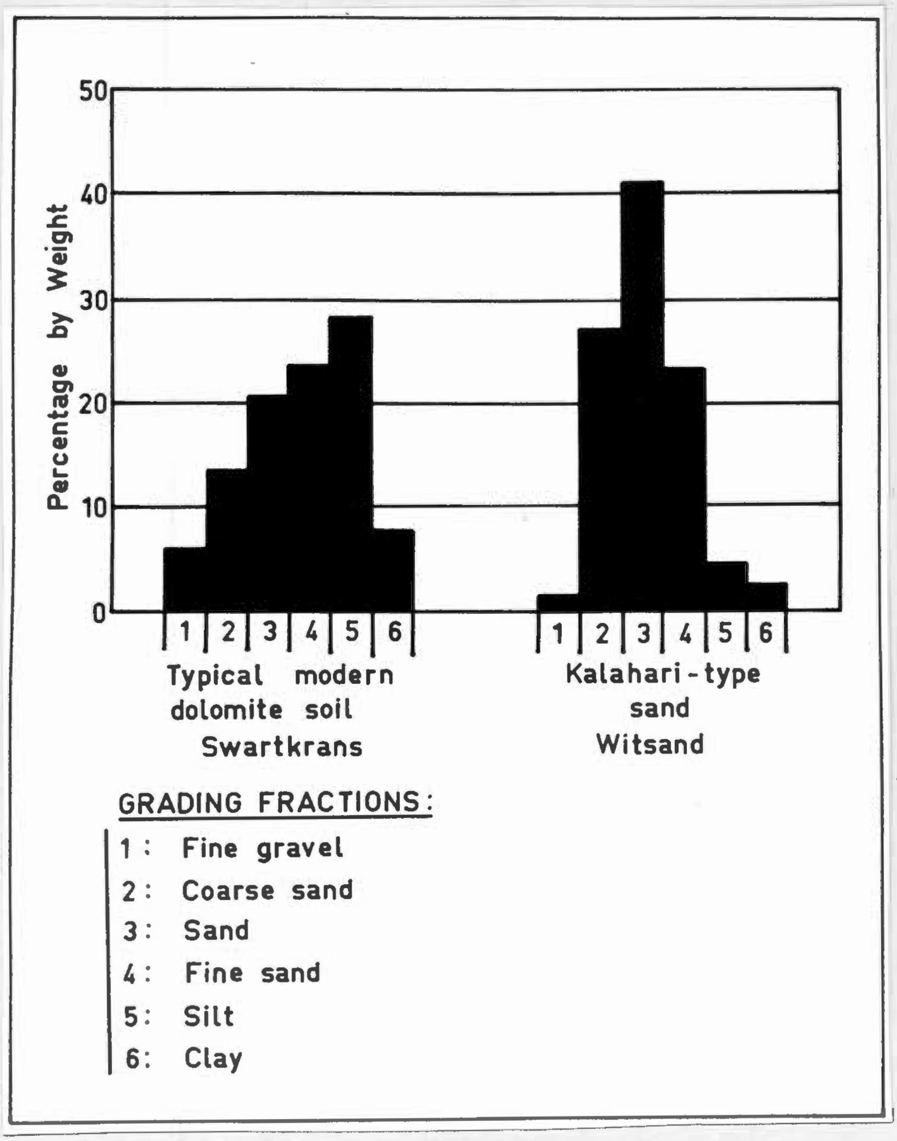


Figure 14

Diagram showing the characteristic grading difference between a normal dolomite soil and a Kalahari-type sand.

usually heavily calcified to form Phase II breccias.

Extensive bone concentrations are unusual in these breccias due to the rapidity of accumulation of the aggregate matrix.

Cave breccias, like normal limestones, weather by solution and revert to decalcified residues.

7.

The Mechanism of Cementation

The object of the enquiry

Previous writers on the subject of the Transvaal cave deposits have appreciated that the very large proportion of carbonate cement, present in the breccias, necessitates that much of it was introduced with the original earth at the time of its accumulation. The reason for this is that once a cave has been filled to capacity with earthy materials, there is not much room left that could be filled subsequently with calcite. But although there has been agreement on the subject of simultaneous accumulation, there has been a difference of opinion as to the form in which the carbonate was introduced. Since King (1951) was of the opinion that all the Transvaal ape-man deposits represented contemporaneous arid-period accumulations, he inclined to the view that all the carbonate was introduced in the form of calcite dust, subsequently to be recrystallised during a humid phase. On the other hand, Robinson (1952) did not consider that the faunal remains indicated such aridity and that the calcite was more likely to have been introduced by percolating solutions, in the same way as it has been in the formation of dripstones.

To elucidate the position, some experimental

work . . .

work was done on the subject. Considering the case of a cave that has been filled up to the top with loose earth, an attempt was made to decide how much calcite could be introduced afterwards, and how much must therefore accumulated simultaneously with the earth. This decision must obviously be based on the percentage volume of voids of the earth in question. It was decided to use the Swartkrans site as an example, since the two varieties of Phase II material present there, the pink and brown breccias, are good examples of Transvaal australopithecine-bearing rock. Evidence from two other caves will then also be considered.

Evidence from the Swartkrans Cave

First, it is necessary to assess the quantitative distribution of carbonate cement in the two breccias at Swartkrans. To do this, eight samples were analysed from each chosen level in the deposits. The analysis results are given in the table on the next page. These are plotted graphically in Fig. 15.

Representative samples were taken of both the pink and brown breccia residues, as well as of the modern dolomite soil. In a specially constructed apparatus, the percentage volumes of voids were determined for these materials in various states of compaction, equivalent to

different . . .

Pink breccia section

Level	1	2	3	4	5	6	7	8	Average
10 Ft	65·3	69·3	74·4	74·5	74·6	74·4	74·1	74·4	72·6
9 ..	78·9	79·1	78·7	80·9	78·6	78·5	77·8	79·1	79·0
8 ..	78·4	81·9	82·2	84·3	78·8	82·7	81·8	80·2	81·3
7 ..	59·8	74·2	68·2	66·5	68·9	67·8	79·6	70·8	69·5
6 ..	87·3	82·7	89·3	79·1	86·4	89·9	88·4	90·0	86·6
5 ..	87·8	87·5	88·0	88·7	82·6	86·6	85·3	80·0	85·8
4 ..	63·5	60·0	67·4	71·5	79·7	77·1	80·0	74·9	71·8
2 ..	69·2	64·9	75·7	59·6	76·2	79·3	76·1	77·7	72·3
Base	74·2	74·3	70·9	72·7	72·2	74·0	72·9	72·3	72·9

Brown breccia section

Level	1	2	3	4	5	6	7	8	Average
16 Ft	52·1	46·8	60·3	51·9	53·6	54·8	56·6	57·1	54·1
14 ..	53·9	56·3	57·4	44·2	54·5	51·5	53·7	52·8	53·0
12 ..	53·1	52·7	48·2	48·9	51·6	49·2	51·8	46·5	50·2
10 ..	51·3	50·1	54·6	47·3	53·5	55·2	53·2	53·1	52·4
8 ..	65·3	68·0	67·8	71·1	64·9	63·2	66·4	58·8	65·7
6 ..	65·9	63·7	64·2	60·8	65·2	65·0	66·1	65·4	64·6
4 ..	65·3	59·1	60·7	62·8	67·8	70·8	68·0	67·5	65·3
2 ..	63·8	51·2	51·8	58·5	48·9	50·3	61·9	59·6	55·8
Base	45·5	55·4	52·0	55·2	51·5	54·1	56·7	52·7	52·9

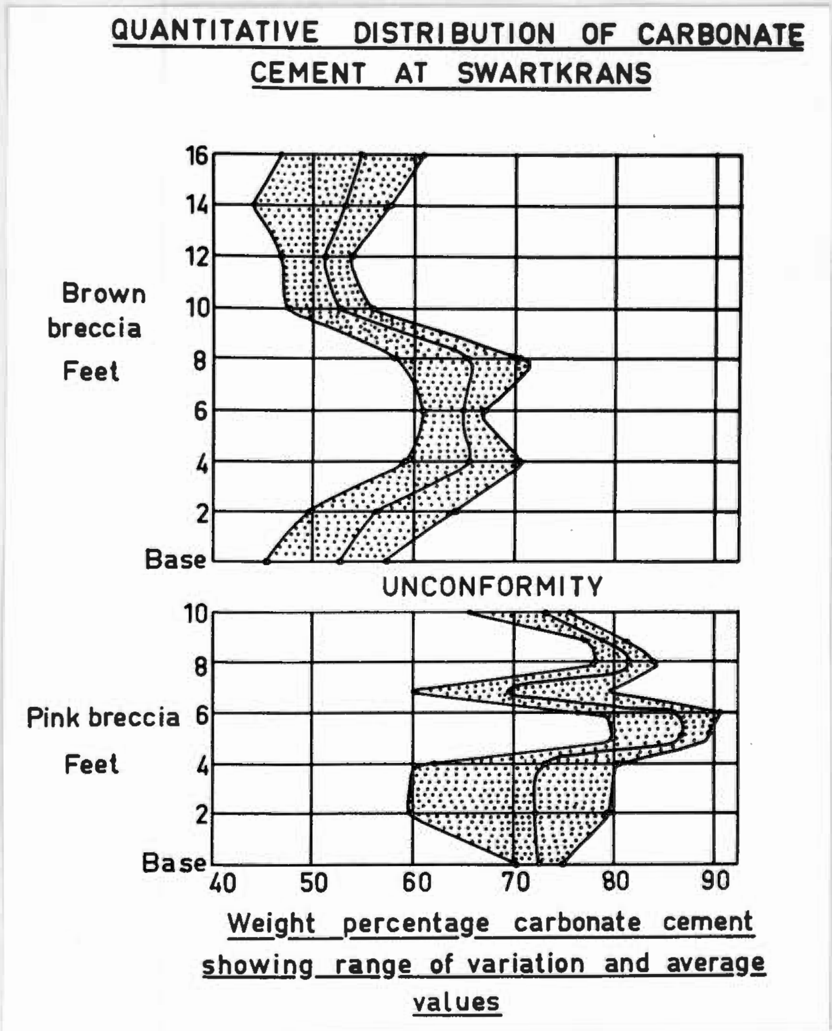


Figure 15.

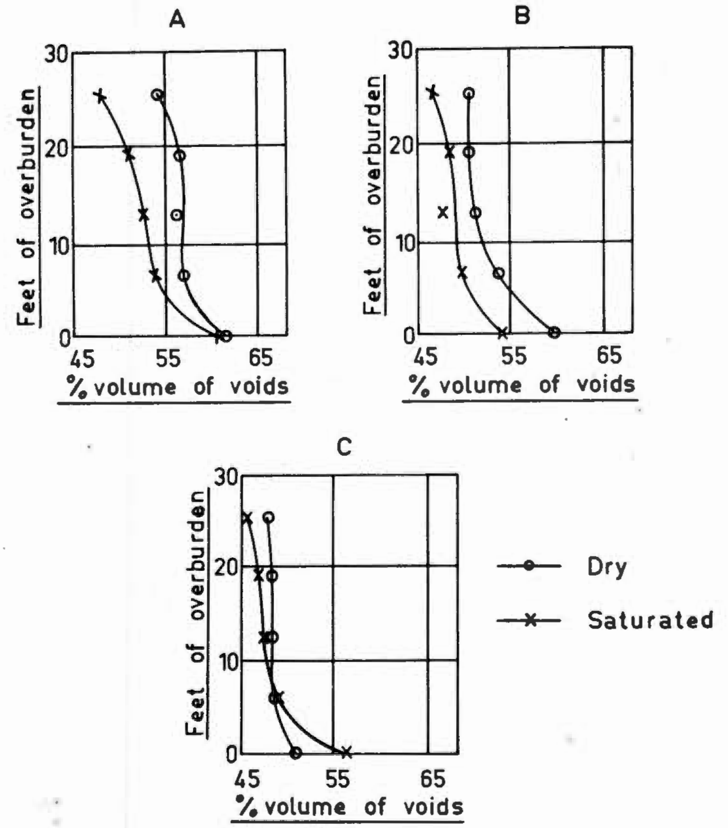
Diagram showing the quantitative distribution of carbonate cement in the Swartkrans breccias. The observed range of variation is plotted.

different overburden pressures. The overburden pressures were applied in a beam-type consolidometer, such as is commonly used in soil mechanics practice.

It was considered that, under natural conditions in the cave, some of the earth would have been introduced dry, while at other times material would have been washed in and deposited in shallow water. In order to simulate these conditions, determinations were done on the material both dry and saturated, the latter having been deposited slowly in water. The results of the voids determinations are now provided and are plotted graphically in Fig. 16.

DRY	Volume of Voids		
Feet of overburden	Pink breccia %	Brown breccia %	Soil %
0	61.2	59.6	51.0
6.4	56.7	53.6	48.3
12.8	56.2	51.2	48.6
19.2	56.9	50.5	48.1
25.6	54.2	50.5	47.8
SATURATED			
0	60.3	54.3	56.3
6.4	53.7	49.8	48.8
12.8	52.6	44.8	47.1
19.2	51.0	48.3	46.6
25.6	48.8	46.6	45.4

It is to . . .



THE EFFECT OF OVERBURDEN PRESSURE ON THE PERCENTAGE VOLUME OF VOIDS IN:

A : PINK BRECCIA RESIDUE
B : BROWN BRECCIA RESIDUE
C : MODERN DOLOMITE SOIL.

Figure 16.

Graphs showing the effect of overburden pressure on the porosity of various materials.

It is to be expected that the values for the modern soil should differ somewhat from those for the breccia residues, since the soil contains a certain proportion of organic matter not present in the residues. Although an attempt was made to use completely representative samples of the various materials, slight grading differences between them will have influenced the results to a small extent.

Supposing now that the specific gravities of the residue and the carbonate cement are the same, then the percentage volume of voids of that residue is a direct measure of the weight percentage of carbonate cement that could be introduced into it subsequently, without increasing its volume. An average for the specific gravity of the breccia residue is 2.65 while that for pure calcite is 2.71. This means that, for the purpose of the present discussion, no correction need be applied, and the percentage voids values may be taken as representing the weight percentages of calcite which could be introduced after accumulation of the earth. Making use of the curves in Figure 16, and reconsidering the breccia sections on which the carbonate determinations were done (Fig. 15), it is possible to decide how much of the carbonate present at each level could have been introduced after the accumulation of the original earth, and how much must therefore have been brought in with it.

For this . . .

For this purpose, average voids values between the dry and saturated conditions will be used, since the conditions inside the cave would certainly have fluctuated from dry to wet, depending on the season of the year. Likewise, average carbonate values are used as these give the best idea of the true state of affairs. The results are now presented, and are plotted in Figure 17.

Level in Feet	Average Weight % Carbonate	Average % Volume of Voids	Weight % Carbonate in excess of available voids
Pink Breccia section			
10	72.9	60.7	12.2
9	72.3	59.6	13.7
8	71.8	58.5	13.3
7	85.8	57.6	18.2
6	86.6	56.9	19.7
5	69.5	56.2	13.3
4	81.3	55.7	15.6
2	79.0	55.1	13.9
Base	72.6	54.6	18.0
Brown Breccia Section			
16	54.1	57.0	0
14	53.0	55.0	0
12	50.2	53.3	0
10	52.4	51.8	0.6
8	65.7	51.0	14.7
6	64.6	50.4	14.2
4	65.3	50.0	15.3
2	55.8	49.7	6.1
Base	52.9	49.6	3.3

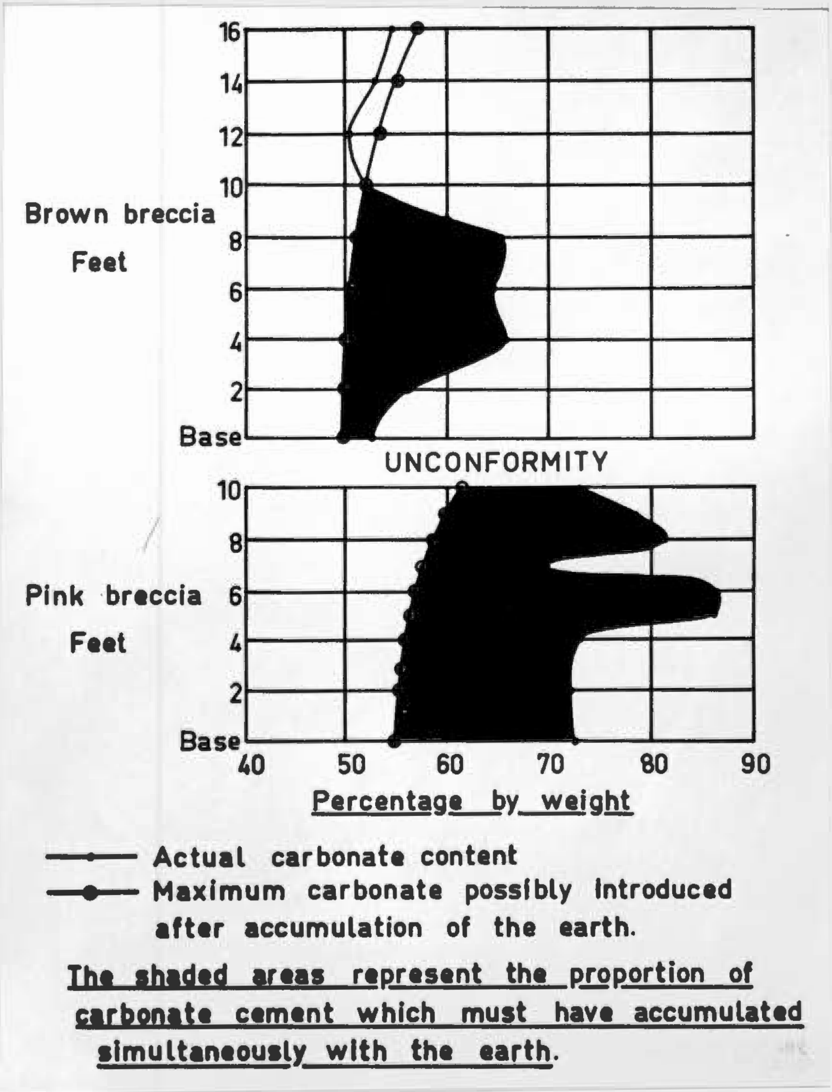


Figure 17.

Swartkrans breccias : graphs showing the percentage of carbonate cement in excess of the available voids.

From these figures it is clear that the maximum quantity of carbonate cement, necessarily introduced simultaneously with the original earth, is 19.7% by weight for the pink breccia and 15.3 % for the brown. All the remaining carbonate present today in the breccias could therefore have been introduced at any time since the accumulation of the earth.

At this stage it is necessary to decide in what form the carbonate, that is in excess of the available voids, was introduced into the earth. Some indications in this direction will now be discussed.

It will be seen from the figures that there is a certain amount of variation in the proportion of carbonate cement from one level in the breccia to another. Close examination of the breccia has shown that at the levels where the carbonate content is low, one almost invariably finds that roof-fall blocks of rock are included in the breccia. This suggested to the writer that these particular levels were composed of material which had accumulated more quickly than usual, as a result of breaking back of the original cave entrance. It is to be expected that the cave entrance would have been periodically enlarged, and that these enlargments would have resulted in large blocks

of rock . . .

of rock collapsing into the cave, together with the dolomite soil that they had been supporting. But in order to be certain that the sudden introduction of outside material depresses the carbonate content in the final breccia composed of that material, further evidence is required. This evidence was forthcoming from the breccia section at the extreme eastern end of the outer cave. This section represents the oldest accumulation in the Swartkrans cave. On the three inches of basal, banded travertine is superimposed fifteen inches of compact grey breccia, which consists of a calcified residual cave earth, deposited before the cave had any direct opening to the surface. Between the grey residual breccia and the pink Phase I breccia above it is a marked and very abrupt transition. This transition represents the point at which the cave acquired its first opening to the surface, and the first surface derived material was admitted.

In the course of routine carbonate determinations on this section it was found that, as one crossed the transition from grey to pink breccia, one encountered a sudden drop in the proportion of carbonate cement, from 89.3 % to 71.3 %. But on passing up through the pink breccia, the percentage again rose to over 80. The values for this section are now provided.

Table . . .

Level	Samples: % carbonate										
	1	2	3	4	5	6	7	8	9	10	Average
3Ft pink breccia	82.2	76.0	87.4	77.5	86.8						82.0
2Ft pink breccia	79.0	80.5	82.1	81.9	80.0						80.7
1Ft pink breccia	81.9	80.9	84.0	80.6	83.1						82.1
Transitional pink breccia	65.6	72.0	76.7	66.2	73.6	74.0	66.7	67.6	77.2	73.3	71.3
Transitional grey breccia	86.2	84.0	83.5	85.2	87.1	84.0	83.8	81.4	81.7	81.9	83.9
Basal grey breccia	82.0	84.1	79.6	82.9	85.0						82.7
Banded travertine	94.0	97.0	95.0	96.1	95.6						95.5

In chapter 6, attention was directed to the distinguishing features of sand grains derived from residual cave earths and ground surface deposits. It was stated that residual earth sand grains could always be recognised by their extreme angularity and fragility, while grains from the surface invariably showed some signs of wear. Thus it is possible, with a Phase I breccia, to estimate the proportion of foreign, surface derived material in it. In the sand grade, this can be done through counts of the two different types of sand grain, or it can be achieved by quantitative assessments of angularity, according to the method described in the next chapter.

This being so, it should be possible to decide how much outside material entered the Swartkrans cave by determining the percentage abundance of recognisable surface-derived material present at various levels in the breccia. This was done for the section in question and the results are provided in the table on the next page. To make the results as reliable as possible, the sand grains were divided into two classes: angular and abraded. The grains in the former class showed little or no signs of wear. Those in the latter fell within Pettijohns roundness grades of "Subrounded, Rounded and Well Rounded". These results, as well as those for the carbonate determinations are plotted in Figure 18.

It will be seen . . .

		Total grains counted per sample	No. angular grains	No. wind rounded grains	% angular grains	% rounded grains	Average % wind rounded grains
3ft pink breccia	1	1586	920	666	58·0	42·0	
	2	1414	880	534	62·2	37·8	
	3	1580	920	660	58·2	41·8	
	4	1488	880	600	59·7	40·3	40·5
2ft pink breccia	1	1578	1246	332	79·0	21·0	
	2	1476	1100	376	74·5	25·5	
	3	1561	1130	431	72·4	27·6	
	4	1466	1026	440	70·0	30·0	26·0
1ft pink breccia	1	1557	1377	180	88·4	11·6	
	2	1498	1350	148	90·1	9·9	
	3	1567	1400	167	88·8	11·2	
	4	1627	1440	187	88·5	11·5	11·1
Transitional pink breccia	1	2606	2076	530	79·7	20·3	
	2	2123	1538	585	72·4	27·6	
	3	2520	1956	564	77·6	22·4	
	4	2567	2011	556	78·3	21·7	23·0
Transitional grey breccia	1	3385	3377	8	99·8	0·2	
	2	3035	3028	7	99·8	0·2	
	3	1878	1869	9	99·5	0·5	
	4	1385	1379	6	99·6	0·4	
	5	2100	2087	13	99·4	0·6	
	6	1950	1938	12	99·4	0·6	0·4
Basal grey breccia	1	1606	1600	6	99·6	0·4	
	2	1541	1536	5	99·6	0·4	
	3	1633	1616	17	99·0	1·0	
	4	1593	1580	13	99·2	0·8	0·7

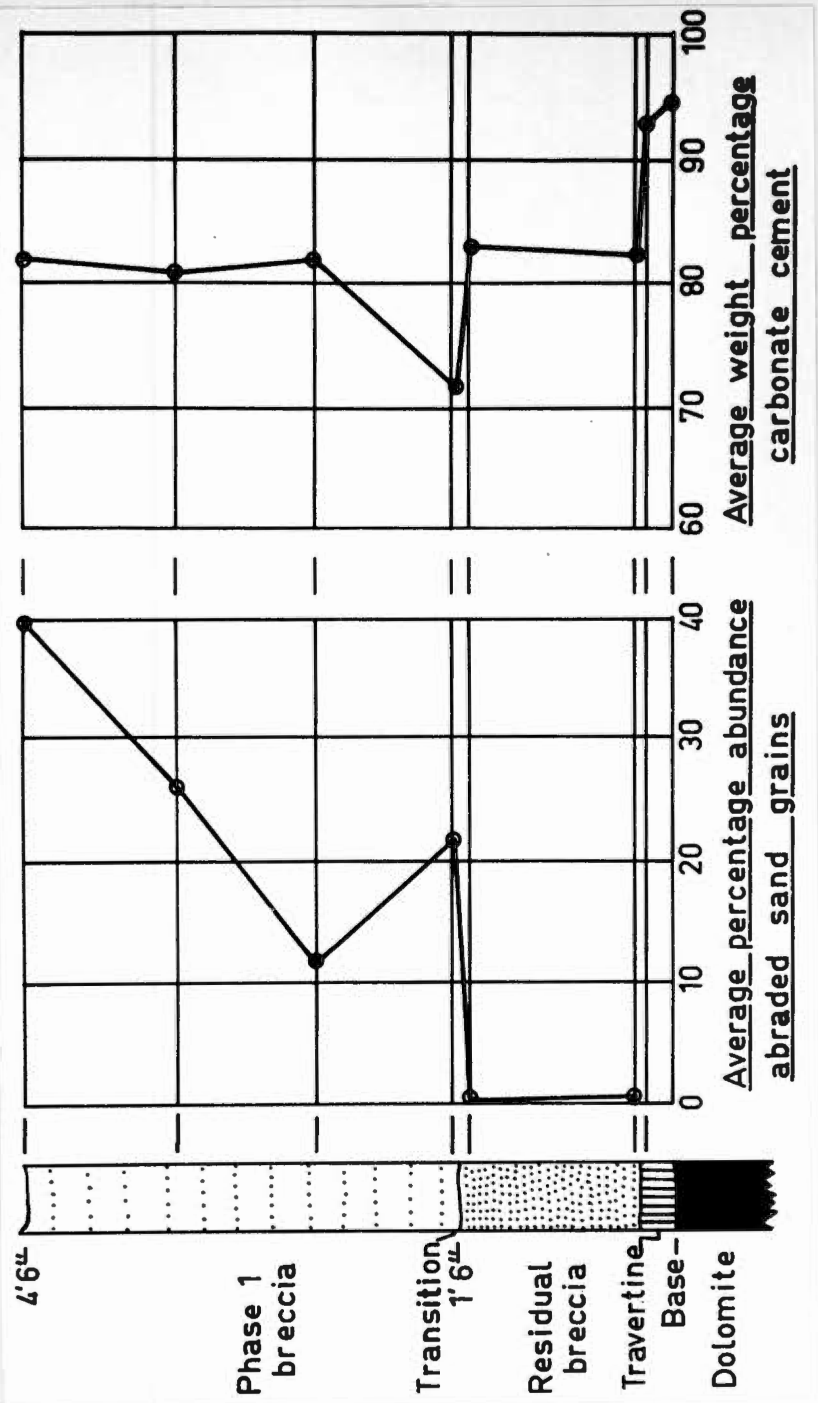


Figure 18.

Phase I breccia at Swartkrans: the relationship between the percentage abundance of surface-derived sand grains and the distribution of carbonate cement.

It will be seen that the percantage abundance of outside sand grains increases from 0.4% in the grey breccia, to 23.0% in the pink breccia immediately above the transition. By one foot up in the pink breccia it has however fallen again to 11.1%. Above that level it gradually increases to 40.5 at the top of the section. On the other hand, it has been shown that the carbonate content drops by 12.6% as one crosses the transition, and then returns to normality above it, no doubt having adapted itself to the changed conditions of the now open cave.

The writer considers that when the first cave opening appeared, a quantity of surface dolomite soil fell into the cave. Some of it penetrated to the eastern end where its presence immediately above the transition has been demonstrated. But once the first opening had appeared and the unstable soil round it had fallen in, then, for a time, the quantity of material entering the cave was reduced, as is indicated by the level one foot above the transition. This level is again composed essentially of the insoluble residue derived from inside the cave. Slowly however, the proportion of outside material again increased, until at the top of the section, it was already abundant.

The most significant point in the evidence discussed above is that there is a marked drop in the

carbonate . . .

carbonate content of the material immediately above the transition. This drop can be correlated with the sudden introduction of demonstrable outside material, which represents in effect sudden more rapid accumulation of the original earth. So one may conclude that where there has been more rapid accumulation of the original earth than normal, the final breccia composed of that earth is likely to show a lower carbonate content than normal.

It has been shown that in the pink and in all but the upper levels of the brown breccias, a certain amount of carbonate must necessarily have accumulated with the original earth. It remains to decide whether this carbonate was in the form of calcite dust, or was deposited by solutions dripping from the roof of the cave. The evidence presented above, which indicates that the faster the material accumulated, the less carbonate was included in it, suggests very strongly that the carbonate was not an indigenous constituent of the surface-derived earth itself. Had it been, the rate of accumulation of the earth within the cave should not have influenced its carbonate content in the way it has done. It suggests rather that the carbonate was introduced from some other source at a more or less constant rate. This other source must have been drip from the roof of the cave.

Under certain climatic conditions it is possible for calcite dust to exist in surface dolomite soils. The necessary conditions and also the quantities likely to exist are considered further on in this chapter.

Evidence from the Hyaena Cave

As at Swartkrans, the Phase I breccia at Hyaena Cave, Makapan, has provided useful information on the mechanism of cementation in breccias. Here, beneath the main Phase II breccia deposit is a layer of banded travertine which is exposed today in the vertical wall of the limeworker's cutting. The part of the section studied showed seven travertine layers varying from one and a half to 18 inches thick between which were sandwiched six layers of dirty Phase I limestone, from 2 to 8 inches in thickness. The alternation of breccia and travertine has clearly resulted from deposition on the cave floor whose contours have repeatedly changed as a result of uneven dripstone accumulation. It is to be expected that Phase I material will collect constantly, though slowly, on the lowest areas of the cave floor. Thus, with changing floor contours, any one vertical section through the floor covering will display an alternation of calcified earth and purer travertine.

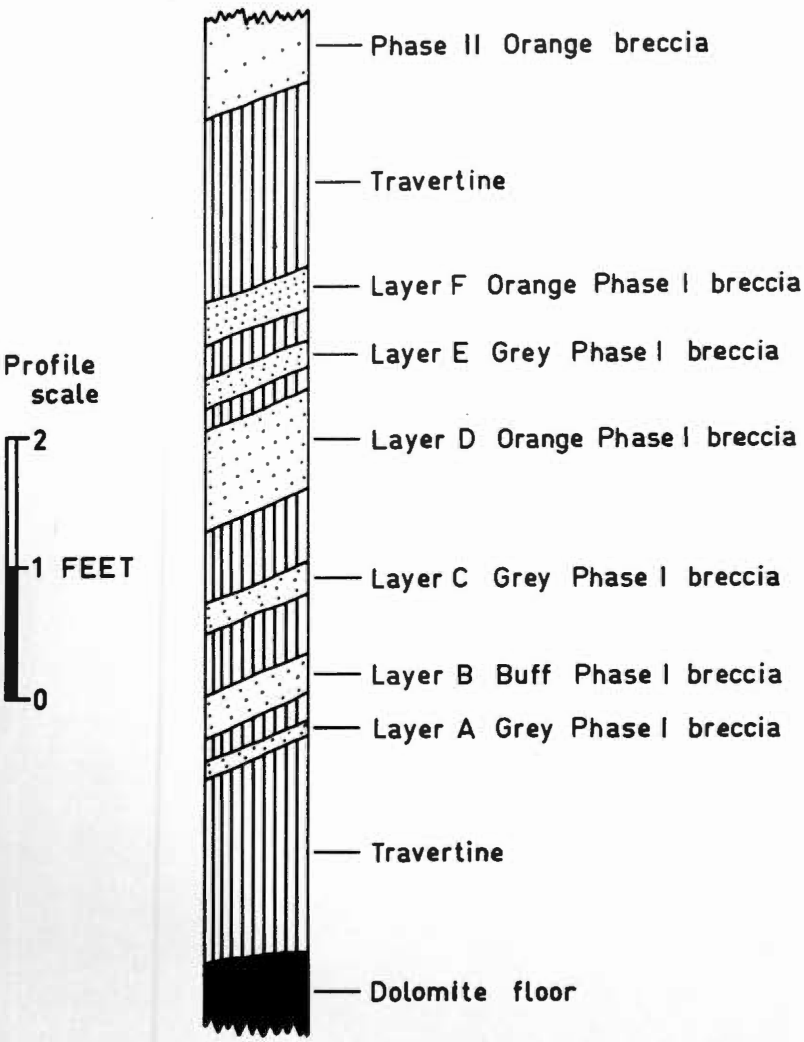
For the purpose of this discussion, the seven

interbedded . . .

interbedded travertine layers may be ignored as in each case their carbonate contents were found to vary from 99.7 to 100.0 %. They represent normal travertines and are not of assistance in this enquiry, except that they indicate that travertine was being deposited from solutions throughout the period of accumulation of the Phase I material. The evidence to be derived from the breccia layers themselves will now be discussed.

Fig. 19 shows a diagrammatic representation of the profile in question. Samples of the various breccia layers were taken and were analysed for weight percentage of carbonate cement and for the proportion of demonstrable extra-spelean material present in the residues. The method used in these analyses was the same as has just been described in the work on the Swartkrans profile.

The carbonate content results are now tabulated and are followed by those for the percentages of outside, abraded sand grains as opposed to the extremely angular residual grains.



The lower part of the profile from the Hyaena Cave, Makapan

Figure 19.

The Phase I profile in the Hyaena Cave at Makapan.

Layer	Weight % Carbonate Cement					
	1	2	3	4	5	Average
F	71.1	68.8	70.3	64.4	73.3	69.6
E	73.5	76.2	74.1	76.4	-	75.1
D	88.3	91.0	79.3	81.3	94.2	86.8
C	77.8	76.0	76.2	77.1	78.1	77.0
B	81.8	84.4	84.5	84.6	84.7	84.0
A	52.0	59.4	46.5	52.5	48.5	51.8

Layer		Total grains counted per sample	No. angular grains	No. abraded grains	% abraded grains	Average % abraded grains
F	1	1391	936	455	32.7	32.8
	2	1872	1257	615	32.9	
E	1	1000	700	300	30.0	29.7
	2	1272	898	374	29.4	
D	1	1010	857	153	15.2	16.1
	2	1273	1056	217	17.0	
C	1	1205	917	288	23.9	22.6
	2	1447	1139	308	21.3	
B	1	1054	855	199	18.9	20.1
	2	1176	925	251	21.2	
A	1	1085	799	286	26.4	28.1
	2	1309	922	387	29.7	

These results are diagramatically presented in Fig. 20. It will be seen that the curves are approximately reciprocal, since when the percentage of outside material increases, the proportion of carbonate cement decreases. Thus it is clear that the effect of accelerated earth accumulation is to reduce the carbonate content of the final breccia. Again, as at Swartkrans, the calcite cannot be regarded as an indigenous constituent of the earth, but is obviously derived from inside the cave itself. It has therefore almost certainly been introduced by solutions dripping from the roof of the cave.

Evidence from the Makapan Limeworks

When Professor King (1951) published his paper on the Makapan Caves, he expressed his views on the origin of the Limeworks breccia cement as follows:

"At this point we should note that the lithification has taken place not by addition of calcite subsequently to the sand accumulation, but by *recrystallisation of calcite which formed an integral part of the deposit*." The italics are King's.

In view of this published opinion, some analytical evidence bearing on the question will now be discussed. It has been shown that useful information on the process of

breccia cementation . . .

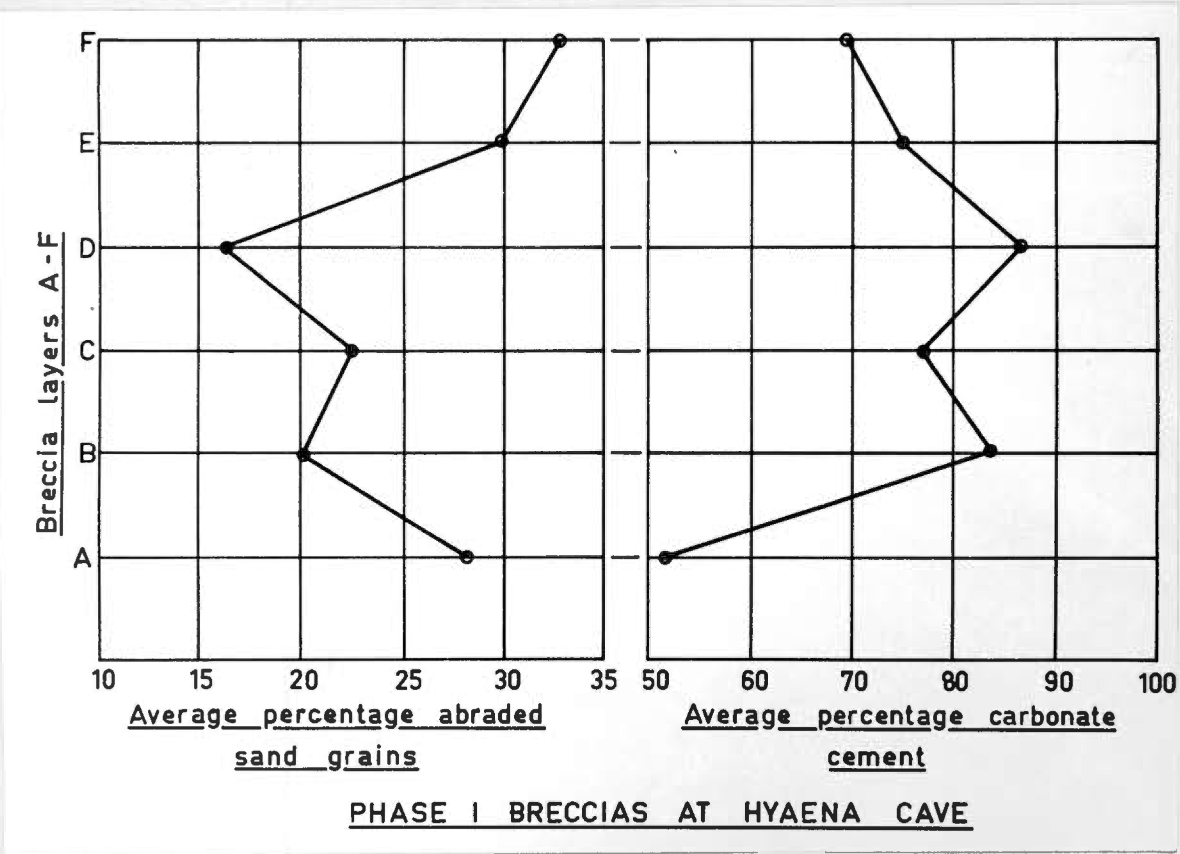


Figure 20.

Hyaena Cave Phase I breccia : the relationship between the percentage abundance of surface-derived sand grains and the distribution of carbonate cement.

breccia cementation can be derived from a study of the characteristics of Phase I materials. If reference is made to the description of the Limeworks site in Part II of this work, it will be seen that Phase I breccias are extremely well developed at Limeworks. The most complete profile at present available in the Limeworks excavation is visible in the northern wall of the central collapsed area. This profile is shown diagrammatically in Fig. 21. Notice that 67 feet of cave deposit rest on the dolomite floor and extend up to the present ground surface.

The thick basal travertine deposit is found to include two bands of residual cave earth in the form of grey breccia. On the surface of the travertine rests 15 feet of heavily calcified Phase I material. This consists of buff or pinkish limestone enclosing numerous blocks of dolomite and chert, as well as a band of waterworn pebbles at the 27 ft. level. The transition from Phase I to Phase II material occurs at 32 ft. above base and is very clearly demarcated. Above this transition the Phase II material is lightly calcified and is packed with waterworn pebbles of dolomite, chert and quartzite.

The profile may be interpreted in terms of cave history as follows: the travertine and grey breccia bands were formed at a stage before the cavern had any

direct opening . . .

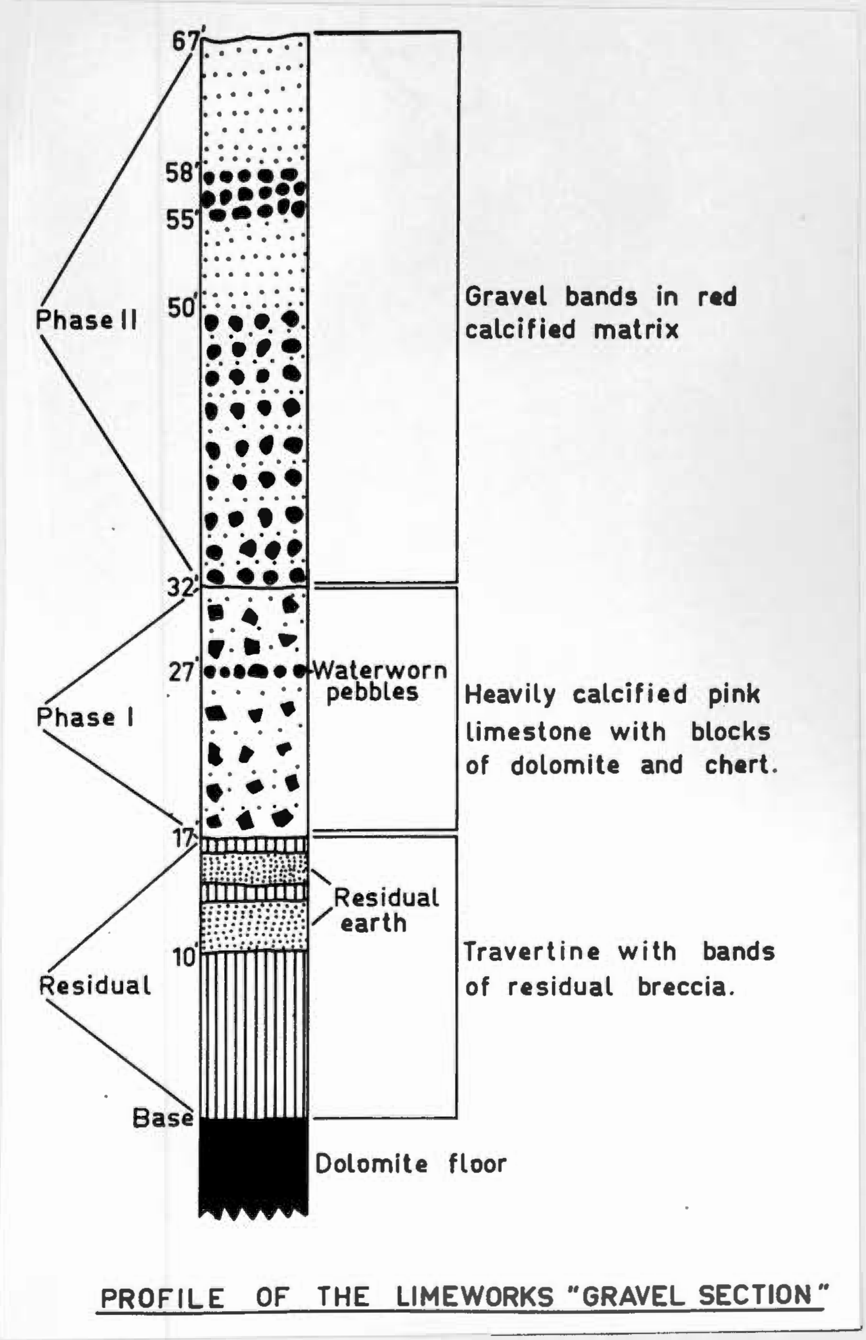


Figure 21

The most complete breccia profile from the Makapan Limeworks.

direct opening to the surface. The acquisition of the first small cave opening is recorded by the beginning of the Phase I accumulation on the surface of the travertine. This opening slowly enlarged as the Phase I material continued to accumulate. Clearly, the surface opening was close to river level as is indicated by the waterworn pebble layer at 27 feet. The abrupt transition from Phase I to Phase II material represents the very sudden and large-scale enlargment of the cave entrance. Surface derived material in the form of river debris now rapidly entered the cavern, in quantities such that the slowly-accumulating residual cave earth became quite insignificant by comparison. This Phase II material continued to accumulate until the top of the profile was reached.

It is found that different levels in the Phase I breccia of the Gravel Section show interesting variations in carbonate content. Results of carbonate content analyses are now provided for different levels of the breccias from the lower 37 feet of the profile. Figures are not given for the travertines, since these are found to consist of calcite of great purity.

Level in feet above base	Weight % Carbonate Cement				Average
	1	2	3	4	
37	60.9	64.6	46.2	38.0	52.4
32	18.6	45.6	21.2	22.8	27.1
31'6''	72.7	74.0	72.4	74.0	73.4
27	73.7	68.7	68.6	66.1	69.4
22	71.9	69.4	70.5	70.2	70.5
17	97.0	92.4	97.8	93.8	95.7
14 -16	94.2	95.8	90.2	97.5	94.4
10 - 13	96.1	96.8	95.7	94.3	95.7

In order to obtain information on the mechanism of cementation at Limeworks, it is necessary to know whether these carbonate content variations are associated with variations in the relative proportions of residuol and extra-spelean material in the breccia residues. In the analysis on Swartkrans and Hyaena Cave, the proportion of outside material in the residue was determined by sand grain counts. This method can, however, be criticised on the ground that a certain personal element is inherent in it. For this reason, an alternative method was applied to the Limeworks material. The method gives an accurate estimate of sand grain angularity, and is completely devoid of any personal element.

Reference . . .

Reference should be made to the next chapter for full details of procedure. Briefly, angularity is estimated in samples of sand of even grain-size and at a standard compaction, by means of porosity measurements. The range of porosity is from approximately 60 % for a residual cave sand to 33 % for a well rounded desert sand. Thus, with Phase I breccias, a relative increase in surface-derived sand grains over residual cave earth grains, will serve to reduce the angularity of the total sample. This is because residual earth grains are far more angular than are the somewhat abraded surface-derived grains. Angularity determinations, in the form of porosity measurements, were therefore done on sand samples, isolated from the various levels at which carbonate contents were determined. Four samples were analysed at each level, except in the lower, very heavily calcified zones, where difficulty was found in obtaining sufficiently large sand samples. From these levels only two samples were analysed. The results are now tabulated:-

Level in feet above base	% Porosity in 35 - 60 mesh sands				
	1	2	3	4	Average
37	43.1	42.5	42.7	42.5	42.7
32	43.5	43.3	43.4	44.0	43.5
31' 6"	45.4	45.4	44.5	44.5	45.0
27	44.3	43.8	43.3	43.2	43.6
22	43.0	42.0	41.2	42.3	42.2
17	48.4	49.1	-	-	48.8
14 - 16	66.7	62.6	-	-	64.7
10 - 13	69.8	68.0	-	-	68.9

These values, . . .

These values, together with those for the percentages of carbonate cement in the breccias are plotted graphically in Fig. 22.

It will be seen that in the residual, and Phase I sections of the profile, a lowering in carbonate content of the breccia is associated with a reduction in angularity of the sand grains contained in that breccia. This clearly indicates that an increase in the proportion of outside material in the Phase I deposit, serves to reduce the carbonate content in the final breccia composed of it. Thus one must conclude that the carbonate cement was derived from inside the cave and not from outside it. The writer feels that it is therefore more likely that the cement, in the lower part of the profile at any rate, was precipitated from percolating solutions, than that it was introduced as calcite dust with the original sand.

One interesting discrepancy exists between the two graphs in Fig. 22. Notice that at the 17 foot level, a marked reduction in angularity is not associated with a corresponding drop in carbonate content. This level clearly reflects the stage at which the cave acquired its first direct opening to the surface. Obviously, the most immediate effect of the newly acquired opening will be to improve the ventilation of the cavern. Since

precipitation . . .

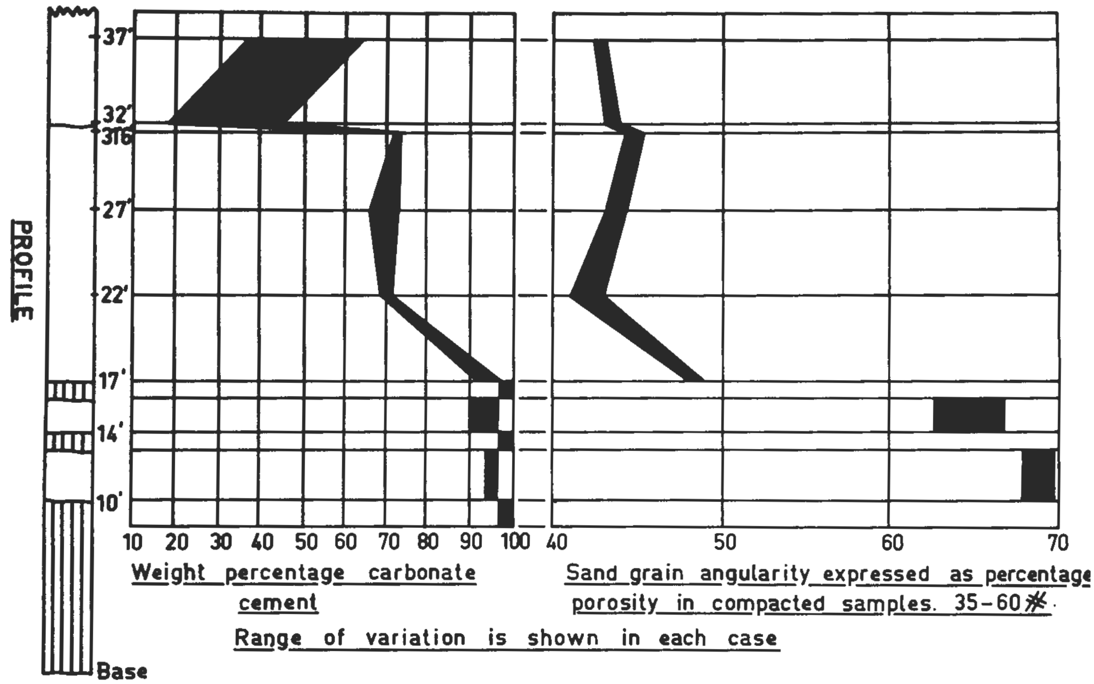


Figure 22.

Phase I breccias at Limeworks : the relationship between sand grain angularity and the distribution of carbonate cement.

precipitation of calcium carbonate from solution is profoundly influenced by the efficiency of the ventilation, it is inevitable that better ventilation will result in greater carbonate deposition.

Thus it is possible that, at the 17 ft. level, accelerated earth accumulation did not have the usual effect of depressing the carbonate content, as this effect was counterbalanced by the opposing influence of improved ventilation.

Calcite dust as an indigenous constituent of dolomite soils and Kalahari-type sands

It has been previously stated that Phase II cave deposits can consist of normal dolomite soil, or of wind-borne sand of Kalahari type. Under certain conditions these materials can contain calcite dust as an indigenous constituent. The two types of sediment will now be discussed separately.

Modern dolomite soils.

In the next chapter, the quantitative distribution of calcite dust in modern dolomite soils will be discussed. The findings are briefly these: calcite dust is not a

significant . . .

significant constituent of modern dolomite soils from areas with rainfall higher than 20 inches per annum. At 20 inches p.a., calcite dust is likely to be present in the soil in small quantities. With decreasing rainfall the quantities present increase considerably. The largest proportion of calcite dust so far found in a modern dolomite soil was in samples from Namaqualand where the rainfall is less than 5 inches per annum. The largest quantity was 19.1 % by weight.

Kalahari-type sands

So far, samples of Kalahari-type sand have been analysed for carbonate content from 9 separate localities. The results of these analyses are now given:-

Locality		Weight % carbonate cement
Olifantshoek,	S. Kalahari	1.4
Upington,	S. Kalahari	0.7
Niekerkshoop,	S. Kalahari	0.4
15 miles S. of Livingstone, S.R.		0.3
25 miles S. of Livingstone, S.R.		Negligible
43 miles S. of Livingstone, S.R.		Negligible
Lupani, S.R.		Negligible
Vorstershoop,	S. Kalahari	Negligible
Inkruip,	S. Kalahari	Negligible

These results . . .

These results suggest that calcite dust is not a significant constituent of this type of sand. More samples must, however, be analysed before completely reliable conclusions can be reached.

Surface Limestone

Calcite dust in soils and sands should not be confused with solid deposits of surface limestone. These limestone deposits are likely to be associated with modern dolomite soils and Kalahari-type sands from areas with less than 25 inches of rain per annum. Surface limestones, since they represent solid, immovable deposits, are not of consequence in the present discussion.

General Conclusions

Evidence on the mechanism of breccia cementation is desirable as there has been disagreement on the subject. King favoured the calcite dust theory; Robinson envisaged deposition from percolating solutions.

Work on the Swartkrans breccia residues has shown that these materials, under normal conditions of deposition, contain approximately 50 % voids. Into these voids, about 50 % by weight of calcite can be introduced after the accumulation of the original earth. Where breccia carbonate contents are in excess of this quantity, the excess must have accumulated simultaneously with the earth.

Work on Phase I breccias from Swartkrans, Hyaena Cave and Makapan Limeworks, has indicated that the rate of accumulation of the earth has influenced the carbonate content of the final breccia. This fact has been taken to indicate that the carbonate has come from inside the cave, not outside it. It is therefore thought to be derived from percolating solutions, and not from calcite dust.

Calcite dust can be shown to exist in certain modern dolomite soils and Kalahari type sands. The highest figure for modern dolomite soil was 19.1 % by weight, in a sample from Namaqualand, where the rainfall is less than

5 inches . . .

5 inches per annum. The largest quantity of calcite dust as yet detected by the writer in a Kalahari type sand is 1.4 % by weight. It is stressed that calcite dust should not be confused with solid surface limestone, commonly found in the dryer regions.

8.

A method for the quantitative assessment of angularity in silicious sands.

The Necessity for a Quantitative approach

Degrees of sand grain angularity are of very great significance in the interpretation of South African dolomitic cave deposits. It has already been shown how the distinction can be made between Phase I and Phase II cave fillings on the appearance of sand grains contained in them. In the next chapter on climatic deduction, it will be demonstrated how the degree of angularity of surface derived sand grains can provide clues to climate prevailing at the time of deposition. Angularity measurements provide a means of distinguishing between Kalahari-type sands and grains from normal dolomite soils. They also show how the sand fractions of modern dolomite soils are modified under the influence of different climatic regimes. Thus the necessity for an accurate and dependable method of angularity estimation is very real.

During the early phases of work by the writer on the Transvaal deposits, angularity estimates were made by visual examination of the sand grains. Uncertainties

in judgment . . . /

in judgment demanded that at least 1,000 grains be counted per sample. This meant that when a large number of samples had to be analysed, one was faced with a most time-consuming and exacting occupation. In addition to this, the count method can be criticised on the grounds that a certain personal element is inevitably inherent in it. The effect of this personal element is that the results are not directly comparable between different observers, nor are they always accurately reproducible.

The alternative method described here is based on porosity measurements in sands of constant grain size and at standardised compaction. Results obtained with this method are both accurate and reproducible. Moreover, personal factors do not enter into them.

A review of some previous literature on particle angularity.

Towards the end of last century, interest was aroused among sedimentary petrologists, on the characteristics of individual grains composing sediments. Daubree (1879) conducted experiments on the artificial abrasion of sand grains in water. He concluded that particles smaller than 0.1 mm. in diameter could not be rounded in water. Nine years later, Mackie (1898) established a number of arbitary roundness classes, into which sedimentary particles could be classified. As this classification did not involve any quantitative roundness determinations, the personal factor was likely to be reflected in the results.

Experimental work, similar to that conducted by Daubree was described subsequently by Galloway (1919). He concluded that particles smaller than 0.05 mm. in diameter could be rounded by abrasion in water. In the same year Wentworth (1919) carried out similar research, using, however, particles of pebble size. He defined roundness as the ratio of the radius of curvature of the sharpest particle edge to the mean radius of the particle itself. This definition was modified by Cox (1927) who expressed roundness as the ratio of the area of the grain's cross section to that of the circle exactly circumscribing the grain. In two subsequent papers, Mac Carthy (1933 and

1935) . . .

1935) applied this definition to beach and aeolean sands.

The authors of these various papers all assumed that the end-product of wear would be a spherical shaped particle. This would be produced irrespective of the original grain shape. In fact the early authors failed to distinguish between sphericity and roundness, as two distinct properties of particles.

The roundness of a particle is normally determined by the degree of wear which it has suffered. This was appreciated by Tester (1831) who devised a means of measuring the degree of particle wear. This involved the outlining of the initial shape of the grain in order to measure the original lengths of the edges. The summation of the ratios between the portion of the edge worn away and the original edge length provided Tester's roundness value. The main limitation of this method lay in the difficulty in estimating the lengths of the original edges.

Wadell (1932 and 1933) was the first to clearly differentiate between the two concepts of sphericity and roundness. Roundness was regarded as the result of wear suffered by a particle under gentle attrition, or in some cases normal solution. The term sphericity was used to denote how closely the grain approached the spherical form.

Wadell defined . . .

Wadell defined roundness (P) as :

$$P = \frac{\sum\left(\frac{r}{R}\right)}{N}$$

$$\text{or} \quad P = \frac{N}{\sum\left(\frac{R}{r}\right)}$$

where r is the radius of curvature of a plane corner, and R is the radius of the largest possible circle that can be enscribed within the area of the grain projection. N represents the number of corners in the particular plane that the radii (r) are measured. Of the two possible formulae, Wadell (1935) prefers the first.

Sphericity is defined as

$$\psi = \frac{s}{S}$$

where s is the surface area of a sphere of the same volume as the particle, while S represents the actual surface area of the particle. Thus ψ is the true sphericity.

For practical purposes, however, the following formula may be used :

$$\phi = \frac{dc}{Dc}$$

dc is the diameter of a circle equal in area to that obtained in the 'standard size' reproduction of the grain, . . .

grain, resting on one of its larger faces, and parallel to the plane of the longest and intermediate diameters. Dc is the diameter of the smallest circle circumscribing the 'standard size' grain reproduction. Wadell has shown that the Ø sphericity figure closely approximates the ψ value for all but very flat shaped grains.

Working on Mississippi River sands, Russel and Taylor (1937) set up five roundness grades for sands. These were defined as follows:-

"Angular. - Showing very little or no evidence of wear; edges and corners are sharp.

Subangular.- Showing definite effects of wear. The grains still have their original form, and the faces are practically untouched, but the edges and corners have been rounded off to some extent though the angles between faces may still be sharp.

Subrounded. - Showing considerable wear. The edges and corners are rounded off to smooth curves, and the area of the original faces is considerably reduced, but the original shape of the grain is still distinct.

Rounded. - Original faces almost completely destroyed,

but some . . .

but some comparatively flat surfaces may be present. There may be broad re-entrant angles between remnant faces. All original edges and corners have been smoothed off to rather broad curves.

Well rounded. - No original faces, edges, or corners left. The entire surface consists of broad curves; flat areas are absent. The original shape of the grain may be suggested by its present form, however."

Although these groups were visually defined, Russel and Taylor showed how Wadell's roundness values could be applied to them:-

"

	P values
Angular	0.00 - 0.15
Subangular	0.15 - 0.30
Subrounded	0.30 - 0.50
Rounded	0.50 - 0.70
Well Rounded	0.70 - 1.00 "

An important conclusion reached by Russel and Taylor was that the Mississippi River sand showed no tendency to become rounded in the course of transportation by the river. "On the contrary, the larger sizes (0.589 - 0.208 mm.)

became slightly . . .

became slightly more angular downstream. The evidence indicates that this condition is chiefly due to fracturing and chipping of the grains."

Wadell's method was further modified by Krumbein (1941). In his method, particles were compared with standard images of known roundness, and roundness values were assigned to them. A chart was provided with ten sets of standard images varying in roundness from 0.1 to 0.9.

A similar comparative method was suggested by Pettijohn (1949) who used a chart with 5 sets of standard images. These corresponded to Russel and Taylor's grades although the class limits were modified according to a geometric rule. Pettijohn's reason for the modification was stated as follows :- "This arrangement has practical justification because the eye can readily distinguish slight differences in roundness when the roundness values are low, but cannot make such distinctions when the values are large." The grades were consequently demarcated as follows:-

Angular	0.00 - 0.15
Subangular	0.15 - 0.25
Subrounded	0.25 - 0.40
Rounded	0.40 - 0.60
Well Rounded	0.60 - 1.00

Literature on . . .

Literature on the measurement of angularity of sand grains in bulk.

The literature on the estimation of angularity of particles in bulk contains descriptions of a variety of different techniques. These may be divided into several groups. References are now provided, but the only technique that will be considered in detail here involves the measurement of porosity in compacted sand samples.

The rate of fall of particles in water

This method is based on the observation that rounded particles will fall through water more quickly than will angular ones. The technique is discussed in two papers by Schiel (1941 a and b).

The rate of flow of water through an aggregate

The rate at which water flows through an aggregate is apparently determined by the angularity of individual particles composing the aggregate. This is true since the angularity determines the volume of voids between the particles. The principle is discussed by Schiel (1948) and Carman (1938).

The behaviour . . .

The behaviour of particles on an inclined plane

The basis of this approach is that rounded particles will move more freely down an incline than will angular ones. The approach has been discussed by Baturin (1942) and Dunagan (1940).

The number of particles in a given volume or weight.

The relationship between the number of particles in a given volume or weight and the angularity of the particles has been investigated by Pickel and Rothfuchs (1938) and by Stern (1937).

The relationship between the surface area and the roundness of particles.

It has been found that the surface area of particles increases with their degree of angularity. Clearly, particles of given volume will have the minimum surface area when they are completely spherical. Work on this subject has been published by the British Road Research Board (1938).

Screening of particles through square- and round-holed sieves.

Schiel (1947) described a method for the estimation

of particle . . .

of particle shape based on the percentages of particles passed through square- and round-holed sieves of the same effective aperture size. The original paper has been published by the U.S. Group Control Council for Germany.

Porosity measurements in compacted samples as estimates of particle angularity.

Previous literature

In 1927 Lamar (1927) described a method for the estimation of sand grain angularity based on the porosity of compacted samples. His experimental technique will now be described.

About 60 ccs. of oven dried sand were carefully screened to a particular size and were placed in a calibrated cylinder. The cylinder was then put on a mechanical device which raised and dropped it by about half an inch at the rate of 100 times per minute. This was achieved by means of a motor-driven plunger. The machine was run until the sand was fully compacted. The volume of the compacted sand was then measured, as was the volume occupied by the grains themselves. These measurements enabled the porosity to be calculated, and Lamar provided the following formula:

Percentage Porosity . . .

$$\text{Percentage Porosity (P)} = \frac{C - V \times 100}{C}.$$

where C is the volume of the sand and voids, and V is the volume of the sand grains themselves. This formula contains an obvious misprint and should read:

$$P = \frac{100\,(C - V)}{C}.$$

'Relative angularity' figures were then calculated from the porosity measurements. These were obtained by dividing the percentage porosities by 25.95, or the theoretical minimum porosity for spheres. Lamar maintained that the closer the relative angularity figure was to 1.0, the rounder was the sand. He therefore considered 'roundness' to be synonomous with 'sphericity'.

Two examples of porosity and relative angularity figures are now given; they apply to the size fraction 0.417 - 0.295 mm.

	% Porosity	Relative angularity
Rounded St. Peter sand:	33.6	0.773
Crushed Cypress sand:	40.0	0.649

A comprehensive paper by Graton and Fraser (1935) was concerned with the relationship between porosity and the systematic packing of spheres. It was shown that there are six possible ways in which spheres may be packed. Of these the 'cubic packing' is the most open, giving 47.64%

porosity, . . .

porosity, while the 'rhombohedral packing' is the densest, providing only 25.95% voids.

In a subsequent paper Fraser, (1935) published porosity measurements on a variety of different aggregates of 18 - 35 mesh size. The measurements, done on dry compacted material, varied from 34.78 % for 'standard marine sand' to 86.62 for crushed mica.

A recent paper by Shergold (1953) was concerned specifically with the assessment of particle angularity by means of porosity measurements. The investigation was restricted to particles of gravel size, and was undertaken to provide information on the use of aggregate in concrete.

The aggregate was screened so that all the particles to be tested were of approximately the same size. The following fractions were used:- $\frac{3}{4}$ - $\frac{1}{2}$ inch, $\frac{1}{2}$ - $\frac{3}{8}$ inch, $\frac{3}{8}$ - $\frac{1}{4}$ inch and $\frac{1}{4}$ - 3/16 inch. In the porosity determinations, a metal cylinder with a capacity of 2830 ccs. was used. The aggregate was introduced into this cylinder in three scoopfulls, and each layer was compacted by being subjected to 100 blows from a metal tamping rod, 24 inches long, which was dropped from a height of 2 inches above the surface of the aggregate. When the cylinder had been filled to overflowing, the aggregate on the surface was levelled off

by means . . .

by means of a straight-edge. The cylinder was then weighed to the nearest gramme.

In calculating the porosity of the aggregate, the following formula was used:-

$$V = 100 \left(1 - \frac{W}{C\,P}\right)$$

where V = percentage voids

W = weight of aggregate in the cylinder.

C = weight of water required to fill the cylinder.

P = gross apparent specific gravity of the aggregate on the dry basis.

Percentage porosity was found to vary from 33 for a well rounded gravel, to about 45 for angular crushed rock. Shergold's "angularity number" was therefore expressed thus :

'Angularity number' = percentage voids - 33.

In this way a scale of from 0 to 11 was set up which provided a rough estimate of gravel angularity useful in concrete technology.

POROSITY MEASUREMENTS AS ESTIMATES OF SAND GRAIN ANGULARITY

The test procedure : Variables and their control

In order to set up an angularity scale, based on porosity measurements for particles of sand size, it is necessary to control several variable factors. If these variables are not controlled, the scale will fail to reflect the amount of abrasion which the individual particles have suffered, and the object of the investigation will not be realised.

The variables to be considered are these:

A : Mineralogical composition

B : Grain size

C : Degree of compaction

A : Mineralogical Composition

When measuring angularity it is very desirable to deal with grains composed of one mineral only. This is because the rate of wear of different mineral grains is dependent on their hardness. At the same time, grain shape as opposed to angularity affects porosity to some extent. The shapes of different mineral grains are likely to vary in

accordance . . .

accordance with their crystal forms, as well as their cleavage and fracture characteristics.

For these reasons the present enquiry is concerned with silicious grains only. The principal deposits to be considered are dolomite soils and wind-borne sands of Kalahari type. The sand fractions of these deposits usually consist of silicious grains to the practical exclusion of other minerals. Certain other sands have been encountered, however, which contain such minerals as felspar and ilmenite, in sufficient quantities to make comparisons difficult. Examples are residual granite sands, and the red dune sand from Port Edward. In the case of such deposits it is advisable to separate the quartz grains out, by means of specific gravity liquids, before porosity measurements are done on them.

B : Grain size

Theoretically, where particles of equivalent shape, angularity and average diameter are concerned, absolute size should not influence their porosity at all. In practice, it is probable that the effect of finer grading is to increase the porosity to a slight extent.

Clearly, in porosity measurements it is essential to use a restricted size fraction so that all the grains are of approximately the same size. At the same time it is necessary to make use of a size fraction that is prevalent in the deposits to be investigated. Where dolomite soils and Kalahari type sands are concerned, the commonest sand size fraction falls about the middle of the sand grade. Thus, in this work, the selected fraction is composed of grains with diameters between 0.417 mm. and 0.246 mm. Such grains are passed by a 35 mesh Tyler screen but are retained on a 60 mesh one.

C : Degree of Compaction

When porosity measurements are used as angularity estimates, it is important to control the degree of compaction very closely. In discussing how sand samples can most conveniently be compacted, consideration will be given first to the type of container used. A description of the compaction machine itself will then be given.

The container.

The most important requirement of the container is that the volume of the sand that it contains can be very accurately measured. Where large sand samples are used, as in the method described by Lamar (1927), the open,

measuring . . .

measuring cylinder type of container may prove sufficiently accurate. In the present enquiry, however, the volume of sand available for analysis is limited by a practical consideration. This consideration is that when a sand sample, of a restricted size fraction, has to be isolated from a consolidated cave breccia, a relatively very large volume of breccia must be dissolved in acid to obtain a small sample of the correct sand grade. Thus unless the size of sand samples required is kept down, hydrochloric acid expenses are likely to be very high indeed.

A type of small container found to be suitable for very accurate sand volume determinations will now be described. Basically it consists of a glass vessel, closed at the bottom, but open at the top by way of a normal burette stop cock. The sand is then introduced through the stop cock at the top. When the vessel is full and the sand has been compacted, the cock is closed and the excess sand above it is thrown out. The vessel together with the bore of the stop cock is then found to be completely filled with sand. The volume of this space, now occupied by the sand can have been previously determined by filling it with mercury. When full, the vessel is accurately weighed and its volume can be calculated, as the density of mercury is known at the particular temperature concerned.

In practice, . . .

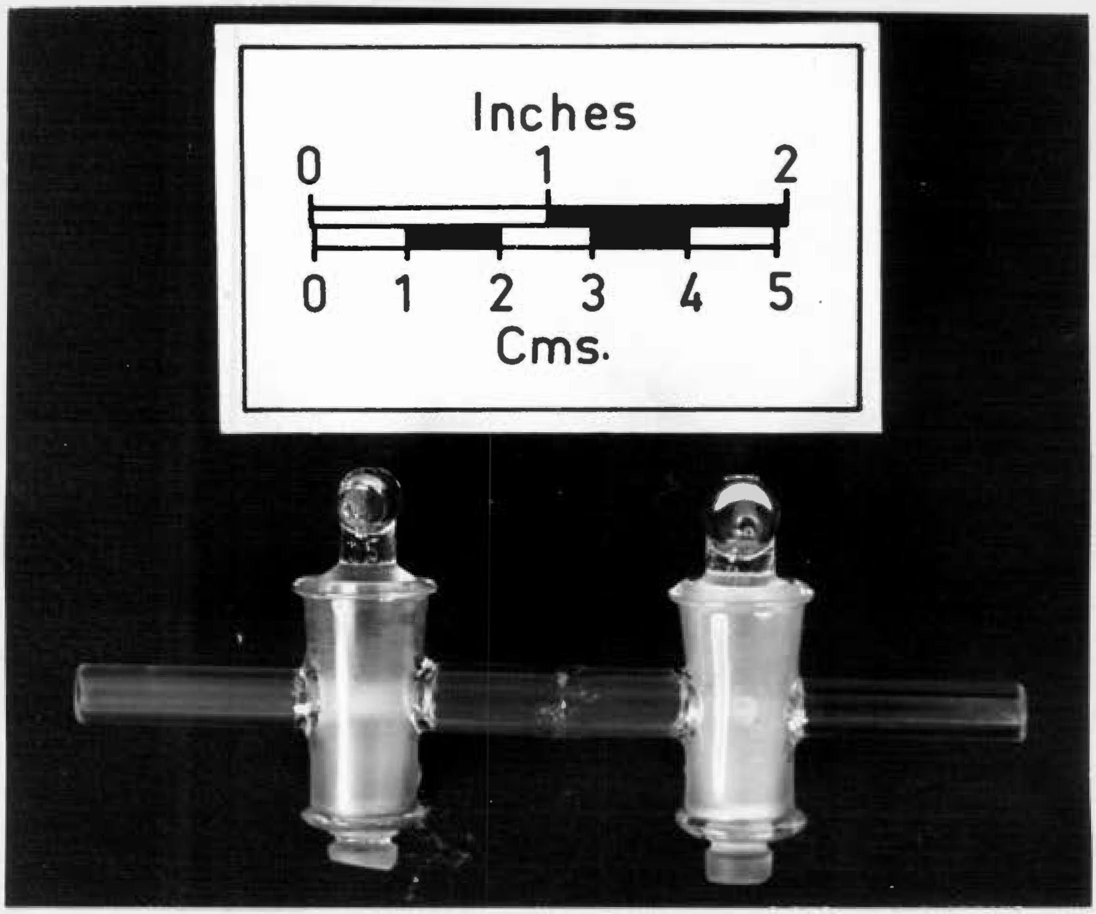
In practice, it is found desirable to use a vessel which has a stop cock at each end. During tests, the lower cock is of course kept closed. Nevertheless it is useful to have it, as it greatly facilitates the periodic cleaning of the inside of the vessel.

One of the glass containers actually used in the tests is shown in Photograph 59. During compaction, the stop cocks are kept in place by means of rubber bands; the sand is introduced through a small funnel and rubber tube. These features are shown in Photograph 60.

<u>The compaction machine</u>

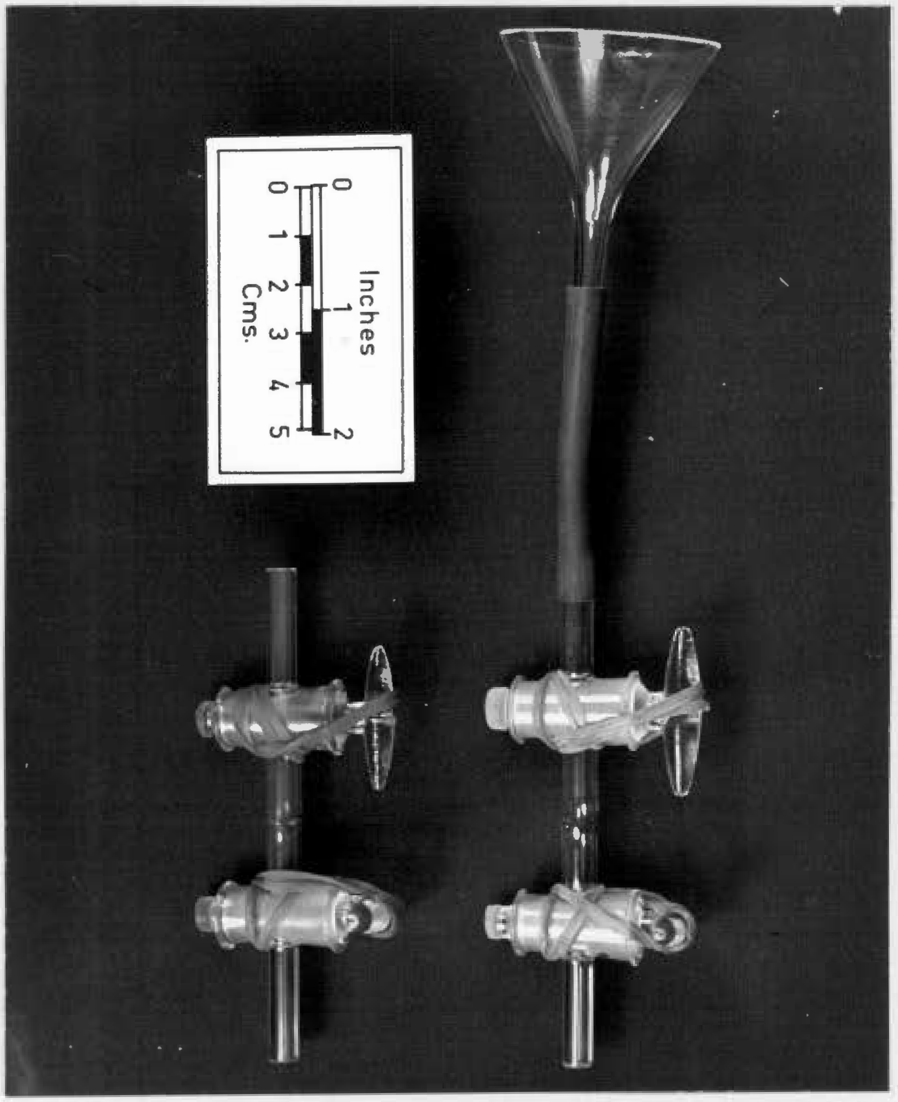
In this proposed method, compaction of the sand in the container is achieved by jarring. The function of the compaction machine is to raise and drop the vessel containing the sand at regular intervals, and by a prescribed amount. This is done by means of a motor-driven cam, revolving at three revolutions per second. The contour of the cam is designed such that the container is raised gently, but is then allowed to fall sharply. This fall is accurately adjusted to half a centimetre.

In its basic form, the compaction machine thus consists of an electric motor driving a cam by means of a chain of gears. Immediately above it, the container is



Photograph 59.

A glass container used in sand grain angularity tests.



Photograph 60.

Two glass containers showing how the stopcocks are held in place by rubber bands. Sand is introduced through the funnel and rubber tube.

fixed into a vertical sliding mount, which is raised and dropped by the cam's rotation. Sand is introduced into the container through a rubber tube and funnel, firmly fixed to the top of the support for the sliding mount. Each complete revolution of the cam is automatically recorded on a mechanical counter, mounted on the baseboard. This allows a check to be kept on the number of compactive blows given to the container.

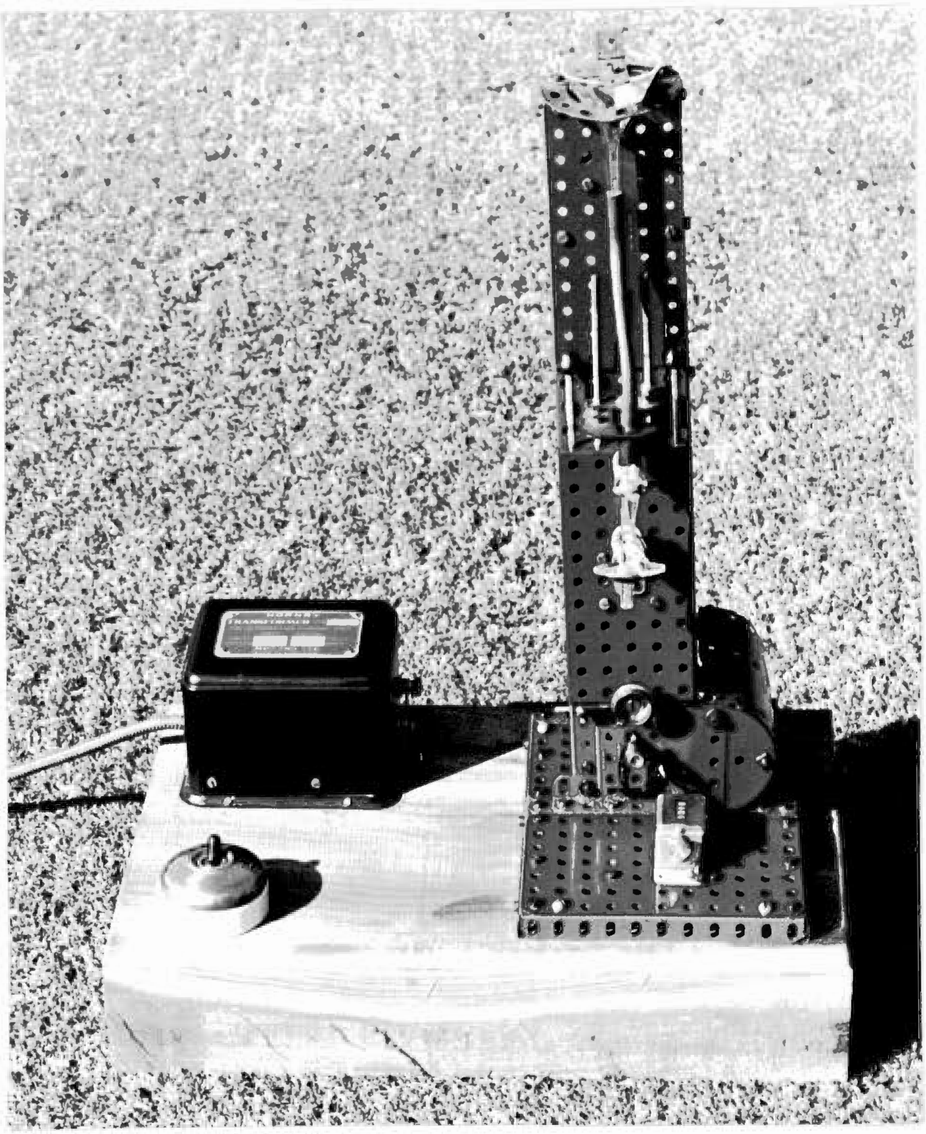
The original prototype of this machine was made in Meccano to the writer's specification by Dr. J.T. Robinson. This machine has proved so completely successful that it has been used without modification for all analyses. Meccano parts have the advantage that they are cheap and easily replaceable when they show signs of wear.

Photograph 61 gives a general impression of the machine. In Photograph 62 the cam in its two positions is shown, while Photograph 63 demonstrates how sand is introduced into the container through a funnel and rubber tube.

The Compaction Process

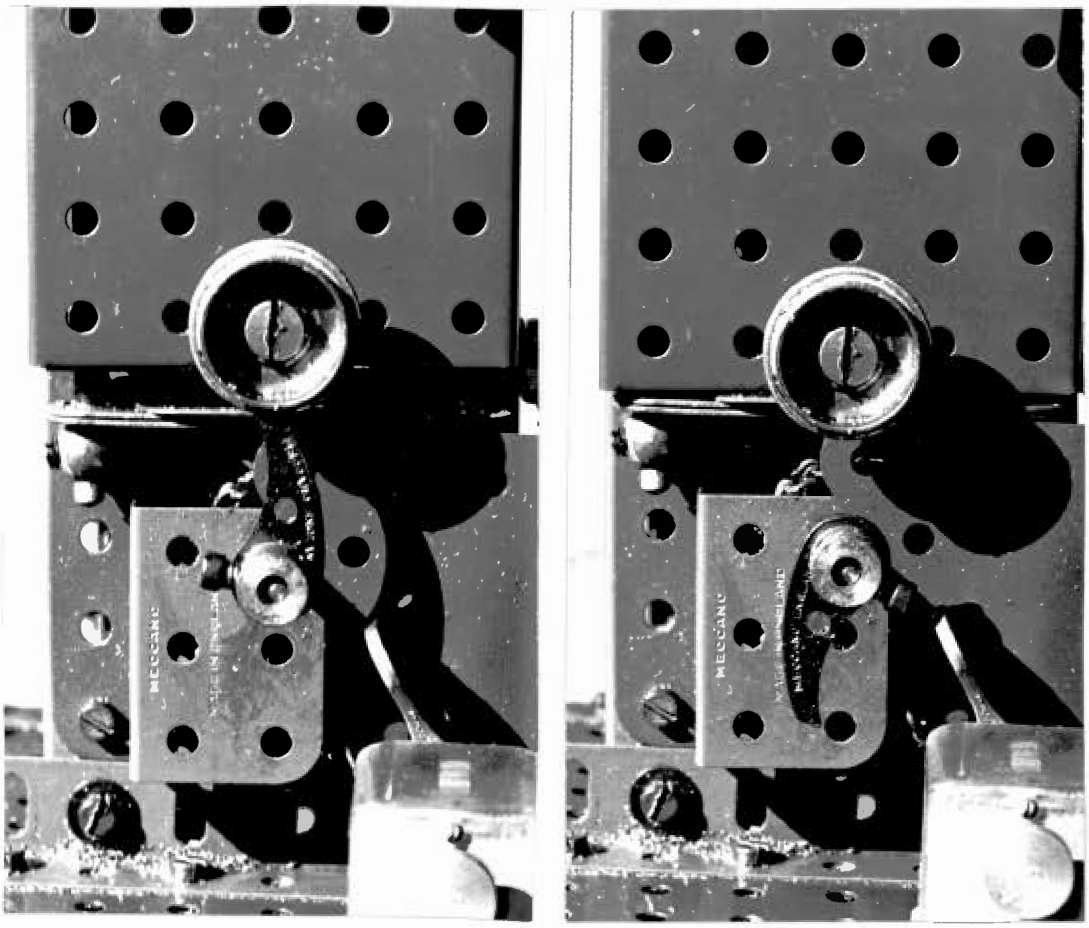
In compacting a sand sample, the funnel is connected to the top of the container by means of the rubber tube. Slightly more sand than is required to fill the container is then placed in the funnel and the motor is

started . . .



Photograph 61.

A general view of compaction machine used in sand grain angularity determinations.



Photograph 62.

The cam of the compaction machine in its two positions.

Photograph 63.

Sand being introduced into the container through the funnel and rubber tube.

started . The number of compactive blows is recorded on the counter and the motor is stopped when the desired number has been reached.

Analyses of South African sands by the writer have been standardised on a 0.7 cc container. The compaction process with this container will now be described.

During preliminary experimental work, a sand sample was compacted by subjecting it to different numbers of compactive blows. After each test, the porosity of the sand was determined. It became obvious immediately that more efficient compaction was obtained if compactive blows were given during the filling process of the container. Tests were therefore done on the container that had been filled with sand under gravity. Once filled porosity measurements were made after the following numbers of compactive blows had been given : 0, 25, 50, 100, 200 and 400.

Further tests were then done on the same sand sample, after equivalent numbers of blows, except that 43 blows were given in each case as the sand was entering the container. It was found that only 43 blows could be delivered in the time taken for the container to fill up. The results are now tabulated :

Sand sample 35 - 60 mesh . . .

Sand sample 35 - 60 mesh

Container filled without compaction then given different numbers of blows :

No. of blows	Percentage porosity
0	50.3
25	46.7
50	46.2
100	46.1
200	45.9
400	45.5

Sand sample 35 - 60 mesh

43 blows given during the filling of the container, then the following numbers of extra blows given :

No. of blows	Percentage porosity										Average % porosity
0	47.8	47.6	48.2	47.0	48.5	47.2	47.8	47.8	47.6	48.0	47.8
25	46.5	46.5	46.4	46.4	46.1	46.4	46.2	46.2	45.9	46.4	46.3
50	46.4	46.1	46.0	45.9	46.0	46.1	46.1	45.6	46.2	46.4	46.1
100	45.9	45.9	45.9	45.2	45.5	45.2	45.7	46.0	45.5	45.5	45.6
200	45.5	45.6	45.6	45.7	45.1	45.1	45.1	45.1	45.3	44.9	45. 3
400	44.9	45.0	44.9	44.9	45.5	45.0	45.2	44.8	44.7	45.5	45.0

These values . ..

These values are graphically presented in Fig. 23. It will be seen that compaction is more efficient if blows are given while the sand is entering the container. In the proposed stabdard procedure, compaction is started as soon as the sand begins to enter the container. This is regulated by placing a spring clip on the rubber tube before the sand is put into the funnel. Sand is then poured into the funnel and the clip is removed as soon as the motor is started.

It is not thought necessary to run the machine indefinitely until no further compaction of the sand will take place. When large numbers of samples have to be analysed, this would be a protracted occupation. Instead it is suggested that all samples are given 193 compactive blows each, of which 43 are delivered during filling. This then corresponds to the 150 blow line in Fig. 23. It will be seen that with this degree of compaction, a probable error of 0.4 % porosity either way can be expected.

Details of the sand samples and of the compactive process can be summarised as follows :

Volume of sand required for testing	:	1.0 cc.
Size fraction of sand	:	35 - 60 mesh Tyler.
Volume of container	:	0.7 cc.
Bore of upper stop cock	:	1.0 mm.
Number of blows given during filling	:	43
Number of blows given after filling	:	150.

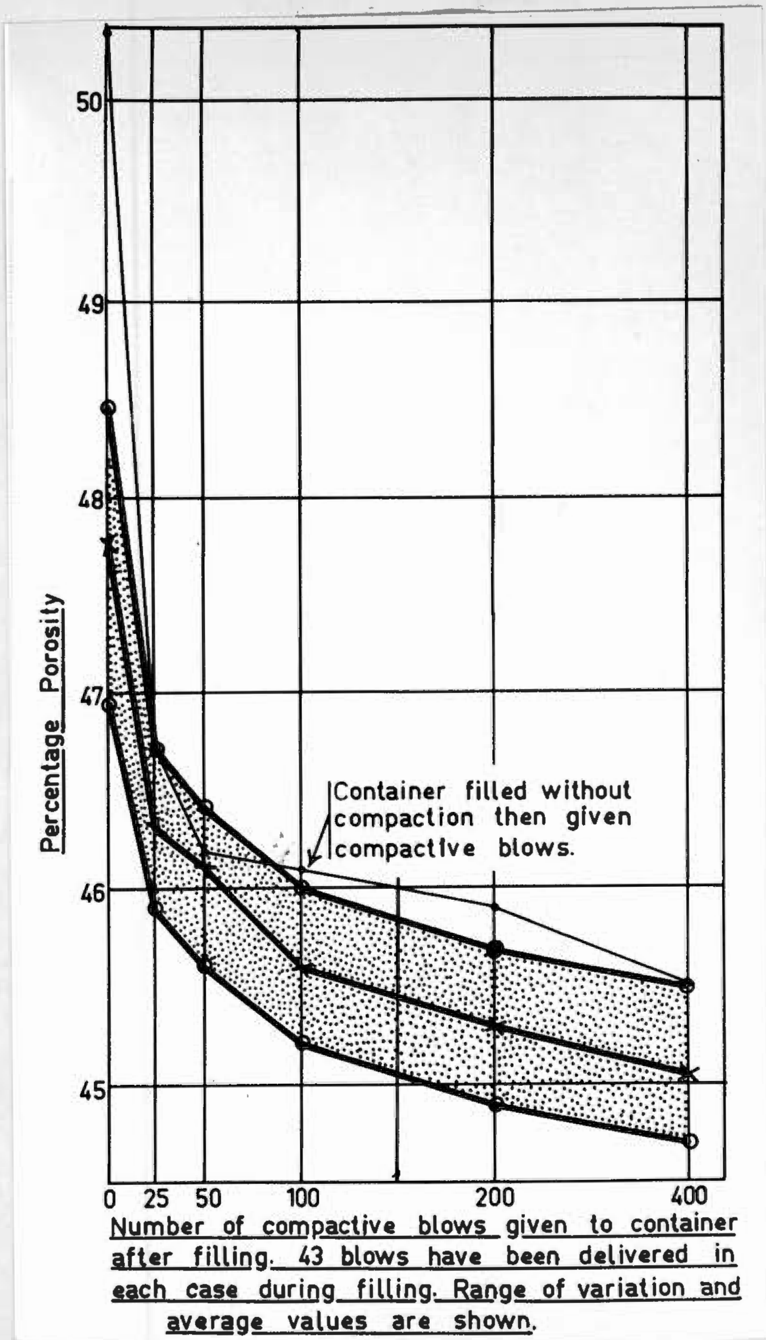


Figure 23.

The effect of compaction on the porosity of sand samples.

The effect of container size on compaction

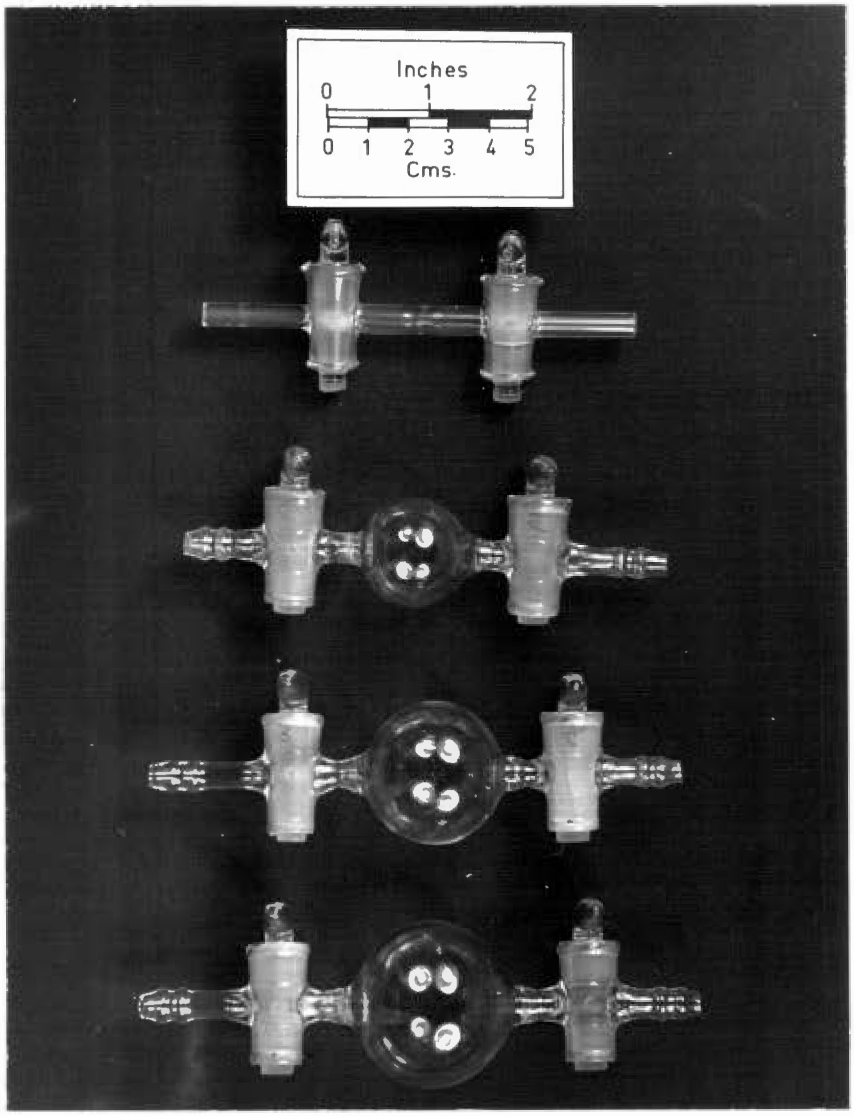
Photograph 64 shows a series of containers used in the experimental work. The volumes of these containers were measured and were found to be as follows: 0.714 ccs, 9.41 ccs, 19.32 ccs and 29.18 ccs.

Four porosity measurements were done with each container on the same sample of Namib desert sand of 35 - 60 mesh size. Compactive blows were given during the filling of the containers, and when full, 150 extra blows were delivered in each case. The following results were obtained:-

Container volume	% Porosity				Average % porosity
0.74 cc.	33.0	33.4	33.4	33.8	33.4
9.41 cc.	32.8	32.5	32.6	32.8	32.7
19.32 cc.	33.1	32.9	32.7	33.3	33.0
29.18 cc.	32.9	33.2	33.0	33.2	33.1

It will be seen that a certain amount of variation exists in the results obtained from different containers. The reason for this is almost certainly that small discrepancies are present in the estimated container volumes. The precise measurement of volume by means of mercury necessitates the removal of all air bubbles. This is sometimes extremely difficult, even under vacuum, as the

stop cocks . . . /



Photograph 64

Containers of different volume used in experimental work on sand grain angularity.

stop cocks are seldom completely air tight.

As was previously pointed out, work on sands extracted from consolidated breccias makes the use of a small container desirable. It is, however, thought that the volume of the container should not be reduced below about 0.7 cc. Lamar (1927) has pointed out that, if the diameter of a container is less than 8 times that of the largest particle to be tested, inaccuracies in porosity measurements are likely to be occasioned by side-wall effects.

Where normal sands are being investigated there is no disadvantage in using a larger container. In fact the size of the container should probably be determined by the accuracy with with it can be weighed when filled with sand. Use of the 0.7 cc. container demands that it be weighed to an accuracy of 0.001 gm. Where the available weighing facilities do not permit such accuracy, a larger container should be selected.

<u>The calculation of percentage porosity</u>

When the sand sample to be tested has been compacted in the container as described above, the upper stop cock is closed and the container is removed from the machine. Excess sand above the stop cock is discarded and

the sand filled . . .

the sand filled container is accurately weighed. As the weight of the empty container is known, subtraction provides the weight of the sand itself.

The sand sample is now removed from the container and a specific gravity determination is done on it. This can conveniently be carried out in a 50 ml specific gravity bottle. When the sand is covered with water it will be necessary to evacuate the bottle to remove all air bubbles entrapped between the grains. Specific gravities of the sands tested, normally vary from about 2.60 to 2.68.

Using the weight of sand in the container and its specific gravity, the volume of the grains themselves can be readily calculated. This volume, subtracted from that of the container, provides the volume of the spaces or voids which exist between the individual grains.

The percentage volume of voids, or the porosity is then derived.

Figures from an actual test are now provided as an example:-

Figures:- material . . .

Material : Kalahari type sand

Locality : Lupani, Southern Rhodesia

Level : Surface

Size fraction : 35 - 60 mesh

Compaction details : Standard

Container : No. 2. 0.714 ccs.

Weight container plus sand in gms	29.012
Weight container in gms...........................	27.782
Weight sand in gms (a)	1.230
Specific gravity sand (b)	2.61
Volume container in ccs (c)	0.714
Volume sand in ccs ($^a/_b$)	0.471
Volume of voids in ccs (d)	0.243
% volume of voids ($^d/_c$ x 100)	34.1

Porosity = 34.1 %

Sand grain angularity and porosity measurements

To demonstrate the effect of sand grain angularity on porosity, the following test was done. Two samples of 35 - 60 mesh sand were selected: one an angular sand from a modern dolomite soil, and the other a well rounded aeolean sand. The angularity difference between these two sands is very clearly apparent as is shown in

Photographs 67 and 71 . . .

Photographs 67 and 71.

Porosity measurements were done on each of these sands, and also on artificial mixtures of them in proportions : 25 : 75 %, 50 : 50 % and 75 : 25 % by weight. The results are now tabulated :

Sand	Porosity %		Average Porosity %
100% Rounded	34.2	34.0	34.1
75% Rounded : 25% angular	36.3	36.6	36.5
50% Rounded : 50% angular	39.9	40.2	40.0
25% Rounded : 75% angular	41.6	42.0	41.8
100% Angular	43.6	43.7	43.7

These values are shown graphically in Figure 24. It will be obvious that an increase in sand grain angularity is associated with an increase in percentage porosity.

The angularity scale

The angularity scale to be discussed now is based on silicious sands only, of 35 to 60 mesh size.

By far the most angular sand so far encountered

is produced . . .

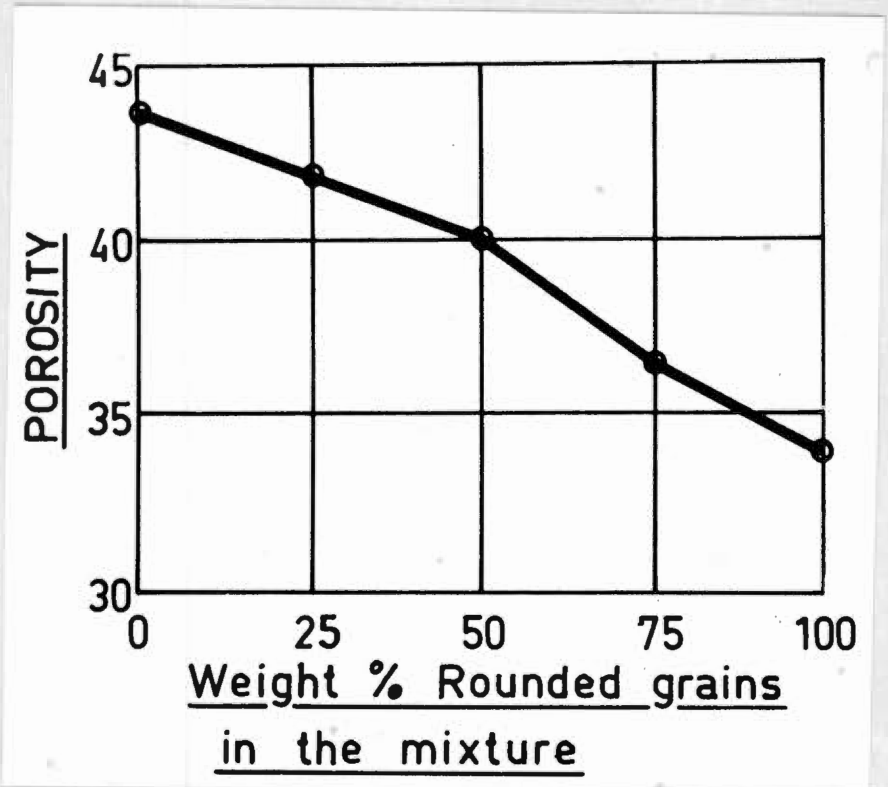


Figure 24.

Graph showing the relationship between sand grain angularity and porosity in artificial mixtures of sand.

is produced by artificially dissolving impure dolomite in acid. Quartz and chert grains are then produced that are incredibly angular and fragile. An average porosity value for this sand is 69.5 %. Residual cave earth sand grains are generally similar, but have usually had some of the most delicate processes removed. An example from Swartkrans gave 61.5 % porosity. Such sands are far more angular than are the most angular examples described by Krumbein (1941) and Pettijohn (1949). It is suggested that the term 'superangular' might be applied to them, and could include all grains giving porosity values in excess of about 42 percent. Pettijohn's classes "Angular", "Subangular", "Rounded" and "Well Rounded" then all fall in the porosity range 42 - 32 %.

The most rounded South African sands so far analysed come from two localities in the Kalahari desert, Sekuma and Boritse Pan. These samples were kindly supplied by Dr. H.B.S. Cooke. Both gave porosity values of 33.2 % and both fall in Pettijohn's "Rounded" class. So far the writer has not been able to find any "Well Rounded" South African sand. A sample was however obtained from America distributed by the Ottawa Silica Co., Illinois, which gave a porosity of 32.0 %. Unfortunately this sand was rather coarser than the other samples, as it fell between 20 and 30 mesh Tyler. . . .

mesh Tyler. Nevertheless, the porosity value of 32.0 % is regarded as being reliable.

It must be pointed out here that any normal South African sand will contain grains of widely differing angularity. A normal Kalahari-type sand giving a porosity figure of about 34 % will contain some "Well Rounded" grains, while others are likely to be "Subrounded". The advantage of the porosity estimates over the methods of individual particle measurement, used by Wadell, Krumbein and Pettijohn, is that a very large number of grains is considered in each porosity test. Using the 0.7 cc. container, the angularity of over 27,000 grains is reflected in the porosity measurements. Thus a much better idea of the angularity of the total sample is obtained.

A list of sand samples covering the angularity range expressed in porosities is now provided. Approximate Pettijohn equivalents are given, although the range of angularity shown by individual grains, in the same sample, makes accurate comparison difficult.

Type of sand and locality	% Porosity	Approximate Pettijohn Equivalent
Artificial sand from dolomite	69.5	
Residual cave earth, Swartkrans	61.5	
Modern dolomite soil, Graskop	58.5	
Modern dolomite soil, Kromdraai	43.7	
Residual quartzite sand, Pretoria	41.9	Angular : 0-0.15
Vaal River Sand, Windsorton	41.7	
Residual sand, Nkana, N. Rhodesia	41.5	
River sand, Virginia, O.F.S.	40.9	
Vaal River sand, Larsens	39.7	
River sand, Virginia, O.F.S.	39.5	
Artificially crushed quartz	39.2	
River sand, Virginia, O.F.S.	39.1	
Red sand, C.S.I.R. site, Pretoria	38.7	Subangular : 0.15 - 0.25.
Granite sand near Pretoria	38.4	
Vlei sand, Paardekop, Tvl.	37.4	
Kalahari- type sand:-		
Olifantshoek	36.7	Subrounded : 0.25 - 0.40.
Mpepu	35.3	
Upington	35.0	
Nojane	34.9	
Inkruip	34.8	
White sand, Hopefield, Cape	34.6	
Namib desert sand, Brandkaross	34.4	
Namib desert sand, Springbok	34.4	
Kalahari-type sand:-		
Niekerkshoop	34.4	
near Livingstone	34.2	
Lupani, S.R.	34.1	Rounded : 0.40 - 0.60
Igusi, S.R.	34.0	
Namib desert sand, Porto Alexandre	33.9	
Kalahari-type sand:-		
near Livingstone	33.6	
near Livingstone	33.5	
Sekuma	33.2	
Boritse Pan	33.2	
Ottawa Standard sand	32.0	Well Rounded : 0.60 - 1.00

A series . . .

A series of photomicrographs of the actual sand samples is now given, so that some impression is gained of how the various angularity grades appear. Wherever possible Pettijohns standard images are provided for comparison.

General Conclusions

A method for the quantitative assesment of sand grain angularity is necessary in work on dolomitic cave deposits. Angularity measurements serve to distinguish between Phase I and Phase II deposits, and are also useful in the identification of different surface-derived materials.

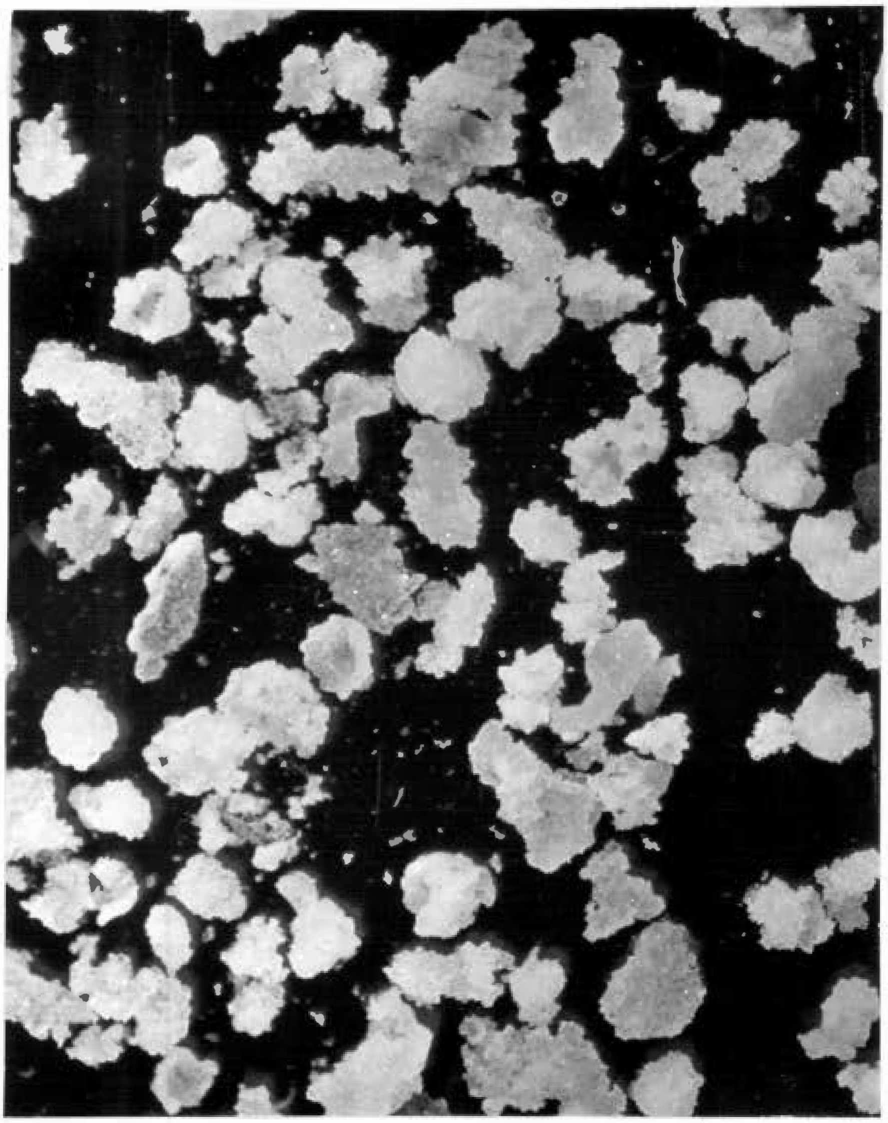
Visual estimates of sand grain angularity were found to be unreliable, as a result of the inherent personal factor. Sand grain counts proved excessively time consuming.

A method for sand grain angularity estimation, based on the porosities of compacted samples is described. In principle it is similar to that used by Lamar in 1927. The test procedure is however much refined. 35 - 60 mesh sand samples are used and in silicious sands (quartz and chert), the porosity range is from 69,5 % for extremely angular

grains . . .

grains, to 32 % for well rounded grains. It is suggested that sands giving porosities of over 42 % should be termed "Superangular" to distinguish them from the more normal "Angular" sands described by Pettijohn. The superangular sands are restricted to natural and artificial dolomite residues.

Porosity figures obtained with the described method are reproducible to within plus or minus 0.4 %. An angularity scale for South African sands is provided. It is shown that all Kalahari-type sands so far analysed have porosities of between 33 and 37 %. They are thus easily recognisable.



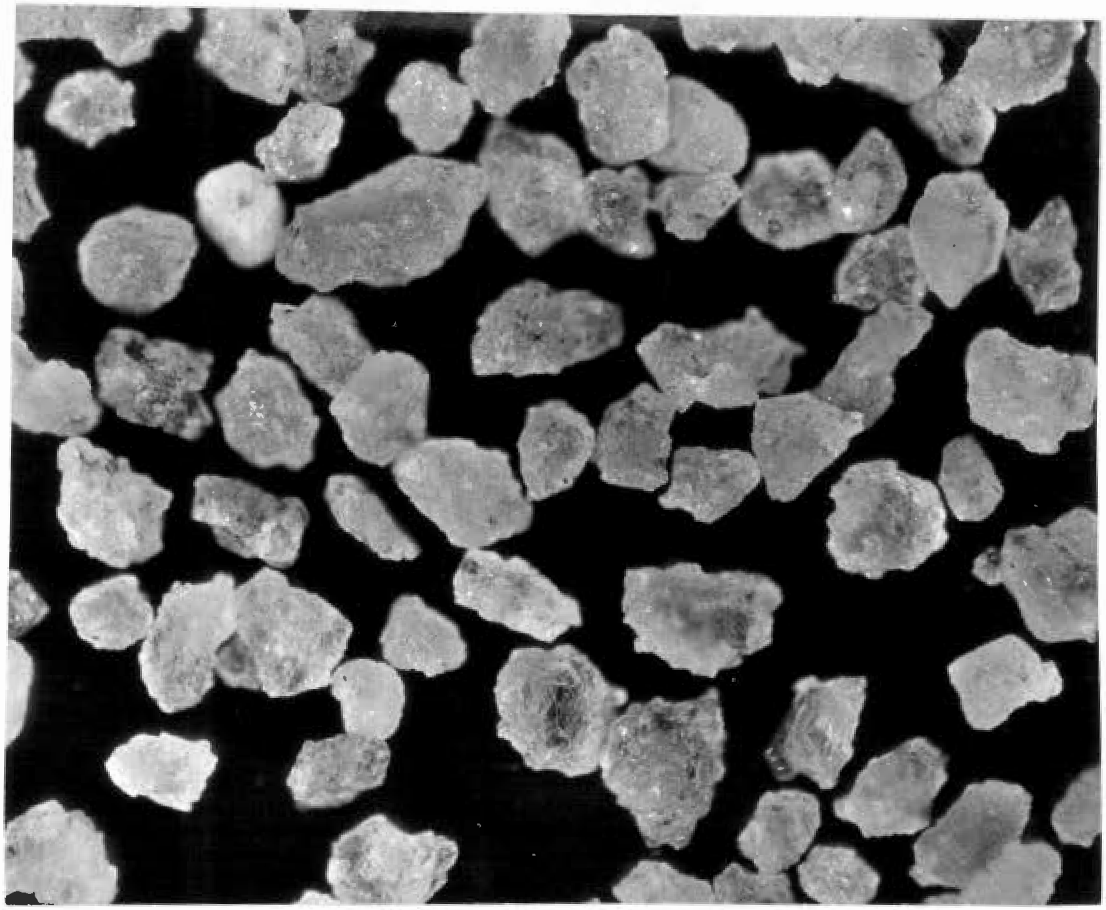
Photograph 65.

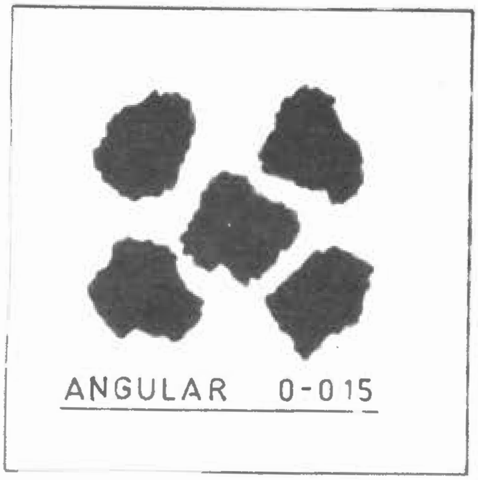
'Superangular' sand grains produced by artificially dissolving impure dolomite. x 40. Porosity = 69.5 %.

Photograph 67.

Sand grains from the modern dolomite soil at Kromdraai.

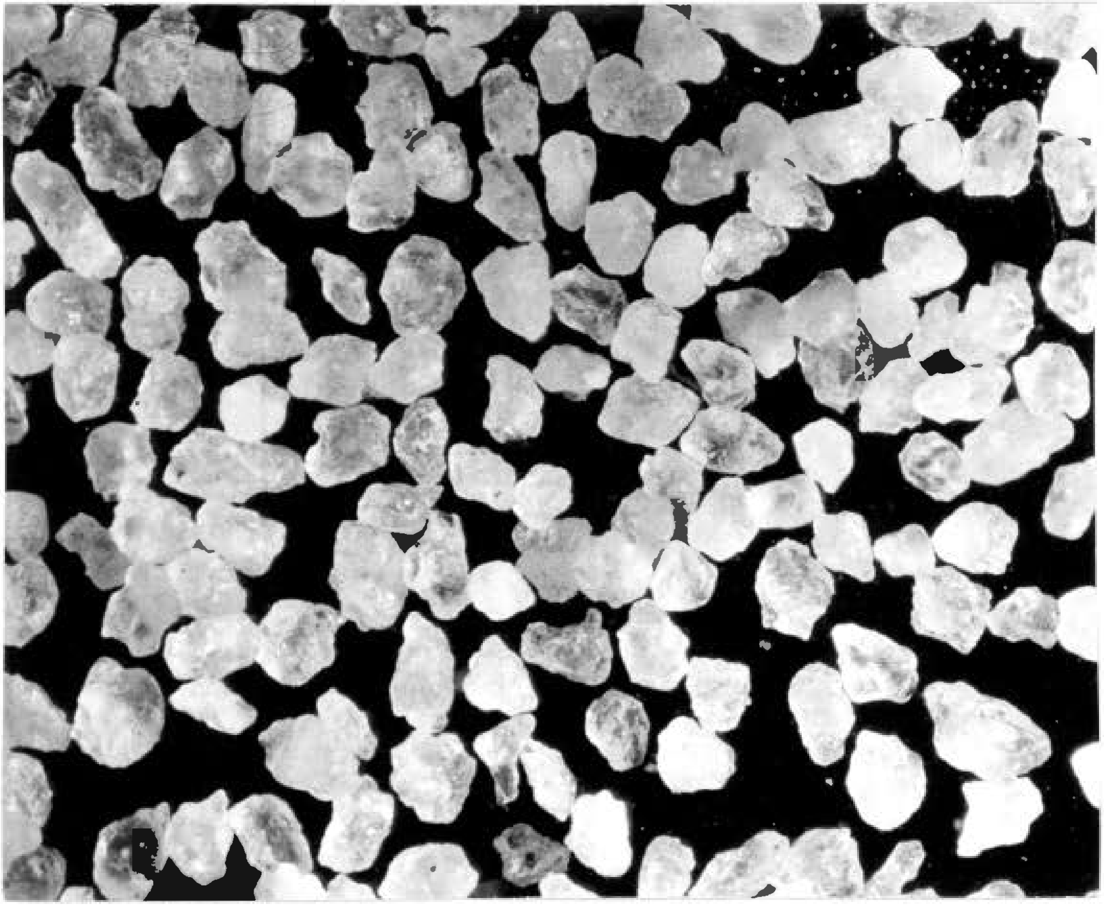
x 40. Porosity = 43.7 %.

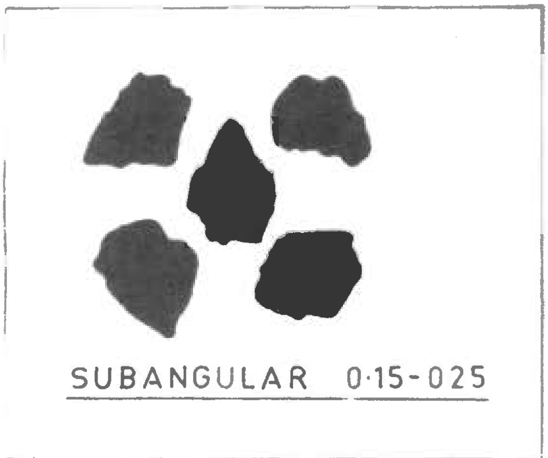




Photograph 68.

Grains from a residual sand on quartzite. Meintjieskop, Pretoria. x 40. Porosity = 41.9 %.

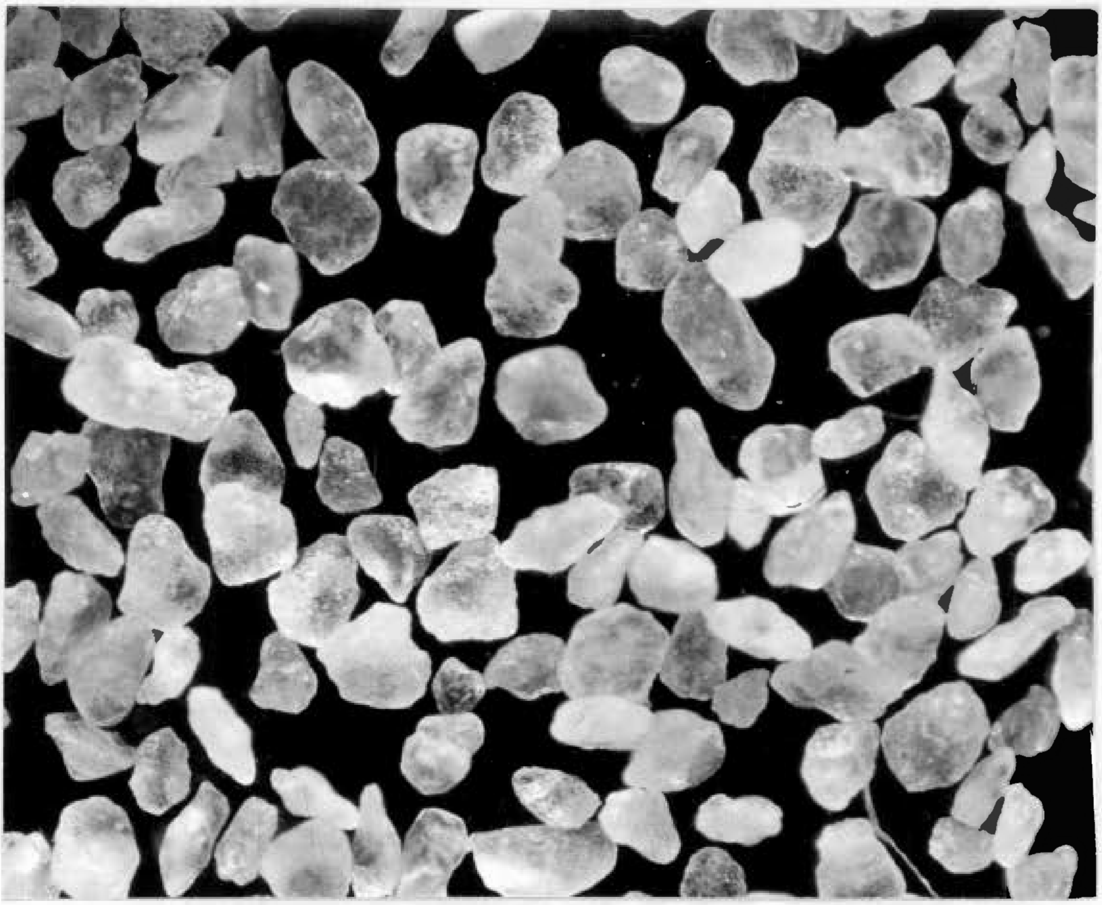




Photograph 69.

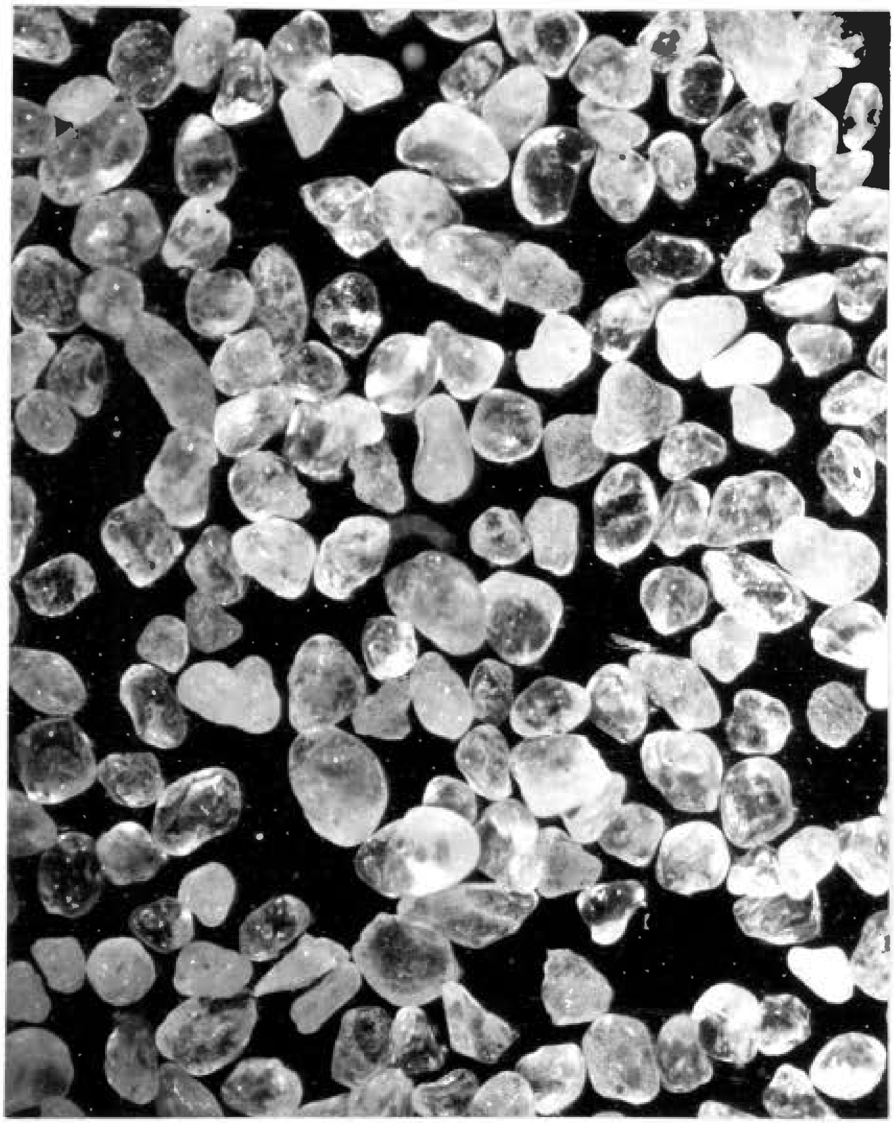
Grains from a red residual sand deposit near Pretoria. x 40.

Porosity = 32.7 %.



Photograph 70.

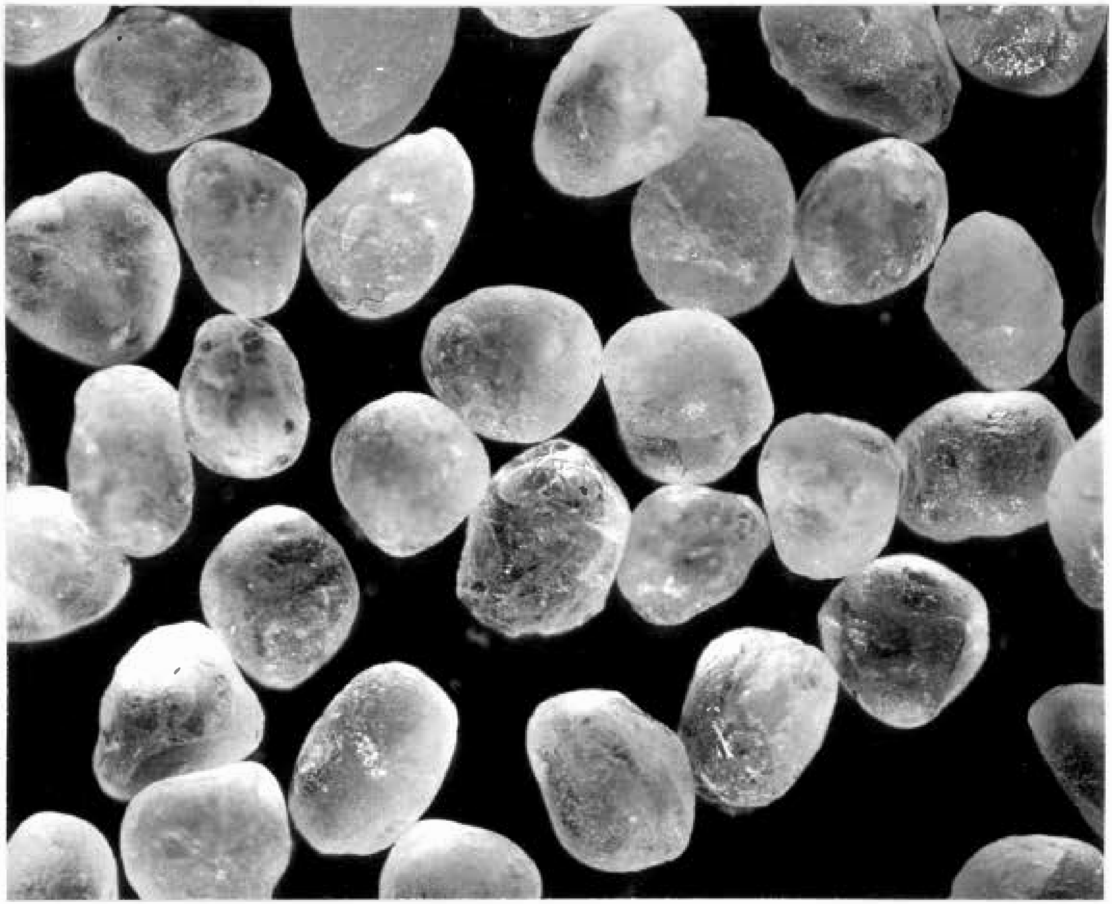
Grains from a Kalahari-type sand, Olifantshoek, near Kuruman. x 40. Porosity = 36.7 %.



Photograph 72.

Kalahari-type sand grains from Sekuma, Bechuanaland. x 40.

Porosity = 33.2 %.



Photograph 73.

Well rounded sand grains. Ottawa standard sand. x 30.

Porosity = 32.0 %.

9.

Special techniques used in the routine investigation of cave breccias.

In the routine investigation of South African cave breccias it has been found necessary to make use of some specialised techniques, not widely used in conventional geological work. As has been previously stated, the most useful information is obtained from the examination of breccia residues, collected after the carbonate cement has been dissolved in acid. Thus although the carbonate fraction of a breccia sample is usually discarded, it is nevertheless important to know how much carbonate was originally present. Thus a simple technique is described for the quantitative estimation of carbonate cement.

Once the cement of a breccia sample has been dissolved away, the residue is collected by filtration through a Buchner funnel, using a suction pump to speed up the process. The residue is then dried in a low temperature oven. Once dry, it is gently disaggregated in a mortar, using a rubber-tipped pestle. A mechanised analysis can then be done on the disaggregated residue. As this analysis is more widely employed in civil engineering than in geology, the technique will be discussed shortly.

It was . . .

It was emphasised in the last chapter that useful distinctions could be made between various types of cave fillings on differences in the shapes and surface textures of the sand grains composing them. In order to be able to examine the shape and texture of individual sand grains the samples have to be prepared and mounted in a particular way. The technique used will therefore be described.

Analysis methods used in the deduction of past climate from cave deposits will be considered in Chapter 10.

The quantitative estimation of carbonate cement in a cave breccia.

At an early stage in the investigation of the cave breccias, various methods were tried for the estimation of the carbonate cement. At the C.S.I.R. laboratory in Pretoria, samples were analysed by means of the conventional muffle-furnace method, commonly used in the analysis of limestones for industrial purposes. Although this method is simple and straightforward it proved to be somewhat laborious where large numbers of samples were involved. An alternative method tried was through differential thermal analysis which can be employed for both quantitative and qualitative estimation of carbonates. Although giving accurate results, the apparatus required was decidedly complicated.

It has been found that by far the simplest and quickest method is as follows. The breccia sample, weighing between 5 and 20 grammes is accurately weighed and is then placed in a 400 ml. beaker. Sufficient 10% hydrochloric acid is added to cover the sample, and the beaker is left to stand until all effervescence ceases. Its contents are then transferred quantitatively onto accurately weighed filter paper in a normal conical funnel. The paper used must be sufficiently fine grained to stop the very finest of sediment. S an S No. 576 is found to be very satisfactory.

Frequently, where fine-grained sediment is involved, the paper becomes blocked and filtration is consequently very slow. The stem of the funnel can then be pushed through a hole in a rubber bung stuck in the top of a Buchner flask. If the flask is attached to a suction pump, the filtration process will be much accelerated, the residue should be thoroughly washed. The folded filter paper containing the residue can then be dried in a low temperature oven. When dry, the paper and residue should be cooled in a dessicator and accurately weighed. The difference in weight between the original breccia and the dry residue represents the weight of carbonate cement. Its percentage weight can then be calculated.

The most . . .

The most obvious precaution to be observed with this method is that the concentration of the hydrochloric acid must not be too great. If the acid is too strong, breccia constituents other than the carbonate cement are likely to be dissolved. The most important of these are oxides of iron and manganese. It is found that 10% hydrochloric acid is sufficiently dilute to dissolve only the carbonate if the residue is filtered off soon after effervescence ceases.

This method has the advantage that a sample can be quickly analysed. When the apparatus is set up, more than 50 samples can be handled in the course of a day. The results obtained are found to be quite adequately accurate, and normally agree to within 2% of those provided by the alternative analysis methods.

The Mechanical Analysis Technique

In expressing the grading of a sediment on the percentage by weight basis, it is necessary to impose an upper limit on the size of particles which are to be included in the sample for analysis, for unless the weight of this sample is excessively large, the presence of even a few pebbles or boulders is going to affect the result considerably. For this reason, working with samples weighing between 500 and 1,000 gms. each, it was found necessary to impose an upper particle size limit corresponding to fine gravel. Thus all particles larger than mesh 4, on the Tyler Standard Screen Series, were excluded. The grading of the remaining sample was then expressed as six fractions ; fine gravel, coarse sand, sand, fine sand, silt and clay. In defining the limits of each fraction, a conventional system was used which is widely accepted in both England and America, and may be expressed thus :-

Grade	Tyler Screen Mesh	Particle size in mm.
Fine gravel	4 - 9	4.7 - 2.0
Coarse sand	9 - 35	2.0 - 0.42
Sand	35 - 100	0.42 - 0.15
Fine sand	100 - 270	0.15 - 0.05
Silt	-	0.05 - 0.005
Clay	-	$<$ 0.005

The sample for analysis is oven dried and is then shaken through a nest of three screens of meshes 4, 9 and 35. The gravel retained on mesh 4 is discarded, but the fractions retained on meshes 9 and 35, together with that passing 35 are carefully weighed. The sum of these three fractions represents the total grading analysis sample.

The fraction finer than 35 mesh is then thoroughly

mixed . . .

mixed and 50.0 gms of it are taken for estimation of the finer grades. This is placed in a large beaker and is covered with about 400 ccs of distilled water. 5ccs of each of solutions of sodium oxalate and sodium silicate are added, and the mixture is well stirred before being left to stand for twenty four hours. During this time, the action of the chemicals is to deflocculate the clay. When this has occurred, the suspension is vigorously mixed for fifteen minutes by a paddle revolving within it at 1450 r.p.m. It is then transferred quantitatively into a tall Bouyoucos cylinder, and more distilled water is added to make the suspension up to 110 ccs. This is well shaken, and placed in a constant temperature bath at 19.5° C.

After precisely one hour, a Bouyoucos hydrometer is placed in the suspension and a reading is taken. This reading, multiplied by two, gives the percentage by weight of clay in the fraction finer than 35 mesh. The suspension is again shaken, and another reading is taken after precisely 40 seconds. This reading, multiplied by two provides the percentage of silt, and concludes the hydrometer analysis.

The suspension is now washed through a 100 mesh screen, and the sand retained on it is oven-dried and weighed. Its weight represents the total sand grade present in the 50 gms of material taken. The analysis result can now be calculated

the only missing . . .

the only missing grade being the fine sand one, the weight of which is arrived at by subtraction.

This technique is applied to both normal soils and breccia residues, after the carbonate cement of the latter has been removed with dilute hydrochloric acid. The accuracy obtained is adequate, since a number of analyses done on the same sample showed agreement in all grades to within 3%

Additional information on this analysis technique may be obtained from the report published by the National Road Board (1948).

The preparation of samples for the examination of shape and surface texture of sand grains.

The conventional method of mounting sand grains in Canada balsam is not particularly suitable when grain shape is being examined, and is quite useless when the surface texture of sand grains is to be studied. For this purpose the grains must be viewed in air, preferably through a stereoscopic-type microscope. The method used for preparing and mounting sand samples was evolved and described by Dr. Bond (1954).

First of all the sand is boiled in 50% hydrochloric

acid . . .

acid to clean the grains of iron oxide coatings. They are then washed and dried. Bond's mounting procedure will now be quoted:-

"The sample is decanted into a large watch glass and by gently tapping one side a rough grading by size of particles is produced. A length of sticky cellophane tape (about 2½" long and ⅝" or more wide is best) is then dipped into the sample. A single layer of grains from the graded sample is thus picked up. The tape is then stretched tightly across a 3" x 1" glass slide and the free ends pressed down. It adheres well to the glass and the grains are imprisoned between the tape and the glass. The slide is examined by reflected light through the glass (i.e. "upside down"), with the cellophane on the stage of the microscope. The surfaces of the grains can thus be seen free of any mounting medium, and individual grains or fields can be marked with ink rings if necessary. A binocular microscope of the ordinary zoological type is very satisfactory because of its depth of focus".

This method has been found altogether satisfactory. In fact only one change was thought to be desirable: where counts are done on the mounted sand grains, it is preferable to screen the grains previous to mounting, to ensure that all the particles will be of about the same size. Where fine

grained . . .

grained sands are being studied, a high-power stereoscopic microscope, giving at least 100 times magnification, will be found necessary.

. . . .

10.

Some methods for climatic deductions from dolomite cave deposits

Reasons for attempting climatic deductions

When dealing with a series of fossil-bearing deposits it is important to be able to arrange them in their correct chronological order. At present, this can only be attempted on the basis of the fossil remains themselves. An accurate means of determining absolute ages of deposits between 500,000 and 1,000,000 years old is not available at the moment. Nor is Dr. Oakley's method of relative flourine dating of much assistance.

It is however well established that the Pleistocene period in South Africa was punctuated by a series of well-marked climatic changes. At present, knowledge of the duration and intensity of these changes is fragmentary, although a broad outline of the major episodes is known. Thus if it is possible to deduce what type of climate prevailed during the accumulation of a cave deposit, and if it is possible to position this deposit roughly in the time scale by means of its included fauna, then the combination of both approaches should lead to a fairly precise dating. It is therefore very desirable to be able to make climatic deductions from the fillings of dolomite caves.

The other . . .

The other advantage in making a climatic deduction from a bone-bearing cave deposit is that, if the nature of the original climate is known, an impression is gained of the type of environment under which the animals existed.

<u>Cave deposits that may be used as climatic indicators.</u>

Clearly, the only type of cave deposit useful as a climatic indicator is one that will reflect conditions as they were on the ground surface. Outside climate, not cave climate is what is important here. For this reason, deposits must be selected that are in equilibrium with surface conditions. This means that Phase II deposits only may be considered. Phase I and residual cave materials are not of any assistance.

In attempting climatic deductions from a cave deposit, therefore, great care must be taken to establish which parts of the deposit, if any, are composed of uncontaminated Phase II material. The distinctive features of this material have already been discussed in Chapter 6. Briefly, sand grains obtained from residual cave earths are characteristically "superangular" and in the 35 - 60 mesh fraction are likely to have porosities of between 60 and 70 per cent. Sands from Phase I deposits will consist of mixtures of residual grains with surface-derived grains.

The bulk . . .

The bulk angularities of such sands will be dependent on the relative proportions of the two components present. Phase II sands will consist of surface derived grains to the practical exclusion of residual cave ones.

As previously discussed, Phase II materials are only likely to accumulate in a cave when the entrance is large, and when the site of deposition is not secluded. Moreover, Phase II deposits are likely to represent fairly rapid accumulations.

Deductions from various types of Phase II materials

A. Transported materials

Aeolean sand

In the Transvaal, deposits of aeolean, Kalahari-type sand can certainly be regarded as good indicators of arid conditions at the time of their deposition. To be classed as a Kalahari-type sand however, a deposit must display certain very characteristic features. The most important of these are:

sorting into a restricted particle size range, and a certain minimum degree of abrasion which the individual sand grains have suffered.

In Chapter 6, . . .

In Chapter 6 grading analyses were given for various samples of Kalahari-type sands.

In Chapter 9, angularity estimates, expressed as percentage porosities, were provided for samples from 13 different localities in and about the Kalahari. Porosities ranged from 36.7 to 33.2 %.

The writer considers that if a Phase II cave deposit consists of a sorted sand, giving a porosity, in the 35 - 60 mesh fraction, of between 37 and 33 %, and made up of grains showing a frosted surface texture, then it can be regarded as a Kalahari type sand. It may be interpreted as indicating arid conditions at the time of its deposition.

So far, the writer has not encountered any cave deposit in the Transvaal conforming to these specifications.

Loess

As was pointed out by King (1942), recent and extensive loess deposits in South Africa are practically unknown. The essential characters of a loess are that it should be a wind-deposited sediment, whose individual particle diameters fall between 0.05 and 0.005 mm. The presence of such a deposit in a cave would certainly indicate dry conditions at the time of its accumulation.

Loess should not be confused with silty, Phase I sediment as is developed in the lower parts of the Limeworks profiles. Although much of this material is of the correct particle size, it is composed very largely of residual earth derived from inside the cavern.

True loess deposits have not been seen by the writer in any South African cave so far.

Alluvium

Caves opening close to river level are likely to have alluvial debris deposited in them during times of flood. This can be observed to occur at present in two caves close to Pretoria, one on the farm Uitkomst, and the other at Hennops River. It has also clearly occurred in the case of the Makapan Limeworks cave.

In general, it will prove most difficult to make reliable climatic deductions on the basis of alluvial debris in caves. This is partly because the material will often become jumbled and confused in the course of being deposited in the cave. Probably, all that one will be able to say is that the river was flowing at the time that the alluvium was deposited.

The position with the alluvial debris at Makapan

Limeworks . . .

Limeworks is, however, most fortunate. At the time that the cave was open, the head-waters of the stream that deposited the alluvium could not have been more than a mile away. Moreover the only rocks traversed by the stream were dolomite and Black Reef quartzite. The source of the alluvium is thus known while the distance over which it was transported was clearly insufficient to cause sand grain abrasion.

B : Residual Materials : Surface dolomite soils.

Surface dolomite soils may be roughly divided into two types of which only one is of much use as an indicator of the climate under which it was produced. The development of each type is dependent on the topography and nature of the parent dolomite. In low-lying areas where the dolomite is largely uncontaminated with chert bands, excessively thick dolomite soils are commonly produced. Standing water has resulted in the large scale disintegration of the underlying dolomite. Soil, reaching the remarkable thickness of 450 feet, has been reported by du Toit (1954). Clearly, thick deposits of this sort cannot be used as climatic indicators. They have remained in place so long that they could not be expected to reflect Pleistocene climatic changes of very short duration from the geological point of

view. . .

view. If a cave was to develop beneath a thick soil mantle of this sort, it is very doubtful is it would ever open to the surface. Overlying soil would probably simply slump into it until the available space had been filled.

The other type of soil cover is present practically wherever caves are found. It is characteristic of undulating or mountainous country. The soil is formed between exposed and conspicuous outcrops of cherty dolomite, and seldom attains a thickness of more than ten feet. An average thickness would probably be about three feet.

Clearly in such situations, new soil is constantly being produced by solution of the dolomite. Nevertheless, soil is being removed by simultaneous erosion, so that the cover can never become unduly thick.

Soils of this type are of great value as climatic indicators for the following reason : the production of soil from the dolomite is dependant on the solutional activity of rain water. Clearly increased rainfall will result in the more abundant production of soil. At the same time, however, a dynamic balance exists between the production of new soil and the erosion of the existing material. Thus the surface soil, on a dolomite hillside, is likely to reflect in one way or another the climatic conditions at that particular time.

Briefly the main difference between the soil covers from a wet dolomite area and a dry one is that the former will be much less mature than the latter. This is because, in a high rainfall area, the production of new soil and the erosion of existing soil proceeds fast. Loose material cannot remain long on the hillsides.

The effect of a dry climate is that the dolomite is dissolved slowly, while the existing soil can remain in place for a long period of time. During this time, it has a better opportunity to become mature.

Clearly, the effect of different climates will be to alter the nature of the soil covers in various ways. Thus, if it is possible to assess what changes are likely to result from climatic differences, then this knowledge may be profitably applied to deposits of fossil dolomite soil found in caves. In this way, climatic deductions may be possible from the cave deposits.

In attempting to establish how different climates affect the nature of the soil covers, samples have been collected from dolomite areas with rainfalls ranging from 60 inches per annum to three inches. Different characteristics of these soils will now be discussed separately.

Sand grain angularity.

It is a well known fact that the degree of rounding of sand grains can be regarded as a measure of their maturity. With alluvial and aeolean sand deposits, which have a varied origin, the angularity of individual grains may not be of very great significance. But in the case of hillside dolomite soils whose main source is accurately known, the degree of sand grain roundness has important implications.

Increasing maturity of hillside dolomite soils should definitely be associated with an increasing degree of roundness of the sand grains contained in them. The rounding process is likely to be caused very largely by wind transport, since where hillside soils are concerned, the possibility of large scale water transport is practically excluded. As Krumbein (1941) has pointed out, sand grain angularity is very sensitive to distance of wind transport.

It is to be expected that progressive dessication of an environment will result in more efficient wind transportation of loose materials. In the same way, it is to be expected that, in a low rainfall area, greater quantities of surface material will be carried by the wind than is the case in high rainfall areas. This is true since the amount of dust and sand that can be picked up by the wind will be determined by the density of the vegetation cover and the moisture content of the soil.

In order to elucidate the relationship between sand grain angularity and rainfall for surface dolomite soils, samples were collected from a variety of dolomite localities with different mean annual rainfalls. Wherever possible, the samples were collected close to long established rainfall recording stations. This was possible in the case of all localities except the two driest ones. It was found that the nearest suitable dolomite to the town of Prieska was in mountainous country about twelve miles away on the road to Merydale. Evidence will shortly be presented which suggests that this locality has a higher rainfall than Prieska does itself.

The driest locality sampled was at a spot called Dolomite Peaks, in the Southern Richtersveld of Little Namaqualand. The nearest rainfall station, of Alexander Bay has an average annual rainfall of 1.6 inches, but is about 40 miles away. It is very probable that Dolomite Peaks obtains a slightly higher rainfall than does Alexander Bay, and the figure of 3 inches per annum has been tentatively used.

All other rainfall figures have been obtained from a Weather Bureau publication (1950). The distribution

of the . . .

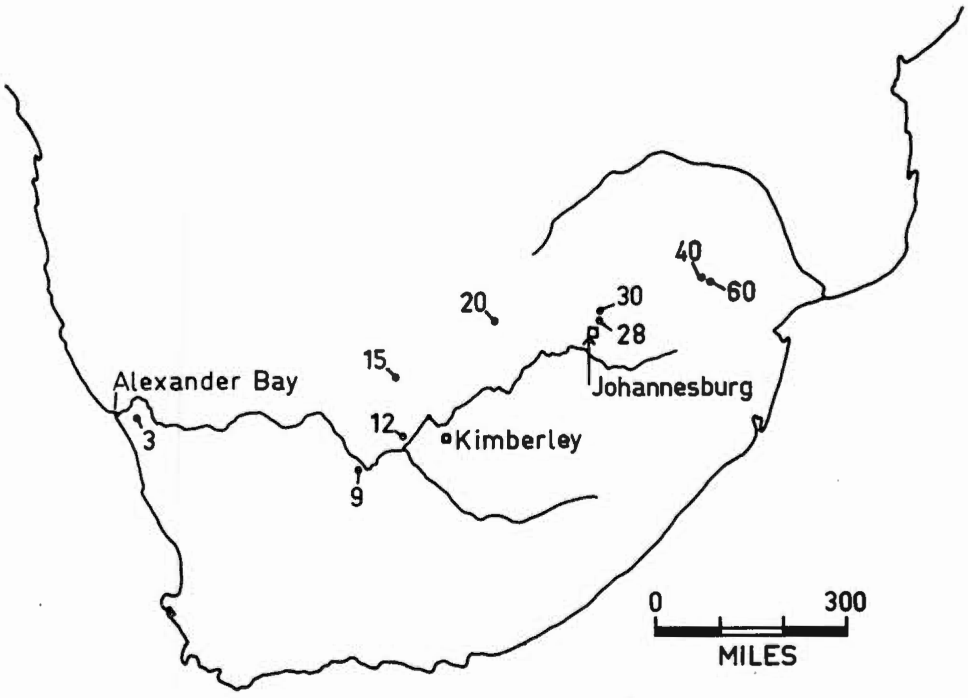
of the various localities in South Africa is shown on the map in Figure 25. A list of the rainfall recording stations used is now given together with figures for the mean annual rainfall in each case.

Station name	No. of years of records up to 1950	Annual mean rainfall in inches p.a.	Annual mean rainfall in mm. per annum
Graskop	30	59.9	1522.2
Pilgrims Rest	58	38.3	972.0
Fountains	47	30.0	763.0
Irene	35	27.3	693.9
Ottoshoop	46	20.6	545.6
Kuruman	24	15.6	396.7
Campbell	38	12.7	322.3
Prieska	68	9.2	232.4
Alexander Bay	20	1.6	41.6

At each of these localities, eight samples of surface dolomite soil were collected. In the laboratory, the 35 - 60 mesh sand fraction was isolated from each, and the sand grains were then cleaned by boiling them in 50 % hydrochloric acid. Angularity estimates, based on porosity measurements, were then done on each sand sample.

It must be stressed that the results obtained from these samples are in a sense artificial. This is because

the original . . .



THE FIGURES ON THE MAP REPRESENT THE ANNUAL RAINFALLS OF THE SOIL SAMPLING LOCALITIES.

Figure 25.

Map of South Africa showing dolomite soil sampling localities.

the original soil samples were carefully selected in each case so that the results would be comparable. They were all taken on fairly gentle slopes between dolomite outcrops containing a certain amount of chert. Conditions are thus comparable with the state of affairs existing in the immediate vicinity of the Krugersdorp area cave sites, and the Makapan Limeworks. The effect of a very steep slope would be to accelerate erosion and thus reduce sand grain maturity. Dolomite completely free of chert bands would certainly be denuded by solution more quickly than would cherty dolomite. This would result in accelerated soil production, with decreased maturity.

Theoretically, it was to be expected that low rainfall dolomite soils would contain better rounded sand grains than would high rainfall soils. Angularity results showed that this was true for the rainfall range of 40 - 20 inches per annum. Above 40 inches, the sand grains remained constantly superangular, while below 20 inches, increasing dryness was, alarmingly enough, associated with <u>increasing</u> angularity. The reason for this is that below 20 inches of rain, calcite dust makes its appearance in the soil, in quantities which become progressively larger with the dryness of the environment. This calcite dust is found to be deposited round the individual silicious sand grains, so that they are protected from abrasion.

Angularity results for the samples from different localities are now provided:

Locality	% Porosity								Average % Porosity
Graskop	58.5	57.5	58.5	56.2	57.5	57.4	58.6,	-	57.6
Pilgrims Rest	55.6	56.3	59.4	66.2	60.2	54.0	61.8	61.9	58.6
Fountains	42.5	43.5	43.1	43.9	44.1	43.3	42.6	43.0	43.2
Irene	41.1	40.7	39.8	40.4	41.2	41.1	41.1	41.9	41.0
Ottoshoop	40.0	41.2	40.9	39.8	37.3	36.6	41.5	39.1	39.6
Kuruman	40.5	40.6	41.7	41.6	42.0	42.0	41.3	41.5	41.4
Campbell	48.2	50.6	46.6	50.0	47.9	46.5	49.0	48.5	48.5
Prieska	45.4	46.5	45.6	45.1	46.6	45.6	45.8	47.4	46.0
Dolomite Peaks	49.6	51.5	54.4	54.1	55.3	58.9	51.9	56.9	54.1

These results are plotted graphically in Figure 26. It will be seen that below 20 inches of rain per annum, the degree of sand grain angularity begins to increase again. Nevertheless the porosity values for the Prieska samples are much lower than would be expected.

In order to establish what the correlation is between the increased angularity below 20 inches, and the weight percentage of calcite dust present in the various soils, samples were analysed for their carbonate contents. Four soil samples, passing 35 mesh, were analysed from each locality.

The results . . .

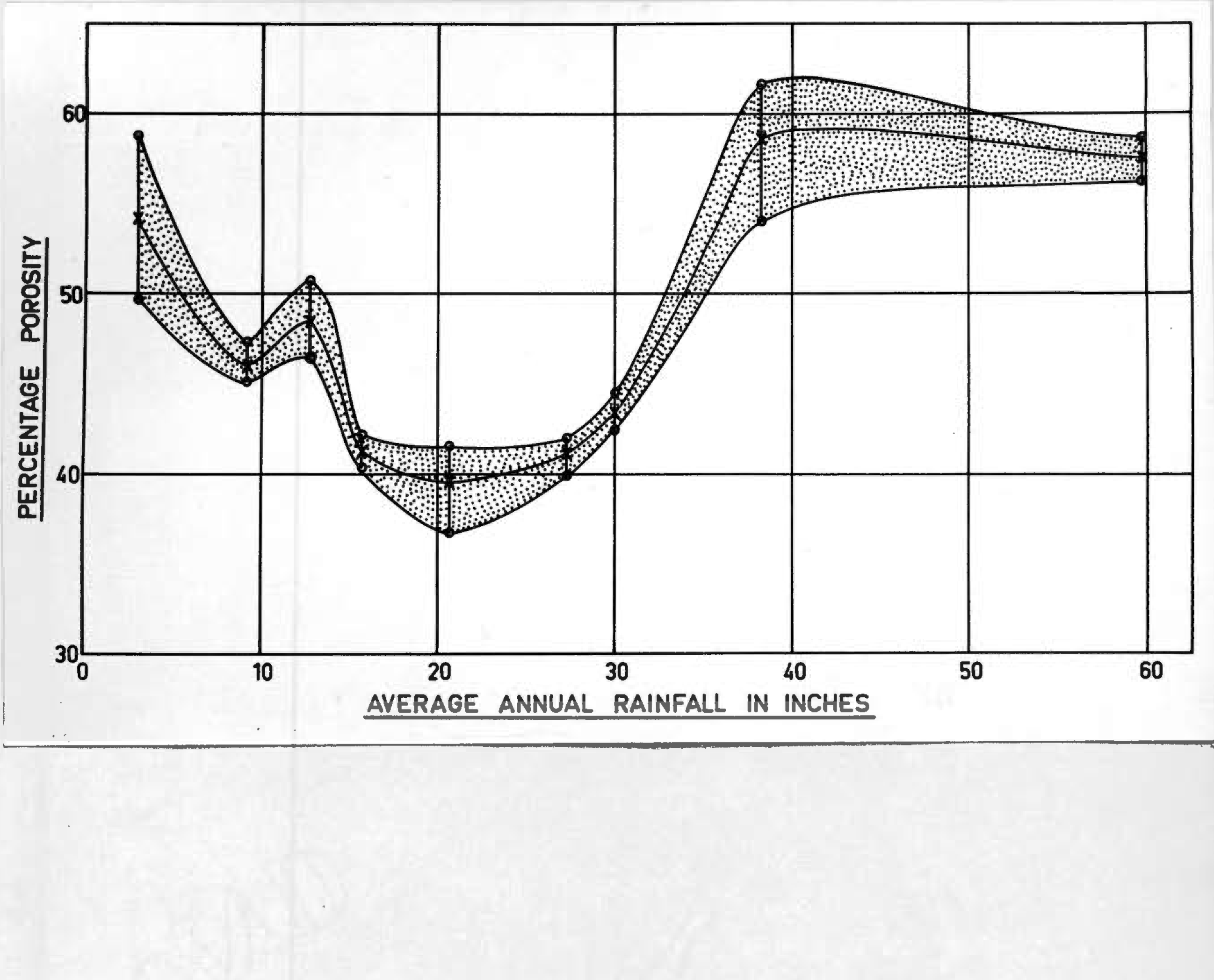


Figure 26.

Diagram showing the relationship between rainfall and sand grain angularity in modern dolomite soils.

The results are now tabulated:-

Locality	Weight % carbonate				Average weight % carbonate
Graskop	Nil				Nil
Pilgrims Rest	Nil				Nil
Fountains	Nil				Nil
Irene	Nil				Nil
Ottoshoop	1.4	1.3	1.6	1.9	1.6
Kuruman	4.1	1.2	4.8	2.7	3.2
Campbell	13.8	11.5	10.3	11.9	11.9
Prieska	7.6	5.5	6.6	7.9	6.9
Dolomite Peaks	16.8	15.4	19.1	18.6	17.4

These results are graphically depicted in Figure 27. It will be seen that calcite dust first makes its appearance in the Ottoshoop samples at a rainfall of 20.6 inches per annum. The soils from the higher rainfalls have clearly had all the carbonate leached out of them. The largest quantities of carbonate however are present in the Dolomite Peaks samples from the 3 inch rainfall area.

Notice that the curiously low porosity figures for the Prieska samples are associated with correspondingly low carbonate contents. The reason for both these discrepancies

is very . . .

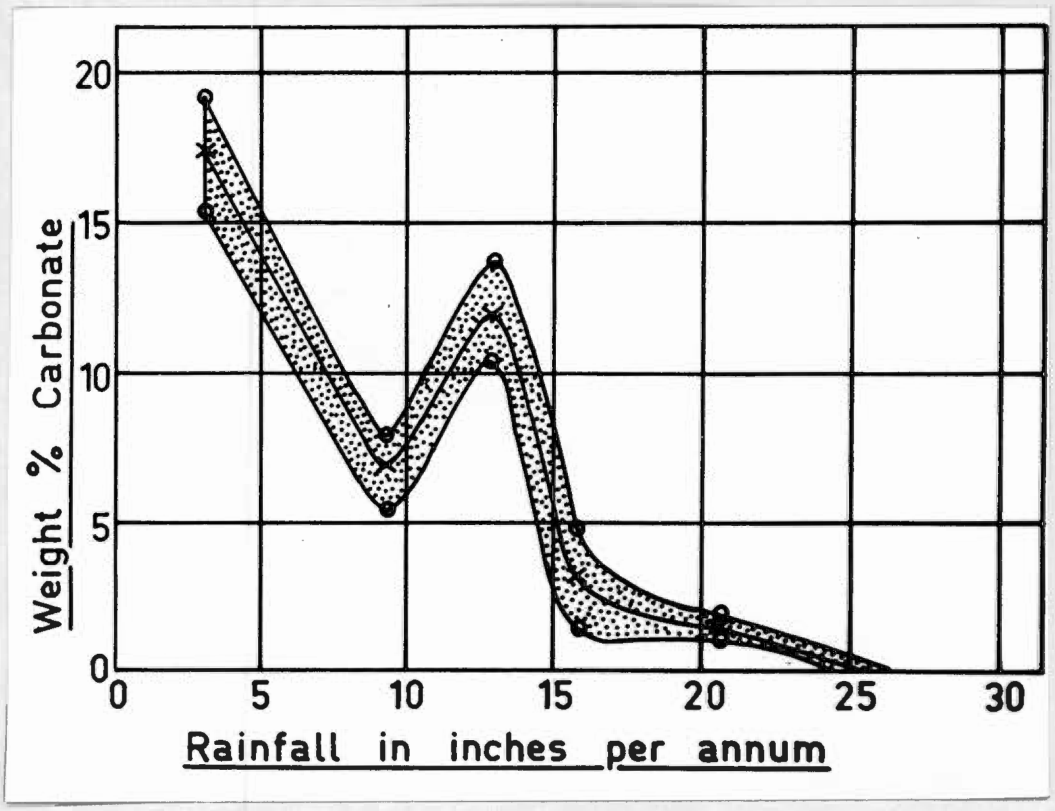


Figure 27.

The relationship between rainfall and the quantity of calcite dust in modern dolomite soils.

is very probably that the locality from which the 'Prieska' samples were obtained does not have the same rainfall as the town itself. As previously mentioned, this dolomite locality is in mountainous country about twelve miles from Prieska. Very probably, it receives a higher rainfall than Prieska, hence the low carbonate content in the soil and the associated increase of roundness of the sandgrains. As there is no way of establishing what the actual rainfall of this locality is, it is probably safer to disregard it for the purpose of this enquiry. The graphs for angularity and carbonate content can then be redrawn, as in Figures 28 and 29.

The graph of angularity values (Figure 28) can now be used as a basis for climatic deductions from fossil dolomite soils. It will be seen that since the graph is flat above about 40 inches per annum, very little could be duduced from a soil falling in this range, other than that it was formed in an environment which had more than 40 inches of rain a year.

The major complicating issue involved in all climatic deductions is that, since the curve is double, some doubt might exist as to what side of it one is dealing with. For instance, a sand with a porosity of 50 % could have been developed at 10 inches or at 35 inches. Fortunately,

there . . .

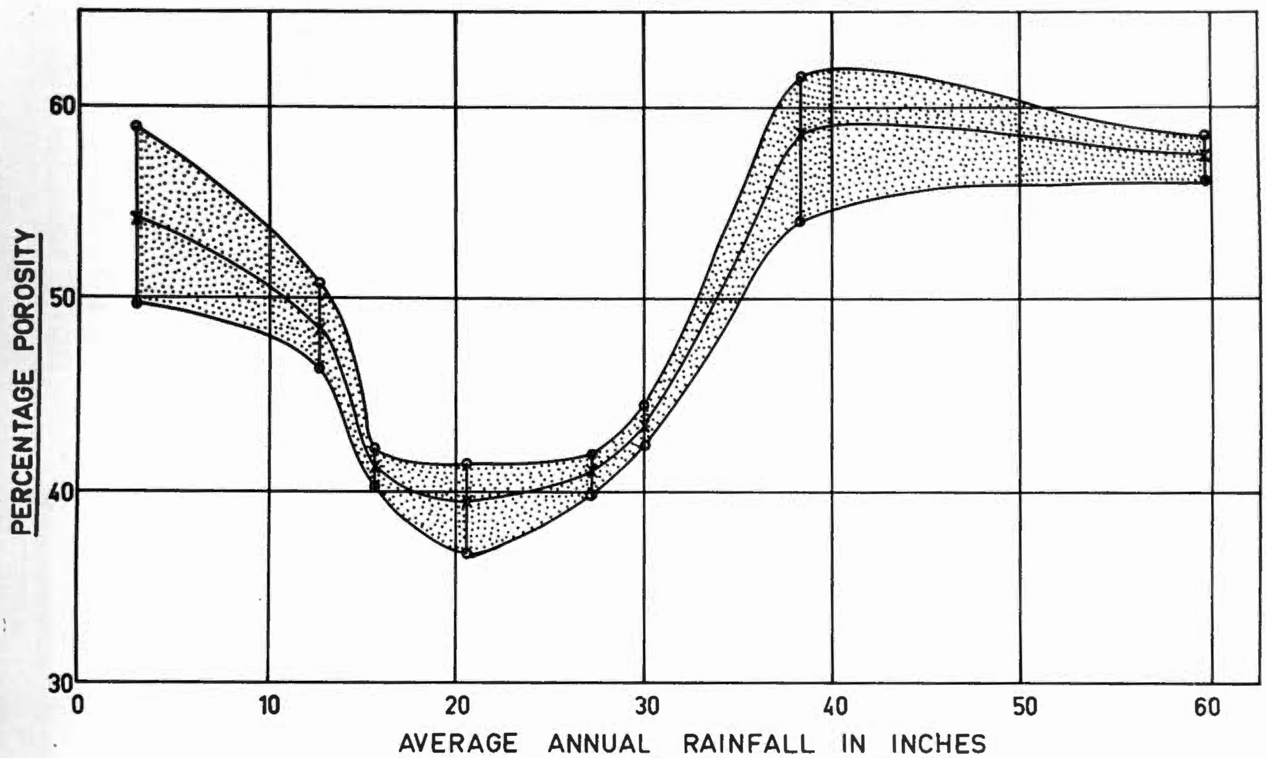


Figure 28.

The relationship between rainfall and sand grain angularity in modern dolomite soils. The Prieska locality is disregarded.

ded.

there ~~are~~ is a variety of ways that may be used to decide such a point. Some of these will now be discussed.

A. Soil colour.

As a result of the examination of a large number of soil samples from various parts of South Africa, some correlations are possible between soil colour and rainfall.

It has been found that practically without exception, dolomite soils developed under more than 28 inches of rain per year are a deep chocolate-brown colour.

Between approximately 28 and 15 inches per annum the soils are characteristically red or brownish-red. Below 15 inches, all soil samples varied between a drab buff colour and a mustard yellow.

To sum up, the typical colours are these:

60 - 28 inches per annum	:	chocolate-brown.
28 - 15 inches per annum	:	red or brownish red.
15 - 3 inches per annum	:	buff or mustard.

Since these colours are certainly likely to be preserved in calcified, fossil soils, they will be of value in placing the soil in its correct rainfall category.

The colour . . .

The colour should however be considered in conjunction with other characters.

B. Sediment grading.

When considering a Phase II soil deposit which has accumulated in a cave, it has been found that grading can be useful as a climatic indicator. In a high rainfall area, soil is likely to be frequently deposited in shallow pools on the cave floor. When this occurs, small scale stratification will be a characteristic of the deposit. Such stratification is usually made up of alternating bands of silt and coarser material.

On the whole, soil accumulating in a cave under dry conditions should lack such signs of stratification.

In interpreting stratification, caution should be exercised for the following reason. Under any environment, if the caves are deep enough, open phreatic water is likely to be present on their floors. Thus, even under dry climatic conditions, stratified sediment may be deposited in a cave. This objection is not, however, as serious as it sounds, since study of modern caves has shown that material deposited beneath the water table is almost invariably Phase I, not Phase II. Consequently, in any event, one would not attempt to use it as a climatic indicator.

C. Weathered dolomite fragments.

It is definitely true that dolomite fragments are more likely to exist in low rainfall soils than in high ones. The reason for this is that such fragments can more easily escape dissolution where the environment is dry. Nevertheless, close to dolomite outcrops, fragments are found in the soil at rainfalls as high as 30 inches per annum. Unfortunately it is not possible to make an accurate correlation between the abundance of dolomite fragments in the soil, and the rainfall. Such factors as the purity of the dolomite and the incidence of chert bands affect the issue too strongly.

Where the abundance of weathered fragments can be used to advantage is in fossil soils preserved in a cave. If these fragments are found only at certain levels and not at others, then a climatic trend is probably indicated. Increased dryness should be associated with more abundant dolomite fragments being preserved.

It must be appreciated that only weathered dolomite fragments, that have been lying in the surface soil, can be considered. These must be distinguished from angular dolomite blocks derived from roof falls in the cave.

Certain types of impure dolomite, as are found at Sterkfontein for instance, produce a whitened rim when

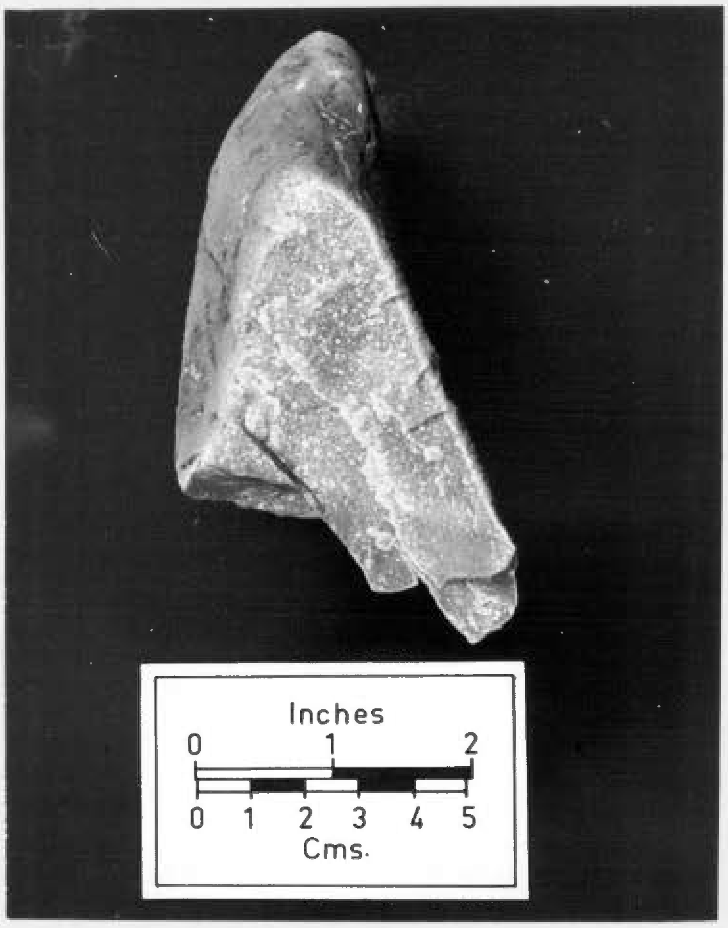
weathered . . .

weathered in the soil. Examination has shown that this rim, as shown in Photograph 74, is made up of silicious impurities in the dolomite, left behind when the soluble fractions of the rock are removed from its surface by solution. Such rims are not usually developed on dolomite blocks weathered on the ground surface, since the crumbly silica crust is then easily removed. They are characteristic of pieces of dolomite weathered beneath the surface of the soil. In a calcified cave deposit, the rims are often well preserved as they become impregnated with calcite. The rim shown in Photograph 75 has been thus preserved in a calcified breccia deposit from Sterkfontein.

Clearly, where silicious impurities are absent from the dolomite, a whitened rim will not be produced. Thus, such rims are indicative, not so much of a particular climate, as of a particular sort of dolomite. When attempting to use the incidence of dolomite fragments in a soil as a climatic indicator, therefore, all weathered blocks should be considered, whether they show whitened rims or not.

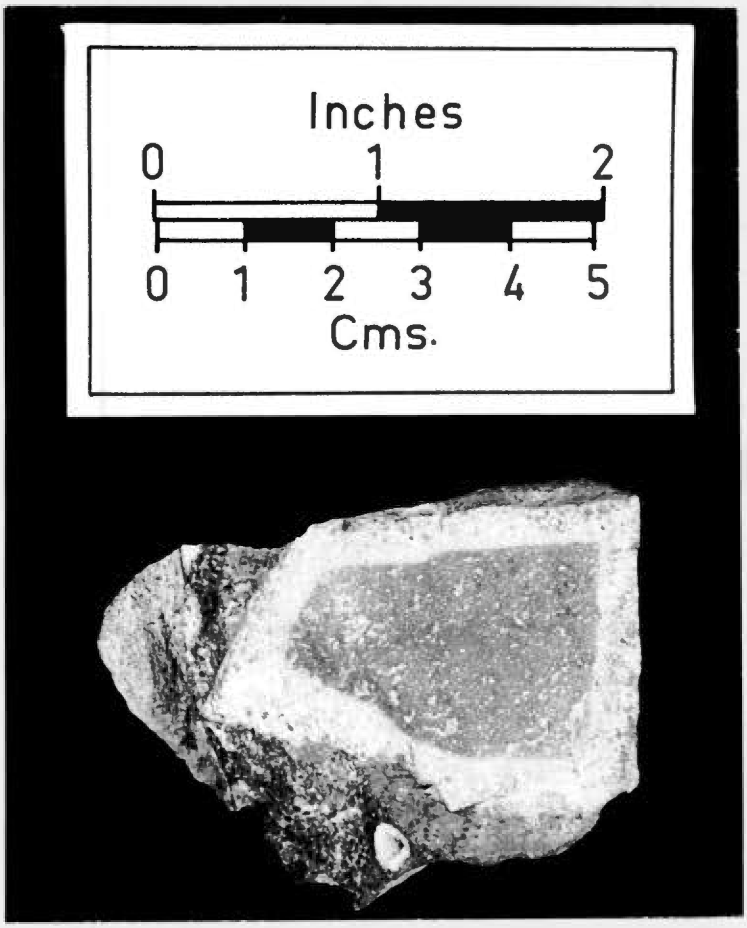
D. <u>The use of heavy minerals.</u>

Under certain circumstances, the heavy mineral suite presented in a soil may be used to reflect the climate



Photograph 74.

A broken block of dolomite from the modern dolomite soil at Sterkfontein, showing the characteristic weathered rim.



Photograph 75.

A block of dolomite embedded in cave breccia and showing a well-defined weathered rim.

under which the soil was formed. The basis of this deductive method is that if the soil contains transported material, derived from non-homogeneous rocks in the area, then heavy mineral grains foreign to the immediate area should be recognisable. When hillside soils are considered, foreign mineral grains are likely to be introduced by wind transport only. Thus an increase in the proportion of foreign heavy minerals, present in a hillside soil, should be associated with more efficient wind transport and drier conditions.

Although the theoretical basis of this assumption is sound, its practical application has certain drawbacks. The biggest of these is that even when a single site is concerned, the investigation has to be conducted on a very large scale. It is not sufficient to isolate a few heavy mineral samples, from different levels in a deposit, and then base conclusions on them. It is essential to establish not only which heavy minerals are present, but also what the range of variation of each type is. This necessitates the isolation of a large number of samples from each level of the deposit, and the counting of an adequate number of grains in each sample. Unfortunately, it is found that such count results are not directly comparable between such sites as Swartkrans and Sterkfontein, although both are in dolomite, and both are within a mile of each other. The Swartkrans heavy mineral assemblage has been profoundly influenced by grains derived

directly . . .

directly from highly metamorphosed shale bands close to the site. Such contamination is not present at Sterkfontein, which means that the percentage abundance of various mineral types is quite different at the two sites. This difference has a purely local, not a climatic significance.

Although difficulties of this sort can certainly be overcome by intensive, systematic research, it is clear that a large scale project is necessary.

The present investigation has been restricted to other methods of climatic deduction. Nevertheless, it is hoped that it will be possible to concentrate on the heavy mineral problem in the near future.

D. The chert-quartz ratio.

In the course of the examination of a number of sand samples, isolated from the hillside soils in the immediate vicinity of Sterkfontein, it was noticed that the proportion of chert to quartz grains appeared approximately constant. Eight soil samples were then collected from the Sterkfontein hill, and the 35 - 60 mesh sand fraction was isolated from each. 500 sand grains were counted in every sample to show up the relative proportions of chert and quartz grains present in them. The distinction between chert and quartz sand grains is usually very apparent, as is shown in Photograph 76. During counting, however, some grains were met with that could be classed as either quartz or chert. In view of this, three categories were established: chert, quartz and indeterminate.

It was found that for the eight samples from the Sterkfontein hill, the proportion of chert to quartz grains was constant within fairly narrow and definable limits. This is a fortunate fact for the following reason: if the climate became appreciably drier at Sterkfontein, it is to be expected that the wind would start carrying sand grains from surrounding rocks into the dolomite area. The nearest contact of the Black Reef quartzites with the dolomite is less than a mile from Sterkfontein, so these grains would not have to be carried very far. Now the chert grains are of strictly dolomitic origin, so that the effect of the introduction of foreign sand grains would be to alter the chert-quartz ratio in favour of the quartz. Thus, if a fossil dolomite soil deposit on the Sterkfontein hill contained a higher proportion of quartz grains than was normal for the modern soil, then the reason would probably be a climatic one, and the implication would be that the cave filled up under conditions drier than those prevailing today.

Sand samples have now been analysed from the hills

of Sterkfontein . . .

Photograph 76.

Sand grains showing the distinction between chert and quartz.
Q = Quartz grains

of Sterkfontein, Swartkrans and Kromdraai. The chert quartz method is well suited to this particular area, as the contact between dolomite and other rocks is nowhere distant. Moreover, the chert bands in the dolomite are sufficiently regular to make it likely that soil produced during previous ages, at a particular spot, would not be materially different from that formed today, if equivalent climates were prevailing.

The chert-quartz method will obviously not be applicable in all dolomite areas, nor is it useful as a comparative method between widely separated sites. In the restricted Sterkfontein area, however, it has been found to provide useful climatic information.

Conclusion

When dealing with a deposit of fossil dolomite soil preserved in a cave, the methods described above should make it possible to decide approximately what the climate was like when the soil was formed. Knowing this, a fairly accurate rainfall estimate should be obtainable when the sand grain angularity technique is employed.

If the rainfall is known, it should be possible to reconstruct the environment that existed when the cave filled up. In doing this, some knowledge of present day dolomite areas, with different rainfalls, will be of assistance. Six photographs are now provided which show how the aspect of dolomite countryside changes under the influence of different annual rainfalls:

Photograph	77	:	Graskop	60 ins. per annum
Photograph	78	:	Pilgrims Rest	40 ins. per annum
Photograph	79	:	Sterkfontein	30 ins. per annum
Photograph	80	:	Kuruman	15 ins. per annum
Photograph	81	:	Campbell	12 ins. per annum
Photograph	82	:	Dolomite Peaks	3 ins. per annum.

Photograph 77.

Dolomite countryside at 60 inches of rain per annum : Graskop, Eastern Transvaal.

Photograph 78.

Dolomite countryside at 40 inches of rain per annum :

Pilgrims Rest, Eastern Transvaal.

Photograph 79.

Dolomite countryside at 30 inches of rain per annum. Krugersdorp area.

Photograph 80.

Dolomite countryside at 15 inches of rain per annum: Kuruman.

Photograph 81.

Dolomite countryside at 12 inches of rain per annum : Campbell.

Photograph 82.

Dolomite countryside at less than 5 inches of rain per annum ; Dolomite Peaks, Richtersveld.

General Conclusions

Climatic deductions from dolomite cave deposits are desirable since:

(a) they provide a means of intersite correlation.

(b) they provide clues to the environment under which the now fossil animals lived.

It is important that only Phase II materials in caves are used as climatic indicators.

Deposits of true aeolean sand or loess in caves can be taken to indicate dry conditions during accumulation. Such deposits have not, however, been seen by the writer in Transvaal caves.

Climatic deductions from alluvium in caves are difficult unless its source is accurately known.

Surface dolomite soils are of two types of which only one - the thin hillside variety - is useful as a climatic indicator. In hillside dolomite soils, the relationship between sand grain angularity and rainfall is elucidated. A calibration curve is provided which allows rainfall estimates to be made from fossil dolomite soils. As this

calibration . . .

calibration curve is double, climatic checks have to be made by other means, of which the following are the most useful :

Soil colour, grading, weathered dolomite fragments, heavy minerals and the chert quartz ratio.

Once it is known how high the rainfall was when the soil was formed, it is possible to visualise the environment of the times. Photographs of dolomite areas at different rainfalls are provided for this purpose.

11.

Observations on excavation technique in bone-bearing breccias

The excavation of a calcified cave filling, or breccia, presents a number of difficulties. The main problem is to recover the bones, and other articles of interest, in an undamaged state, while at the same time ensuring that they are referable to their correct stratigraphical horizons. Until recently breccia deposits have been excavated by means of dynamite. Holes were drilled and small explosive charges placed in them. These had the effect of dislodging large blocks of rock that could then be further broken up with hammers.

The use of dynamite has several obvious disadvantages:

(a) elaborate safety precautions have to be taken during the transport and storage of the explosives.

(b) it is difficult to avoid damage to fossils in the immediate vicinity of the exploding charge.

(c) the roofs and walls of ancient dolomite caves are frequently unstable so that the use of explosives increases the danger of rock falls during the period of excavation.

Clearly it would be desirable to excavate the rock

without . . .

without making use of explosives. A method will now be described that has been used successfully throughout the excavation of the Kromdraai B deposit.

In the place of dynamite, metal wedges are used to break the rock. First a series of holes is drilled in the breccia to a depth of about two feet. The holes are normally spaced at one foot intervals, and to save time it is recommended that a power drill should be used. Photograph 83 shows a Warsop power drill being operated at Kromdraaai. This tool was most generously donated to the department by Mr. Jack Scott and has proved indispensable. It enables a two foot hole to be drilled into breccia in rather less than five minutes.

The wedges, known as "plugs and feathers" are then placed in the holes, and are driven down in turn with blows from a 16 pound hammer. This process is shown in Photograph 84.

If the holes have been positioned correctly, it should be possible to detach a large block of breccia immediately, particularly where one is able to work backwards from a vertical breccia face. Where no such face exists it is likely that the breccia will shatter somewhat, as shown in Photograph 85. It should however be possible to quickly create a face to work from.

Photograph 83.

A power drill being used at the Kromdraai B site.

Photograph 84.

Wedges being driven down with a 16 lb. hammer.

Photograph 85.

Breccia broken by wedges driven into previously drilled holes.

Once a block of breccia has been removed from the site it can be broken up with hammers. If a bone is broken through the two pieces should be put together immediately with Glyptal cement. Bones enclosed in matrix can then be cleaned out in the laboratory by any of the usual means.

The method described above is particularly suited to the excavation of a fairly small, bone rich deposit. With a large deposit, where a considerable volume of sterile overburden has to be removed, the use of dynamite is a practical necessity. Wherever possible however, the writer has used the wedge method for preference, as damage to specimens is reduced to a minimum, while greater control can be exercised during the removal of breccia from the site.

A suggested procedure for the investigation of a dolomite cave deposit

Prospecting for a new site

Since most ancient dolomite caves have had their roofs removed by erosion, the consolidated fillings are likely to be exposed on the ground surface. The search for new sites thus resolves itself into a program of prospecting for breccia outcrops. In some areas, many breccia deposits have been partially opened up by limeworkers, who have exploited the cave travertines. Likely sites in such areas are then easily located.

In more remote areas, where travertine prospectors have not been active, the task of finding new cave sites tends to be more tedious. Since breccia outcrops are usually inconspicuous, it is necessary to cover the ground on foot. Air surveys are not likely to be productive.

The co-operation of farmers in dolomite areas is invaluable when prospecting for cave breccia deposits. Although they will not usually be able to say where breccia outcrops are, they will frequently know the location of modern caves, and there is a most important connection between the two features. Breccia deposits almost invariably occur in localised areas where modern caves are

found. . . .

found. This is because caves are most likely to be developed in areas where the dolomite is structurally weak. In such places caves will be constantly formed and remanants of ancient filled caves will be closely associated with modern caves in different stages of development. Therefore areas known to contain recent caves should be concentrated on when a search is made for ancient deposits.

Stages in the exploitation of a site

When a promising-looking site has been discovered a trial excavation should be undertaken, to determine the palaeontological potential of the deposit. Normally, about a cubic yard of material should be removed, using the wedge method in preference to dynamite. The excavated breccia can then be broken up into small pieces with hammers. If interesting bones or implements are forthcoming, a full scale excavation program may be started.

First it is usually advisable to clear all soil or debris from the site so that the dolomite walls of the cave are exposed and some idea of the extent of the deposit is gained. Loose soil should, however, be removed with care from above the breccia. Frequently it will be found to contain bones that have weathered naturally from the breccia itself. Once the extent of the deposit

is known . . .

is known a horizontal grid system can be set up, and excavation commenced.

During excavation, breccia should be removed in such a way as to provide the maximum information about the stratigraphy of the site, while at the same time the yield of bones or implements is as large as possible. It is very desirable to leave adequate witness sections so that stratigraphical details of the site may be checked in future years.

All objects of interest removed from the breccia should, of course, be labelled so that they are referable to their correct stratigraphic horizons.

The geological interpretation

During excavation, and when the work is complete, breccia samples should be taken for analysis.

The first step is to decide which parts of the deposit are composed of residual, Phase I and Phase II material. In order to do this, sands should be isolated from the breccia samples and examined with a stereoscopic microscope. The diagnostic features of the various deposits have already been discussed.

If residual and Phase I deposits are well developed, analyses should be done to throw light on the mechanism of cementation at the particular site.

Representative samples of Phase II breccia should then be taken at different levels. The properties of the residues from these breccia samples should be investigated to establish what the nature of the original material was. It will be possible to decide whether the deposit is composed of surface dolomite soil, alluvium or wind-borne material.

At least four samples should be taken at each five foot level throughout the Phase II breccia profile. These samples should be analysed for carbonate content, sand grain angularity, chert-quartz ratio and heavy mineral assemblage. Observations should also be made on the breccia colour, residue grading or stratification and the incidence of weathered dolomite fragments. When all this has been completed, representative samples of the modern surface soil, in the immediate ~~neighbourhood~~ vicinity of the cave, should be collected and similarly dealt with. These samples must be taken from places where the possibility of contamination from weathering breccia is excluded.

On the completion of the analytical work it should be possible to decide, with some certainty, what the climate and environment was like when the deposit was formed. An attempt should also be made to reconstruct the sequence of

events...

events in the formation of the cave and its contents.

Establishing the age of the deposit

If the deposit appears fairly recent, and contains carbonaceous material, an accurate absolute age may be possible by means of the radio-carbon method. Where this approach is not applicable, two other means of dating may be employed :

(a) An investigation of the nature of any cultural material that may have been obtained,

(b) A detailed assessment of the complete fossil fauna derived from the site.

If the second method is used, it is most important to consider every aspect of the fauna. It is most inadvisable to attempt to date a deposit on the presence or absence of isolated animal forms, particularly in the African environment.

When by cultural or faunal means it has been possible to decide whether the deposit was formed in Lower, Middle or Upper Pleistocene times, then climatic knowledge can be used to position the site more accurately in the timescale. The broad outline of Pleistocene climatic changes is now understood, so that if it is known what sort of climate prevailed when the deposit was formed, this knowledge can be put to good advantage so far as dating is concerned.