MINISTRY OF MINES AND ENERGY

GEOLOGICAL SURVEY OF NAMIBIA

Director : Dr G I C Schneider

MEMOIR 21

KARST GEOLOGY AND PALAEOBIOLOGY OF NORTHERN NAMIBIA

by

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Obtainable from the Geological Survey of Namibia
Private Bag 13297, Windhoek, Namibia

ISBN 978-99945-71-35-2

2010

PREFACE

19 years ago, Martin Pickford and Brigitte Senut founded the Namibia Palaeontology Expedition and since then have carried out a long period of pioneering research in the north of the country. Water has in effect, dissolved the dolomitic and limestone massifs, creating a karst network ideal for the deposition and preservation of sediments and their contained fossils. Cave breccias have been known in South Africa since the 1920s, infilling caves in Bechuanaland, the Transvaal (Gauteng) and the region of Makapansgat ; it was these that yielded – and continue to do so – the first known fossil prehumans, the so-called australopithecines. But after thirty years of intensive research in the south of the continent, the focus of research shifted for another thirty years to East Africa. 1991 represented a kind of 'return' to the karst and a renewed realisation of its potential ; all southern Africa from the Equator to the Cape, Botswana - Angola - Zimbabwe - Zambia - South Africa, shows indications of being fruitful for research into the history of life, a new and immense field of investigation that this expedition opened.

It is in the Otavi Mountains, initially for two years in collaboration with an American team from the University of Washington, that the Namibia Palaeontology Expedition started its research, and without delay, it resulted in the unearthing from its breccia of the earliest known hominoid south of the Equator, *Otavipithecus namibiensis*, 12 to 13 millions years old. Since 1991, dozens of localities have been mapped, studied, and sampled ; not only in the Otavi Mountains, but also in Kaokoland, and they have yielded hundreds of thousands of fossils spanning the past 14 million years - the Middle Miocene, Late Miocene, Pliocene, Pleistocene and Holocene.

The breccias are notably the source of the most complete and richest succession of micromammalian faunas from Africa for this span of time, which of course witnessed climatic change, floral and faunal turnovers, shifts in palaeoenvironment and several generations of karstic activity, of which certain are impressive, since the authors speak of 15 metres of erosion per million years, followed by infilling.

Let us salute not only the quality (and the quantity) of this work, but also its originality and the opening that it brings. Let us also salute the realisation of a frequently arduous task, represented by the completion of a monograph : Martin Pickford and Brigitte Senut have made us used to the accomplishment of this duty.

Finally, let us salute the effort taken to provide a glossary which takes into account the particular nature of bone breccia, the conditions in which it forms, upstream, and of its treatment, downstream. A veritable small treatise on karstology, with of course, its specific terminology, in effect terminates the memoir which ought to encourage others like it.

Yves Coppens

PREFACE

Il y a 19 ans, Martin Pickford et Brigitte Senut fondaient la Namibia Palaeontology Expedition et conduisaient dans le nord de ce pays une longue recherche pionnière. Les eaux avaient en effet aménagé, dans les massifs calcaires et dolomitiques, un réseau karstique idéal pur le dépôt et la conservation de sédiments et de leurs contenus fossilifères. On connaissait bien sûr depuis longtemps (les années 20) les brèches sud-africaines, produits des remplissage des karsts des grottes du Bechuanaland, du Transvaal (Gauteng) et de la région de Makapansgat ; ce sont elles qui avaient livré – et continuent de le faire – les tout premiers préhumains connus, dits Australopithèques. Mais après trente ans de recherche intensive dans le sud du continent, les chantiers avaient migré et s'étaient établis pour une autre trentaine d'années dans l'est de l'Afrique. C'était donc en 1991 une sorte de retour au karst et à la prise de conscience de ses potentiels ; toute l'Afrique méridionale, de l'Equateur au Cap, Botswana-Angola- Zimbabwe – Zambie – Afrique du Sud, se présentait soudain comme susceptible d'offrir à la recherche de l'histoire de la vie, un nouveau et immense champ d'investigation que cette mission ouvrait.

C'est dans les monts Otavi, en collaboration deux saisons avec une équipe américaine de l'Université de Washington que la Namibia Palaeontology Expedition débuta ses recherches et bien lui en prit puisqu'elle dégagea, sans délais, d'un bloc la brèche, les restes du plus ancien Hominoïdé du sud de l'Equateur, *Otavipithecus namibiensis*, vieux de 12 à 13 millions d'années. Depuis 1991, des dizaines de sites ont ainsi été repérés, répertoriés, étudiés, prélevés ; ils appartiennent soit aux Monts Otavi, soit au Kaokoland et ils ont livré des centaines de milliers de fossiles répartis sur les 14 derniers millions d'années, le Miocène moyen et supérieur, le Pliocène, le Pléistocène et l'Holocène.

Ils sont notamment à l'origine de l'établissement de la séquence la plus complète et la plus riche qui soit des faunes de micromammifères de cette tranche de temps qui a bien sûr vécu des changements de climats, de flores, de faunes, d'environnements et plusieurs générations d'activité karstique, dont certaines impressionnantes puisque les auteurs parlent de 15 mètres de creusement, donc de remplissage, parfois par million d'années.

Saluons tout à la fois la qualité (et la quantité) de ce travail, son originalité et l'ouverture qu'il apporte. Saluons comme chaque fois l'aboutissement de l'exercice souvent ingrat qu'est la réalisation d'une monographie : Martin Pickford et Brigitte Senut nous ont toujours habitués à l'accomplissement de ce devoir.

Saluons enfin l'effort de rédaction du glossaire tenant compte de la nature particulière de la brèche à ossements et de ses conditions de fabrication, en amont, et de traitement, en aval. Un véritable petit traité de karstologie, avec bien sûr, sa terminologie spécifique, termine en effet la mémoire qui devrait en susciter beaucoup d'autres.

Yves Coppens

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Geology and history of study

Motivation for study of Namibian karst fillings

Introduction

Many countries in Africa have little potential for Cainozoic palaeontological research on account of the lack of sediments in them (Fig. 1). Well over half of the continent has crystalline basement or Palaeozoic and Mesozoic sediments exposed at the surface. Namibia is no exception to this general rule, with most of the country being comprised of rocks of Mesozoic and older formations. However, in several African countries where conventional sedimentary basins of Cainozoic age do not exist, or are poorly exposed (Fig. 1) there are outcrops of calcareous rocks.

Because calcareous rocks are prone to karstification, localised depositional basins can be formed where normally no sediments would be preserved. In many of the world's karst fields, sedimentary karst infillings are richly fossiliferous. Africa is no exception, with numerous palaeontological localities already mapped in the Maghreb and South Africa. Known karst fields of Africa are illustrated in figures 1 and 2 which highlight the fact that many of these fields occur outside conventional sedimentary basins, and thereby help to fill up the

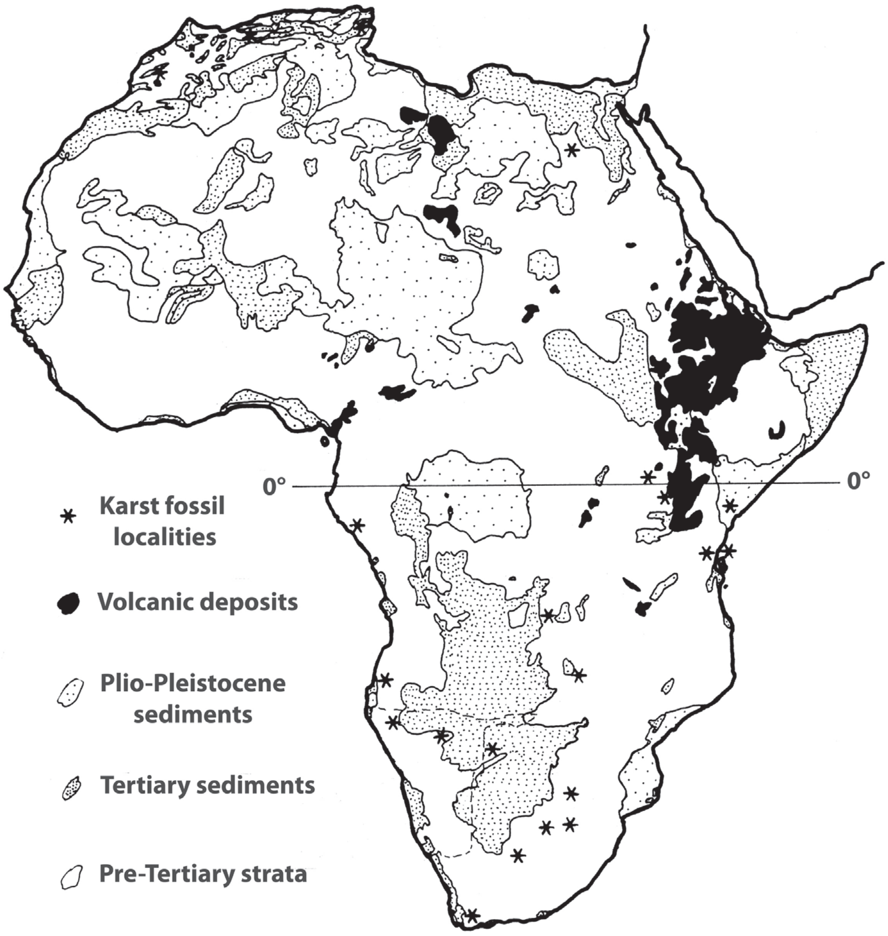


Figure 1.- Map of Africa showing the distribution of Tertiary and Plio-Pleistocene sedimentary occurrences, Cainozoic volcanics and fossiliferous karst deposits. Note how the majority of the karst deposits occur outside known sedimentary basins, thus filling out the palaeontological map of the continent. A great deal of palaeontological potential exists in other African countries not noted for possessing a Cainozoic fossil record, and these could usefully be prospected.

blank spaces in the map.

Namibia, being well endowed with calcareous rocks (Figs 3-4) is an obvious target for the attention of palaeontologists. The more so because it lies between Botswana to the east and Angola to the north, both of which are known to have fossil-rich karst deposits.

Economic Geology

The Otavi Mountainland is famous as a world class base metal province, with major deposits of sulphides including galena, sphalerite, chalcopyrite and associated minerals including a highly diverse suite of supergene minerals. It is also justly renowned for having possessed the largest known vanadium ore bodies in the world, now mined out.

The base metal sulphide bodies accumulated in subterranean karst features. That is, the karst hollows in which the minerals accumulated were not open to the surface, as far as is generally accepted, although it should be noted that the so-called pseudo-aplite, a fine-grained clastic rock which accompanies the ores in certain of the deposits, has been taken by some researchers to indicate that a few of the ore bodies such as Tsumeb and Kombat were formed in cavities open to the ancient

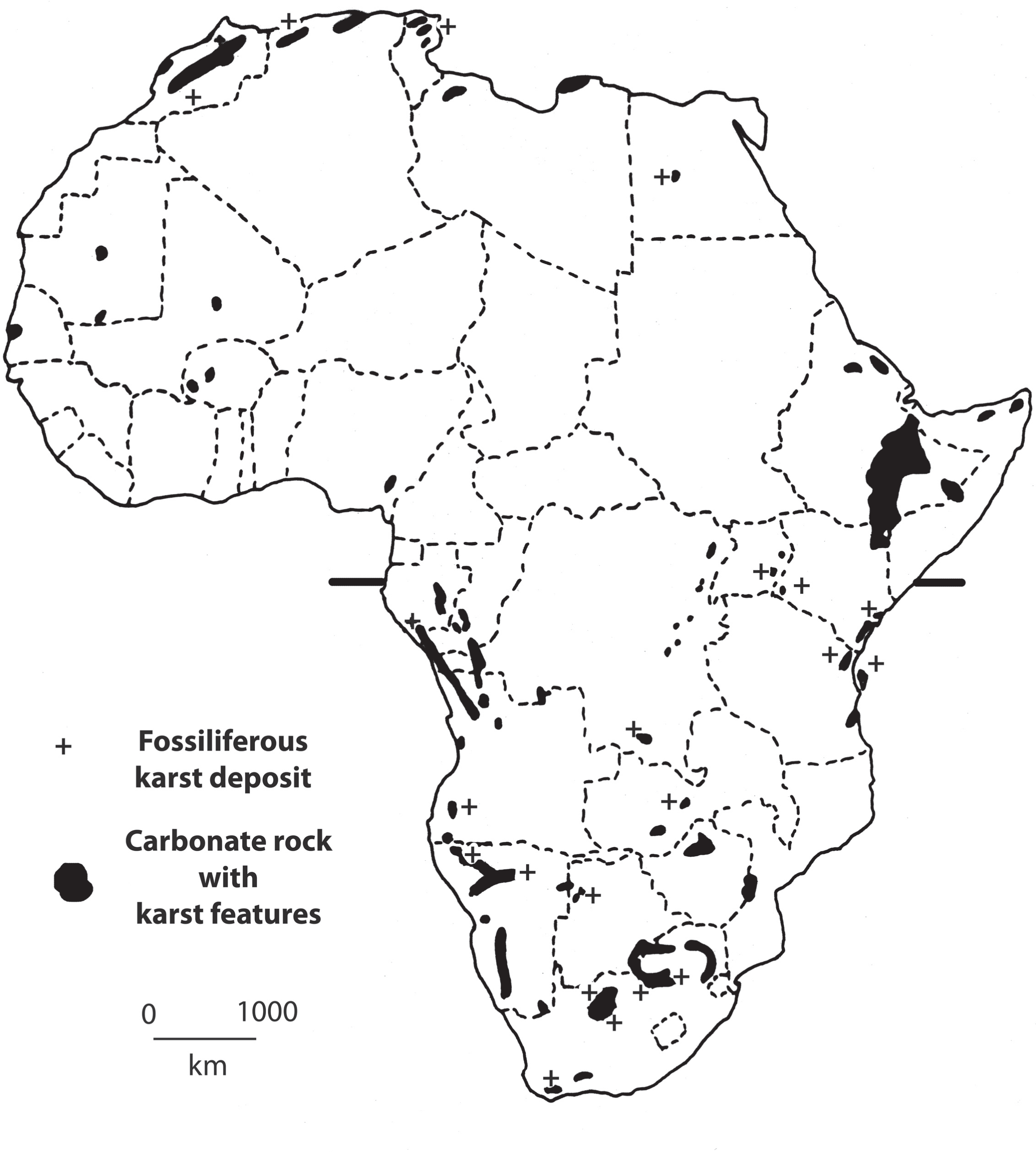


Figure 2.- Karstic regions of Africa. Carbonate rocks are widespread in Africa. The bulk of African karsts occurs in marine sediments, but in East Africa, some fossiliferous karsts have been discovered in Carbonatite volcanic rocks. The importance of karst fields to African palaeontology is related to the fact that they tend to occur in areas outside Cainozoic sedimentary basins, and they thus help to fill out the palaeontological map of the continent.

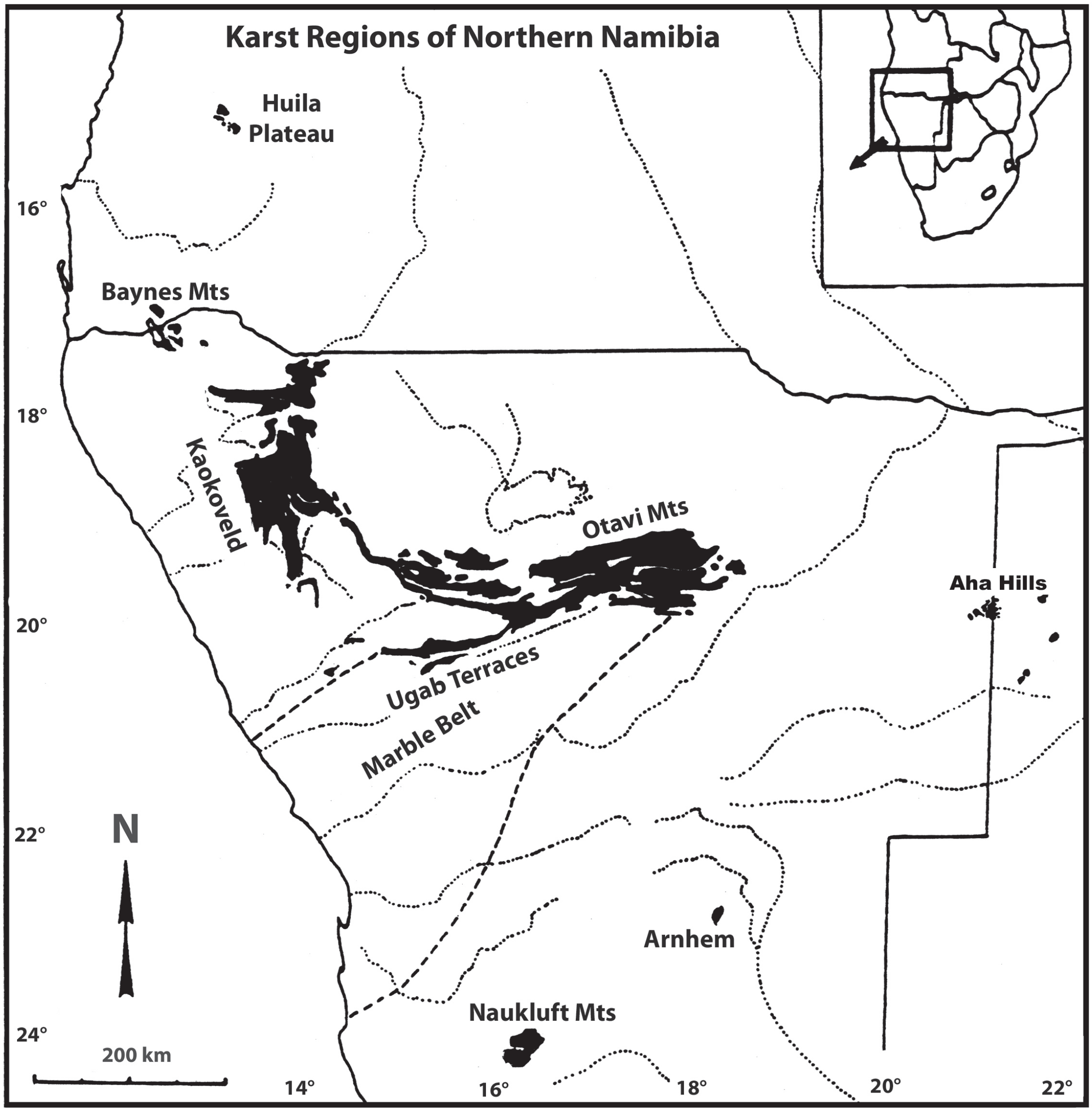


Figure 3.- Detailed distribution of dolomites and limestones in the northern half of Namibia. Fossiliferous karstfill breccias have been noted in the Aha Hills (Botswana only) the Otavi Mountains and Kaokoland.

land surface.

The vanadium-rich karst deposits are clearly of much more superficial origin, all the ore bodies having features associated with running water or open cave systems. Spatially, most of the vanadium ores occur close to sulphide masses, the heavy metals (lead and copper) that occur in the latter acting as precipitating agents to form complex lead and copper vanadates and other vanadium minerals.

For this reason, Berg Aukas started out as a vanadium mine, and ended up as a lead mine once the miners got below the spelean sediments in which the vanadium was concentrated. Much of the spelean sediment was of poor mineral quality and was rejected onto dumps along with dolomite wall rocks and other gangue. Most of the sediment that remains in the Berg Aukas dumps is rich in fossils which reveal that the main mineralising activity took place during the Middle Miocene.

Other vanadium deposits in the Otavi Mountains yield fossils which show that mineralisation also occurred during the Upper Miocene and the Plio-Pleistocene, although these later deposits tend to be sub-economic or only workable on a small scale. However, many of the Namibian vanadium prospects such as Abenab and Baltika are unfossiliferous, and some of them could be of pre-Miocene age.

Whilst the fossil record of the Otavi Mountains is not, in its own right, of immediate economic interest, it nevertheless provides information which may be useful for prospectors and miners. In effect, because the Otavi vanadium deposits occur in near surface karst settings, they are often associated with fossils. The study of these fossils and of their enclosing sediments throws light on the processes and timing of ore genesis, two aspects which are of critical importance for the mining industry. Furthermore, because the vanadium deposits are spatially associated with underlying heavy metal sulphide bodies, they are in their turn of importance for predicting the possible whereabouts of subsurface sulphide masses.

Palaeontological potential of Namibian karsts

In many parts of the world karst systems which were open to the surface are often rich in fossils. There is an interplay of several factors at work which when taken together have generated an extremely rich fossil record spanning much of geological time and most land masses on Earth. Not only do karst systems make ideal sediment depositories, but they also provide homes to a variety of animals as well as forming traps into which animals and plants can fall or be transported. Furthermore, the geochemical environment inside caves and other karst features is ideal for the preservation of bones and teeth.

Thus the presence of extensive karstveld in Namibia was 'a priori' an encouraging sign that it would be rich in fossils.

Biogeography and Palaeoecology

The Namibian karst system occurs in a part of Africa which was hitherto a palaeontological void. For this reason, fossils from the region would have immediate interest for African palaeontology, biogeography and palaeoecology.

Fossils from the Otavi karst may well throw light on past ecological conditions in the region. Preliminary studies have already shown that the mountainland was more humid during the latter part of the Middle Miocene than it is today, and that it was more tropical in nature. At that time, it could well have been covered in vegetation of Zambesian or even Guineo-Congolian/Zambesian affinities, in which case its biogeographic affiliations would have been very different from what they are today.

Biostratigraphy

The practice of biostratigraphy is dependent upon comparison of faunas from diverse time periods. If various faunas from a geographically restricted area can be compared, then a biostratigraphic column can be drawn up which avoids the problem of correlating between assemblages that are far apart, and which thus might be contemporary but different in composition for biogeographic reasons. The Namibian karst fillings are ideal for biostratigraphy in that some of the sites such as Berg Aukas, contain faunas that accumulated at different times within the same cave system.

Rates of evolution

If a sufficiently comprehensive fossil record which can be dated occurs in a region, it may be possible to estimate rates of evolution and to identify periods of faunal change. Although such studies are inherently difficult to undertake on account of the possibility of circular argument, they may nevertheless be worth pursuing, because they can throw light on evolutionary processes and perhaps some of the forces which drive evolutionary and faunal changes.

Evolution of African Miocene to Pleistocene faunas

An understanding of the evolution of African faunas during the late Neogene cannot be obtained by studying the fossil record from a restricted part of the continent. It is essential to have as wide a geographic coverage of the continent as possible. For this reason, the Namibian karst systems are of great potential, because they fill what used to be a huge blank area on the palaeontological map of Africa.

Taphonomy

Although cave taphonomy has been the subject of much research in recent years, there is still much to be learnt. The Namibian karst field is of interest on account of the vanadium-rich spelean sediments in which the fossils occur which provide an unusual geochemical environment for fossilisation. Classic taphonomic conditions occur in the Otavi breccias, with evidence for the collection of small mammals by nocturnal and diurnal raptors and for amphibians, reptiles and mammals that lived within the caves, both near their mouths and deep underground. In addition, there are fossils representing mammals that fell into crevices and avens and died therein.

Palaeohydrology

An understanding of the evolution of karst systems requires comprehension of the hydrological conditions at the time of cavern formation and subsequently. In general terms, such conditions are well understood, but each region has its peculiarities. There can be little doubt that karst processes have been active in the Otavi Mountains since at least the Middle Miocene, and it is possible that some of the spelean sediments, such as Abenab and Baltika, may represent pre-Miocene or even Mesozoic karst infillings.

The sulphide-rich karst network of the Otavi Mountainland was active during the Late Proterozoic and early Palaeozoic periods (Pirajno and Joubert, 1993), far removed in time from the vanadium-rich karsts. There has been much debate about these earlier karsts, on account of their economic potential, but there is no general agreement concerning their development and subsequent history (Van der Westhuizen *et al.*, 1984).

Palaeoclimatology

In situations such as the Otavi region, where a series of faunas occurs spanning long periods of geological time, it is possible to document periods of climatic change based on changes in faunal assemblages. It is clear from preliminary studies that the region was appreciably more humid during the latter part of the Middle Miocene than it is today. Detailed analyses may reveal additional evidence regarding palaeoclimates in northern Namibia.

Rates of Carbonate Downwasting

The Otavi Mountains are deeply eroded, yet still display considerable relief. The study of cave breccias of known age and altitude should yield useful evidence concerning the rates of downwasting that occurs in the region. Similar studies in Botswana suggested downwasting rates of about 15 metres per million years (Pickford, 1990). It is noteworthy that Miocene cave breccias in the Otavi region tend to occur near the tops of hills. Judging from the spelean sediments, these breccias accumulated at or near the ancient water table, below the general level of the ancient land surface. Their present day distribution near the tops of hills thus represent interesting examples of differential weathering and inverted relief.

Tectonics

The Otavi Dolomites were folded and faulted during the Damara Orogen (Late Proterozoic) (Figs 5-6). It is difficult to recognise younger tectonic events in the region, but it is evident that geologically young uplift of the Otavi Mountains occurred at the time that the Waterberg Thrust Fault was active. This fault, which traverses Namibia from the Erongo Mountains northeastwards towards the Aha Hills, resulted in Proterozoic strata being overthrust southwards onto Late Mesozoic continental sediments by distances of up to four kilometres. The country north of the fault experienced widespread uplift, and it was during the activity of the fault that the Otavi Mountains were uplifted relative to the country south of the fault. Although it is not known when the Waterberg Fault was active, it may well have been during the Cainozoic, and perhaps even within the Neogene.

Geomorphology

The Otavi Mountains comprise a typical karst scenery developed in folded and faulted carbonate bedrock (Figs 5-6). Karst development in the region has been fractal, in the sense that typical karst geomorphology can be observed at various scales ranging from millimetres up to tens of kilometres. The control exerted by stratigraphy and structure on the development of palaeokarst and modern karsts in the Otavi Mountains is evident, with many of the features concentrated at particular stratigraphic intervals or horizons, or in strata with favourable inclination (Deane, 1993; Hughes,

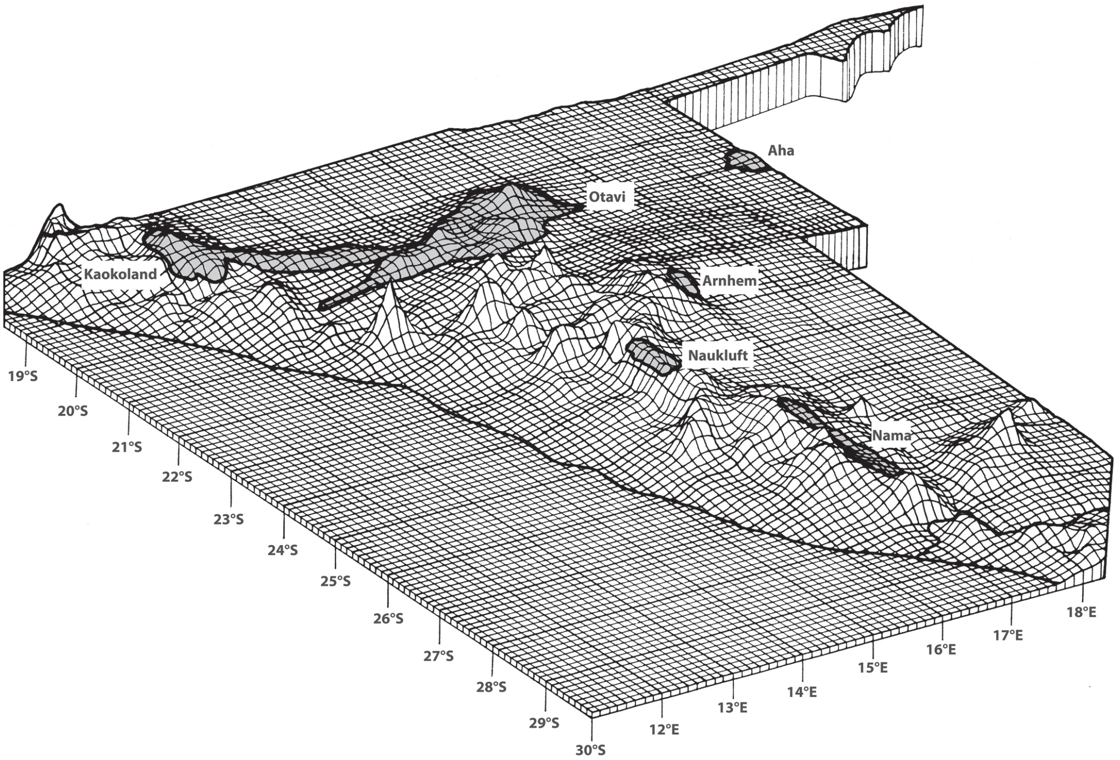


Figure 4.- Relief map of Namibia showing the distribution of carbonates in which karst features have been developed. The main areas of palaeontological interest are the Otavi Mountains and Kaokoland. The Aha Hills have yielded Plio-Pleistocene fossils, but so far only on the Botswana side of the border. Arnhem, Naukluft and Nama karsts have not yet yielded fossils.

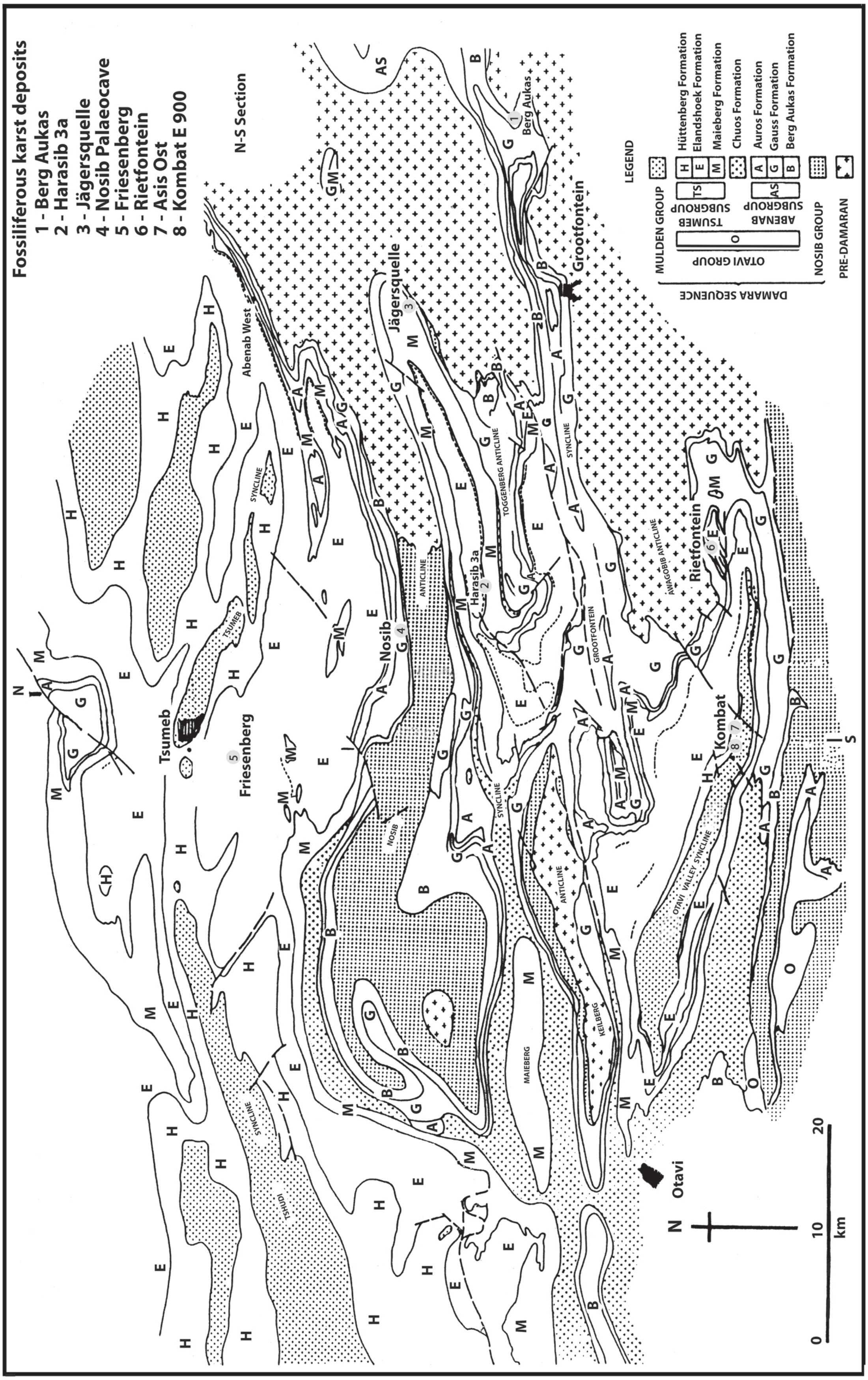


Figure 5.- Geological map of the Otavi Mountainland (based on a map by Hughes, 1987) and distribution of some of the more important fossiliferous karst deposits. N-S = line of section in Fig. 6.

1987; King, 1990; Misiewicz, 1988; Schwellnus, 1946; Sönghe, 1958; Verwoed, 1957; Van der Westhuizen, 1984).

Because of the economic potential of the region, its geomorphology has been closely studied (Schneiderhöhn, 1929).

Origins of the Namibian karsts

There have evidently been several generations of karst activity in Namibia (Van der Westhuizen *et al.*, 1984). Leaving aside the karst forms developed during the Late Proterozoic and Palaeozoic, there has been karst activity in the region since at least the Middle Miocene, if not earlier during the Cainozoic and Mesozoic.

Judging from the types of karst features developed during the Cainozoic, the Namibian karsts are typical near-surface manifestations of the dissolution of dolomite and limestone by vadose and surface waters. All the classic karst forms are well represented in the region (see definitions of karst terminology in Annex 1).

The processes of karstification are still active in the country today, even though much of the region is semi-arid. This is partly because subsurface waters are efficient at dissolving carbonates, and partly due to the poor vegetation cover which allows rapid penetration of rain water into the sub-surface zone.

Sedimentation in Namibian karst systems

Preliminary examination of cave and fissure fillings in Namibia reveals that they consist of a variety of epikarst and spelean sediments. Virtually all types of spelean sediment have been identified, including waterlain strata, speleothems, collapse breccias, sunken crystal rafts, and others (Verwoerd, 1957). Epikarst infillings tend to be rich in carbonates, and are essentially calcretes of one sort or another or fissure and valley infillings.

Climatic zones

At present, the Otavi Mountains lie within the southern sub-tropical or warm-temperate zone of Africa. It experiences summer rainfall. The region is semi-arid, with woodland vegetation. It juxtaposes the Namib Desert to the southwest and the Kalahari Desert to the southeast.

The Kaokoland karst field borders the elevated part of the northern Namib Desert which is to the west. It is considerably more arid than the Otavi Mountains.

It is clear from the fossil record that the Otavi area used to enjoy an appreciably more humid climate during the latter part of the Middle Miocene than it does today. Available evidence suggests that it may well have been forested with fruiting trees yielding crops for much of the year. By Plio-Pleistocene times, in contrast, it appears that it had become semi-arid.

A better understanding of the palaeoclimates of Namibian karst regions may throw some light on the development and history of Africa's ecoclimatic zones.

Summary

The Namibian karst systems are of tremendous palaeontological interest on account of their geographic position and the wide range of geological time that is preserved in their sedimentary record. They fill what used to be a huge blank space in the palaeontological map of Africa. Their mid-latitude position is of interest, as the region is well placed to record changes in the latitudinal distribution of African faunas. At times the region appears to have been more tropical than it is now, while at others it seems to have been more temperate.

The known karst deposits of Namibia are extremely richly fossiliferous. There can be little doubt that our understanding of African microfaunas will undergo major improvement as the fossils are studied and published.

The fact that many of the Namibian micromammal lineages were geographically widespread means that biostratigraphic correlations between Namibian, East African, Maghrebian and Southern European faunas will be possible.

It will also be possible to make comparisons between faunas from different latitudes at various time intervals in order to determine regional to continental variations in faunal composition, and thus to determine the extent to which the biogeography of Africa varied during the past.

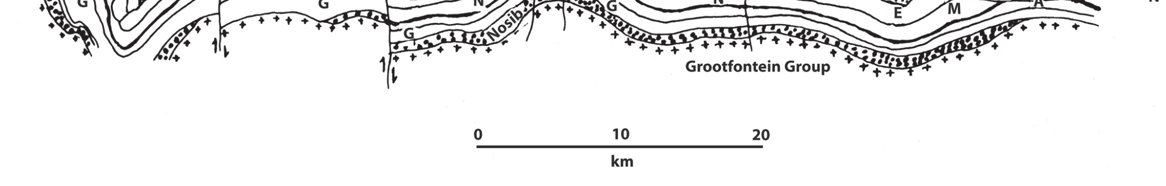


Figure 6.- North-South cross section of the Otavi Mountain fold belt. (No vertical exaggeration). For position of the section and stratigraphic succession, see N-S in Fig. 5.

For these and other reasons, the Namibian karst systems are proving to be of the greatest palaeontological interest.

The Study Area

Location of Namibian karst fields

The Namibian karsts occur in four main regions of the country (Fig. 3). By far the best developed karst areas are the Otavi Mountainland, Ugab and Kaokoland. Less well developed, but nonetheless spectacular, karst features are developed in the Aha Hills, Arnhem, the Naukluft Mountains, and dolomites of the Nama Group (Fig. 4). Neighbouring countries such as Botswana, Angola, Zimbabwe, Zambia and South Africa also possess important karst terrain (Fig. 2) (Pickford *et al.*, 1993).

All the Namibian karsts are developed in Proterozoic to early Palaeozoic carbonates, mostly dolomites. Where these have been uplifted above the surrounding countryside, such as in the Otavi Mountains and the Kaokoland, huge areas of karst have developed - to such an extent that the local inhabitants refer to these areas as the "karstveld".

Climate of the Otavi Mountains and Kaokoland

The Otavi and Kaokoland areas lie within the warm-temperate or sub-tropical part of Africa (Fig. 7). Otavi enjoys a semi-arid climate with summer rainfall of about 500 mm per annum, and its growing season is between 3 and 6 months per year (Fig. 8).

The climate of Kaokoland is considerably drier than that of Otavi, occurring as it does at the inland edge of the Namib Desert. In Köppen's classification, the Kaokoland is a true desert while Otavi is steppe or semi-

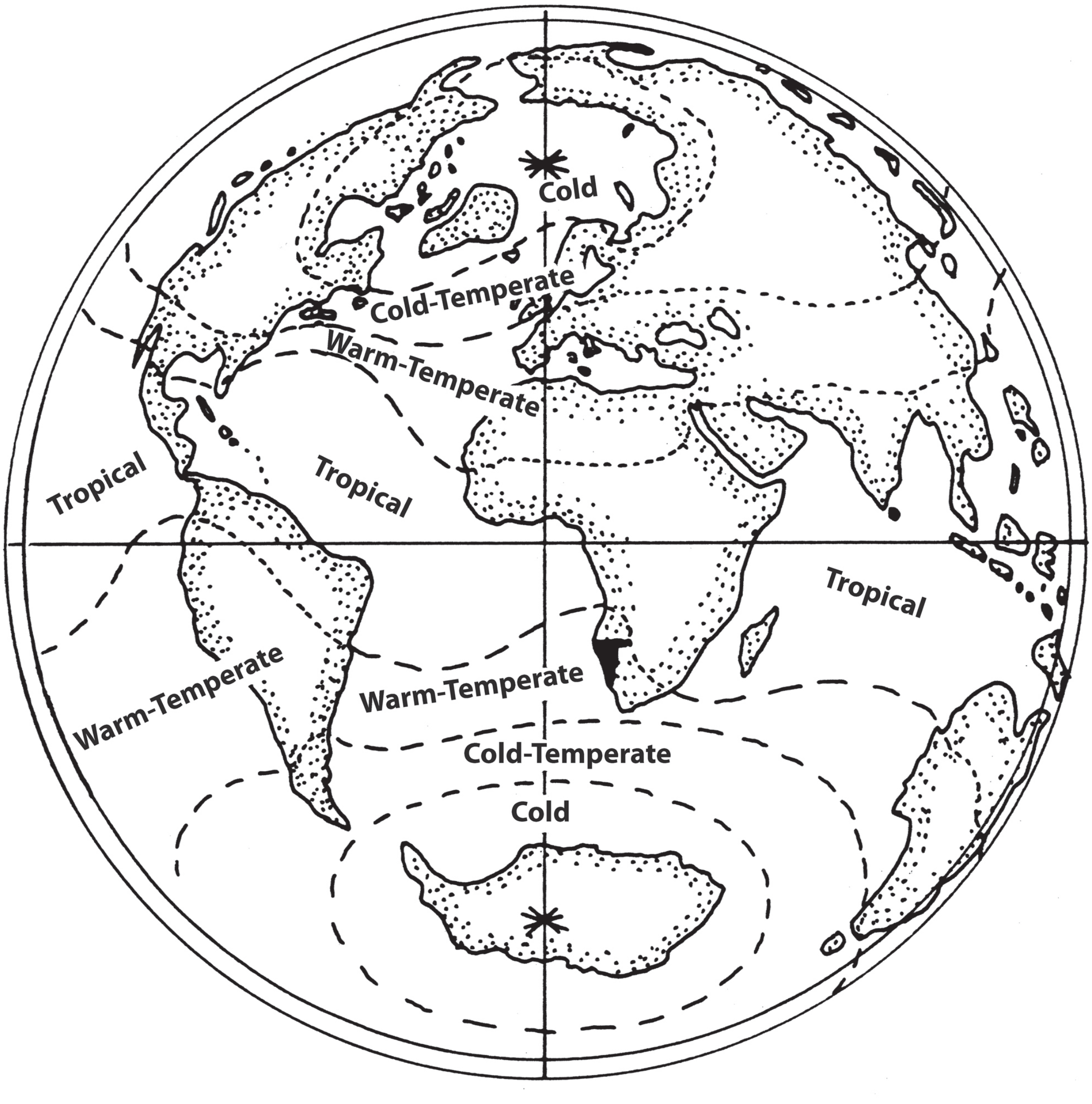


Figure 7.- The karst fields of northern Namibia occur within the warm-temperate (or sub-tropical) zone of southern Africa. In the middle Miocene, however, it would appear on the basis of fossil mammals, that the region was tropical, being both warmer and more humid than it is today.

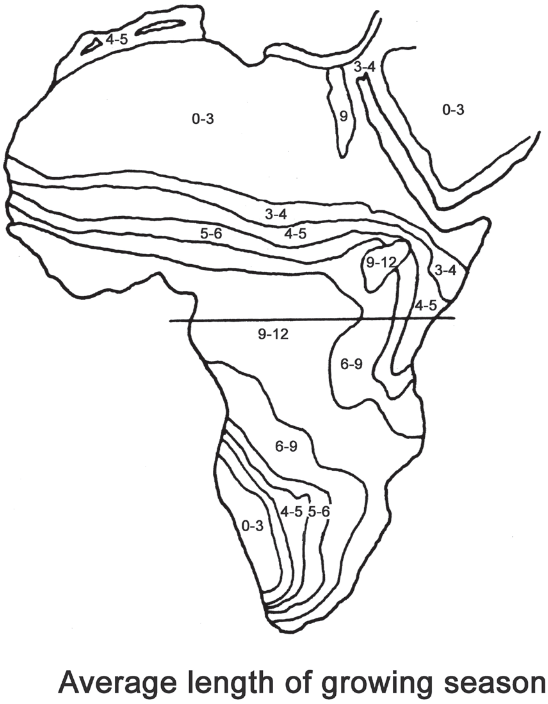
desert (Fig. 11). In both areas, rain falls during the summer months (Fig. 12) and the annual mean temperature is above 18°C.

Ecology of the Otavi Mountains and Kaokoland

The Otavi vegetation falls within the Kalahari-Highveld regional transition zone (White, 1986), being transitional between the Zambezian regional centre of endemism and the Karoo-Namib regional centre of endemism (Fig. 9, 10, 12, 13).

The Otavi Mountains, being strongly karstified, have little surface water and soils tend to be thin or absent except in poljes and through valleys. Partly because of this, the region has developed a peculiar vegetation characterised mostly by *Syringa*, *Moringa*, fig trees, marula, leadwood, sickle, *Terminalia* and aloes. There are also high annual and perennial grasses. Schlenter (1987) describes the vegetation of the Otavi region as mountain savanna and karstveld.

Much of Kaokoland, in contrast, is vegetated by mopane savanna. The commonest trees are, as the name implies, the mopane, but many other species are present including ringwood, corkwood, makalani palm, bottle tree and baobab. Short grass types also occur.



Average length of growing season in months

Figure 8.- Namibia lies within the southwestern arid zone of Africa where the growing season is usually less that 4 months per year. However, faunal remains from the Otavi Mountains suggest that during the latter portion of the Middle Miocene, the region was appreciably more humid than it is today, and that it enjoyed between 6 and 9 months of growing season per year, if not more.

Biogeography of the Otavi Mountains and Kaokoland

The biogeographic affinities of the Otavi region are close to those of the Zambesian district to the north-east. As one traverses westwards towards the Namib Desert, these affinities become weaker while those with the Northern Namib become stronger. However, Kaokoland has weak biogeographic affinities with the Southern Namib, the vegetation and endemic fauna of which are more closely related to those of the Cape Zone. This is because the Northern Namib is a summer rainfall, sub-tropical region, whereas the Southern Namib experiences winter rainfall and is more temperate (Fig. 12).

Neogene Sedimentary record in Namibian karsts

Until 1990, the only important occurrences of fossiliferous Neogene strata known in Namibia were located in the Southern Namib. A few sites were recorded outside the Coastal strip, including conglomerates at Usakos, and other superficial, very young strata, such as the Zoo Garden at Windhoek, which yielded a proboscidean skeleton. Much of the east of the country is covered in calcrete and aeolian sands, but very few fossils have been recorded from these areas.

Even though much of Namibia's mineral wealth came from karst fillings, the nature of these deposits was poorly understood by the majority of workers. Schneiderhöhn (1929) and Verwoerd (1957) realised that the so-called "sand sacks" rich in vanadium minerals were of karstic origin, and more recently vanadium mineralisation in the Otavi Mountainland has been closely linked to karstic processes (Van der Westhuizen, 1984). It is now known that all the vanadium deposits of the region owe their formation to near-surface karstic processes (Pickford, 1993), most of them active during the Miocene to Recent periods, but some of them perhaps formed in pre-Miocene times.

The fossiliferous content of the Otavi karsts has been known at least since 1929, but the few references to the presence of fossils in the region appear to have been ignored or were considered to be of little interest. It is now appreciated that the Otavi fossil record is one of the most comprehensive in Africa for the period spanning the Middle Miocene to Recent, and that the information the deposits yield regarding geochronology and depositional environments are of direct interest to the mining and prospecting industry. They are of inestimable scientific interest.

Summary

The karstveld of Northern Namibia is of great palaeontological interest on account of its geographic location far from other known African fossil occurrences, its ecoclimatic position at the interface between the sub-tropical (warm temperate) and temperate zones, and because the area possesses sedimentary deposits ranging in age from Middle Miocene to Recent. It therefore

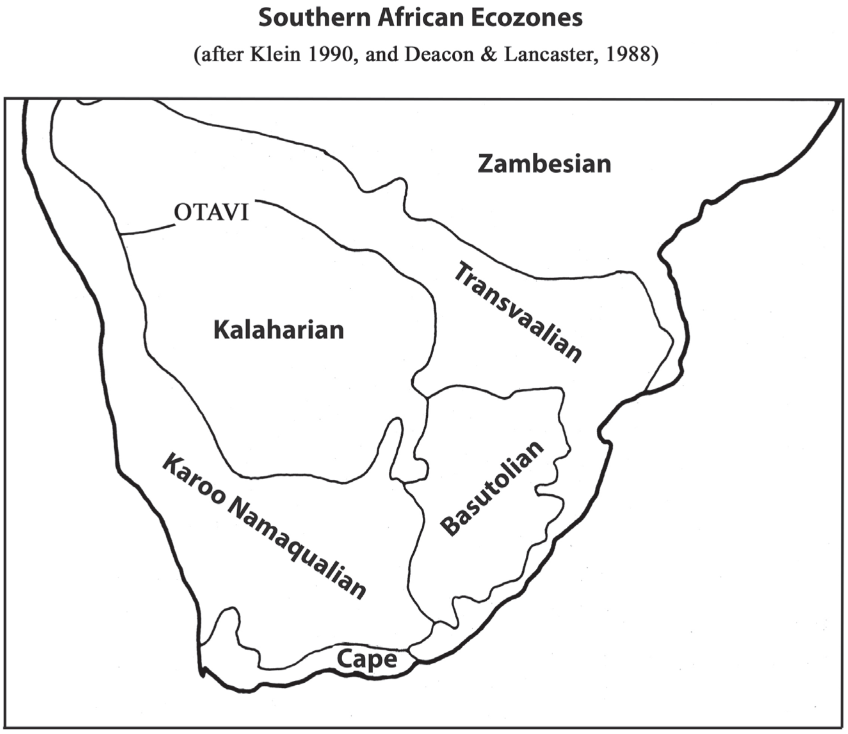


Figure 9. Southern African Ecozones. The Otavi Mountains were more humid during the Middle Miocene, and were probably probably part of the Zambezian zone.

holds tremendous potential for contributing to our understanding of African faunas and palaeoenvironments during the past 14 million years.

Methods

Laboratory methods

Because the stratigraphy of karst deposits tends to be complex, a method of collection and study of fossils was required that minimised the chances of mixing samples of faunas from different time periods. An additional source of complication in the Otavi Mountain karsts is that many of them have been mined, and the fossiliferous breccias are no longer in their original geological context. The above problems are not unique to Namibian karsts - similar difficulties attend the karst deposits of South Africa, Angola and other countries.

The Namibia Palaeontology Expedition decided that the basic unit of research would be the breccia block, since treatment of two or more blocks together could result in an admixture of fossils from different periods. Thus each block was numbered with a locality prefix, a number and the year of collection, all of which accompanied the fossils from the raw block through the various stages of treatment to curation. If a block of breccia consisted of two kinds of sediment cemented together, then it was split into two component parts which were treated and analysed separately.

By this means several hundred samples were obtained and treated as though they came from distinct sites. Many of the blocks are rich in fossils and comprehensive faunal samples could be obtained from them. For example, the breccia block that contained the holotype mandible of *Otavipithecus namibiensis* weighed about 1 kg, yet it yielded 262 teeth and jaws of micromammals, enough to allow estimation of the age of the block and to reconstruct the palaeoenvironment at the time of its deposition. Thus, even though the breccia sample was out of context and was relatively small, it yielded more faunal remains than many of the stratified sites of East and North Africa. A large block of breccia from Berg Aukas, weighing some 30 kg yielded a frontal bone and several isolated teeth of *Otavipithecus* as well as over 10,000 microfaunal remains - a sample that is orders of magnitude more comprehensive than has yet been recorded from any stratified site in Africa.

The validity of this approach to the sampling and study of cave breccias was soon made evident. From Berg Aukas at least seven different faunas are known to occur ranging in age from Middle Miocene to Recent. If all the breccia blocks had been treated together, as was done during one of the field seasons when the authors were not present, then an incomprehensible and irresolvable mixture of faunal elements would have resulted.

Although at first glance this method of treating blocks separately might seem to be a tremendous waste of time, it takes no longer than treating blocks together. It uses no more acid and it does not add to the time-con-

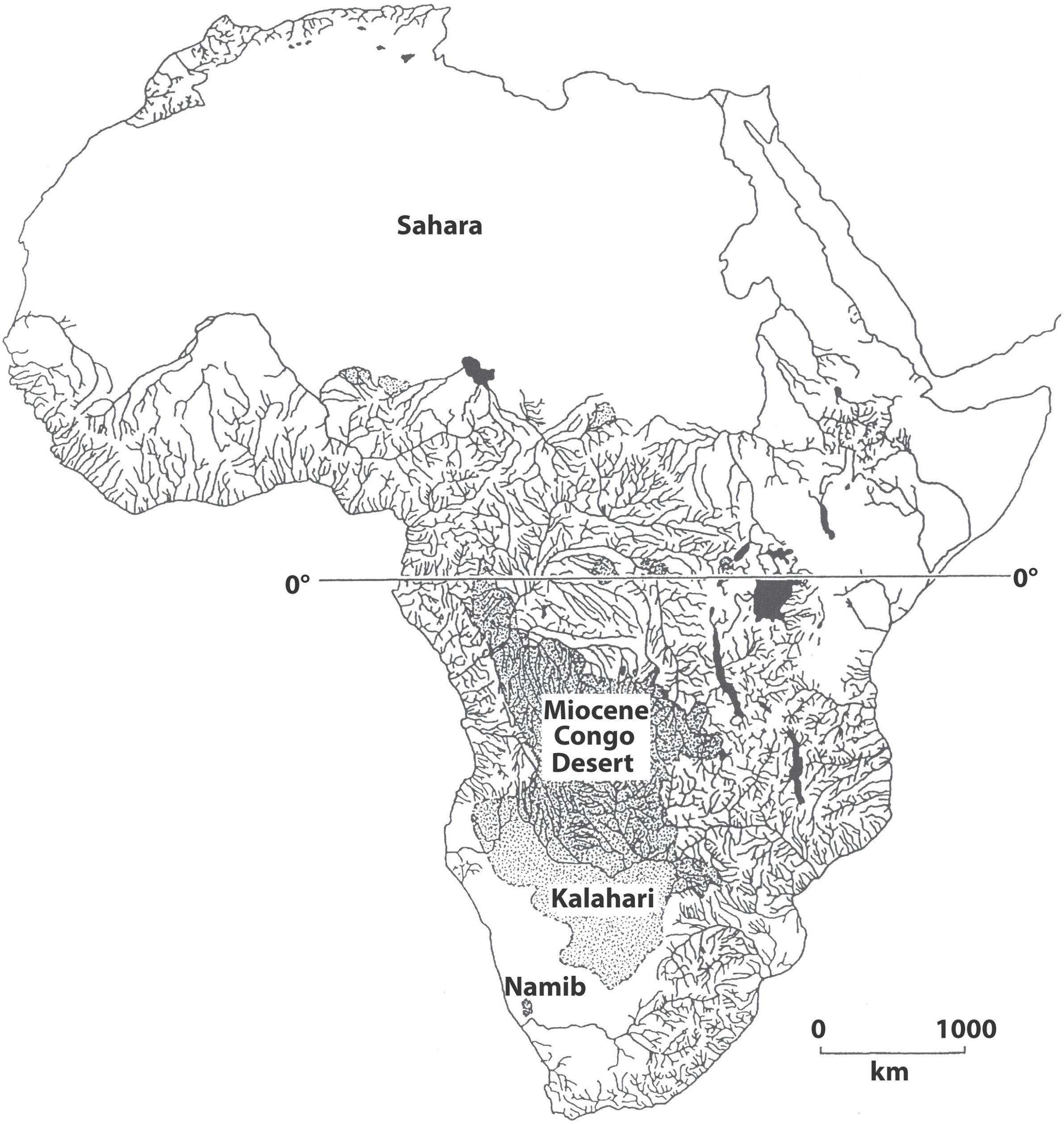


Figure 10.- The distribution of stabilised dunes in Africa superimposed on a map of the perennial rivers and streams of the continent to show how different the climate must have been during the past. Dunes occur as far north as 1°N in Gabon, and Congo, where they underlie the tropical forest. As was pointed out by de Heinzelin in 1952, this evidence for widespread desert conditions in Congo and neighbouring countries, refutes the myth of a tropical forest belt firmly rooted in the equatorial zone since the Oligocene. Namibia, which today lies within the southwestern arid zone, undoubtedly experienced major climatic fluctuations. At times in the Middle Miocene, northern Namibia was more humid than it is today.

suming task of picking through the concentrates after acid digestion. All that is required is a larger quantity of receptacles in which to digest the blocks.

After several experiments, it was found that most of the Otavi breccias dissolved readily in a 10% solution of acetic acid. Some samples required a calcium phosphate buffer to prevent damage to the fossils, but the faunal remains in most samples were not affected by the acid.

There were some exceptions to the general rule of 10% acetic acid. Some of the Berg Aukas and Jägersquelle breccias are insoluble in acetic acid. The insoluble Berg Aukas breccias were treated in 100% (glacial) acetic acid for three weeks, and then dunked in water. This led to the "explosion" of the blocks into tiny pieces which could be sorted in the normal way after washing and drying. The Jägersquelle breccias can be dissolved in hot acetic acid at 10% concentration, but the process

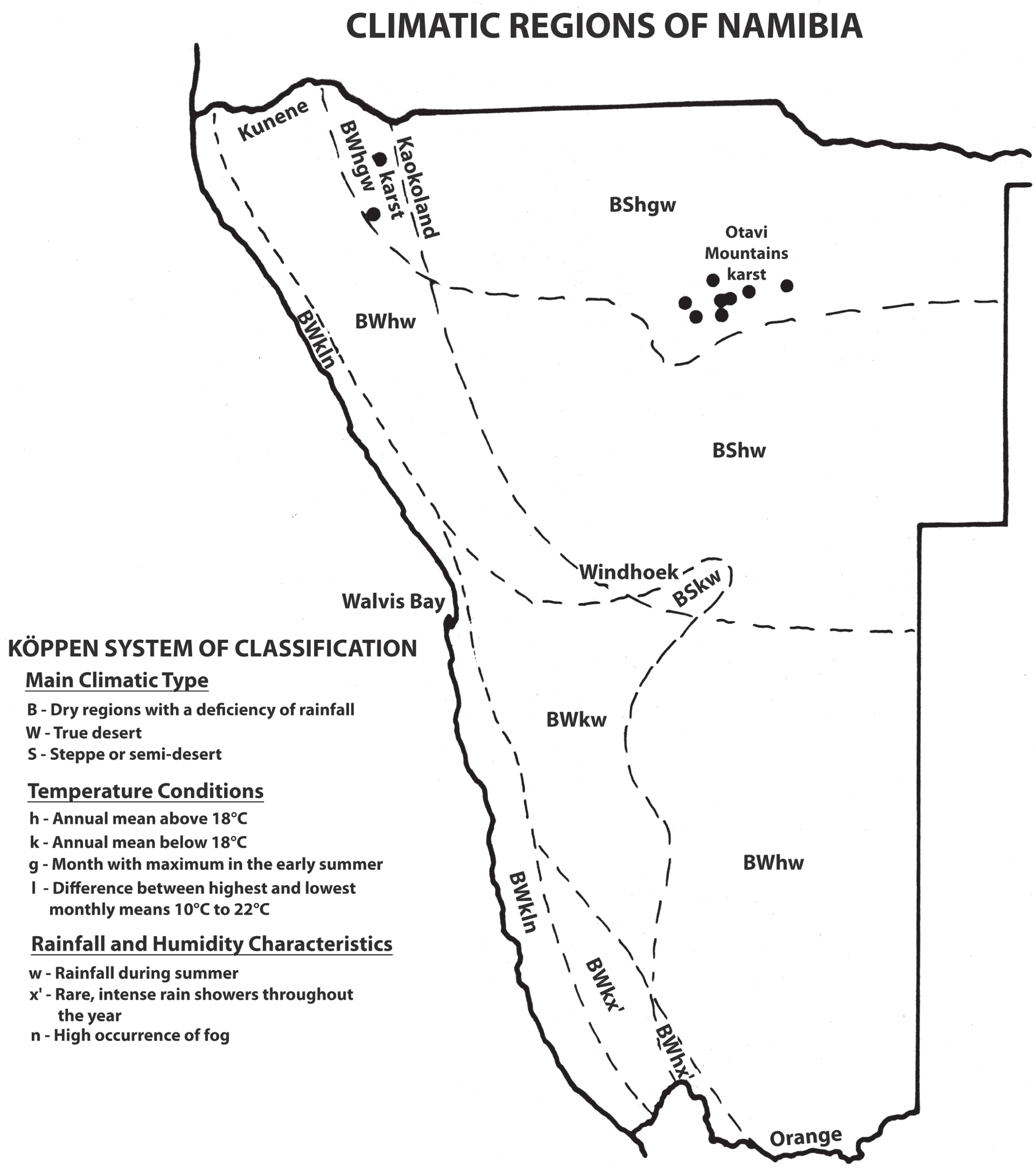


Figure 11.- Climatic regions of Namibia using the Köppen system of classification. Karst deposits in the Otavi Mountains and Kaokoland are shown by filled circles. Both regions are dry. Otavi is steppe to semi-arid, while Kaokoland is true desert. Both areas enjoy summer rainfall and the mean annual temperature is above 18°C. In the Middle Miocene, the Otavi region was probably more humid than it is today.

is slow and large fossils tend to suffer badly. Thus at the latter site, the large fossils are extracted manually while blocks with microfaunal remains are treated using hot acetic acid with a Ca_3PO_4 buffer.

The faunal remains from each block of breccia are subsequently kept together as an assemblage sample. If necessary, individual fossils can receive an additional letter or number to identify them among the mass of specimens from the same block.

Only by being rigorous about the above sampling methods and curation techniques can the Otavi breccias yield information of use to biostratigraphy and palaeoecology. Abuse the breccias, and one is in the presence of irremmediably mixed fossils from which no useful data can be extracted.

Field prospecting

After many days searching for breccias in the Otavi Mountains and Kaokoland, the NPE found more than

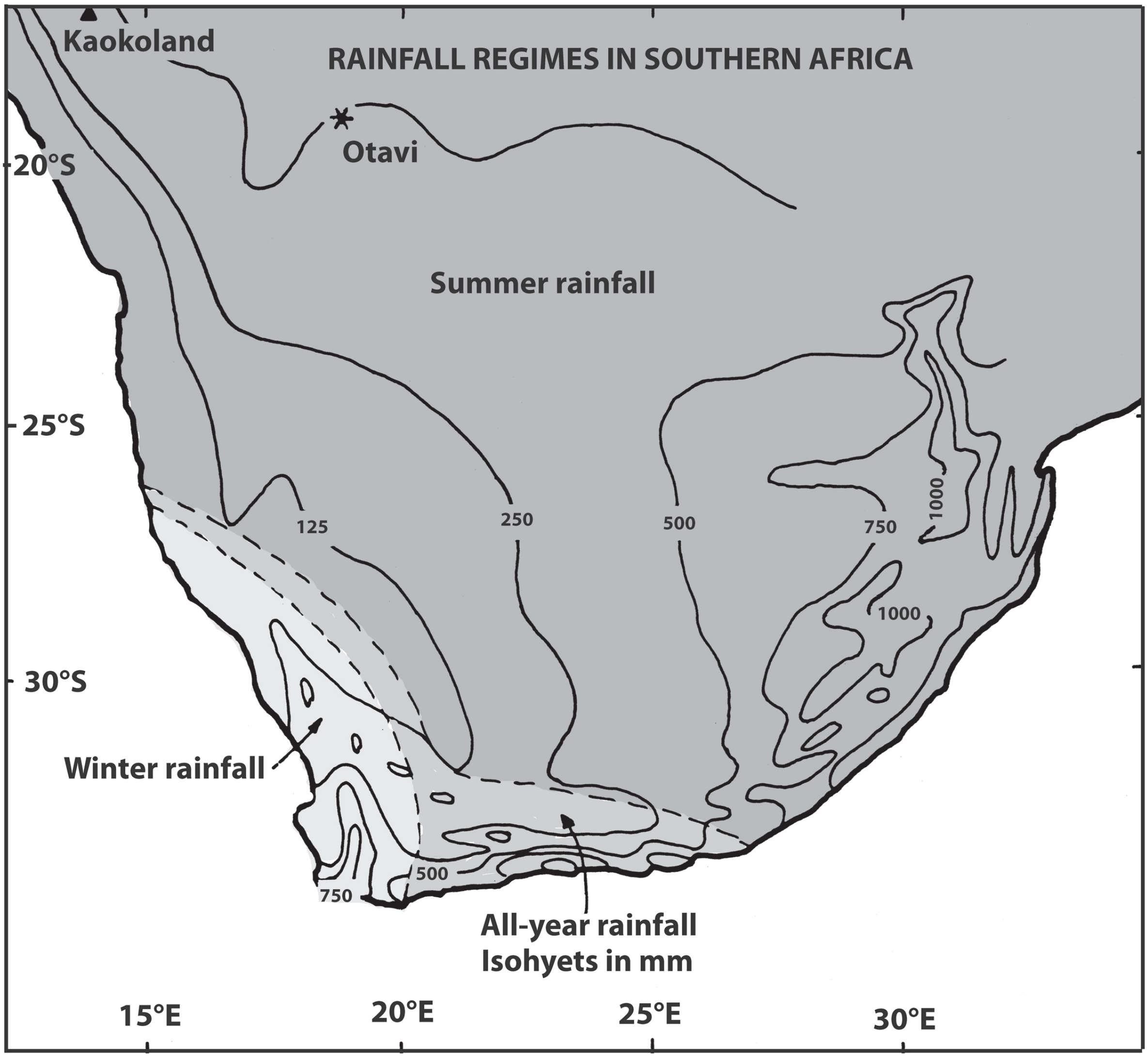


Figure 12.- The Otavi Mountains and Kaokoland receive summer rainfall. However, the Otavi region is more humid than Kaokoland, but both areas have little surface water on account of the karst systems which characterise them.

30 fossiliferous localities. Of these, the most richly fossiliferous ones were spelean breccias. Most of the spelean deposits found occurred near extant caves, but not inside them. Searches in the vicinity of caves occasionally resulted in the discovery of breccias, such as those at Nosib Palaeocave, Aigamas, Tim's Cave, Berg Aukas and Rietfontein. Since the locations of many of the Otavi caves are already known, it was relatively simple to target such areas and thus save much time. However, not all spelean deposits found by the NPE occurred near caves. The Friesenberg breccias, which are extremely rich, provide an example. The study of aerial photographs, which was so useful in Botswana, did not yield significant results in the Otavi Mountains.

Previous Study

Background

The presence of fossils in cave breccias of the Otavi region was reported on several occasions prior to the 1950s (Schwellnus, 1946; Spencer, 1929), but no detailed survey was attempted until 1991. The fossil site at Jägersquelle, which contains extinct baboons and leopards, has been known to local farmers for over a century, but according to Mrs Schickerling, who ran the farm in 1991, attempts to interest scientists at the State Museum, Windhoek, failed to result in any action. In the late 1950s, J.T. Robinson (1959) visited the Otavi Mountains to carry out a survey of cave breccias at Kombat, but little of interest was found. In 1975, a human femur was reported from Berg Aukas (Malan, 1975; Mason, 1976) but, once again, little follow-up work was undertaken. It wasn't until 1991 that the Namibia Palaeontology Expedition discovered the full palaeontological potential of the region, thereby opening up a fossil field of immense significance to African palaeontology (Pickford, 1994; Pickford *et al.*, 1993). Since 1991, hundreds of thousands of fossils

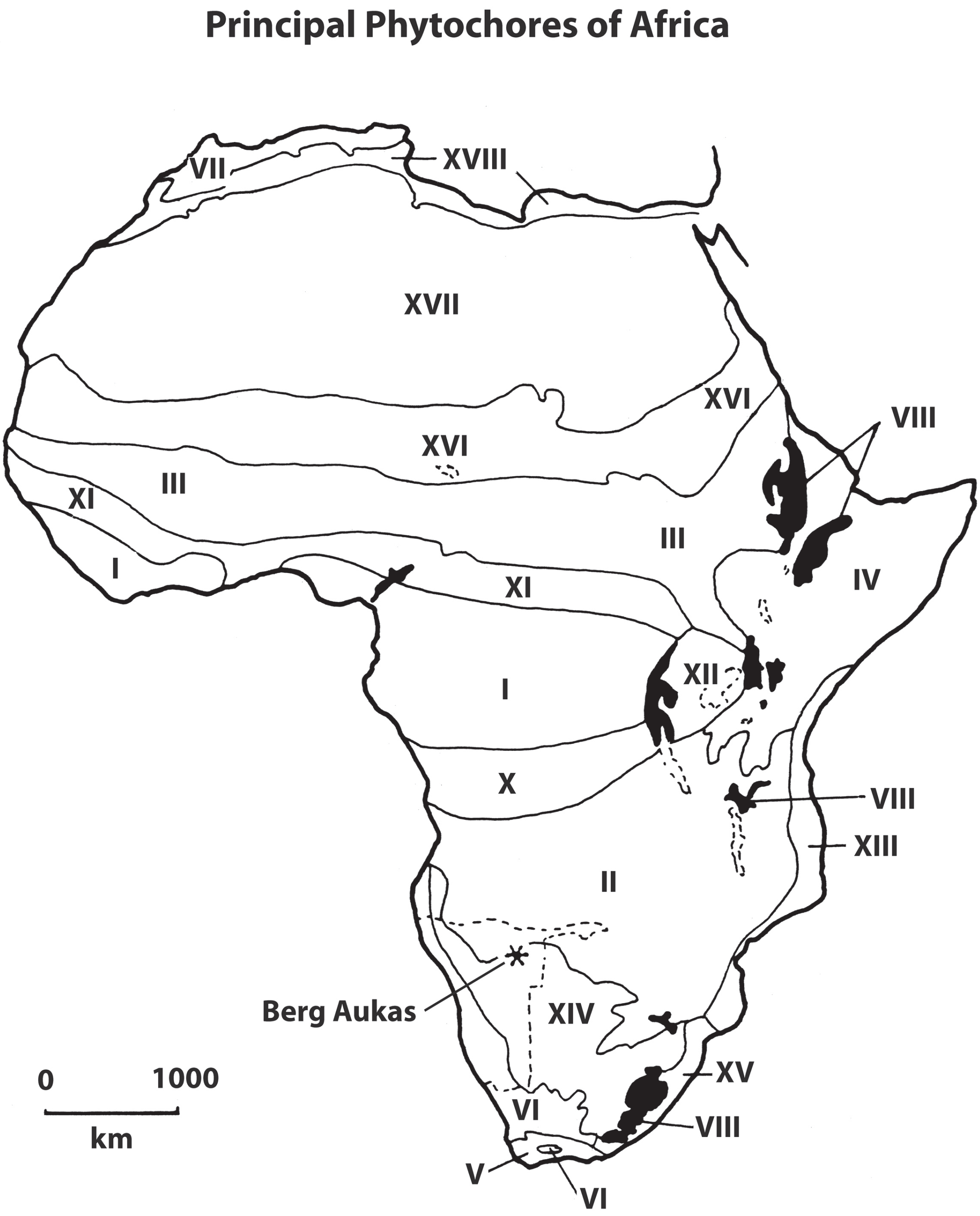


Figure 13.- Principal phytochores of Africa highlighting the position of Namibia and Berg Aukas (based on White, 1986).

Regional Centres of Endemism	Regional Transition Zones
I – Guineo-Congolian II – Zambezian III – Soudanian IV – Somali-Masai V – Cape VI - Karoo-Namib VII – Mediterranean VIII – Afromontane	X – Guineo-Congolian/Zambezian XI – Guineo-Congolian/Soudanian XII – Victoria Regional Mosaic XIII – Zanzibar-Inhambane regional mosaic XIV – Kalahari-Highveld XV – Tongoland-Pondoland XVI – Sahel XVII – Sahara XVIII – Mediterranean-Saharan

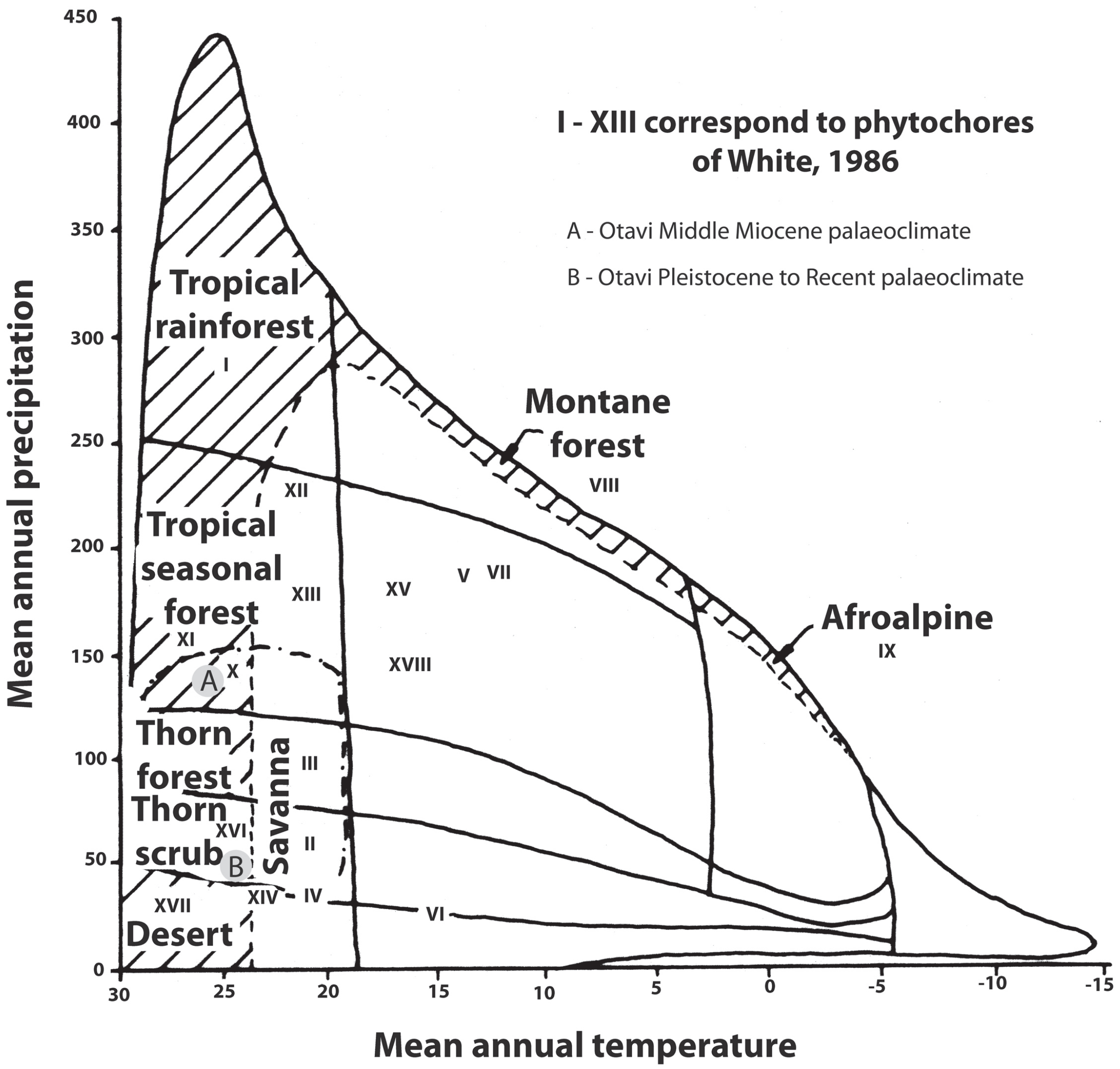


Figure 14.- Relationships between mean annual precipitation and mean annual temperature. Superimposed on this chart are the positions of the principal phytochores of Africa (Fig. 13). The Otavi Mountains today fall within phytochore XIV (arid, warm) but during the Middle Miocene the region was probably within phytochore II (Zambesian) or X (Guineo-Zambesian). Although the mean annual temperature might have been about the same as it is today, the region was probably appreciably more humid.

have been recovered from dozens of sites, ranging in age from Middle Miocene to Holocene (Conroy *et al.*, 1992, 1993). There are undoubtedly many more fossil occurrences to be found in the region, only a minor part of which has been surveyed in detail (Pickford *et al.*, 1992; Senut *et al.*, 1992; Conroy *et al.*, 1993).

Geological context

Because of its economic importance (Table 1) the geology of the Otavi Mountainland has been extensively studied (Schneiderhöhn, 1921, 1929; Deane, 1993; Hughes, 1987; Misiewicz, 1988; Schwellnus, 1946; Sönghe, 1958; Verwoed, 1957; Chadwick, 1993; Emslie, 1979; Wartha and Schreuder, 1992; Pirajno and Joubert, 1993; King, 1990; Le Roex, 1948; Van der Westhuizen, 1984). In addition to these published accounts, mining companies have developed extensive archives which are generally unavailable for study.

The Otavi region is the type area for the Otavi Group (Fig. 5) (Table 2) a series of strata rich in carbonates which accumulated in a shelf setting on the northern flank of a sea which separated the Angola and Kalahari cratons. The site of this sea or ocean was to become the Damara orogen, with its highly folded and tectonised strata. The Otavi region was also tectonised, but to a lesser extent than the Damara Belt. In general the fold structures in the Otavi Mountainland consist of rather open synclines and anticlines. Far to the north, in Angola, carbonate strata equivalent to the Otavi Group crop out in the Humpata Plateau. Here they are flat-lying and untectonised.

The Otavi Group accumulated during the Late Proterozoic (Pirajno and Joubert, 1993). It overlies Early Proterozoic and Archaean metamorphic rocks of the Grootfontein Group. In the Otavi and Kaokoland regions, the Otavi Group is exposed subaerially, but in places it is covered by Mesozoic and younger strata. The group is inferred to be continuous between the Otavi Mountains and the Aha Hills on the Namibia-Botswana Border, but it lies under a variable thickness of Mesozoic sediments and Kalahari sands.

The Otavi Group crops out as a continuous belt forming the southern and western margins of the Etosha Basin (Fig. 3-4). Strata of equivalent age occur within the Swakop facies of the Damara Orogenic Belt, where they have been highly tectonised and metamorphosed. Smaller outcrops occur in the Aha Hills.

Wherever the Otavi Group crops out, it has developed impressive karst topography. In many areas various sedimentary infillings have accumulated within karstified carbonates. Most of these are of Cainozoic age, but some of them may have formed during the Mesozoic. Thus the Otavi Group plays host to an interesting series of Miocene to Recent spelean and epikarst sediments which are often rich in fossils.

Geomorphology

The karst geomorphology of the Otavi Mountains and Kaokoland has been studied by numerous researchers, principally for three reasons. Firstly, scientists such as Schneiderhöhn (1921, 1929) were interested in the karst because the backbone of the economy of the region was dependent upon the Pb-Zn-Cu-V minerals that occur in palaeokarst depositories. Secondly, in an arid environment such as the karstveld, the most secure source of water lies in the vadose zone. Many farmers have explored caves on their land in the hope of locating underground water, and pumps have been installed

Table 1. Vanadium occurrences in the Otavi Mountainland and their karst settings.

Mineral Occurrence	Host Rock	Karst Setting	Associated Sulphides	Fossil Content
Abenab	Maieberg	Spelean	Zn, Pb, Cu	-
Abenab West	Auros	Spelean	Zn, Pb, Cu	-
Alt Bobos	Hüttenberg	Epikarst	Pb, Cu, Fe	-
Asis Ost	-	Epikarst	Cu, Fe	+
Auros	Maeiberg	?	Zn, Pb, Cu, Fe	-
Baltika	Hüttenberg	Spelean	Zn, Pb, Cu, Fe	-
Berg Aukas	Gauss	Spelean	Zn, Pb, Cu, Fe	+
Dreihoek	Gauss	Boxwork	-	-
Farkfontein 10	-	?	Zn, Pb	?
Friesenberg	Elandsfontein	Spelean	Pb, Cu	-
Gauss	Gauss	?	Zn, Pb, Cu	-
Gross Otavi (Andvord)	Hüttenberg	Epikarst	Zn, Pb, Cu, Fe	-
Guchab	-	?	-	?
Harasib I	-	?	-	?
Harasib II	Hüttenberg	?	Zn, Pb, Cu	?
Harasib 3a	Auros	Spelean	Zn, Pb, Fe	+
Hoepker	Hüttenberg	?	-	?
Karavatu	Hüttenberg	Epikarst	Pb	-
Kombat	-	Epikarst	-	+
Kupferberg	-	?	Zn, Pb, Cu, Fe	?
Nageib	Elandsfontein	?	-	?
Nosib	Berg Aukas	Spelean	Zn, Pb, Cu	-
Odin	-	Epikarst	-	?
Okambongora 43	-	?	Zn, Pb	?
Okarundu	Maieberg	?	-	?
Olifantsfontein	-	Epikarst	-	-
Otjirukaku 42	-	?	Zn, Pb	?
Pick Axe	-	Epikarst	-	-
Rendezvous 528	-	?	Zn, Pb	?
Rietfontein	Elandsfontein	Spelean	Zn, Pb, Cu	+
Rodgerberg	-	Epikarst	Cu, Fe	-
Saragosa 537	-	?	Zn, Pb	?
Schlangental	Elandsfontein	?	Cu	?
Tiger Tunnel Tiger-	Elandsfontein	?	-	?
schlucht	Elandsfontein	Epikarst	Zn, Pb, Fe	-
Toggenberg	-	Epikarst	Pb	?
Tsumeb	Hüttenberg	?	-	?
Tsumeb West	Hüttenberg	Epikarst	Zn, Pb, Cu	-
Uitsab Opencast	Elandsfontein	Epikarst	Pb, Cu	-
Uitsab Pad	Auros	Epikarst	Zn, Pb	?
Uris	Elandshoek	Epikarst	Zn, Pb, Cu, Fe	-
Witzapad Claim 1	-	?	-	?
Wolkenhaben	Elandsfontein	Epikarst	Zn, Pb, Cu	-

in several of the caves. Thirdly, karst environments act as irresistable attractions to speleologists, mostly the sporting kind, but also more serious scientifically motivated ones (Jeutter, 1995, 1998). Reports of speleological activities in the Namibian karsts are fairly abundant (see reference list) but most of them deal either with the adventure of caving, or provide topographic details, with or without surveyed maps, or deal with cave faunas. Little work has been published on other aspects of the Namibian karst fields, including regional sub-surface water flow.

Van der Westhuizen (1984) proposed a link between groundwater flow and vanadium mineralisation in the Otavi region. He pointed out that two valleys lead out of the highlands, one towards Abenab, the other towards Berg Aukas. No such valley leads towards Tsumeb, which, he argued, is thus poorly endowed with vanadium minerals. Whilst this hypothesis is, at face value, of some interest, it is based on circumstantial evidence (presence of valleys) rather than a secure knowledge of groundwater flow in the region. It is perhaps more likely that most of the vanadium in the Abenab and Berg Aukas deposits was transported into the vicinity of the sulphide bodies by vadose water, and not in surficial valleys. The small vanadium deposits such as Harasib 3a formed in soils and near-surface spelean settings and were thus probably above the vadose zone at the time of formation.

Geochronology

Estimates of the ages of the Otavi karst deposits have varied greatly, ranging between post-Damaran (Verwoerd, 1957) to Quaternary (Schwellnus, 1946; Van der Westhuizen, 1984). Most of the estimates were based on geomorphological evidence or on the indurated appearance of fissure fillings. More direct evidence of the age of the deposits was provided by microfaunal remains found in cave breccias at various localities in the region. Spelean sediments at Berg Aukas range in age from Middle Miocene (ca 12-13 Ma) to Holocene, those at Harasib 3a are Late Miocene (ca 9-10 Ma) and the others are Plio-Pleistocene (Tables 4-5) (Pickford, 1993).

Karst sediments

Even though many of the surficial and spelean sediments of the Otavi Mountains have been studied by geologists at one time or another, only three localities were previously recognised to contain fossils, Berg Aukas Upper Cave, Kombat and Rietfontein. There are basically two main categories of sediment in the Otavi Mountainland - epikarst and spelean.

Many of the vanadium prospects in the region consist of epikarst sediments more or less richly endowed with vanadium minerals. Many of the prospects occur in rundkarren settings, and the minerals appear to have crystallised within the soil profiles. A few deposits such as the Central prospect (Fig. 15) are valley fill breccias, consisting of well cemented fluvial deposits with reworked crystal masses encased in calcified sediments. Others, such as Harasib 3a are composite deposits which contain a mixture of reworked epikarst sedi-

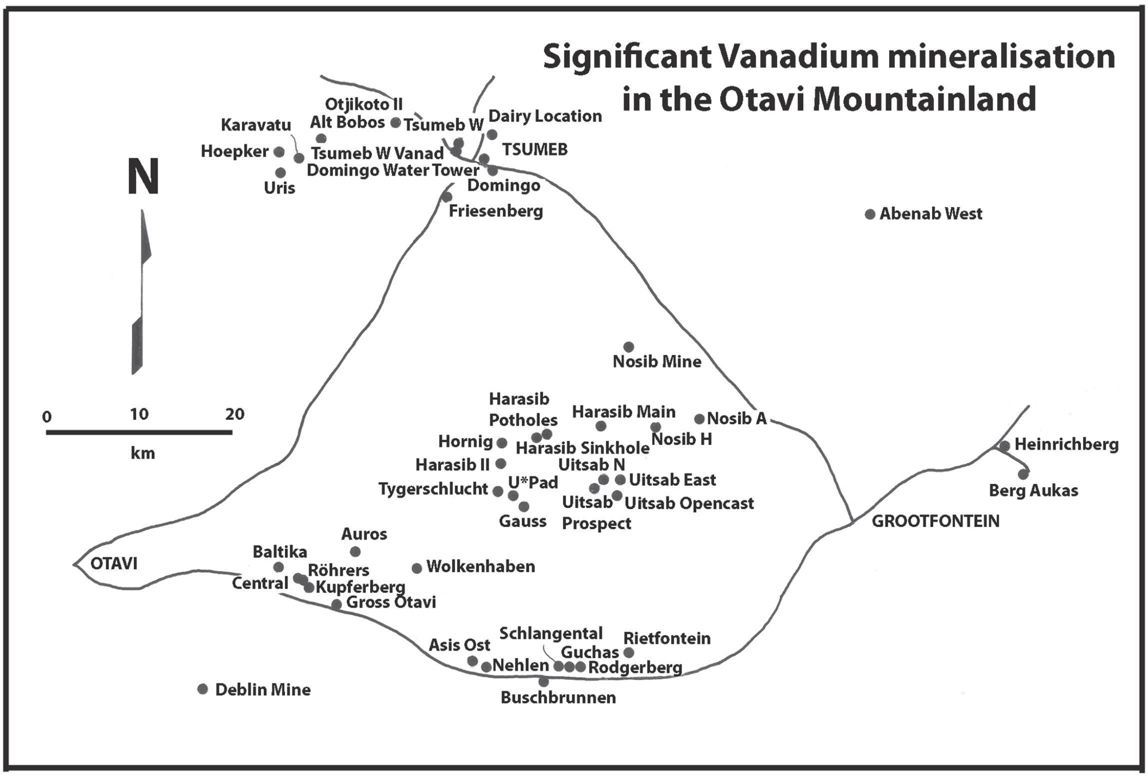


Figure 15.- Distribution of some of the more important vanadium occurrences in the Otavi Mountainland.

Table 2. Stratigraphy of the Otavi Mountainland. Distribution of vanadium and fossiliferous deposits

Formation	**Lithology**	**Average Thickness (m)**	**Mineralised localities**	**Vanadium**	**Fauna**
Kombat and Tschudi	Kombat Fm - slate, sub-arkose and pebbly sandstone near base Tschudi Fm - feldspathic sandstone, sub-greywacke, interbeds in basal portion	>700			
Hüttenberg T8	Dolomite, bedded light to medium grey, oolitic chert and stromatolite layers near top	240	Baltika	+	-
			Tsumeb Mine	+	-
			Tsumeb West	+	-
			Tsumeb W Vanadium	+	-
			Karavatu	+	-
			Tönnesen	+	?
			Dairy	-	?
			Domingo Water Tower	-	?
			Domingo	-	-
			Alt Bobos	+	?
			Gross Otavi	+	?
			Otjikoto II	-	?
			Röhrer's	+	?
			Kupferberg	+	+
			Asis Ost	+	+
			Nehlen	-	
Hüttenberg T7	Dolomite, bedded dark grey, limestone, shale and chert interbeds	300			
Hüttenberg T6	Dolomite, bedded light grey, abundant chert, stromatolite interbeds in lower part	300			
Elandshoek T5	Dolomite, bedded and massive light grey	1200	Harasib Main	+	+
			Harasib Pothole	-	-
			Harasib Sinkhole	-	-
			Harasib II	+	?
			Schlangental	+	?
			Rietfontein	+	+
			Hörnig	-	?
			Rodgerberg	+	-
			Central Prospect	+	?
			Schneiderhöhn	+	?
			Uris	+	-
			Friesenberg	+	-
			Wolkenhaben	+	-
			Nosib A	-	?
			Nosib H	-	?
			Tigerschlucht	+	-
			Nageib	+	?
			Uitsab East	-	?
			Uitsab North	-	?
			Uitsab Open	+	-
			Guchas	+	?
			Buschbrunnen	-	?
			Karuchas Zone	-	?
Elandshoek T4	Dolomite massive light grey				
Maieberg T3	Dolomite, thinly bedded light and dark grey	180	Uitsab Prospect	-	?
			Auros	+	?
			Abenab Pipe	+	-
			Okarundu Pipe	+	?
			Border	+	?
			Pick Axe	+	?
Maieberg T2	Limestone, bedded light and dark grey	700			
Chuos T1	Tillite, quartzite, shale, minor dolomite and limestone	200			

Table 2. (Continued)

Auros	Dolomite, bedded and massive light to medium grey, limestone, marl, shale, oolite and stromatolite interbeds	350	Uitsabpad Abenab West Harasib IIIa	+ + +	- - +
Gauss	Dolomite, massive light to dark grey, local oolite and stromatolite interbeds	750	Driehoek Gauss Prospect Berg Aukas Mine Beacon Kopje Kopje 1	+ + + - -	- ? + ? ?
Berg Aukas	Dolomite, laminated and massive light and dark grey, black limestone, shale	550	Nosib Heinrichberg Odin	+ - +	? ? -
Varianto	Quartzite, conglomerate, arkosic mixtite, dolomite, ferruginous shale				
Askevold	Phyllitic conglomerate, tuff, epidosite	750	Deblin Mine	-	?
Nabis	Feldspathic quartzite, arkose, conglomerate		Nosib Mine	+	?
Grootfontein Basement Complex	Granite, gneiss, mafic schist				

ments and spelean deposits.

The largest and economically most interesting karstic sediments are spelean - Berg Aukas and Abenab West for example. Although Verwoerd (1957) recognised the sedimentary features in the Abenab West deposit and concluded that the environment of deposition was an ancient karst, his lead was not generally followed by those who studied other deposits in the region. Thus, the Berg Aukas breccias largely escaped notice in the literature, perhaps because geologists concentrated their energy on the sulphide ores rather than on the vanadium-rich spelean deposits.

Palaeontology and allied disciplines

Although fossils have been known to occur in the Otavi Mountains for nearly 70 years, virtually nothing was described in detail. The only paper to illustrate Otavi fossils in a block of breccia was a short report by Robinson (1959) but none of the fossils was identified. Because of this nothing has been written about the palaeoenvironment, palaeoecology, biostratigraphy and other aspects of the Otavi fossil record. Thus, when the NPE visited the area in 1991, it was in every sense of the phrase a palaeontological ‘terra incognita’.

Results of the Namibia Palaeontology Expedition

Economic geology

The karst environment of vanadium mineralisation in the Otavi Mountains, Namibia

Most, if not all, of the vanadium ores of the Otavi Mountainland accumulated in karst environments. Whilst it has often been suggested that individual deposits were either associated with karstic features, or even that they owed their origin to karst related processes such as leaching, there has not been a study devoted solely to examining, documenting and analysing the rôle that karstification played in the genesis of Namibian vanadium ores.

The present work is the result of observations made during palaeontological field work in the Otavi Mountainland since 1991, during which notes were made on the sedimentary environment of the bone breccias, many of which also carry vanadium concentrates. There can be little doubt that in the Otavi region, there is an intimate relationship between karst processes and the genesis of economic deposits of vanadium-bearing minerals during the Tertiary and to a lesser extent the Quaternary periods. The possibility exists that similar processes occurred during the Mesozoic, but most of the deposits of this age have eroded away or have been reworked into younger deposits, the Otavi region being subject to extremely rapid regional erosion (ca 15 vertical metres per million years) predominantly by a process of carbonate downwasting.

In the Otavi Mountains, the oldest vanadium-bearing occurrence of which the age is known, is middle Miocene (ca 12 +/- 1 Ma, Berg Aukas). A slightly younger deposit occurs at Harasib 3a (10 +/- 1 Ma, late Miocene), whilst several uneconomic prospects of Plio-Pleistocene age are known (Rietfontein, for example). Abenab West and Baltika might be older than Berg Aukas, but there is no direct evidence for this possibility. However, it should be noted that the spelean sediments at both Abenab and Baltika look very similar to some of the sediments that accumulated at Berg Aukas, and they may be coeval with it.

Aim

The purpose of this section is to document the evidence for karst processes within the Otavi Mountainland, and to show how these relate specifically to vanadium mineralisation and how knowledge of this is essential information for prospectors. A glossary of terms is appended (annex 1), since it will be of use for those people interested in the Otavi karst phenomena and processes.

Previous work

Schneiderhöhn (1929) devoted a great deal of time to discussing the karst of the Otavi Mountainland and its relationships to ore genesis, especially at Tsumeb. He documented many of the surface karst features, including dolines, cenotes, poljes, various karren, including deckenkarren and rinnenkarren, as well as some of the subterranean karst features. In investigating the origin of the Tsumeb supergene ores, he examined the rôle played by oxidation of sulphide ores in the presence of water, especially in the dissolution of dolomite country rock to form cavities which could then act as depositories for sediments and ores.

Subsequent authors have generally gone into less detail concerning karst processes and the relationships between karst geomorphology and supergene ore genesis. In so doing, some researchers have tended to lose sight of the close relationship between the two, or have on occasion paid lip service to the relationship. Indeed, it has almost become traditional to provide a table of the stratigraphic relationships of the various vanadium ore bodies and mineral occurrences within the Otavi Group (Wartha and Schreuder, 1992; Misiewicz, 1988) without detailing that the relationship is a spatial one and not a chronological or stratigraphic one. Without exception, all the known vanadium-bearing deposits in the Otavi Mountains are Tertiary to Quaternary in age, and this is where they should appear in stratigraphic charts (Tables 1-2).

This point may not at first glance seem important, but the discovery of additional deposits in the future depends heavily on knowing that prospecting should be carried out in Tertiary and Quaternary strata, and not in Late Proterozoic ones. Up til now, most if not all surveys have been done in positive relief settings, or in areas where the soil mantle is thin, such as at the edges of poljes and through valleys. This is precisely where such deposits will have been most subjected to erosion. Whilst this makes them easier to see, it also makes them more prone to partial or total destruction, although in a few cases, letdown during erosion may actually enhance the tenure of ore in the occurrences. Letdown enhancement of ore grades appears to have happened at Friesenberg and perhaps at Uris. Some of the Berg Aukas ore was also concentrated into workable deposits by letdown processes.

Schwellnus (1946) summarised the ideas concerning vanadium ore genesis in the Otavi Mountains. These fell into two main categories : a) the hydrothermal theory which could explain several aspects of the deposits, and b) the supergene theory. He specifically supported the latter theory, and suggested that the vanadium was leached from the Otavi Mountain country rock, thus supporting the earlier work of Schneiderhöhn (1929). Among the features cited in support of the supergene theory, Schwellnus mentioned the fact that all the vanadium deposits pinch out within a short distance of the surface, that they occurred in fissures in the dolomites and that in some cases the crystals of psittacinite or cupriferous-descloisite had crystallised *in situ* in the reddish sandy material, and could not have been reworked. He also reported that the primary massive sulphides at Tsumeb had no vanadium in them, whereas all the reported occurrences of mottramite from the mine came from secondary deposits fringing the main sulphide ore body, the implication being that the vanadium had been transported secondarily into the vicinity of the sulphide body. At Tsumeb West, Schwellnus reported that the vanadium ores occurred in "fantastically shaped sand-filled depressions in the dolomite surface". Similar near-surface mineral occurrences were described at Uitsab, Bobos-Karavatu, Toggenburg and Rietfontein. At the latter site, Schwellnus (1946) reported that the deposits cannot have any great age, because the red and grey ore-bearing 'clay' contained recent mammal bones, one of which was said to have been coated in vanadium ore.

Verwoerd (1957) reported that the vanadium mineralisation at Abenab occurred a long time after the mesothermal lead/zinc sulphides were emplaced. He suggested that the vanadium was leached from the neighbouring country rock, in particular the shale horizons of the Otavi System. Among the sedimentary textures recorded by him were typical karst interior sediments consisting of cross-bedded silts, sands and breccias. Thus the vanadium was the mobile element and was brought in towards the lead/zinc orebody, in the vicinity of which it precipitated to produce the vanadium-rich capping to the sulphide ores.

Van der Westhuizen (1984) concluded that, in the Otavi region, the vanadium is a late-stage mineralisation commonly forming coatings on fragments within karst breccias.

King (1990) reported that two of the many mineral prospects on Olifantsfontein occurred in palaeokarst and Recent karst. He described how "minor quantities of descloisite have coated fragments within ferricrete-filled karsts in areas where moderate Pb/Zn mineralisation crops out. These karst features form along fractures and in a few places enlarge to pockets up to 2 m in depth".

Deane (1993) reported that the vanadium mineralisation at Röhrers workings, Central and Northern workings, Kupferberg, Guchab, Rodgerberg and Gross Otavi were associated with karst-fill muds developed during Cretaceous to Recent times. In contrast, he wrote that the Baltika vanadium minerals are associated with calcite veins. It should be noted however, that, contrary to what Deane concluded, much of the Baltika deposit consists of bedded spelean sediments and speleothems and not of calcite veins.

Chadwick (1993) mentioned that at Berg Aukas the Central Ore Body, and to a lesser extent the Northern Ore Horizon, were extensively oxidised and enriched in vanadiferous muds, but he did not discuss the genesis of the vanadium, other than stating that it was part of the supergene mineralisation.

Wartha and Schreuder (1993) considered that the vanadium content of the various Otavi deposits was introduced by oxidising groundwater from remote areas. Unfortunately, the authors did not specify whether these remote areas lay within the Otavi Mountainland, or whether they considered them to be far removed from the region. They realised the importance that the pre-Karoo to Tertiary palaeogeomorphology had on the location of vanadium mineralisation, and reported that most of the deposits were associated with rocks of the Tsumeb Subgroup, while those associated with the Abenab Subgroup were less frequent but usually much larger. Furthermore the largest vanadium mines were associated with large bodies of mixed lead-zinc sulphide.

Pickford (1993) demonstrated that descloisite mineralisation at Berg Aukas occurred during the middle Miocene, on the basis of micromammals which occur in bone breccia on which descloisite crystals have grown. An upper Miocene age was determined for the Harasib 3a pipe, also using micromammals contained within the descloisite-rich breccias. It should be pointed out, however, that the Harasib 3a deposit, besides containing unabraded fossils and descloisite crystals, also yields rounded and abraded, reworked, descloisite crystals and fossils, suggesting the presence of at least two periods of mineralisation separated by an erosive episode.

Vanadium mineralisation and paragenesis

Several vanadium-bearing minerals have been recorded from the Otavi mountains, the two commonest being mottramite (Pb(Cu,Zn)(VO_4)(OH) and descloisite (PbZn(VO_4)(OH) together with minerals of intermediate copper and zinc compositions, such as cuprodescloisite (Pb(Zn,Cu)(VO_4)(OH). The following less common vanadium-bearing minerals are known from the region :- vanadiferous germanite (types A and B), (Cu_3(Ge,V,Fe)(S,As)$_4$?), sulvanite (Cu_3VS_4), and germanium sulvanite ((CuGe)$_3VS_4$), vanadinite ($Pb_5(VO_4)_3Cl$), vanadinocker (V_2O_5), and the informal species “maygreen” (Cu(Ga,Sn,Zn,V)S_2). All of them occur in the oxidation zones of Tsumeb, and some of them, such as descloisite, are common at other localities in epikarst and spelean settings such as Berg Aukas, Abenab, Uitsab, Baltika, Gross Otavi, Tygerschlucht, Rodgerberg, Karavatu, Uris, Friesenberg and Wolkenhaben.

Whilst the paragenesis of all these vanadium-bearing minerals is not well understood, there can be little doubt that they formed in oxidation zones (Keller, 1977), and are consequently of much later genesis than the primary sulphide ores with which they are spatially associated. Keller (1977) gave the paragenesis of mottramite at Tsumeb as follows :- “quartz -> mottramite -> olivenite I and II -> duftite -> malachite -> azurite -> malachite (pseudo)”. This indicated to Keller that during the crystallisation of secondary minerals at Tsumeb, the weathering solutions changed from acidic to basic. However, it is possible that the crystallisation of quartz occurred long before that of the other minerals, and was not therefore temporally nor genetically related to their accumulation. Harasib 3a and Berg Aukas breccias often contain euhedral quartz crystals, but these have evidently been reworked as they are isolated and usually have one broken end. Descloisite crystals from these same breccias are often in clusters or occur as euhedral single crystals. Thus they are very probably considerably younger than the quartz crystals.

Karst processes in the vicinity of sulphide masses

Keller (1977) mentioned that at Tsumeb, the “oxidation of primary minerals (mainly sulphides) occurs in association with a very typical karst hydrology (Schneiderhöhn, 1929). Solution cavities in ore with carbonate-type gangue (or country rock) exist in the ore-body to a considerable depth. Within these karst canals is a quiet, slow moving, watercourse of constant temperature and having many side branches (Schneiderhöhn, 1958). The water has been oxygenated at the surface and is also in equilibrium with atmospheric carbon dioxide.”

Of the primary sulphides, Keller reported that “sphalerite is the most soluble and galena the least soluble of the primary ore minerals at Tsumeb....the path for Zn ions is the longest (i.e. they remain in solution the longest) and the path of Pb ions is the shortest (i.e. they remain in solution only a short time).” It is for this reason, more than any other, that the commonest vanadium bearing minerals in the Otavi mountains are also lead-bearing and often occur near primary lead sulphide deposits, such as at Berg Aukas and Abenab. Where copper ions are common, cupriferous vanadium minerals will also form close to primary copper-bearing sulphide deposits, such as at Tsumeb, Karavatu and Uris. There can be little doubt that in general the vanadium was brought in aqueous solution from a distance into close proximity of the primary sulphide ores by groundwaters, and that the copper, zinc and lead in the various vanadates was transported only short distances from their mother ores before the vanadium-bearing minerals crystallised.

Keller (1977) also mentioned the rôle of oxidation of sulphide ores in the presence of water in the development of karst cavities in the proximity of sulphide bodies which are hosted in carbonate rocks such as dolomite. “Sulfate (sic) ions develop through the oxidation of sulfide ores and an acidic solution (sulfuric acid) develops with a pH of about 4. By reacting with carbonate country rock along the more or less lengthy path through the karst canals it is possible for most of the acidic solution to eventually be neutralized to a pH of about 8."

During the low pH (acidic) phase, cavities were formed not only in the sulphides, but also in the enclosing carbonates, producing ideal spelean environments for the accumulation of sediments and secondary minerals. When such subterranean cavities broke through to the surface, usually as a result of lowering of the land surface due to carbonate down wasting, or to upwards dissolution of avens, then surficial material could enter the cavities, producing typical cave fillings, often with concentrations of reworked minerals, soil particles, insoluble residues derived from the country rock, lithic clasts, iron oxide nodules and fossils.

In areas where there are no sulphides, more normal karst processes function to produce cavities (Ford, 1988), the dissolution of the dolomite being carried out by carbonic acid (derived from the atmosphere) rather than by sulphuric acid.

Discussion and Conclusions

The vanadium ores of the Otavi Mountainland are clearly spatially associated with spelean and epikarstic geomorphological features. The largest ore bodies, such as Berg Aukas and Abenab are spelean accumulations close to massive sulphide ore bodies. Baltika is also a spelean deposit, but is not known to be associated with a large massive sulphide body. Much of the late Miocene Harasib 3a vanadium ores crystallised in epikarst settings and were subsequently transported into a soil-clogged sinkhole where a second generation of mineralisation occurred. Thus Harasib 3a is a composite deposit, combining elements of epikarst and spelean mineralisation. At Berg Aukas and Harasib 3a, a great deal of reworking of vanadium minerals took place, as shown by the presence of broken and abraded crystals in the breccias. Many of these crystals probably formed both within the cave system and in soils near the entrance, and were reworked by processes of spelean erosion, transportation and deposition until they came to rest in breccias which subsequently became indurated (calcified).

Many of the smaller vanadium prospects in the Otavi Mountains accumulated in epikarst settings, usually under a shallow soil profile. As carbonate downwasting proceded, these smaller deposits have become exposed at the surface (Fig. 20-21) and many of them have been found on the lower exposed slopes of dolomite massifs and along the dolomite-alluvium interface. Fossil evidence indicates that most of the lower slope ore occurrences such as Rietfontein are of Pliocene or Pleistocene age. It is probable that most small pre-Pliocene deposits have either been eroded away or that their ores have been reworked into later deposits in more or less the same area as their original formation.

It is likely that vanadium mineral genesis is still going on near the dolomite-soil interface in many of the alluvium filled valleys of the Otavi region. The deeply buried occurrences will of course be difficult to observe, while many of those near the margins of the alluvium have already been prospected. However, in view of the spatial relationship between vanadium minerals and massive sulphide ores, it is possibly of interest to search for vanadium ores in deeper soils in the hope that they may indicate the presence of sulphides at depth within the Proterozoic strata, even if the vanadium ores themselves are of little economic interest.

Palaeontology

Otavi Mountainland Karsts

Sixteen fossiliferous karstic localities have been located in the Otavi Mountains (Table 3)(Senut *et al.*, 1992). Several of these are epikarst deposits which tend to contain only land gastropods or limited samples of micromammals and large mammals. The localities of the greatest palaeontological interest are the ancient cave deposits which tend to be extremely rich in microfauna, but poor in macrofaunal remains. Among large mammal samples, primates predominate.

Berg Aukas

Berg Aukas Geology

A witness section of breccia which occurs in the open cast pit at Berg Aukas (Fig. 16, 17) was examined from the surface of the pit (Fig. 18). The placage is approximately 19 metres from top to bottom and varies from 1.5 to 6.5 metres wide. Its top is 2.5 metres below the edge of the opencast pit. It consists principally of red sandy to silty breccia, with four main layers or pods of coarse dolomite chunk breccia. In places the red breccia is well bedded and the strata have been deformed by compaction due to the accumulation of coarse breccia, possibly due to roof falls, especially numbers 3 and 4 in Fig. 18. The lower part of this fissure filling was mined out to a depth of approximately 40 metres.

Comparison of the breccia in this witness section and breccia blocks collected from the mine dump and subsequently treated in acid indicate that the entire section exposed in the Glory hole is likely to be of Miocene age. However, collection of *in situ* blocks needs to be made before this can be confirmed. The provenience of the Pleistocene faunas remains in doubt, although it is probable that they were extracted from the same pit. The position of a concentration of such blocks within the main dump suggests this probability.

Acid treated blocks were described from a gross sedimentological perspective (grain size, clast type, structures, colour etc.) and preliminary identifications of their faunal content made. Breccia blocks rich in vanadium mineralisation are common, and it is clear from several of these that part of such mineralisation was contemporary with the deposition of the clastics and fossil vertebrates, while part represents reworked fragments of pre-existing ores. Rodents from these blocks indicate a middle Miocene age for the later stages of mineralisation. Most of the breccias which yield middle Miocene faunas are cemented by calcium carbonate, and are thus easy to treat in acetic acid. Several blocks contain layers of flowstone, suggesting that breccia accumulation was contemporary with speleothem activity. In contrast, the breccias which yield upper Miocene faunas (Vallesian equivalent) are poor in calcium carbonate and rich in clay minerals. They thus either dissolve in acetic acid very slowly or not at all. Further attempts to treat these blocks must be tried, including the use of hydrogen peroxide or hot acid. However, their existence suggests that the depositional environment changed from middle to upper Miocene times, possibly as a result of climatic change. Plio-Pleistocene breccia blocks are rich in calcium carbonate, and dissolve readily in acetic acid. Bones and teeth of Plio-Pleistocene age are often dark brown to black in colour, in contrast to the pale grey to rose colour of middle Miocene fossils.

Breccia from the Upper Cave (Berg Aukas II) is a coarse dolomite chunk breccia with clay and silt interfilling, containing abundant micro- and macrofauna and stone tools made from quartzite and vein quartz. Rodents from this breccia indicate a late Pleistocene age for the Upper Cave.

A study of the distribution of breccia blocks in the mine dump at Berg Aukas reveals that most of the Plio-Pleistocene ones are concentrated near the east end close to the workshops. Miocene blocks are concentrated further to the west, while the westernmost end of the mine dump is devoid of breccia blocks. It would appear that as mining activity proceded in the open cast pit, waste material was initially dumped close to the workings, and that waste from deeper and deeper levels was dumped further and further from the pit. There has been a certain amount of mixing of waste from different levels so the position of a block within the dump is not a sure indication of its age, but in general it is a useful initial guide for prospecting purposes.

Some of the breccia, principally the insoluble well-bedded kind, was used to build up a flat working area immediately to the south of the open cast. This is thought to have come from the well-bedded red silts which now crop out from a depth of 5 to 7 metres in the witness section in the opencast pit.

Berg Aukas palaeocave has yielded by far the most comprehensive series of micromammal faunas known in Africa (Fig. 16-19). These range in age from late Middle Miocene (12-13 Ma) to Recent (Tables 4-5). The fossiliferous breccias came from the Central Ore Body, half way up the northwestern flank of Berg Aukas. A witness section of breccia is preserved in the south wall of the glory hole, which is all that is left of the COB (Figs 15-17). This section contains bedded spelean sediments of Middle Miocene age, as well as evidence of roof and wall collapse. The part of the palaeocave that contained Plio-Pleistocene breccias was cleaned out completely by the miners, all the sediment blocks being dumped onto the north side of the hill.

The breccias at Berg Aukas (Table 4) are highly variable in both granulometry and colour. The Middle Miocene breccias tend to be shades of purple and rose with abundant crystal masses of descloizite, vanadinite and other minerals. There are also masses of sunken crystal rafts which attest to the presence of quiet pools of water in the palaeocave. Some of the Middle Miocene breccias are well bedded and show typical fluviatile structures such as cross-bedding, attesting to running water in the palaeocave, at least for some of the time. One of the richest types of breccia at Berg Aukas is a well bedded deep pink rock. Because it breaks into tabular blocks it was used by the miners to build floors, especially around the Central Ore Body. It proved to be insoluble in acid.

Upper Miocene breccias, in contrast, tend to be brick red and massive. They often contain associated skeletal elements, notably of *Heterohyrax auricampensis*, a small hyracoid which probably inhabited crevices near the cave mouth. Indeed, the breccias that yield these hyracoids appear to be derived from soils in the vicinity, without much reworking. They often contain irregular nodules of silica. Several blocks of well bedded greenish breccia were collected at Berg Aukas. Although this type of breccia is rare, it yields many fossils of Upper Miocene age as shown by the faunas contained within it, notably grooved incisors of dendromurines. These breccias probably came from deeper parts of the palaeocave, but they have not been seen *in situ*.

The Plio-Pleistocene breccias of Berg Aukas tend to be pale in colour, brownish, yellow, cream and pink. Many of the blocks are traversed by small tubes, perhaps the foraging tunnels of termites. These breccias do not contain any macroscopic vanadium minerals. Some of the Plio-Pleistocene breccias are extremely coarse, being little more than angular dolomite chunks cemented together with flowstone.

Finally, the Holocene breccias in the small cave near the top of Berg Aukas contains a coarse breccia rich in dolomite clasts. This deposit is unusual for Berg Aukas in that it yields many remains of large mammals, such as kudu (*Tragelaphus strepsiceros*). It has also yielded microlithic implements fabricated from quartz.

Berg Aukas made world headlines in 1991 when it yielded the first known Miocene hominoid south of the Equator. The specimen was a mandible with the cheek dentition. Since then a few more pieces have been recovered, including a proximal ulna, a phalanx, an atlas vertebra, a frontal bone and several isolated teeth. In addition to these specimens, the Berg Aukas breccias have yielded a few isolated teeth of a large hyracoid (*Prohyrax* or *Parapliohyrax*) (Pickford, 1996) and some carnivore teeth. The bulk of the mammals from the site consists of microfauna, in particular rodents. It would appear that most of the fossils were carried into the cave by owls and other raptors. Some of them, such

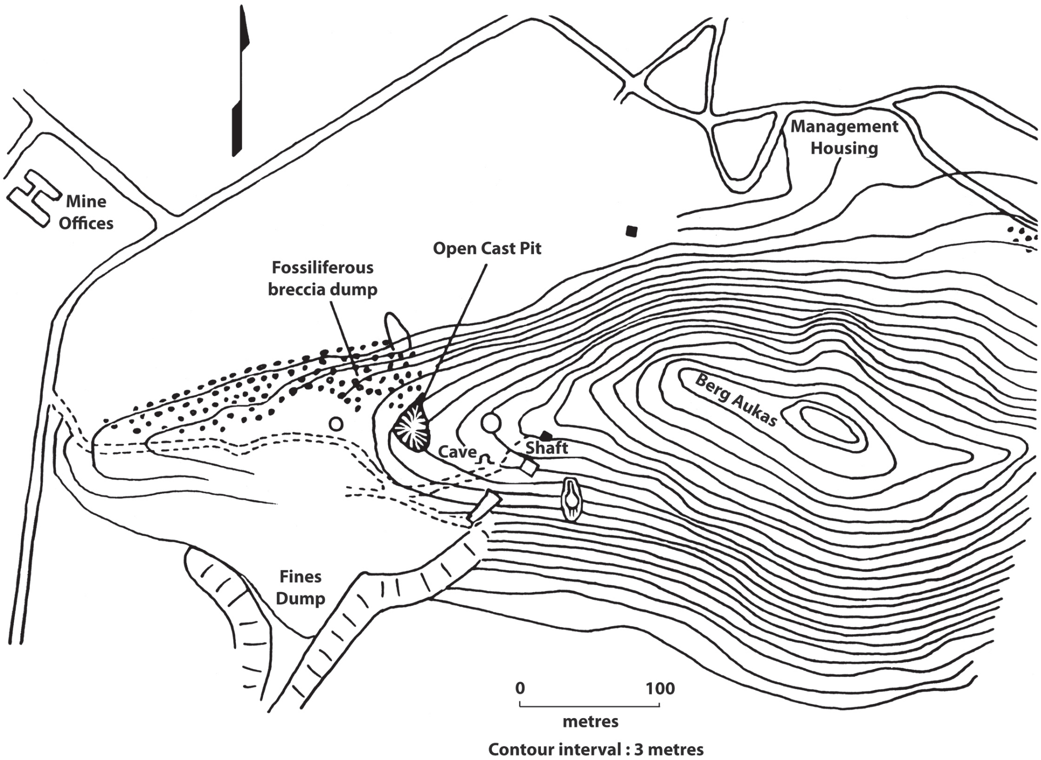


Figure 16.- Topography of Berg Aukas showing the Open Cast Pit, the cave near the top of the hill and the fossiliferous dump on its northwest flank.

Plate 1. Berg Aukas, Otavi Mountains, Namibia, view of the northern flank of the hill with old mine superstructures and breccias covering the slopes of the hill, view southeastwards (figure for scale).

Plate 2. Berg Aukas, Otavi Mountains, Namibia, view of the northern flank of the hill, view eastwards. The figures are in breccia dumps which yielded late Miocene procaviid dassies (*Heterohyrax auricampensis*).

Table 3. Fossiliferous karst deposits of the Otavi Mountains, Namibia.

Locality	**Co-ordinates Latitude Longitude**	**Estimated Age**	**Fossil content**	**Sedimentary environment**
Berg Aukas 1 (Several levels)	19°30’58”S 18°15’10”E	Mid-Miocene to Pleistocene	Hominoids Hyracoids Microfauna	Spelean
Berg Aukas II	19°31’00”S 18°15’08”E	Late Pleistocene	Bovidae Microfauna Artefacts	Spelean
Jägersquelle	19°25’37”S 18°04’01”E	Plio-Pleistocene	Papionines Bovidae Microfauna	Spelean
Aigamas I	19°29’15”S 17°13’05”E	Pleistocene	Rodents	Epikarst
Aigamas II	19°27’30”S 17°17’30”E	Pleistocene	Microfauna Gastropods	Spelean fissure
Nosib Palaeocave	19°25’45”S 17°48’32”E	Pleistocene	Microfauna Cercopithecids	Spelean fissure
Harasib 3a	19°34’00”S 17°48’20”E	Late Miocene	Cercopithecids Bovids Microfauna	Sink hole
Gabus	19°32”15”S 17°17’30”E	Pleistocene	Gastropods	Epikarst fissure
Uisib	19°33’10”S 17°14’10”E	Pleistocene	Microfauna Gastropods	Epikarst fissure
Asis Ost	19°42’35”S 17°43’52”E	Late Pleistocene	Bovidae Hyacoidea Microfauna	Epikarst fissure
Elefantenberg Nord	19°42’40”S 17°24’20”E	Late Pleistocene	Bovidae Gastropods	Epikarst fissure

Table 3. (continued)

Rietfontein	19°41'36"S 17°52'38"E	Pleistocene	Bovidae Cercopithecids Microfauna Gastropods	Spelean
Friesenberg Hilltop	19°17'24"S 17°40'54"E	Plio-Pleistocene	Bovidae Microfauna	Spelean
Rodgerberg		Pleistocene	Gastropods	Epikarst valley fill
Dogleg		Pleistocene	Gastropods	Epikarst calcrete
Kombat E 900	19°42'35"S 17°43'55"E	Pleistocene	Hyracoidea Microfauna	Epikarst fissure

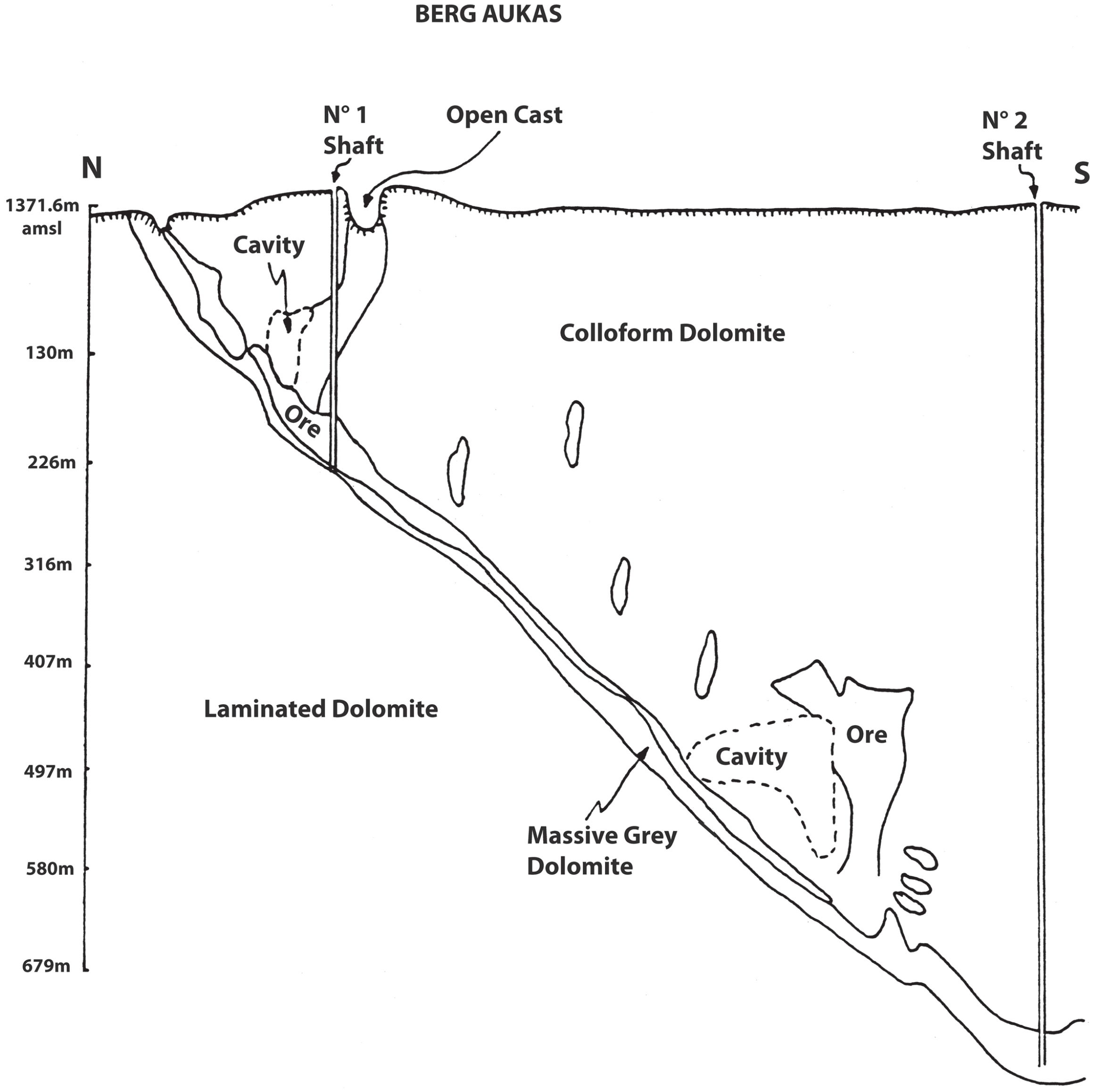


Figure 17.- Section through the Berg Aukas mine showing the relationship of the vanadium-rich Open Cast pit to the underlying sulphide ores.

Table 4. Provisional age determinations of karst fill deposits in Botswana, Angola and Namibia. (* = Primate fossils).

Myr	ANGOLA	NAMIBIA	BOTSWANA
0		Berg Aukas II(*?) Asis Ost	
1	Cangalongue*	Berg Aukas I Tim's Cave Uisib*, Aigamas	
2	Tchiua* Malola* Ufefua	Nosib* Jägersquelle*, Rocky II	Gcwihaba Koanaka*
3		Berg Aukas I	
4			
5		Berg Aukas I	
6			
7			
8			
9		Berg Aukas I	
10		Berg Aukas I* Harasib 3a*	
11			
12			
13		Berg Aukas I*	

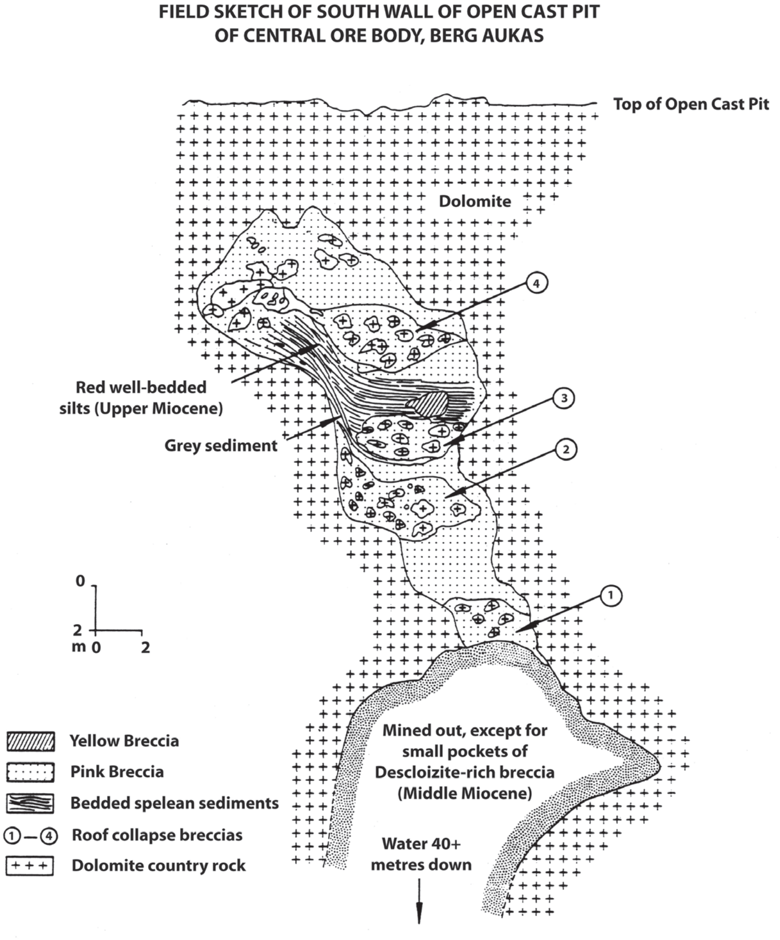


Figure 18.- Field sketch of the south wall of the glory hole at Berg Aukas, showing the disposition of the spelean sediments of Middle Miocene age. At least four episodes of roof and wall collapse are documented within the preserved section. All breccia types are fossiliferous.

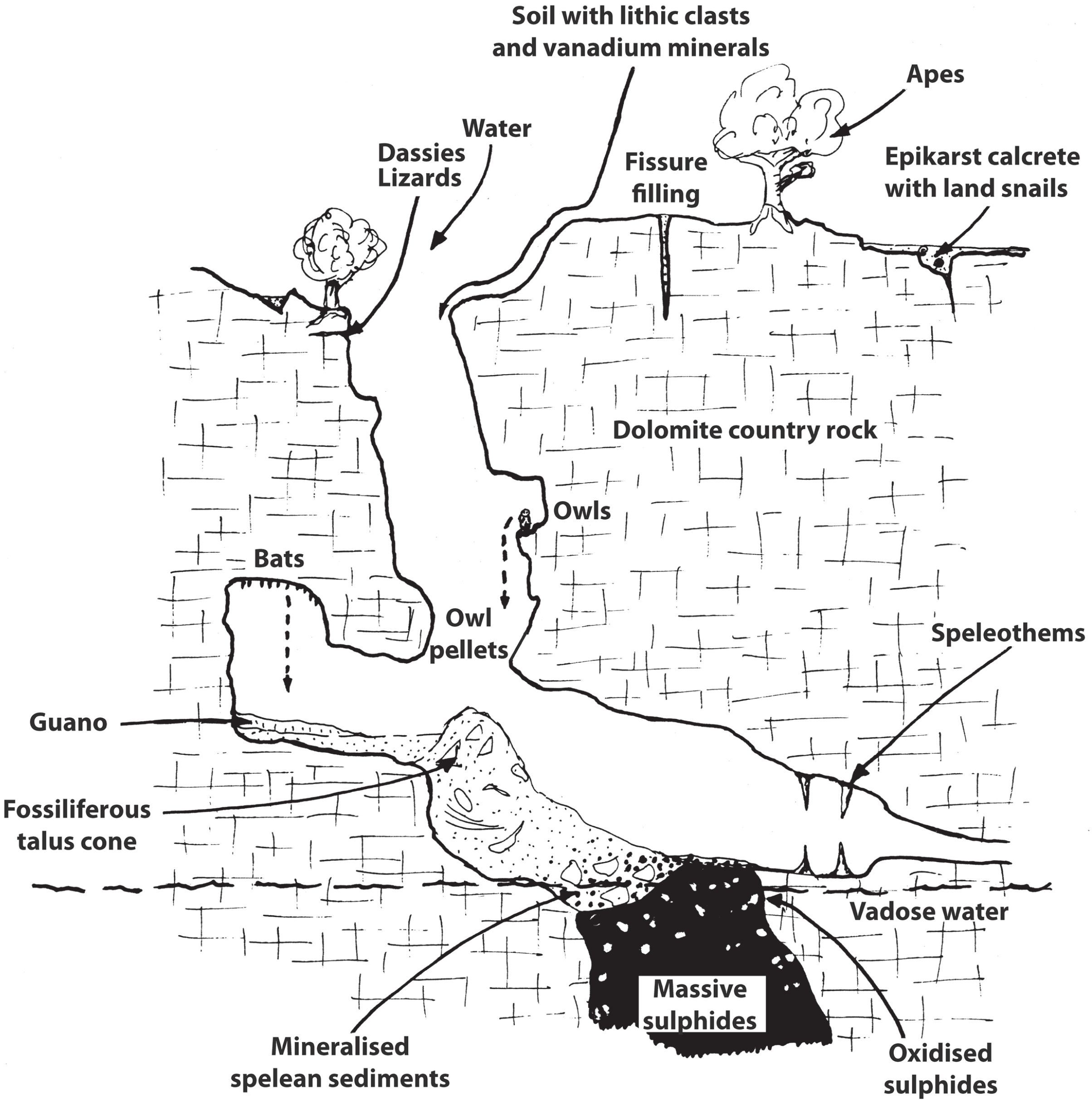


Figure 19.- Reconstruction of the Berg Aukas palaeocave ca 12 Ma. Note that the position of the cave is controlled to some extent by the location of the massive sulphide body which, upon oxidising in the presence of water, released sulphuric acid into the dolomite country rock which dissolved to form cavities. Once one of these cavities broke through to the surface by upwards dissolution of a chimney to form an aven, access to the cavity by fauna (owls, bats etc.) became possible and the mouth of the cavity was attractive to a variety of animals (lizards, hyraxes). In addition, soil and other surface materials could be washed into the cave, contributing to sedimentation inside the cavity. Near the sulphide body, the spelean sediments were mineralised with various lead, zinc, vanadium compounds, the lead and zinc coming from the sulphide mass while the vanadium was transported in by ground waters.

as the frogs and lizards may well have lived in or near the cave mouth. The dearth of large mammal remains suggests that the approaches to the cave were difficult or forbidding for large terrestrial animals. Even today, parts of the Otavi Mountainland are difficult to traverse on account of the exposed karst terrain.

The presence of cross-bedded fluviatile sediments at Berg Aukas indicate that parts of the cave were above the vadose zone, but below the general level of the surrounding countryside. Today the spelean sediments are well above the water table (Fig. 19, 20) and the local base level. This indicates that the middle Miocene land surface was higher than it is today. Although it is difficult to be precise, we estimate that there has been regional down wasting of at least 25 metres since the Middle Miocene.

Large mammals from Berg Aukas

The vertebrate faunas from Berg Aukas are dominated by micromammals. However, a few medium

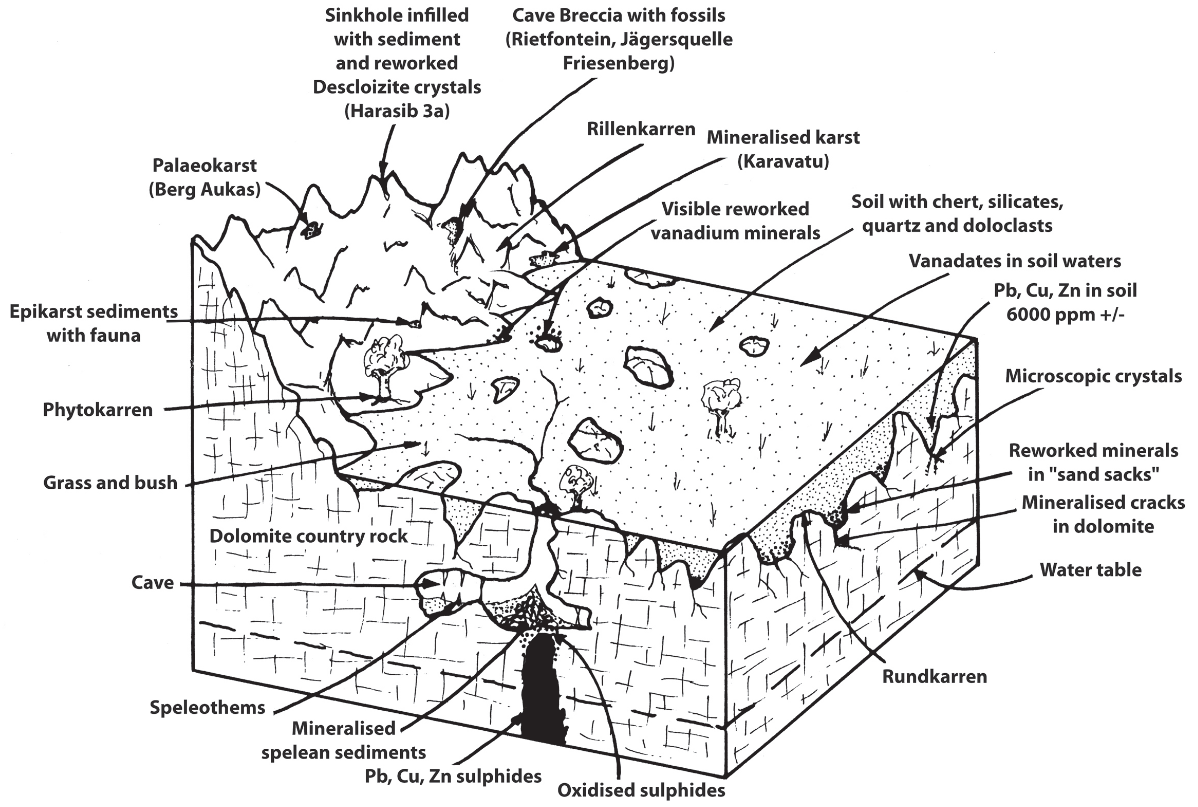


Figure 20.- Reconstructed geomorphology of a karst terrain in the Otavi Mountains showing some of the main features including locations of massive sulphides, vanadium mineralisation and fossiliferous karst infillings. There is a clear karstic control on the localisation of vanadium deposits and fossil sites.

Table 5. Preliminary Faunal Lists of Breccia Blocks Berg Aukas (taxa in brackets are intrusive)

Block N°	**Sedimentology**	**Fauna**	Age
91-4a	yellow sandy breccia with blocks, ulna	*Hipposideros, Rhinolophus, Otavipithecus, Protarsomys, Myocricetodon, Apodecter, Vulcanisciurus*, Giant Sciuridae, *Elephantulus*	Middle Miocene
91-4b	medium coarse dolomite breccia filling holes in 4a	*Megaderma*, 2 Microchiroptera, *Protarsomys*, 2 Cricetidae Anomaluridae? *Elephantulus*, Frog, Lizard	Middle Miocene
91-7		Thryonomyidae, Cricetidae, *Harasibomys*, Cricetomyidae cf *Saccostomys*, Dendromuridae cf *Steatomys, Elephantulus*	Late Miocene
91-12		Molossidae, Small Microchiroptera, *Megaderma, Apodecter, Protarsomys*, Sciuridae, *Vulcanisciurus, Myocricetodon, Notocricetodon*?, Viverridae, *Parapliohyrax* sp., Macroscelididae, Snake	Middle Miocene
91-23		Molossidae, Small Microchiroptera, Viverridae, *Otavipithecus namibiensis*, Sciuridae, *Protarsomys*, *Notocricetodon*	Middle Miocene
91-24		Rhinolophidae, *Tatera, Mystromys, Otomys, Aethomys, Malacothrix, Steatomys, 2 Crocidura, Elephantulus*, Birds (*Megaderma, Asellia, Myocricetodon*)	Pleistocene
91-31	red sandy breccia	*Heterohyrax auricampensis*	Late Miocene
91-32		*Parapliohyrax or Prohyrax*	Middle Miocene
91-40		*Tatera, Otomys, Elephantulus*	Pleistocene
91-57	pink silt-sand, slow acid reaction	Thryonomyidae, *Myocricetodon*, Bathyergidae, *Elephantulus*, ?Hyracoidea	Middle Miocene
91-76	red microconglomerate with cobbles, rolled fossils	*Parapliohyrax* or *Prohyrax*, *Myocricetodon*, Cricetidae, 2 or 3 spp. Microchiroptera	Middle Miocene
91-84		*Otomys, Tatera, Mystromys, Crocidura*, Microchiroptera	Pleistocene
91-94		Unidentified large bone	?

Table 5. (continued)

91-98	stratified red sand, white fossils	Small Microchiroptera, *Myocricetodon*, Hyracoidea	
91-103		Rodentia, Hyracoidea	
91-112	red sand and microconglomerate	*Myocricetodon*	Middle Miocene
92-1	pale yellow microconglomerate, many fossils	*Megaderma, Asellia*, Intermediate Microchiroptera, Sciuridae, *Vulcanisciurus, Myocricetodon, Protarsomys*, Macroscelididae	Middle Miocene
92-2	pink/yellow silty, sandy microconglomerate	*Hipposideros, Myocricetodon*, Thryonomyidae (*Otomys, Malacothrix, Mystromys*)	Pleistocene
92-3	yellow sandy conglomerate breccia, many fossils	Small Microchiroptera, Large Microchiroptera, *Apodecter*, *Vulcanisciurus, Myocricetodon*	Middle Miocene
92-4		*Hipposideros*, Small Microchiroptera, *Vulcanisciurus*, Large Sciuridae, *Myocricetodon, Protarsomys*, Macroscelididae	Middle Miocene
92-5	yellow sandy conglomerate breccia, many fossils	*Megaderma*, Small Microchiroptera, *Myocricetodon*, Macroscelididae, *Parapliohyrax* or *Prohyrax*	Middle Miocene
92-6	layered pink sandy/silty breccia with black bones	*Saccostomys*	Pleistocene
92-7	pink silty breccia with minerals, white bones	*Steatomys, Mus, Elephantulus, Crocidura*	Pleistocene
92-9	pink bedded microconglomerate with mineral	*Myocricetodon*	Middle Miocene
92-10	red silt and conglomerate with dolomite chunks	Small Microchiroptera, *Mystromys, Steatomys*	Pleistocene
92-11	grey silty limestone with dolomite microbreccia	*Mystromys, Otomys, Mus, Gerbillurus, Malacothrix, Tatera, Crocidura, Elephantulus*	Pleistocene
92-12	red silty breccia with medium dolomite cobbles	*Mystromys, Tatera, Otomys, Mus or Dendromus, other Muridae?, Crocidura, Elephantulus*	Pleistocene
92-13	red silty breccia with large dolomite blocks	*Myocricetodon*, 2 Microchiroptera	Middle Miocene
92-14	pink silty breccia with small dolomite chunks	*Mystromys*, Large Muridae, *Steatomys, Mus, Crocidura*, Artiodactyla	Pleistocene
92-15	pink silt with yellow bones	Large Thryonomyidae, *Myocricetodon*, ?Anomaluridae, Microchiroptera	Middle Miocene
92-16		*Megaderma, Asellia, Myocricetodon*, Thryonomyidae, *Vulcanisciurus, Elephantulus,* Birds	Middle Miocene
92-18	red silty breccia with large dolomite blocks	Microchiroptera, *Protarsomys*, Hyracoidea	Middle Miocene
92-19	yellow sandy conglomerate breccia, many fossils	*Megaderma, Asellia, Vulcanisciurus, Protarsomys, Myocricetodon, Elephantulus*	Middle Miocene
92-20		Small Microchiroptera, Large Microchiroptera, *Apodecter, Vulcanisciurus*, Xerinae, *Myocricetodon, Protarsomys*, Macroscelididae, *Otavipithecus namibiensis*, Frog, Lizard (92-20 = 91-23)	Middle Miocene
92-22	red sandy breccia with medium dolomite chunks	Small Microchiroptera, Thryonomyidae, 2 or 3 *Myocricetodon*, Muridae, Macroscelididae, Hyracoidea	Middle Miocene
92-23	red-brown silty breccia with small dolomite chunks and cobbles	Microchiroptera, *Myocricetodon*	Middle Miocene
92-25	brown sandy breccia with black and white blocks	Large Microchiroptera, *Asellia*, 2 spp. *Myocricetodon*, Macroscelididae	Middle Miocene
92-26	red sandy breccia with fine conglomerate, and mineral	*Myocricetodon*	Middle Miocene
92-27	red silty breccia, slow acid reaction	*Myocricetodon*, Muridae, Macroscelididae	Middle Miocene
92-30	dark brown coarse conglomerate with large bones	Large Microchiroptera, Small Microchiroptera, *Vulcanisciurus, Myocricetodon*	Middle Miocene
92-31	light grey sand with medium dolomite blocks, many fossils	Small Microchiroptera, *Myotis*, Rhinolophidae, *Steatomys*?, *Mastomys, Tatera, Mystromys, Mus, Otomys, Elephantulus, Crocidura*	Pleistocene

Table 5. (continued)

92-35	red sandy breccia with medium dolomite chunks	Large Muridae, *Mystromys*	Pleistocene
92-38	pale pink microconglomerate	Molossidae, Small Hipposideridae, *Protarsomys, Elephantulus*	Middle Miocene
92-42	red sandy breccia with dolomite and authigenic minerals	Muridae, *Saccostomus, Mus*, Dendromuridae, *Steatomys, Elephantulus*	Pleistocene
92-45	yellow-pink microconglomerate breccia	*Hipposideros, Asellia*, Anomaluridae?, *Vulcanisciurus, Apodecter, Protarsomys, Myocricetodon, Elephantulus*	Middle Miocene
92-52		Large Microchiroptera, *Asellia, Myocricetodon, Protarsomys, Apodecter*	Middle Miocene
92-53		*Megaderma*, Small Microchiroptera, Sciuridae, *Apodecter, Protarsomys / Myocricetodon*, Leporidae, Viverridae, Macroscelididae	Late Miocene
92-55		Small Microchiroptera, *Protarsomys*	Miocene
92-56		Dendromuridae	?
92-58		Muroidea	?
92-60		*Myocricetodon*	Miocene
92-61		Muridae, *Steatomys*	Pleistocene
92-63		Insectivore or bat, Muridae	?
92-66		Molossidae, *Mastomys, Mystromys*, Muridae?, *Elephantulus*	Pleistocene
94-52		*Parapliohyrax or Prohyrax*	Middle Miocene
94-60		*Parapliohyrax or Prohyrax*	Middle Miocene
95-1		*Parapliohyrax or Prohyrax*	Middle Miocene
95-2		*Parapliohyrax or Prohyrax*	Middle Miocene
05-1	Red sandy breccia	*Heterohyrax auricampensis*	Late Miocene
Berg II (cave)		Bird, *Tatera, Otomys*, 3 or 4 Muridae, *Mystromys*, 2 *Crocidura, Elephantulus, Tragelaphus*	Late Pleistocene

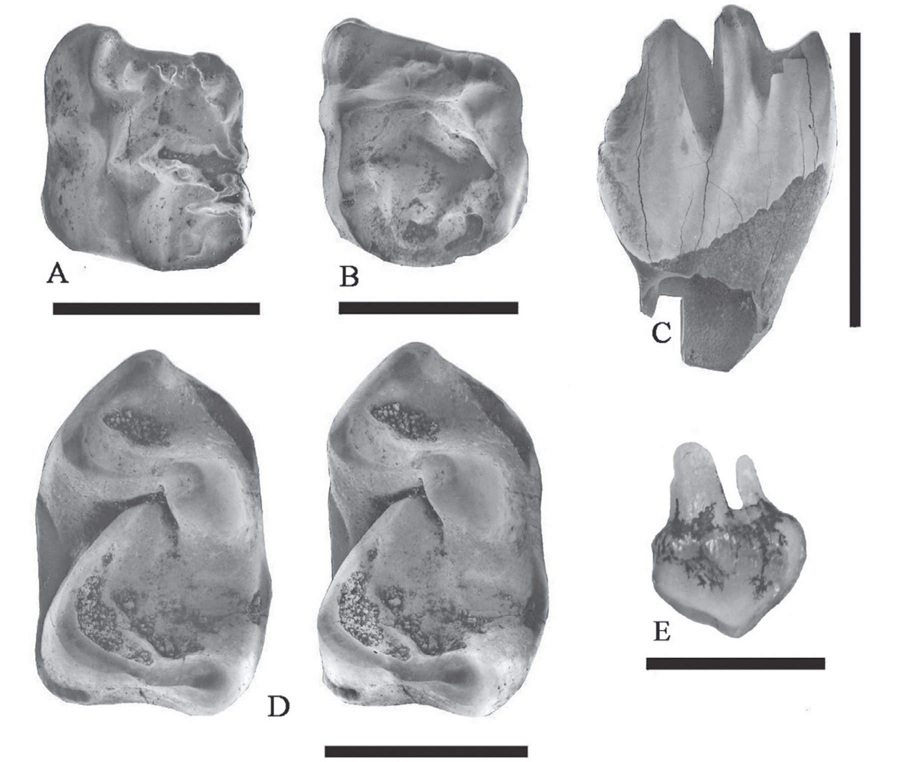


Plate 3. Pliohyracidae from Berg Aukas, Otavi Mountains, Namibia. A) BA 5’92, right dC1/; B) BA 60’94, right C1/; C) BA 1b’95, left di/1; D) BA 52c’95, left lower deciduous molar; E) BA 32’91, left upper dI2/ (scales – 5 mm).

sized mammals were found including the hominoid *Otavipithecus namibiensis*.

Pliohyracidae

Pickford (1996) described several isolated teeth of a pliohyracid from Berg Aukas (Plate 3). The specimens could represent either a large species of *Prohyrax* or a small species of *Parapliohyrax*. The associated microfauna indicates an age of ca 12-13 Ma for these remains.

Procaviidae

Rasmussen *et al.*, (1996) described the species *Heterohyrax auricampensis* from basal Late Miocene breccias from Berg Aukas. Material consisted of cranial, mandibular and post-cranial remains associated with a rodent fauna indicating an age of ca 10 Ma. Additional material has since been found (Plate 4, 5).

Hominoidea

Several papers have been published on the remains of *Otavipithecus namibiensis* from Berg Aukas (Con-

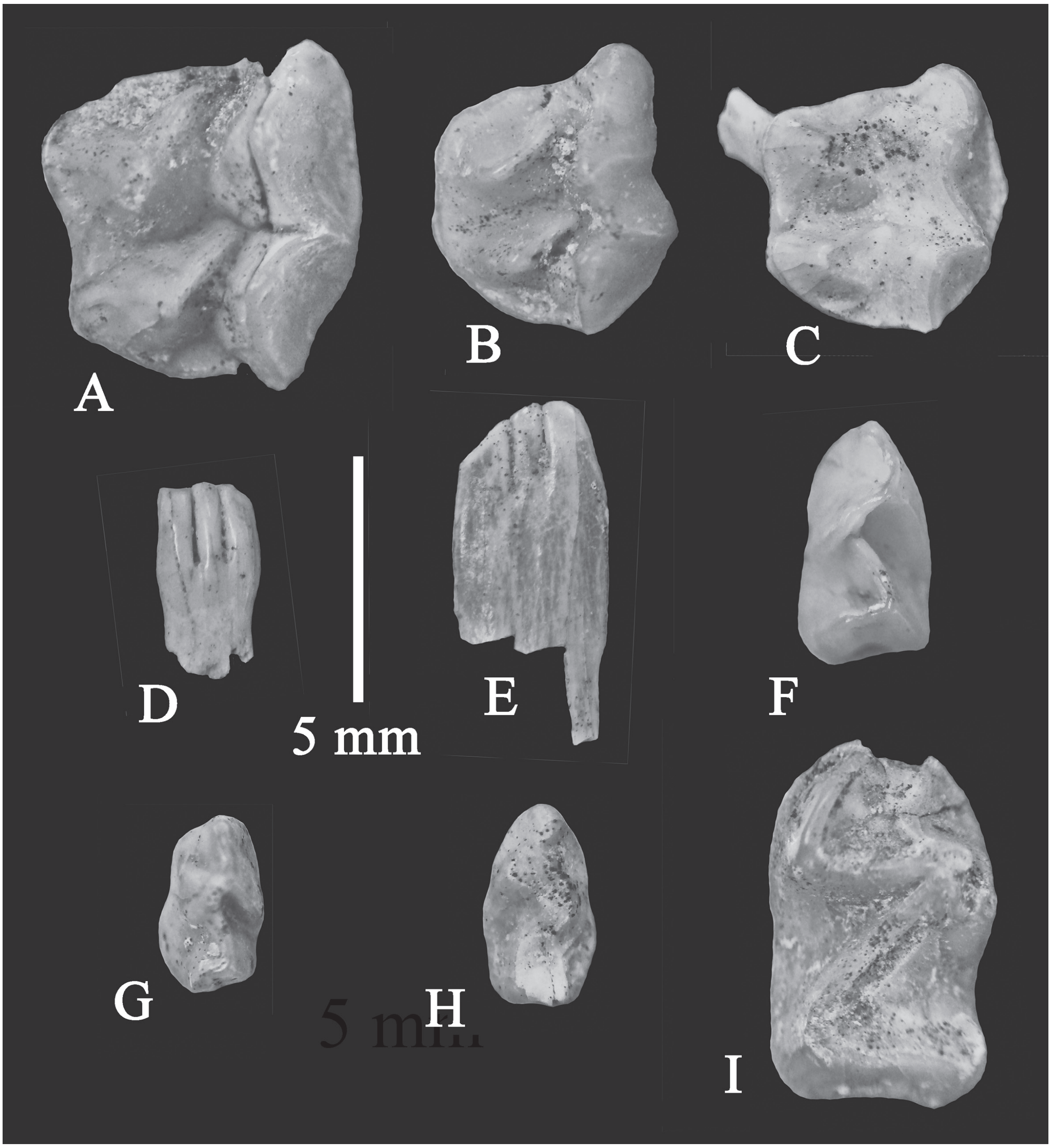


Plate 4. Procaviidae from Berg Aukas, Otavi Mountains, Namibia. BA 1'05, *Heterohyrax auricampensis*, A) left upper molar; B) left upper deciduous molar; C) left upper deciduous molar; D) right di/1; E) left i/2; F) right lower premolar; G) right lower deciduous molar; H) right lower deciduous molar, I) left lower molar.

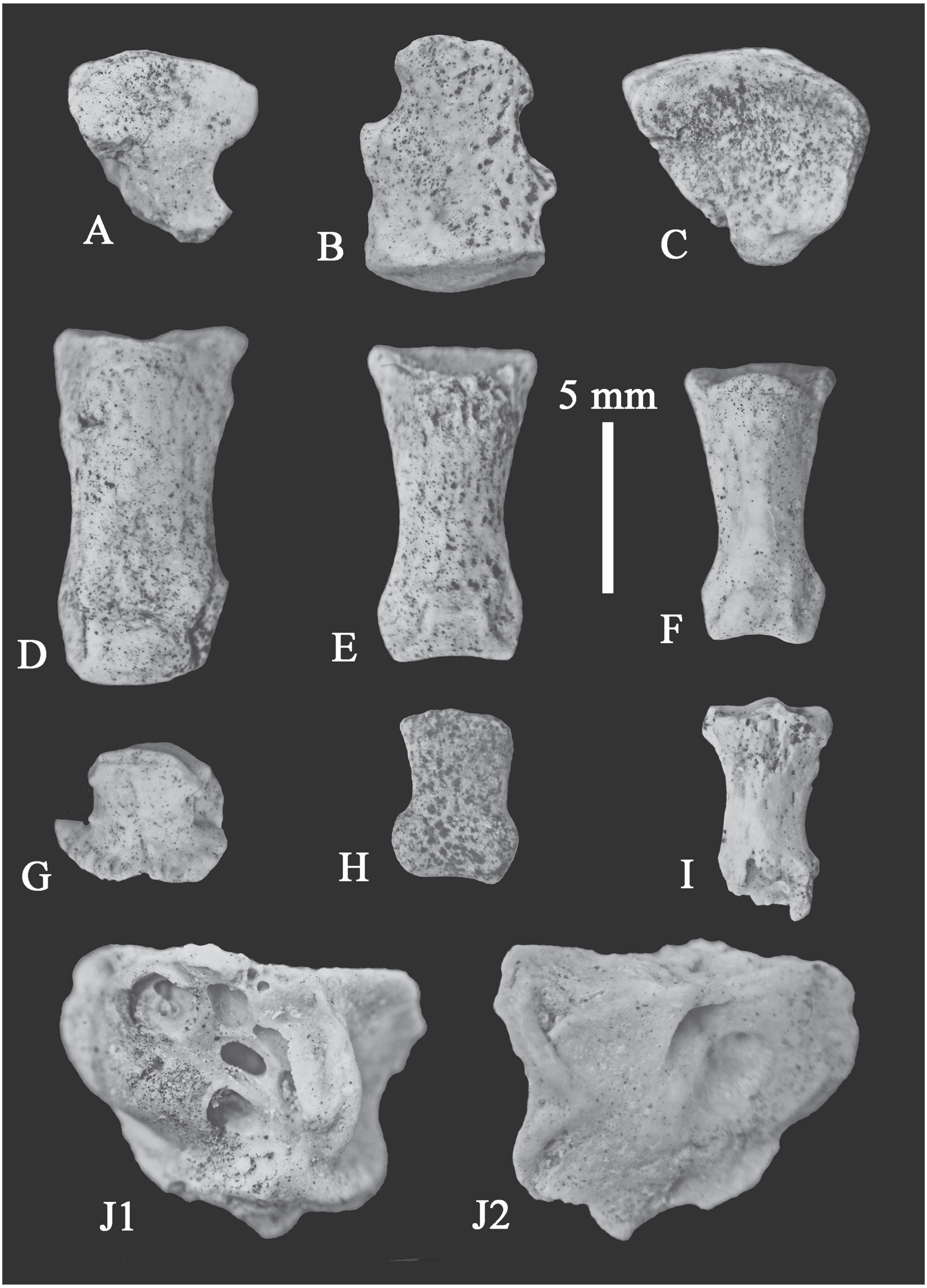


Plate 5. Procaviidae from Berg Aukas, Otavi Mountains, Namibia. *Heterohyrax auricampensis*, BA 1'05, A) metapodial proximal articulation; B) cuboid anterior view; C) navicular; D) first phalanx dorsal view; E) first phalanx dorsal view; F) first phalanx dorsal view; G) ungual phalanx dorsal view; H) second phalanx plantar view; I) second phalanx dorsal view; J) petrosal.

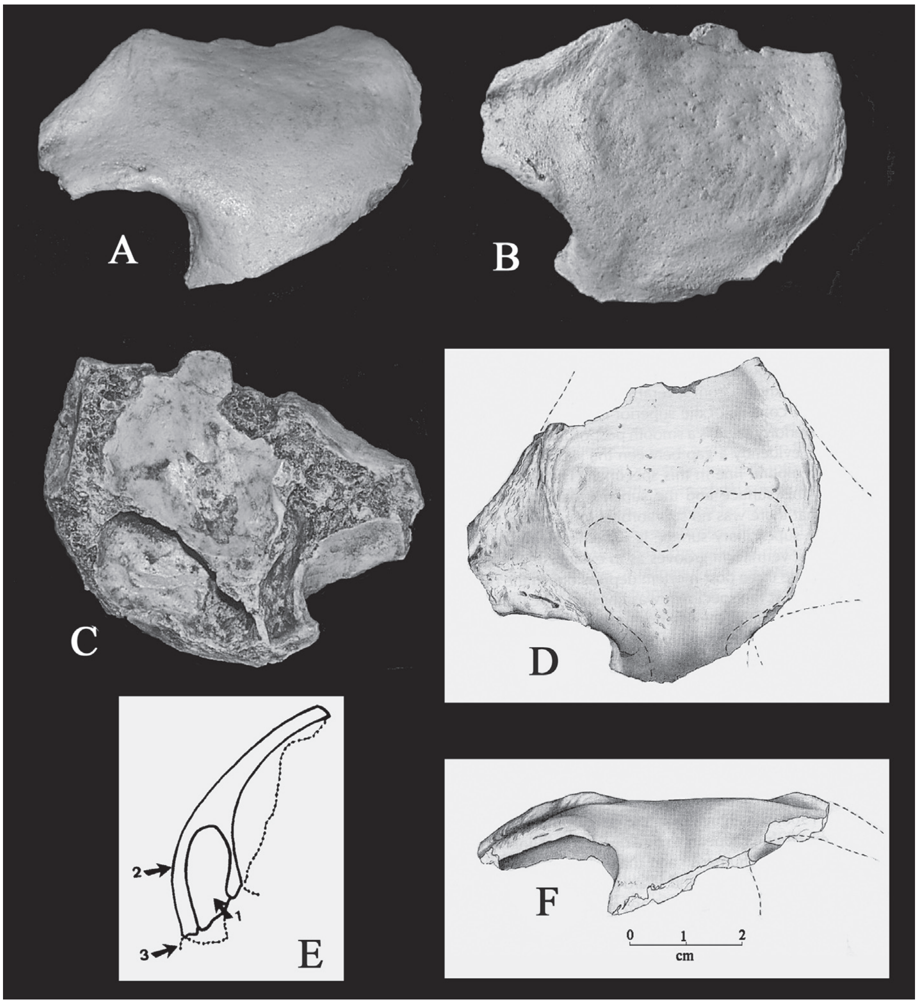


Plate 6. *Otavipithecus namibiensis*, from Berg Aukas, Otavi Mountains, Namibia, frontal bone. A) anterior, B) dorsal, C) internal view, D) interpretive drawing of dorsal view to show extent of frontal sinus, E) sagittal section through frontal to highlight frontal sinus, F) anterior view interpretive drawing to show breadth of nasal pillar.

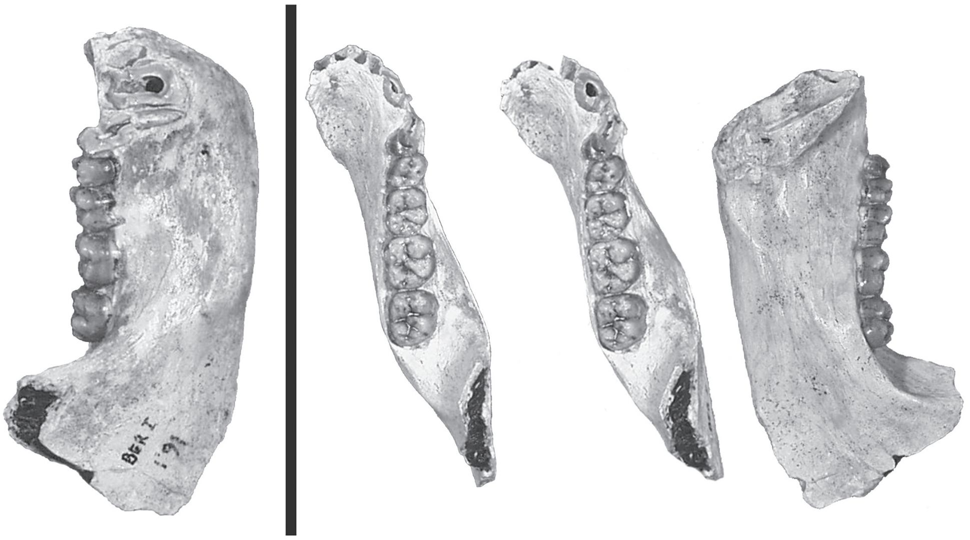


Plate 7. BER I 1'91, holotype right mandible, *Otavipithecus namibiensis*, from Berg Aukas, Otavi Mountains, Namibia, buccal, stereo occlusal, and lingual views. Scale 10 cm.

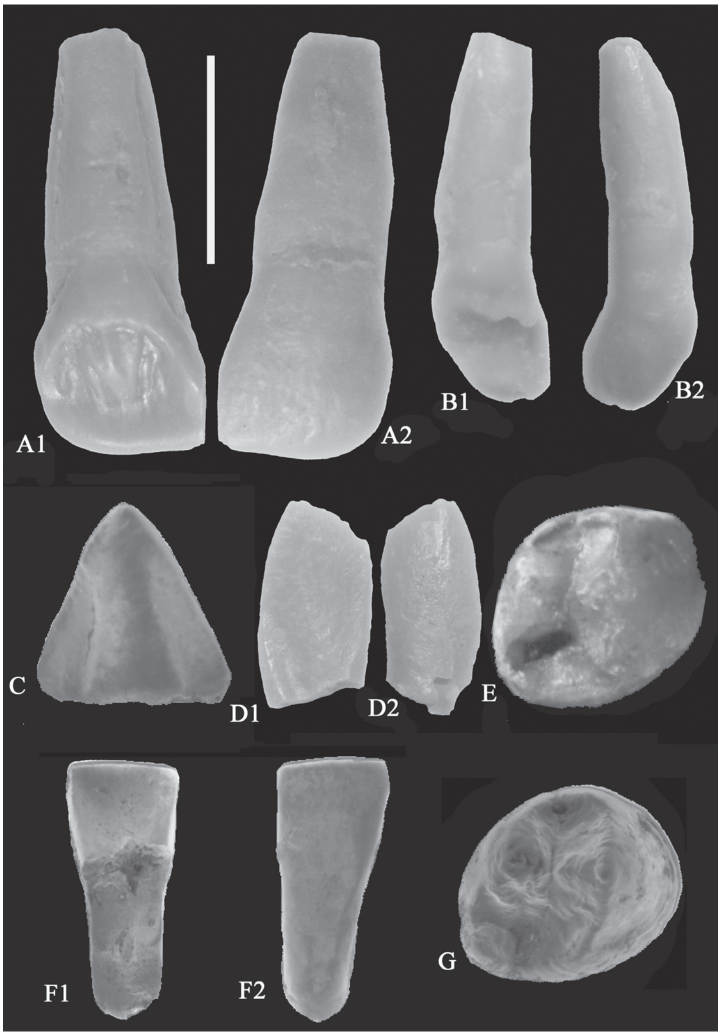


Plate 8. Hominoidea from the Middle Miocene of Berg Aukas, Otavi Mountains, Namibia. A-F) *Otavipithecus namibiensis*, A) left I1/ A1) lingual, A2) labial views; B) left I2/, B1) lingual, B2) labial views; C) lower canine tip;, D) left i/2, D1) lingual, D2) labial views; E) right p/4 occlusal view) F) lower central incisor, F1) lingual, F2) labial views G) *Kenyapithecus* sp., right p/4 occlusal view (scale : 10 mm).

roy *et al.*, 1992a, 1992b, 1993, 1996; Pickford *et al.*, 1994, 1997) (Plates 6-11). Undescribed material consists of a few isolated teeth (Plate 8) found in association with abundant microfaunal remains which indicate an age of ca 13-12 Ma. A lower right p/4 belongs to a second hominoid, here identified as *Kenyapithecus* sp. (Plate 8, G)

Harasib 3a

The fossiliferous breccias of Harasib 3a occur at the summit of a steep hill (Figs 19-20) some 150 metres above the local plains. At the time of their formation, these breccias were close to base level, as shown by the nature of the sediments. The breccias are brick red with abundant locally derived dolomite and pisolitic sandstone clasts, chert nodules and reworked, abraded crystals of descloisite. There are also unabraded crystals of the same mineral suggesting that there are at least two generations of mineralisation of the breccias. The abraded crystals are similar to descloisite that forms in soils overlying rundkarren (Fig. 21) while the euhedral crystals appear to have formed *in situ* in the Harasib 3a aven.

Although the breccia at Harasib has been removed from its original setting by mining activities, the glory hole from which it came contains enough material in place for the determination of the environment of deposition. The quarry is some 20 metres across and 15 to 20 metres deep. The overall appearance of the deposit suggests that it was an aven that never became an open cave, but was rather a sinkhole that filled with sediment as it formed. There are many of these types of aven in the Otavi Mountains, and they often contain disappearing streams. The faunal content of the deposits is in accord with this reconstruction, because there are very few spelean species such as bats. In contrast with Berg Aukas which has yielded tens of thousands of bat fossils, Harasib 3a has yielded barely a dozen specimens. Macroscelideans are however, extremely common at Harasib, being on a par with rodents. The site has also

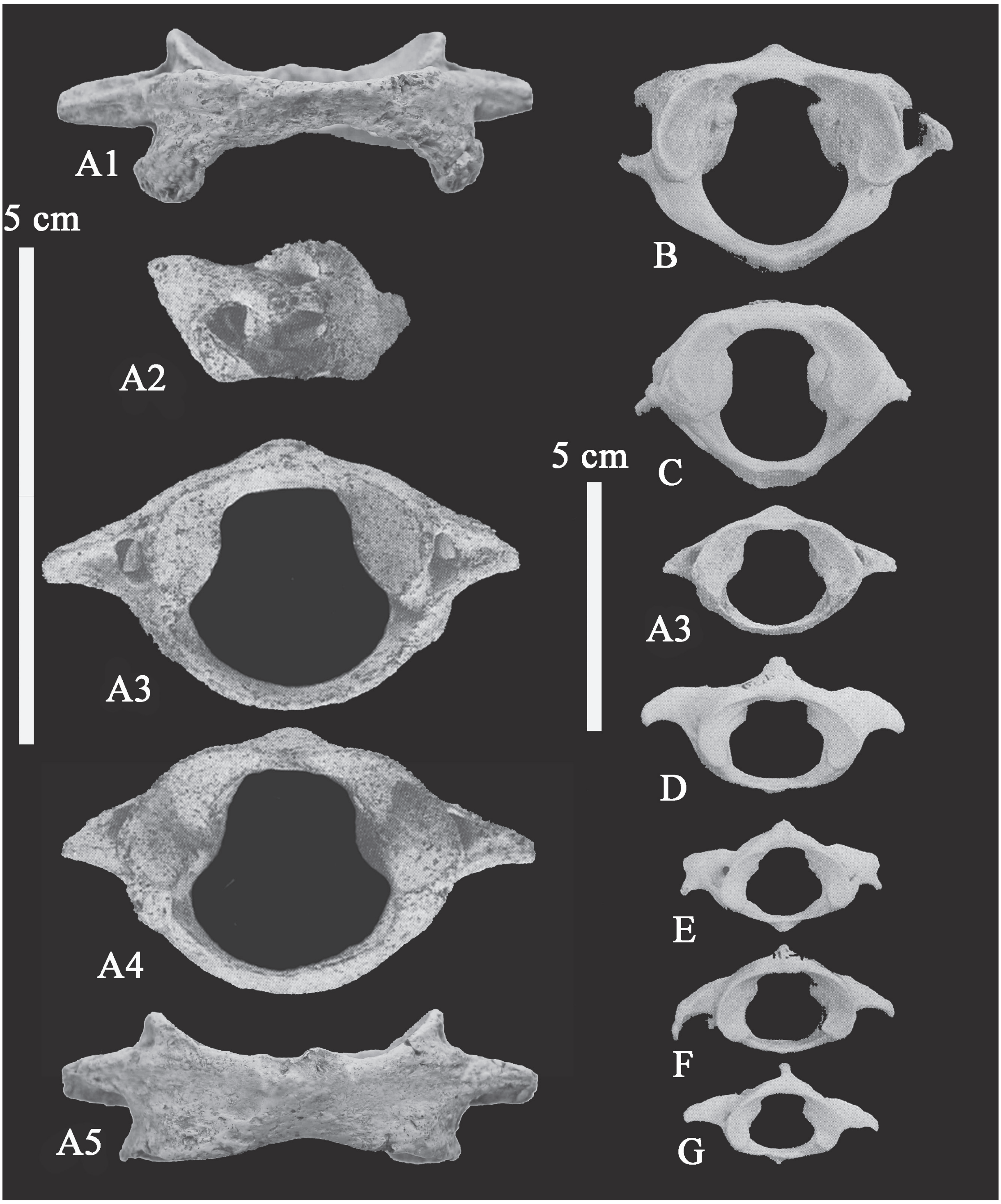


Plate 9. *Otavipithecus namibiensis*, from Berg Aukas, Otavi Mountains, Namibia, BA 104'91, axis vertebra. A1) left lateral, A2) inferior, A3) superior views, B) *Homo*, C) *Pan troglodytes*, D) *Papio ursinus*, E) *Colobus guereza*, F) *Mandrillus sphinx*, G) *Cercopithecus albogularis* (B-G superior views).

yielded several cercopithecid specimens, some bovids and a dozen or so galagid teeth.

If our reconstruction of the environment of deposition is correct, then there can be little doubt that regional down wasting of some 150 metres has occcurred since the Upper Miocene, at a rate of some 15 metres per million years. This is a similar figure to that determined for the Koanaka and Gcwihaba regions of northwestern Botswana (Pickford, 1990).

Jägersquelle

Jägersquelle is a richly fossiliferous locality, notable for the quantity of papionine fossils that it has yielded in coarse breccias that accumulated below a chimney in

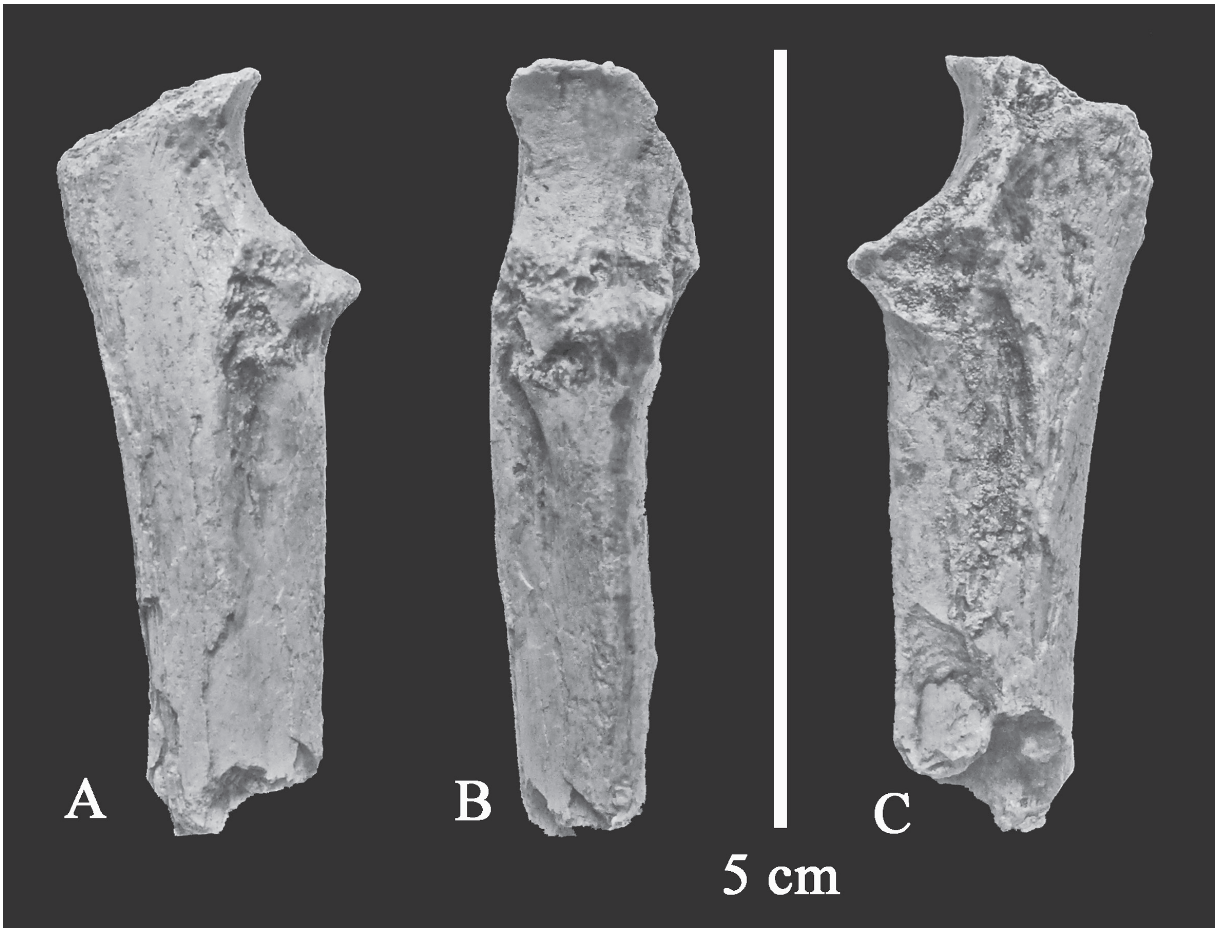


Plate 10. *Otavipithecus namibiensis*, from Berg Aukas, Otavi Mountains, Namibia, BA 4a'91, proximal right ulna, A) lateral, B) anterior and C) medial views.

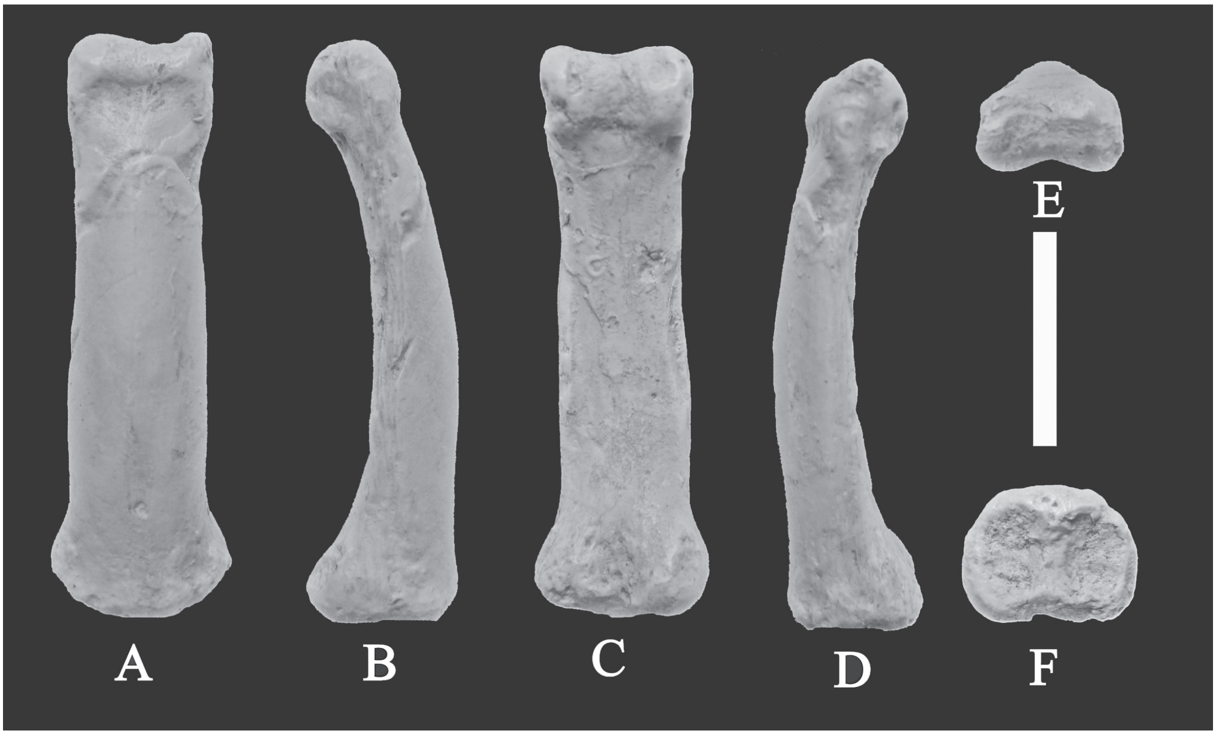


Plate 11. *Otavipithecus namibiensis*, from Berg Aukas, Otavi Mountains, Namibia, BA 23'91 + 20'92, second manual phalanx cast, A) dorsal, B) medial, C) palmar, D) lateral, E) distal, F) proximal views. (scale : 1 cm).

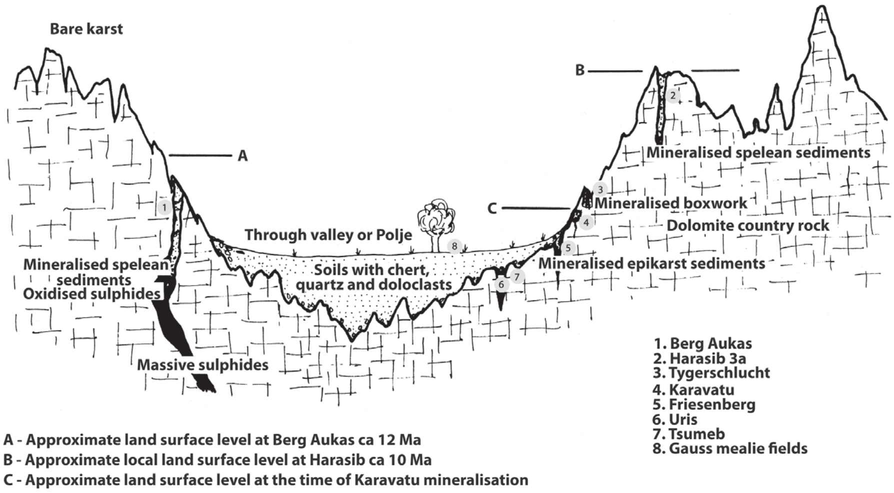


Figure 21.- Reconstruction in section of the geomorphological position of some of the Otavi Mountain vanadium occurrences. The older deposits, such as Berg Aukas and Harasib 3a evidently formed when the surface of the land was appreciably higher than it is now as shown by the nature of the spelean sediments that occur in them. At Berg Aukas it was some 150 metres higher than at present while at Harasib 3a it was about 300 metres higher. Low level deposits such as Friesenberg and Uris appear to have formed below the soils, suggesting that there is potential for the discovery of additional deposits hidden under the soils in poljes, through valleys and other low lying areas of the Otavi Mountains.

the roof of a former cave, the walls and roof of which have long since been eroded away (Fig. 22). Lateral to the coarse breccia there are masses of finer grained pink breccia containing abundant microfauna. At the time of deposition, Jägersquelle was an active cave, in which stalagmites were forming. Some of the baboon skulls are preserved in pure speleothems, while others occur in coarse dolomite breccia.

Much of the sediment at the site has been dolomitised, so that it is insoluble in cold 10% acetic acid. It will dissolve slowly in heated acid, but this treatment tends to cause damage to the fossils. For this reason, the larger specimens from the site must be extracted mechanically.

This locality was apparently found by a school boy over 100 years ago while out hunting. He noted a fossil jaw in the coarse breccia and passed the knowledge on to his father, the owner of the land. Each time that the farm changed hands information about the presence of the fossil was passed on, and it reached the attention of the NPE in 1991 who were told about it by Mrs P. Liebenberg of Nosib Farm. The owner of the farm at this time was Mrs Schickerling, who kindly gave the NPE permission to prospect the site. Excavation was carried out in 1993, by which time the farm had been sold to Mr Jos Van Zyl, who permitted the expedition to remove the material for research purposes. There remains much breccia *in situ* at Jägersquelle and there are abundant blocks of breccia washing down the slope below the former cave.

We estimate that there has been about 15-20 metres of down wasting in the region since the beginning of the Pleistocene. The Plio-Pleistocene breccias accumulated below a hole in the roof of a cave, but the only remain-

Table 6. Faunal List Harasib 3a, Otavi Mountains, Namibia.

- Rhinolophidae
    - *Rhinolophus* sp.
- Tenrecoidea
- Soricidae
- Macroscelididae
- Sciuridae
    - *Heteroxerus karsticus*
- Cricetomyidae
    - *Saccostomus geraadsi*
- Gerbillidae
    - Myocricetodontinae
        - *Mioharimys milleri*
        - *Mioharimys schneideri*
        - ?*Afaromys guillemoti*
    - Petromyscinae
        - *Harimyscus hoali*
    - Namibimyinae
        - *Namibimys angustidens*
- Dendromuridae
    - Dendromurinae
        - *Steatomys harasibensis*
        - *Steatomys jaegeri*
        - *Dendromus denysae*
    - Otavimyinae
        - *Otavimys senegasi*
- Muridae
    - *Aethomys* sp.
    - *Preacomys* cf *kikiae*
    - *Preacomys karsticus*
    - *Preacomys griffini*
- Rhizomyidae or Spalacidae
    - *Nakalimys* cf *lavocati*
    - *Harasibomys petteri*
- Gliridae
    - *Otaviglis daamsi*
- Pedetidae
    - Genus indet.
- Thryonomyidae
    - *Paraphiomys roessneri*
    - *Paraphiomys australis*
    - *Paraulacodus* cf *johanesi*
- Bathyergidae
    - *Proheliophobius* or *Richardus* sp. A
    - *Proheliophobius* or *Richardus* sp. B
- Galagidae
- Cercopithecidae
    - ?*Microcolobus* sp.

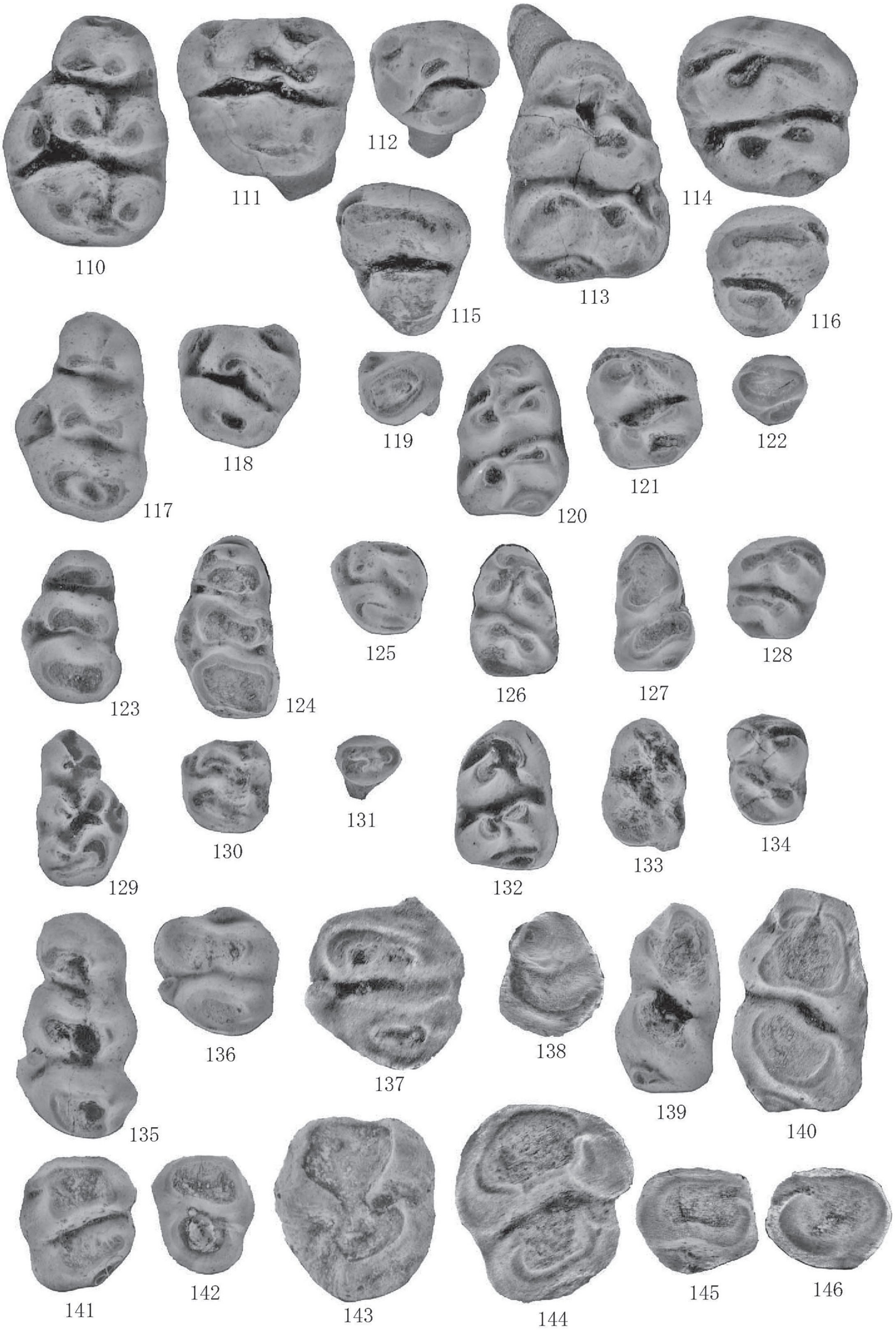


Plate 12. Rodents from Harisib 3a, Otavi Mountains, Namibia. 110-116) *Saccotomus geraadsi*, left M1/, left M2/, right M3/, right m/1, left m/2, left m/3, right m/3 respectively ; 117-122) *Steatomys harasibensis*, left M1/, left M2/, left M3/, left m/1, left m/2, left m/3 respectively ; 123-128) *Steatomys jaegeri*, left M1/, left M1/ left M2/ right m/1, left m/1, right m/2 ; 129-134) *Dendromus denysae*, right M1/, left M2/, right M3/, left m/1, right m/1, left m/2 ; 135-146) *Otavimys senegasi*, left M1/, left M2/, left M2/, left M3/, right m/1, right m/1, left m/2, right m/2, left m/2, left m/2, right m/3, left m/3 respectively.


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Plate 13. Rodents from Harisib 3a, Otavi Mountains, Namibia. 147-148) *Aethomys* sp. right M1/, right m/1 respectively ; 149-153) *Preacomys* cf *kikiae*, right M1/, left M2/, right M3/, left m/1, left m/2 ; 154-159) *Preacomys karsticus*, left M1/, left M2/, left M3/, right m/1, right m/2, left m/3 ; 160-168) *Preacomys griffini*, left M1/-M2/, left M1/, right M1/, left M2/, left M3/, right m/1, right m/1, left m/2, left m/3 respectively ; 169) ?*Afaromys guillemoti*, left M2/.

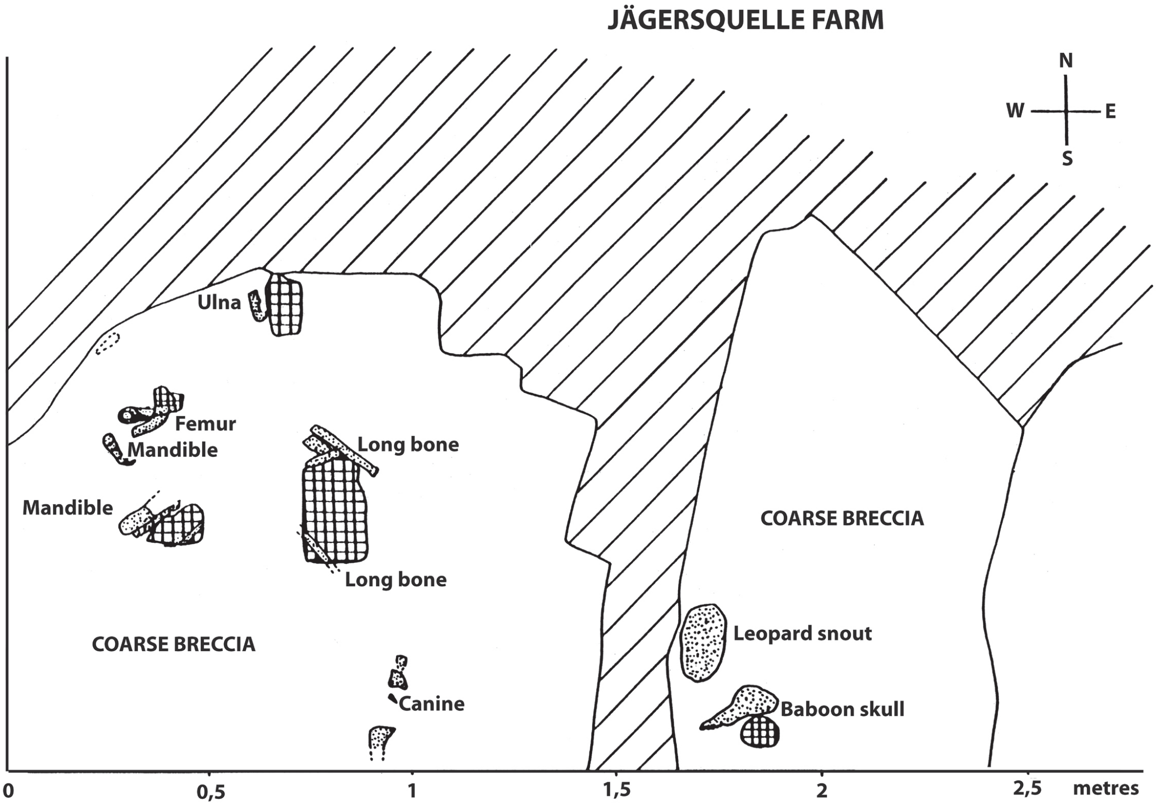

Figure 22.- Jägersquelle fossil site. The plan shows the positions of papionine skulls, jaws and post cranial elements in coarse breccia representing a talus cone in a former cave, the roof and walls of which have eroded away since the period of deposition.

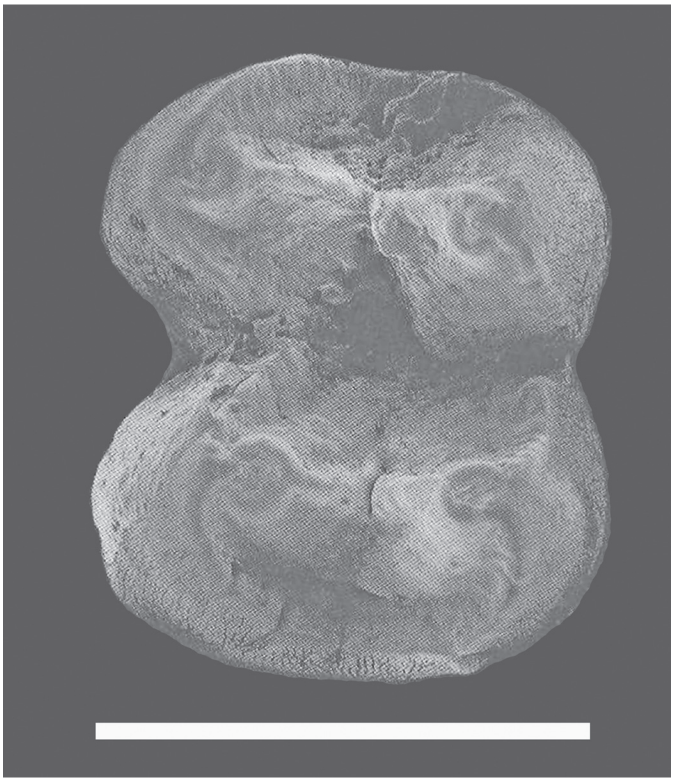

Plate 14. Harisib 3a, Otavi Mountains, Namibia, Colobinae upper molar germ, occlusal view. (Scale 1 cm).

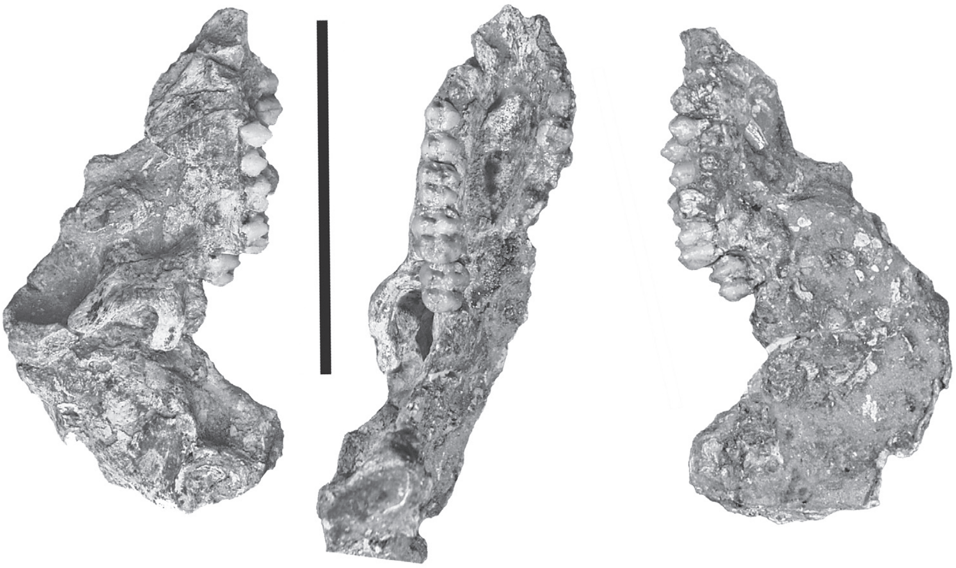

Plate 15. Jagersquelle papionine skull, right lateral, occlusal and left lateral views. (scale 10 cm).

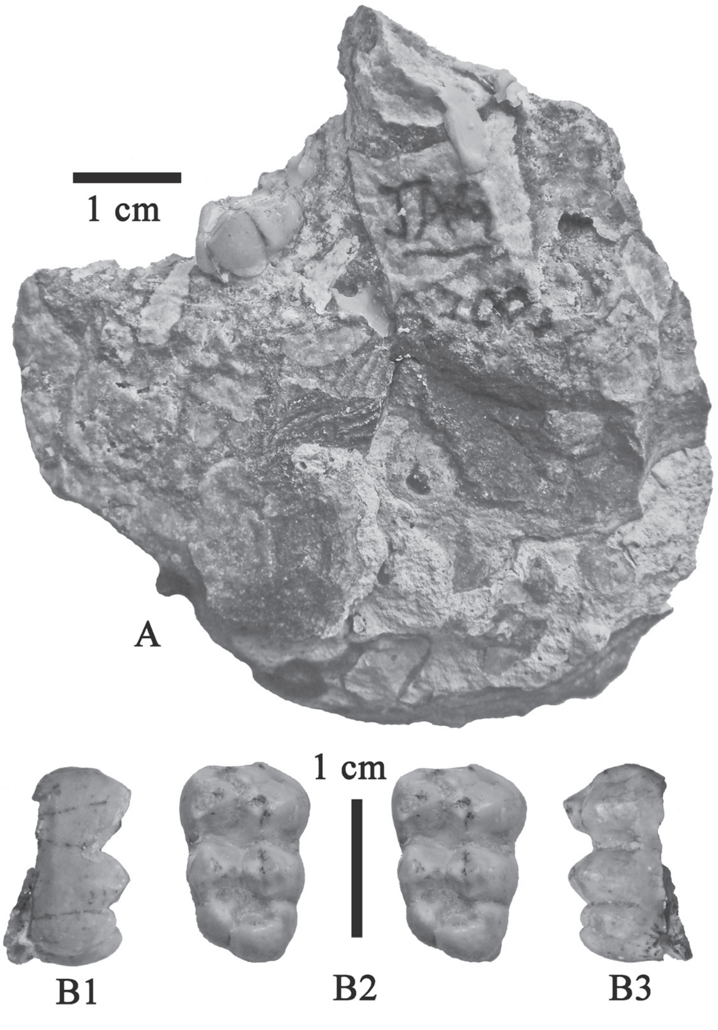

Plate 16. Cercopithecoids from Jägersquelle, Otavi Mountains, Namibia. A) *Parapapio* p/4-m/1 in coarse breccia; B) *Parapapio* sp. isolated right m/3, lingual, stereo occlusal and buccal views.

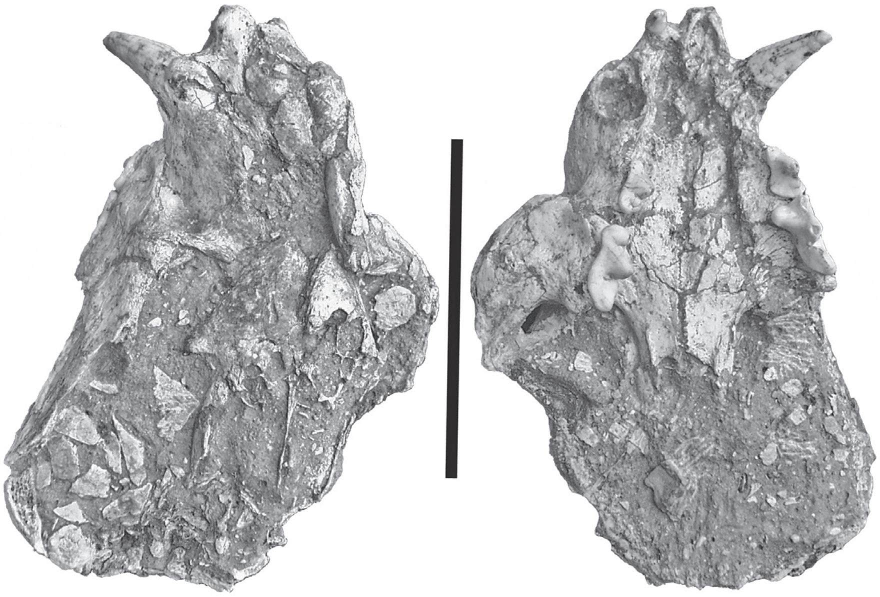

Plate 17. Jägersquelle leopard skull (*Panthera pardus*), dorsal (left) and palatal (right) views. (scale 10 cm).

Table 7. Fauna from Jägersquelle, Otavi Mountains, Namibia.

- Snake
- Lizard
- Bird
- Molossidae
    - *Miniopterus*
- Rhinolophoidea
    - *Rhinolophus*
- Insectivora
    - *Crocidura*
- Macroscelididae
    - 2 species
- Rodentia
    - *Malacothrix*
    - *Steatomys*
    - *Dendromus*
    - *Petromyscinae*
    - *Mystromys*
    - *Gerbillurus*
    - *Otomys*
    - *Acomys*
    - *Mus*
    - *Zelotomys*
    - *Aethomys*
    - *Micaelamys*
    - *Cryptomys*
- Carnivora
    - *Panthera pardus*
- Cercopithecoidea
    - *Parapapio*

ing part of the former cave is its floor, which now forms a resistant platform in the flanks of the hill.

Nosib

The Nosib palaeocave occurs on the flanks of a steep hill not far from the Nosib Aven, a favourite speleological target. There is no sign of a cave left, only breccia blocks and fragments of speleothems which litter the hillside. Parts of the former floor of the palaeocave are preserved, but most of the observed breccia occurs as float in the surface rubble of the hillside. As with Jägersquelle, an appreciable rate of erosion is inferred to have occurred since the Pleistocene when the cave deposits were accumulating. The Nosib faunas comprise predominantly microfauna, but a few large mammal bones, including papionines were found.

Aigamas

The Aigamas breccias occur in a long, metre wide fissure lying above the extant Aigamas Cave. It is evidently part of a former cave which follows approximately the same fracture in the country rock that controls the orientation and position of the extant cave. The breccias crop out for some 150 metres over the hillside above the modern cave, and there are several avens cutting through the red breccia into the cave below. These breccias are impressive, but they are poorly fossiliferous, only a few micromammals having been found in them. These breccias are insoluble in 10% acetic acid.

Also on Aigamas, near the summit of one of the hills south of the farmhouse, there are some fossiliferous epikarst deposits rich in micromammals, but the extent of the deposits is very restricted.

Table 8. Fauna from Nosib, Otavi Mountains, Namibia.

- Amphibia
- Snake
- Bird
- Rhinolophoidea
  - *Rhinolophus*
- Vespertilionidae
- Insectivora
  - *Crocidura* 2 spp.
- Macroscelididae
- Rodentia
  - *Malacothrix*
  - *Staetomys*
  - *Dendromus* 2 spp.
  - *Mystromys*
  - *Stenodontomys*
  - *Tatera*
  - *Gerbillurus*
  - *Otomys*
  - *Mus*
  - *Zelotomys*
  - *Praomys*
  - *Rhabdomys*
  - *Aethomys*
  - *Dasymys*
  - *Graphiurus*
  - *Cryptomys*
- Cercopithecidae
  - Papioninae

Table 9. Fauna from Aigamas, Otavi Mountains, Namibia.

- Snake
- Lizard
- Bird
- Microchiroptera
  - *Miniopterus*
- Insectivora
  - *Crocidura*
- Macroscelididae
- Rodentia
  - *Malacothrix*
  - *Steatomys*
  - *Saccostmus*
  - *Stenodontomys*
  - *Tatera*
  - *Gerbillurus* 2 spp.
  - *Desmodillus*
  - *Thallomys*
  - *Acomys*
  - *Mus*
  - *Zelotomys*
  - *Rhabdomys*
  - *Graphiurus*

Table 10. Fauna from Rietfontein, Otavi Mountains, Namibia.

- Macroscelididae
- Rodentia
- Carnivora
  - *Panthera pardus*
- Hyracoidea
  - *Procavia*
- Bovidae
  - *Oryx*
  - *Antidorcas*

Rietfontein

The presence of fossils at Rietfontein was first noted by Schwellnus (1946) although no detailed work or description of the fossils was ever published. Schwellnus considered that the fossil evidence indicated that vanadium mineralisation probably occurred in the Quaternary period, a good insight considering that the fauna from the site is indeed of Plio-Pleistocene age. In fact the Rietfontein breccias are spelean sediments. There are two kinds of breccia, one of which is insoluble in 10% acetic acid, while the other, younger breccia dissolves readily in the same acid. Micromammals dominate the faunal assemblage at Rietfontein, but unusually for the Otavi breccias, large mammal bones and teeth are quite common. Bovids predominate among the large mammals. Unfortunately, miners have broken the breccia blocks into small chunks in their search for vanadium minerals, so that what used to be relatively complete skulls and limb bones are now broken into hundreds of pieces.

Nearby the main Rietfontein site there is a second locality close to a modern aven. Here pink breccia rich in micromammals crops out which also appear to be of Plio-Pleistocene age.

Friesenberg

At the top of the hillock above the vanadium prospect of Friesenberg (Fig. 15) there are the remains of an ancient cave with enormous quantities of fossiliferous breccia. Most of the fossils belong to micromammals, but there are a few scattered remains of proboscideans and bovids in places. Much of the breccia has eroded out as blocks which litter the surface below the former cave in which it accumulated, but near the summit of the hill, appreciable quantities are still *in situ*. This breccia dissolves readily in 10% acetic acid. As with other Plio-Pleistocene caves in the Otavi Mountains, Friesenberg has very little of the original cave structure preserved. The roof and the downhill and lateral walls have all disappeared, with only a few centimetres of the back wall remaining in place. Even though this cave formed

Table 11. Fauna from Friesenberg, Otavi Mountains, Namibia

- Rodentia
- Macroscelidea
- Carnivora
  - cf *Lycaon* sp.
- Proboscidea
- Bovidae

Table 12. Fauna from Kombat, Otavi Mountains, Namibia

- Megachiroptera
- Rodentia
- Macroscelididae
- Hyracoidea
  - *Procavia*
- Bovidae
  - *Antidorcas*

Plate 18. Fossiliferous red sandy breccia at Rietfontein, Otavi Mountains, Namibia. Note the bovid long bone in the block between the figures.

Plate 19. Breccia dumps at Rietfontein, Otavi Mountains, Namibia.

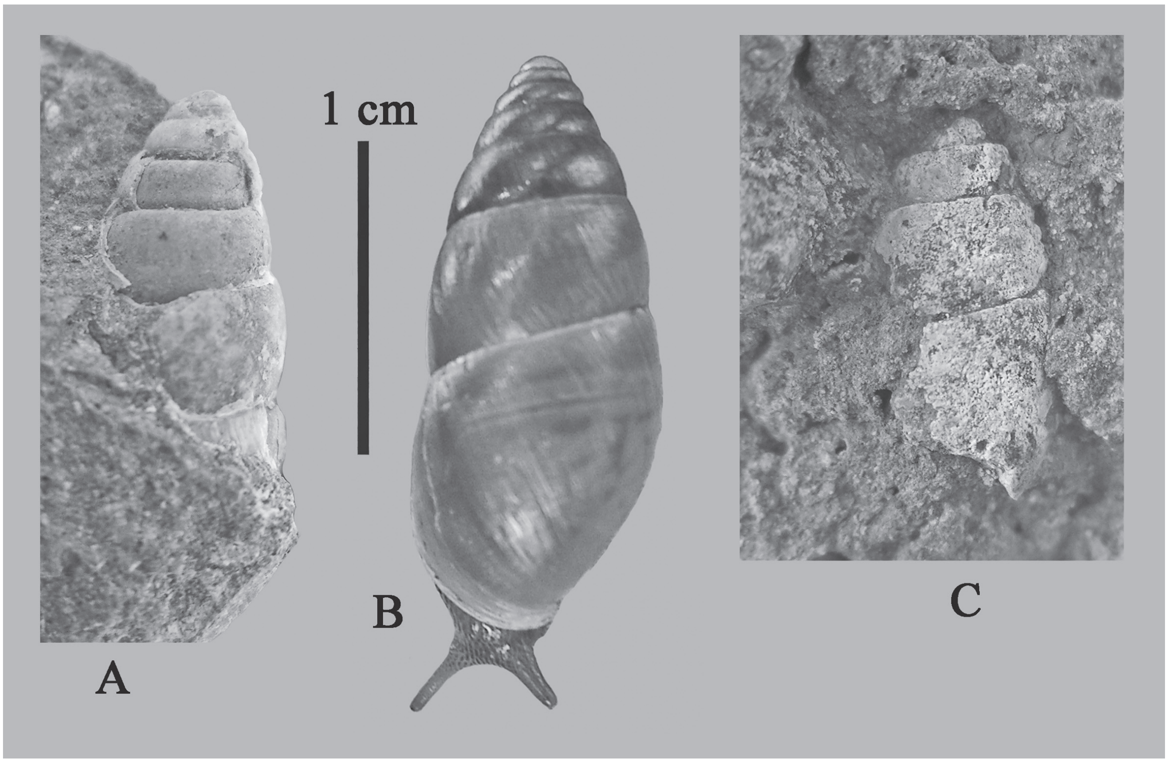

Plate 20. Rietfontein, Otavi Mountains, Namibia, *Xerocerastus burchelli*, two fossils in red sandy breccia, and a living example from Kombat.

Plate 21. Rietfontein, Otavi Mountains, Namibia, leopard (*Panthera pardus*) proximal left ulna, medial, anterior and lateral views

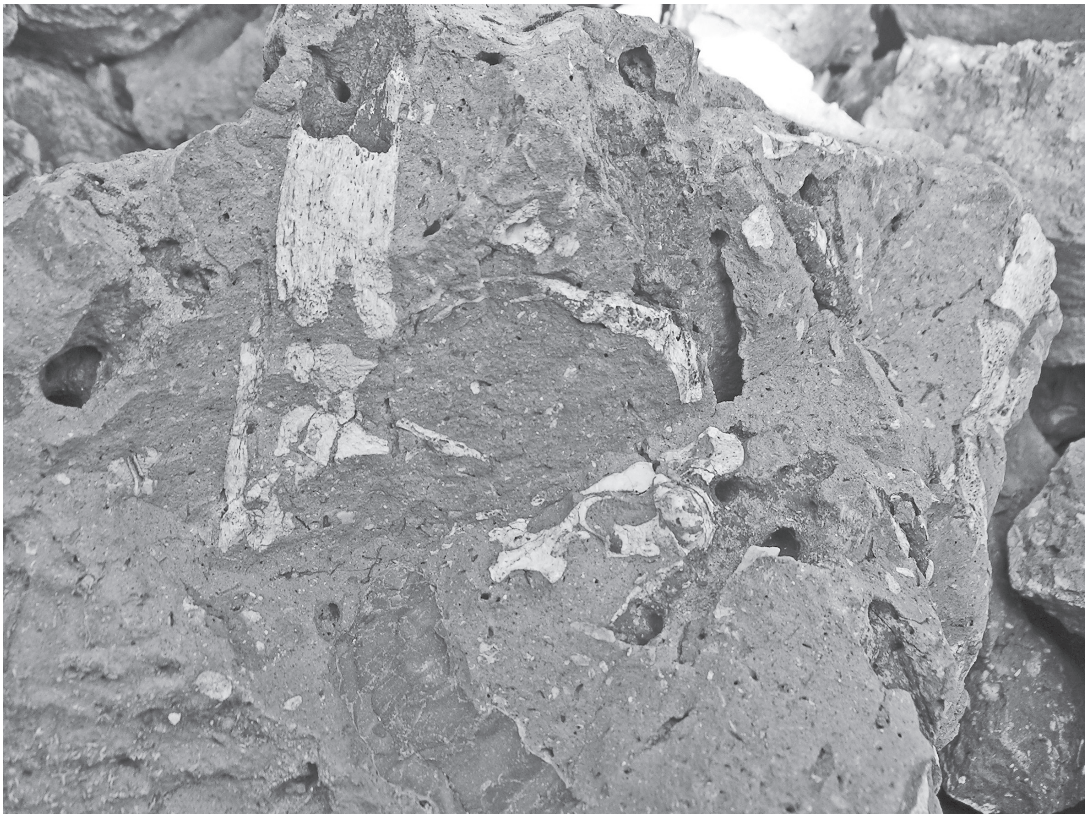

Plate 22. Rietfontein, Otavi Mountains, Namibia, bovid skull in red sandy breccia.

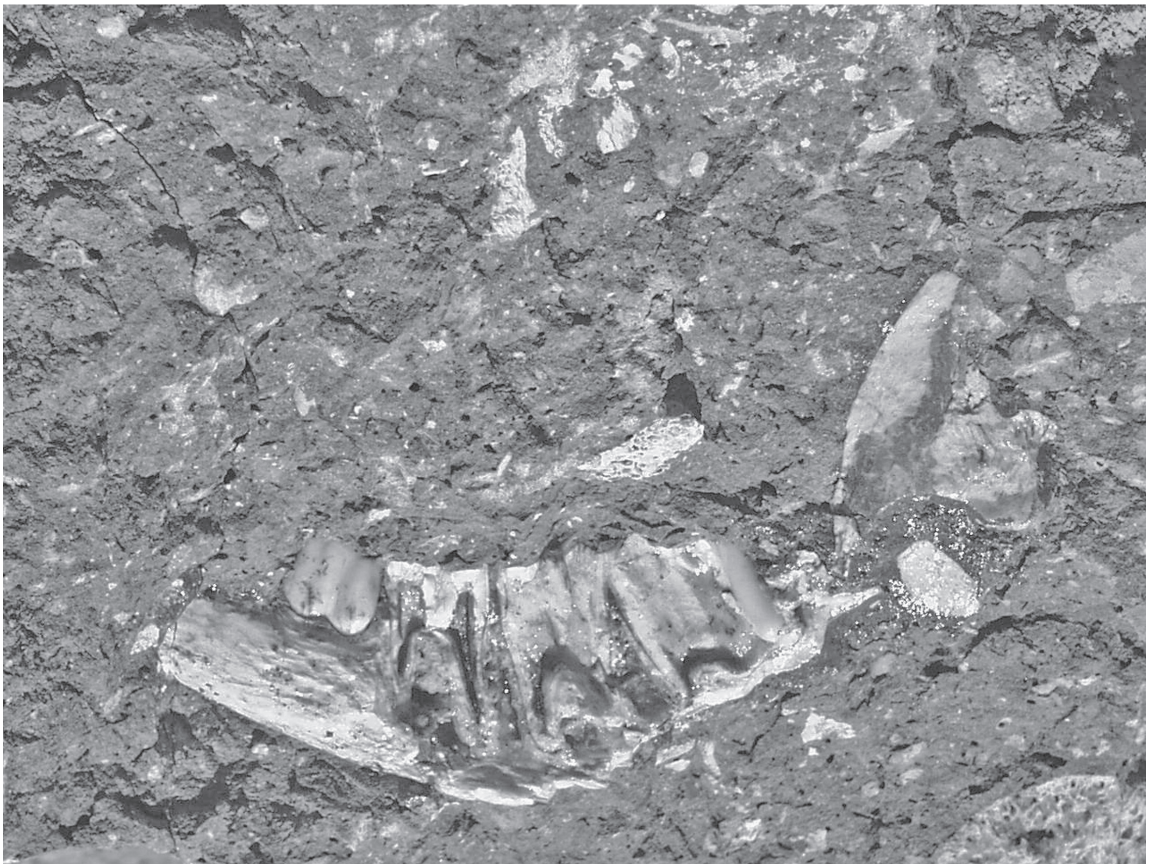

Plate 23. Rietfontein, Otavi Mountains, Namibia, bovid mandible in red sandy breccia.

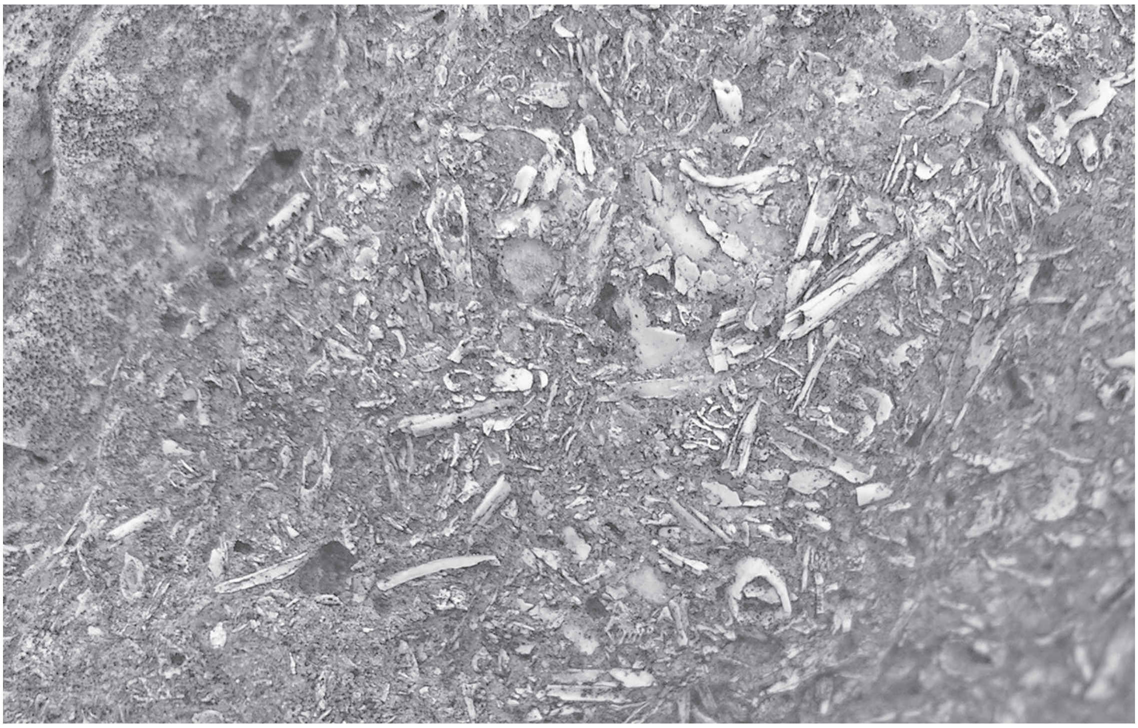

Plate 24. Friesenberg, Otavi Mountains, Namibia, grey sandy breccia containing abundant microfauna.

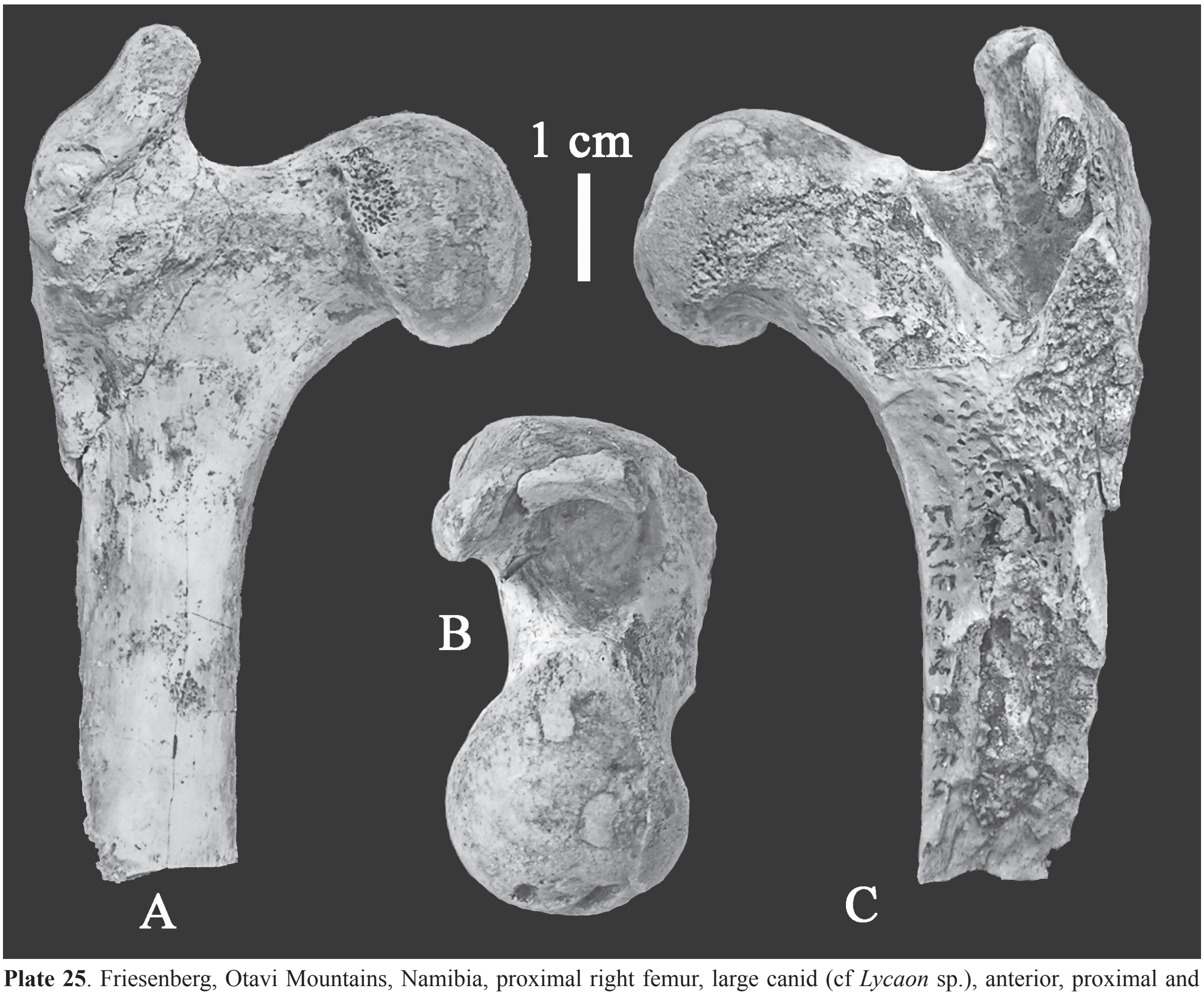

Plate 25. Friesenberg, Otavi Mountains, Namibia, proximal right femur, large canid (cf *Lycaon* sp.), anterior, proximal and posterior views.

Plate 26. View from the fossil site at Kombat E900, westwards towards the headgear of Kombat Mine. Note the thick vegetation typical of relatively undisturbed karstfeld.

near the present hilltop, it is evident that there has been several metres of erosion since the Pleistocene.

Gabus

Gabus is a series of epikarst fissures exposed in the walls of a quarry. These fissures contain reworked soil and clasts from the surrounding country rock which have been extensively burrowed by termites which have built a network of tubes through the breccia. In places at Gabus there are patches of flowstone and these can yield rich assemblages of gastropods including *Acha-*

Table 13. Fossiliferous localities and faunal content : Kaokoland, 1992.

Locality	**Depositional environment**	**Fauna**	**Age**
Rocky I	Valley fill breccia	Giraffidae, Bovidae, gastropods	Pleistocene
Rocky II	Fissure filling	*Rhinolophus*, Molossidae, *Elephantulus, Crocidura*, Leporidae, *Procavia*, Microchiroptera, *Pedetes*, 3 Muridae, *Steatomys, Malacothrix*, Gastropoda	Pleistocene
Rocky III	Cave rampart breccia	Bovidae, Giraffidae, *Otomys, Tatera, Aethomys*, ?*Steatomys*, Dendromuridae, *Crocidura, Elephantulus*, Microchiroptera, Centipede, Gastropods, Artefacts	Pleistocene
Rocky IV	Epikarst breccia	Bovidae, Gastropods	Pleistocene
Ondera	Fissure filling	*Procavia, Achatina, Xerocerastus, Truncatellina*	Pleistocene
Otjimatemba S	Fissure filling	Gastropods	Pleistocene
Otjimatemba N	Epikarst fillings	Gastropods	Pleistocene
Robbie’s Pass	Cave breccia	Gastropods	Pleistocene
Erova	Epikarst fillings	Gastropods	Pleistocene
Sesfontein	Lake beds	Molluscs, Artefacts	Pleistocene
Warmquelle	Travertine	Plants, freshwater snails	Pleistocene
S. of Warmquelle	Travertine Cliffs	Plants, Artefacts	Pleistocene

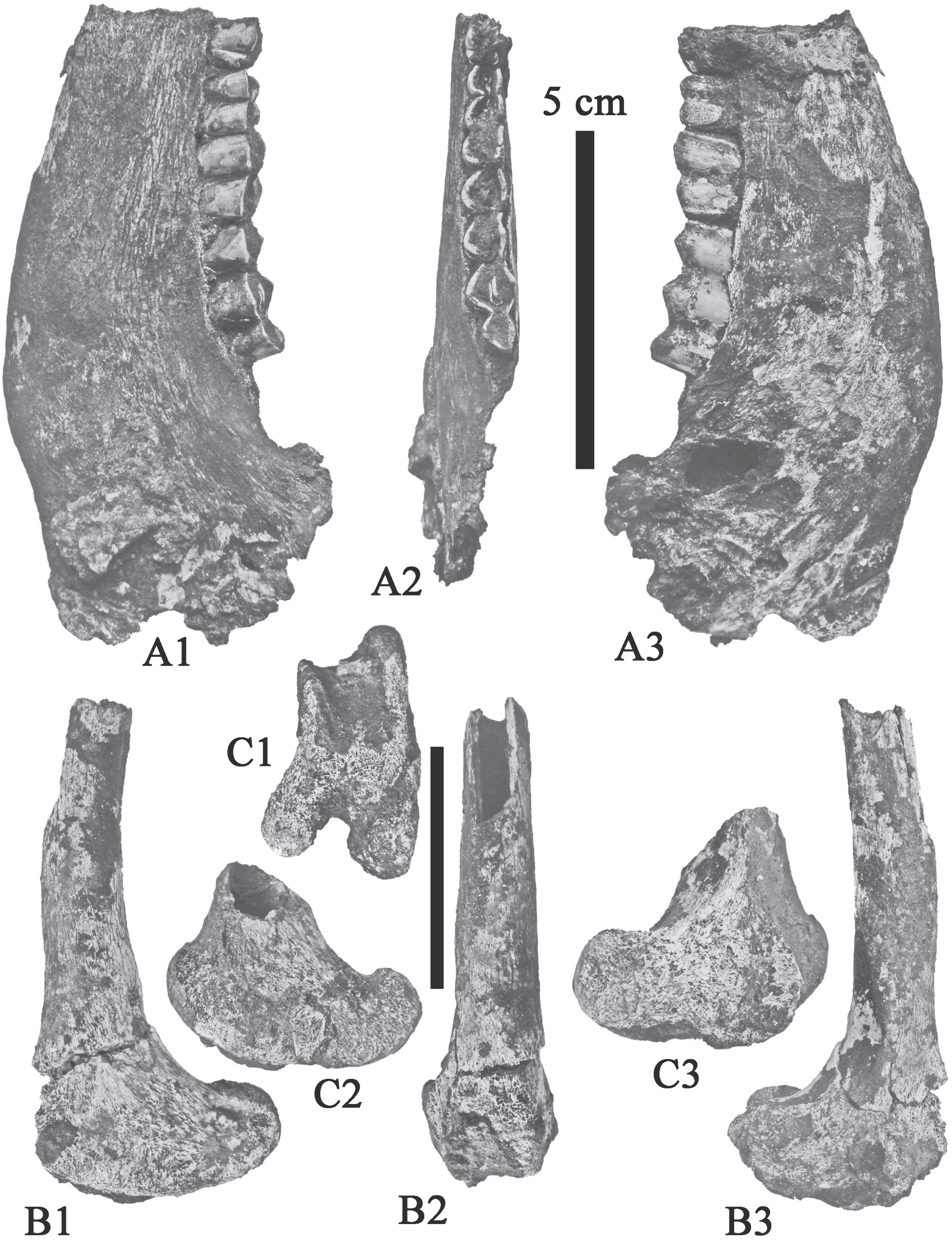

Plate 27. Mammals from Asis Ost, Otavi Mountains, Namibia. A) bovid left mandible containing p/4-m/3, buccal, occlusal and lingual views; B) bovid distal femur; C) bovid distal femur (scale : 5 cm).

tina, *Xerocerastus* and *Sculptaria*. No mammals were found at Gabus.

Asis Ost and Kombat E 900

The fossiliferous breccias at Asis Ost and Kombat E 900 occur in epikarst settings so rich in copper that many of the fossils are stained blue or green. The breccia itself is dark brown to black and dissolves readily in acetic acid. This deposit was first noted by Robinson (1959) but none of the fossils collected was ever described. More recently, F. E. Grine collected some fossils from the site and identified a Recent assemblage of mammals including springbok (*Antidorcas*) among other large mammals. The NPE collected a few samples of breccia which yielded remains of hyracoids (*Procavia capensis*), bovids, rodents and macroscelideans.

The Asis Ost and Kombat breccias are evidently of Recent age.

Kaokoland karsts

Only a minor portion of the immense Kaokoland karst has been prospected for fossiliferous breccia. The potential of the region is evidently great, since new deposits were found each field season spent there, even though the conditions for search are far from easy. All the sites found thus far are of Plio-Pleistocene age (Table 13).

Tim's Cave (13°59'E : 17°47'S)

With the help of Dr and Mrs E. Freyer, fossiliferous breccia was discovered at Tim's Cave, a small cavern in dolomites northeast of Opuwo. The dolomites at the cave entrance dip vertically, and the cavern follows the trend of a particularly soluble horizon. Following this layer westwards led to the discovery of two other caves with breccia, but in both these cases the breccia was unfossiliferous.

Tim's Cave is a small cavern with three main chambers following a horizon of easily soluble dolomite. The same area was the site of a former cave during the Plio-Pleistocene, the former cave floor sediments now forming the roof of the extant cave. An outcrop of pink and grey breccia some 10 metres long and 2 metres wide is sparsely fossiliferous and has yielded a faunal assemblage typical of post-Miocene times. Identified mammals include *Lepus*, *Otomys*, a large murid rodent and *Procavia*. An epikarst breccia nearby yielded the shells of *Xerocerastus*.

Inside the cave at a depth of about 15 metres there are speleothems and layers of pink breccia which are probably younger than the breccia exposed at the surface.

At present, Tim's Cave is inhabited by bats, owls and hyrax. Baboons often enter the cave, judging by the large piles of dung at the bottom. Animals sometimes fall into the cave where they are trapped, as witnessed by kudu, python and baboon skeletons.

Rocky (13°41'15"E : 17°48'02"S)

The Rocky area is so named because of the cliffs of dolomite that crop out in the area, marked as 'Rocky' on the topographic sheet of the region. Rocky I is an epikarst deposit which accumulated in a shallow valley draining the southern slopes of the hills. It contains a few macromammalian remains of Recent aspect. Rocky II is a fissure filling near the summit of the cliffs. Although the fissure was of small size, only a few metres long by half a metre wide, it yielded a rich faunal assemblage of small and medium sized mammals. Among the latter were abundant hyracoids (*Procavia capensis*) and lagomorphs (*Bunolagus* sp.) It is evidently broadly of Plio-Pleistocene age. This site also yielded a variety of gastropods including *Xerocerastus* and *Sculptaria*.

Rocky III comprises a hillslope breccia below the mouth of a large cave. It is poorly fossiliferous but did yield rodents, bovids, gastropods and a centipede. Rocky IV is an epikarst deposit on the opposite side of the valley from the cave which yielded a bovid fossil and some gastropods.

Ondera (13°38'50"E : 18°39'05"S)

Near Ondera waterhole, there is a low dolomite hill traversed by a mass of pink breccia. Even though this breccia accumulated in a former cave, it is remarkable because of the lack of fossils in it. All that the NPE found was a hyracoid mandible (*Procavia capensis*) and some gastropods (*Xerocerastus*).

Other localities

Several other karst infillings were found in Kaokoland, but these proved to contain gastropods, but no mammals. The main occurrences are at Otjimatemba, Robbie's Pass, and Erova (Table 5) and all are Pleistocene to Recent in age.

Pan deposits

Soavis and Abenab

In many parts of the low lying countryside surrounding the Otavi Mountains, there are calcareous deposits which accumulated near springs and in pans. These deposits often contain fossil freshwater snails and occasionally yield fossil mammals. Soavis is one such site which has yielded bovid teeth and bones, while Abenab is another which has yielded fossil warthog teeth (*Phacochoerus* sp.) (Pia, 1930). Most of these pan deposits are late Pleistocene to Recent in age.

Calcretes

Otavi, Aha and Kaokoland Regions

There are extensive but thin deposits of calcrete scattered throughout the Otavi Mountains and surrounding countryside. In many places these calcretes contain fossil terrestrial gastropods such as *Achatina, Xerocerastus* and *Sculptaria*, all of which are taxa which occur in the region today. There can be little doubt that most if not

Table 14. Fossiliferous karstic localities of Kaokoland

Locality	**Co-ordinates Latitude Longitude**	**Estimated Age**	**Sedimentary environment**	**Faunal content**
Rocky I	17°48'07"S 13°41'55"E	Late Pleistocene	Epikarst valley fill breccia	Giraffidae, Bovidae, gastropods
Rocky II	17°48'02"S 13°41'15"E	Pleistocene	Fissure filling	Bats, Macroscelidids, Insectivores, Leporids, Hyracoidea, Rodents, gastropods
Rocky III	17°47'55"S 13°41'21"E	Late Pleistocene	Cave rampart breccia	Bovidae, Giraffidae, bats, rodents, centipede, gastropods
Rocky IV	17°48'00"S 13°41'35"E	Pleistocene	Epikarst breccia	Bovidae, gastropods
Ondera	18°39'15"S 13°38'50"E	Pleistocene	Fissure filling	Hyracoidea, gastropods
Otjimatemba S		Pleistocene	Fissure filling	Gastropods
Otjimatemba N		Pleistocene	Epikarst infilling	Gastropods
Robbie's Pass		Pleistocene	Cave breccia	Gastropods
Tim's Cave	17°47'S 13°59'E	Pleistocene	Spelean	Microfauna
Erova		Pleistocene	Epikarst infilling	Gastropods

all of these calcretes are of Pleistocene to Recent age. Similar calcretes and epikarst deposits occur in the Aha Hills on the Namibian-Botswana border and in the Kaokoland.

Palaeoclimatology and palaeoenvironments

At present the Otavi Mountains are semi-arid, with summer rainfall (Fig. 12). The flora and fauna is typical of steppe to savanna settings with bovids such as kudu and eland, monkeys such as the vervet (*Cercopithecus aethiops*), bushbabies (*Galago moholi*), hyracoids, warthogs and various rodents, insectivores and macroscelideans. Among the rodents there are both ground and tree squirrels (Stuart and Stuart, 1988).

At present the growing season in northern Namibia is about 3-5 months depending on the rainfall which is highly variable from year to year. In the Middle Miocene, it is evident from the fossils preserved at Berg Aukas that the climate was appreciably more humid and tropical than it is now (Fig. 14, 24). Not only could hominoid primates live in the area, but the fossil teeth found up to now belong to thin enamelled forms which were probably obligate soft fruit eaters. The deposits have also yielded abundant and diverse squirrels, and a high diversity of bats. Taken together, the Berg Aukas Middle Miocene faunas suggest that the growing season was perhaps more than 9 months per year, which would mean that rainfall occurred almost throughout the year. If this is so, then the region would have enjoyed a much more tropical climate, perhaps akin to that of parts of northern Angola and Zaire. It is doubtful that the region was covered in tropical rainforest, and the most likely vegetation type would have been of the kind that today occurs in the regional transition (X in Figs 10-11) between the Guinean (I in Figs 10-11) and Zambesian (II in Figs 10-11) centres of endemism (White, 1986).

All the fossil gastropods found in karst and epikarst deposits of the Otavi region are of Late Pleistocene to Recent age. *Xerocerastus* (Fig. 25) and *Achatina* are widespread taxa that occur in savanna to woodland throughout much of mid-latitude Africa (Van Bruggen, 1969). *Sculptaria* (Fig. 26) is endemic to Namibia and at present it occurs within the Otavi Mountains.

By the Plio-Pleistocene, the Berg Aukas and other Otavi faunas suggest that the climate had already become semi-arid. The timing of the transition from tropical humid to sub-tropical sub-humid conditions has not yet been precisely determined.

Geomorphology

The geomorphology of the Otavi Mountains was well described by Schneiderhöhn (1921, 1929). The main contribution that the Namibia Palaeontology Expedition has made to Otavi geomorphology is to determine the rates of down wasting of the dolomites. Basing our estimates on the position of spelean sediments above modern base levels we estimate a figure of some 15 metres of down wasting per million years. This figure has been reached for Upper Miocene and Plio-Pleistocene localities. However, given the amount of relief in the Otavi Mountains, erosion was not uniform, some areas such as Berg Aukas experiencing rates of down wasting lower than this, perhaps as low as 3 metres per million years. Pickford (1990) estimated a similar rate of down wasting in the Gcwihaba and Koanaka Hills, northwestern Botswana.

Rates of carbonate downwasting in the Johannesburg-Pretoria region and in the High Plateau of Angola were apparently much lower than in the Otavi region. Many of the Plio-Pleistocene caves in South Africa

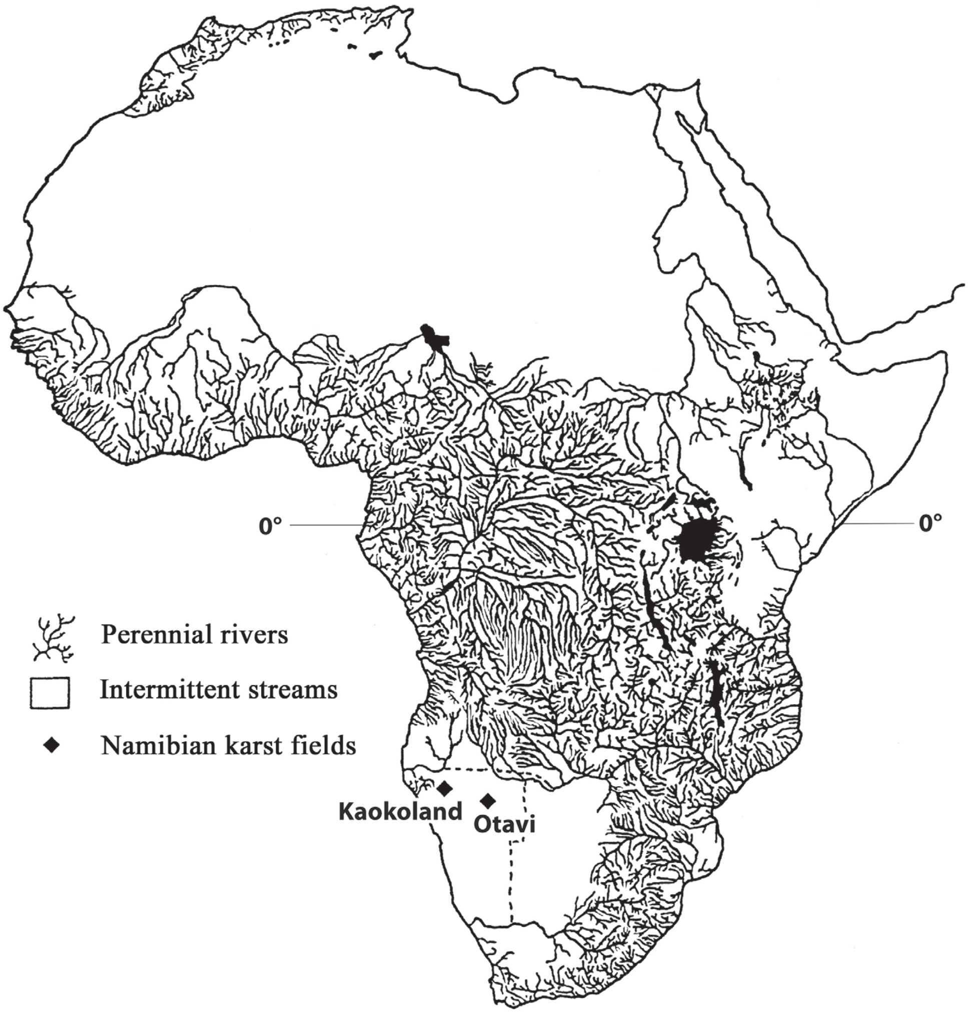

Figure 23.- Perennial rivers and deserts of Africa. Namibia lies in the southwestern arid zone. The Otavi Mountains and Kaokoland (diamonds) are semi-arid to arid, yet faunal evidence from Otavi indicates that it was appreciably more humid during the latter part of the Middle Miocene.

and Angola still have their walls and roofs, proving that rates of erosion were much lower in these regions. The reasons for the major differences are not clear, but the climate must play an important role, erosion being much more rapid in semi-arid settings than it is in more humid places.

Tectonics

Very little evidence of tectonic activity was noted during the NPE survey. Perhaps the main item of interest is the idea that the Waterberg Thrust was active during the Tertiary, and that one of the effects of this tectonic activity was to uplift the Otavi Mountains, thereby exposing them to subaerial erosion. Prior to the uplift, there was possibly a plain in the Otavi region, as revealed by the concordance of isolated summits in the Central Otavi Mountains. The region has since been deeply incised and subjected to regional downwasting.

Geochronology

An important result of the Namibia Palaeontology Expedition has been the determination of the periods of spelean activity in the Otavi Mountains. Whilst some of the deposits such as Baltika and Abenab West remain undated, others such as Berg Aukas, Harasib 3a and Jägersquelle have yielded faunas of relatively precise biostratigraphic affinities. Indeed, Berg Aukas has yielded at least seven types of breccia containing faunas of different ages, spanning the late Middle Miocene to Recent period (13-0 Ma) (Table 5). Nowhere else in Africa has such a complete succession of microfaunas been found. The sequence is so rich that it will take much effort spread out over several years to complete the studies. Provisional results have already been published (Pickford *et al.*, 1993) and there will undoubtedly be some refinement of the time scale.

A second major discovery was that of Harasib 3a which is of Upper Miocene age. It has yielded an ex-

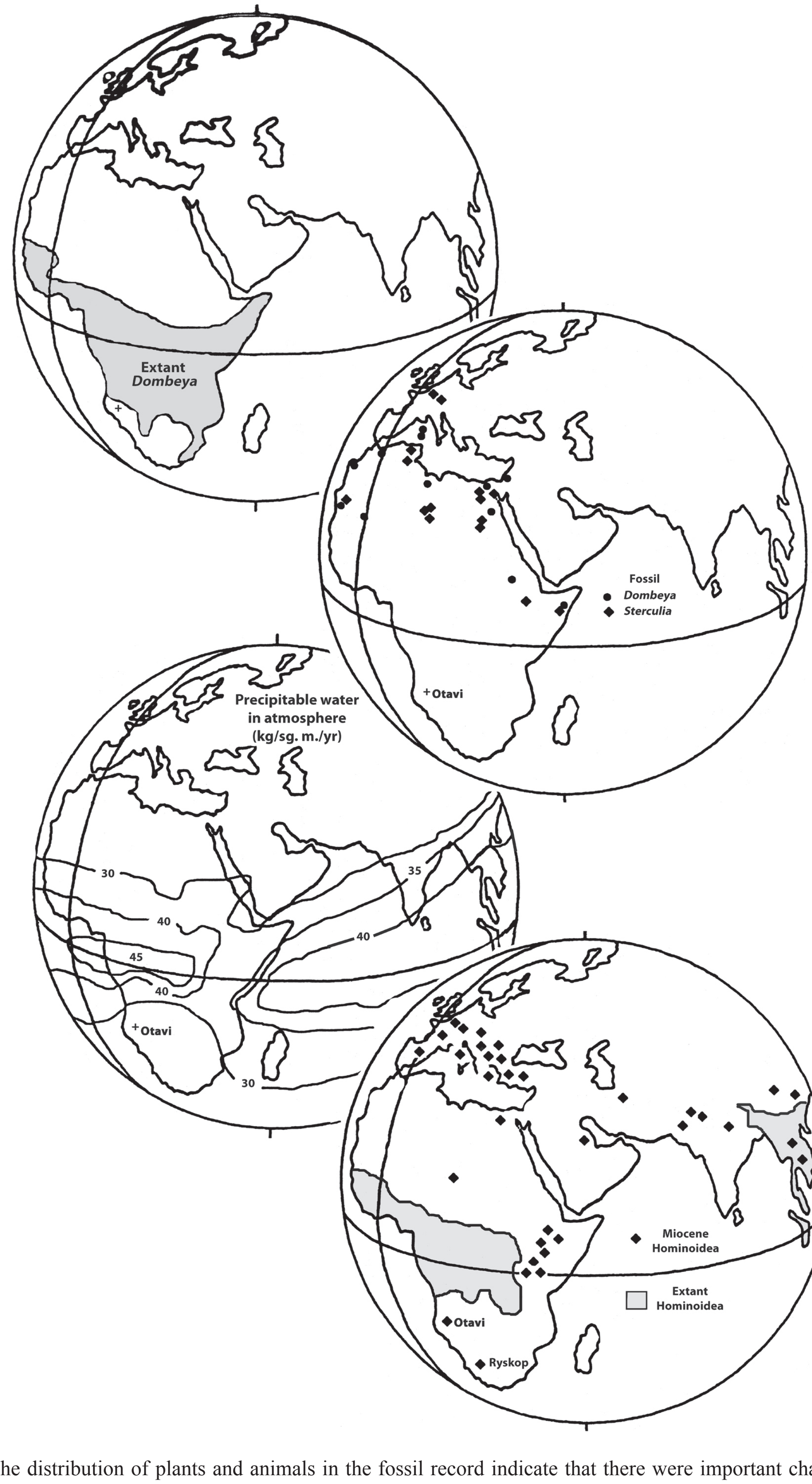

Figure 24. The distribution of plants and animals in the fossil record indicate that there were important changes in African palaeoclimates during the Miocene. The distribution of the Cocoa tree (*Dombeya*) and of hominoids, indicates that northern half of the continent was considerably more humid in the middle Miocene than it is today. The same can be said of the Otavi Mountainland. Precipitable water in the atmosphere shows a strong latitudinal control, and it is clear that, during the Middle Miocene, the humid tropical belt was appreciably broader latitudinally speaking than it is today.

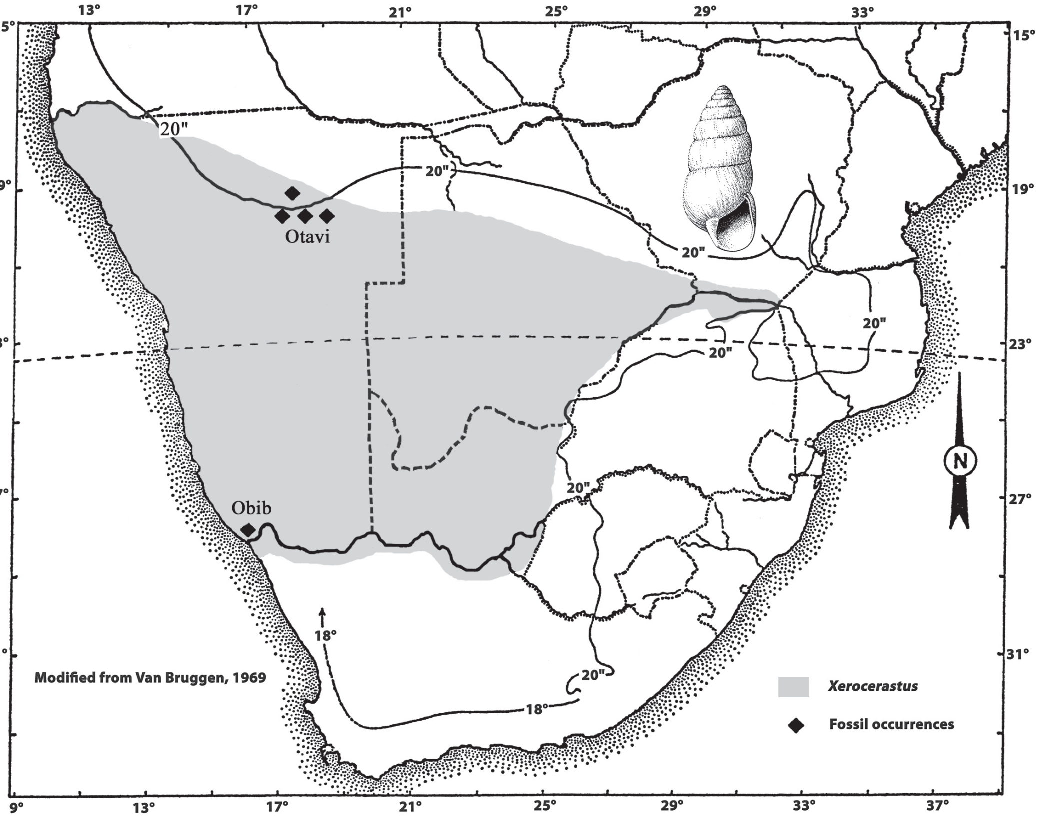

Figure 25.- Distribution of *Xerocerastus*. Fossils of this subulinid are common in epikarst breccias of the Otavi Mountains and the Kaokoland.

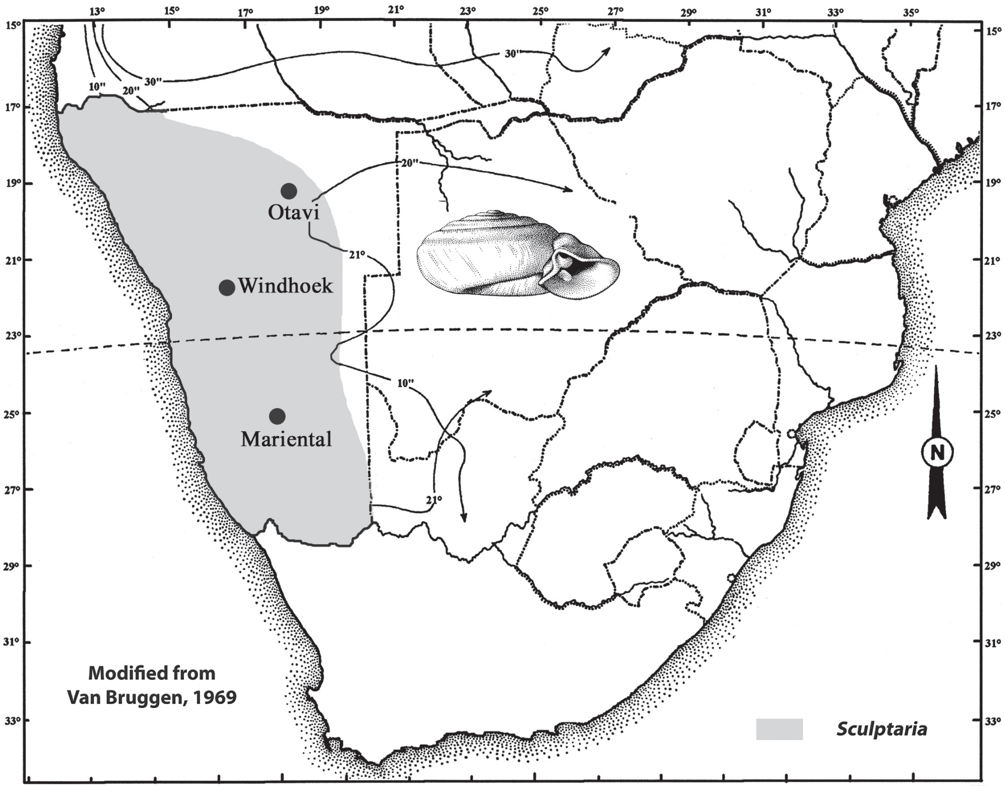

Figure 26.- Distribution of *Sculptaria*. This snail is common in superficial breccias of the Otavi Mountains.

ceptionally rich and diverse micromammal fauna which contains many species of rodents that are new to science. The Plio-Pleistocene micromammalian assemblages, in contrast, appear to contain forms that are closely related to extant lineages of Southern Africa.

Palaeoanthropology

Until the discovery of *Otavipithecus namibiensis* in 1991, all Miocene hominoids came from the northern hemisphere or from localities close to the equator (Fig. 27). The distribution of sites as far north as 45° of latitude throughout what is now the mid-latitude belt of Eurasia, gave rise to several hypotheses concerning the origins of the great apes and humans. The debate is still with us, with some authors suggesting that the extant African apes and humans can trace their ancestry back to European or Asian hominoids (Begun, 2001; de Bonis *et al.*, 1981) from the Miocene, while others see no close connection between the various lineages (Pickford and Senut, 2005).

The hominoid fossils from Berg Aukas are of interest because they reveal that *Otavipithecus* possesses morphology of the skull and postcranial skeleton which is derived away from the morphology documented for the Eurasian hominoids such as *Dryopithecus, Oreopithecus, Lufengithecus* and *Sivapithecus*. All the latter taxa share derived features of the skull and limbs with the extant Asian great ape *Pongo pygmaeus* and they are thus highly unlikely to represent the ancestors of African apes and humans. *Otavipithecus* in contrast, even though it is still relatively poorly known, is a potential ancestor for the extant African apes and humans. The atlas vertebra from Berg Aukas, in particular, is close in morphology to that of chimpanzees.

An isolated right p/4 from Berg Aukas (Plate 8, G) is broader than the tooth in the holotype mandible of *Otavipithecus namibiensis*, the proportions and dimensions resembling teeth of *Kenyapithecus* from Kenya. We attribute this specimen to *Kenyapithecus*, but clearly a better sample is required in order to strengthen the case for the presence of two hominoid taxa in the Middle Miocene deposits of the Otavi Mountains.

Summary and conclusions

The karstveld of northern Namibia contains major palaeontological resources, perhaps the most comprehensive in Africa for the period spanning the Middle Miocene to Recent. Research done between 1991 to 1995 led to the discovery of over a score of extremely richly fossiliferous spelean and epikarst deposits which have yielded literally hundreds of thousands of fossils. Vast areas of the karstveld remain to be prospected, the efforts of the Namibia Palaeontology Expedition being focussed on two principal areas, the Otavi Mountainland and a small part of Kaokoland north of Opuwo. There is little doubt that many new localities remain to be discovered. The Namibian karst breccias are located in an area that was formerly a huge blank area on the palaeontological map of Africa. The nearest known fossil sites are in northwestern Botswana, Taungs in South Africa and Humpata in Angola.

For some reason yet to be determined the Namibian breccias yield few large mammal fossils. Numerically they represent a trace among all the microfaunal remains. However, the few large mammals that have been collected, primates predominate, with both hominoids and cercopithecoids represented. Galagids have also been found, but these are small species which under normal circumstances would be counted among the micromammals. Bovids, proboscideans, carnivores and hyracoids have been recovered, but in very low numbers and in fragmentary condition for the most part.

The Middle Miocene breccias of the Otavi region have yielded faunal assemblages which indicate that the climate was more humid and tropical during the period of deposition than it is today. By Plio-Pleistocene times, the faunas are of more open country arid affinities. When the faunas have been studied in detail, there is little doubt that more palaeoclimatological information will emerge.

The Otavi faunas yield evidence that vanadium mineralisation in the region occurred principally during the Middle Miocene and subsequent periods. Plio-Pleistocene mineral occurrences tend to be of low grade and small volume, while the Miocene deposits at Berg Aukas comprised the largest vanadium ore body in the world. There are two vanadium occurrences of substantial size that had no fossils associated with them, Baltika and Abenab West, and these could be older than the Miocene. The Otavi faunas have also yielded evidence regarding the rates of geomorphological change in the region, principally the rates of carbonate down wasting, which is as high as 15 metres per million years.

In conclusion, the discovery of the fossiliferous Namibian karst deposits represents a major advance in African Neogene palaeontology. The success of the NPE indicates that other karst fields of Africa could well be of interest.

Acknowledgements

The Namibia Palaeontology Expedition is a Franco-Namibian venture jointly supported by French and Namibian organisations. The first two field seasons of research in the Otavi Mountains were done in collaboration with an American team from the Washington University, St Louis, under the leadership of Professor Glenn Conroy, to whom we are grateful.

Funding for the fieldwork was generously granted by the Chaire de Paléoanthropologie et de Préhistoire of the Collège de France (Prof. Yves Coppens), the Laboratoire de Paléontologie du Muséum National d'Histoire Naturelle (Prof. Philippe Taquet), Bonus Qualité Recherche M4 - Muséum, 1991, GDR 983 of

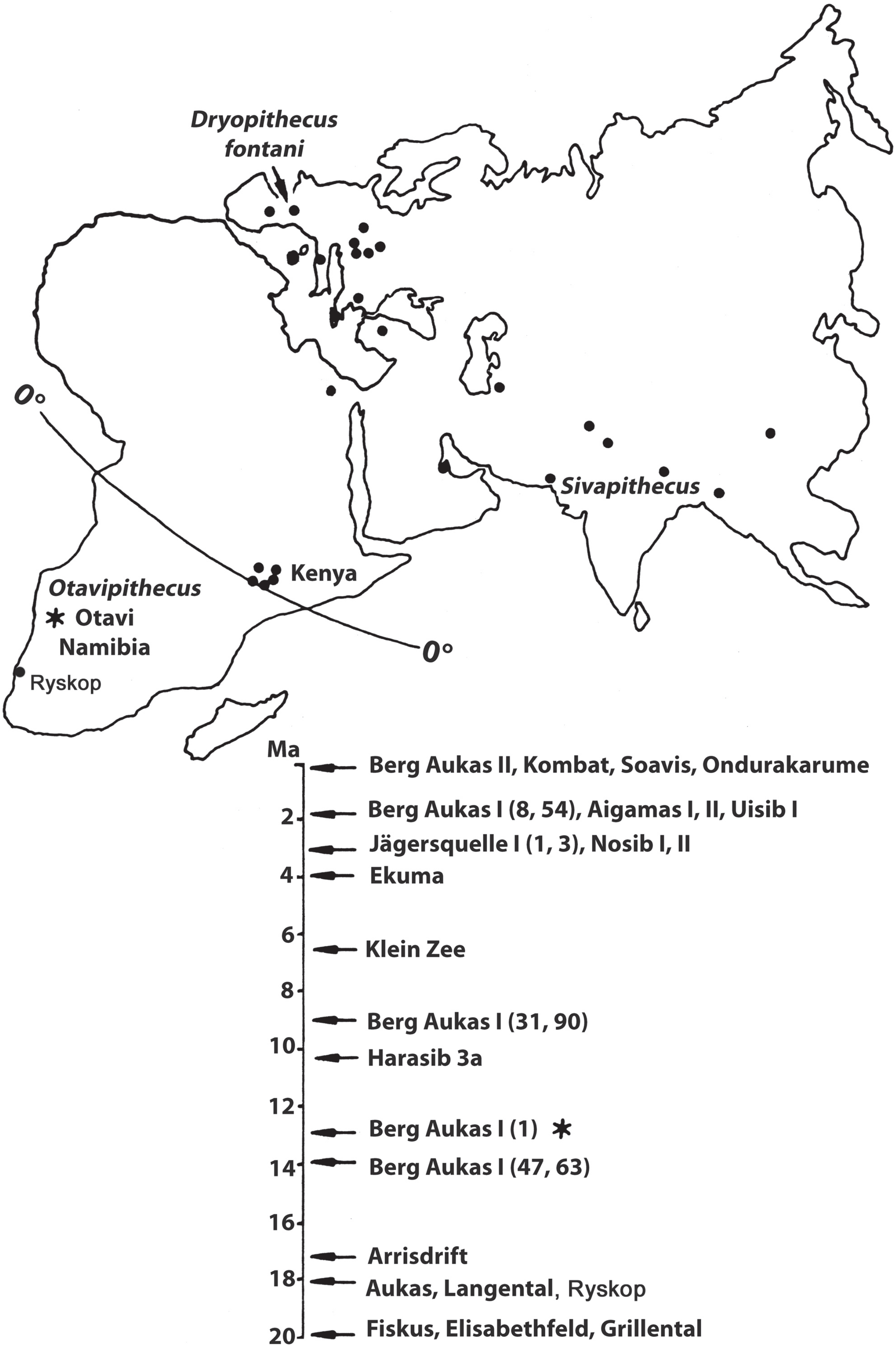

Figure 27.- Miocene hominoid localities (map) and mammalian biochronology of Namibia (stratigraphy). Until *Otavipithecus* was found, no hominoids were known from the southern hemisphere. This discovery lead to a major rethinking about the past distribution of great apes.

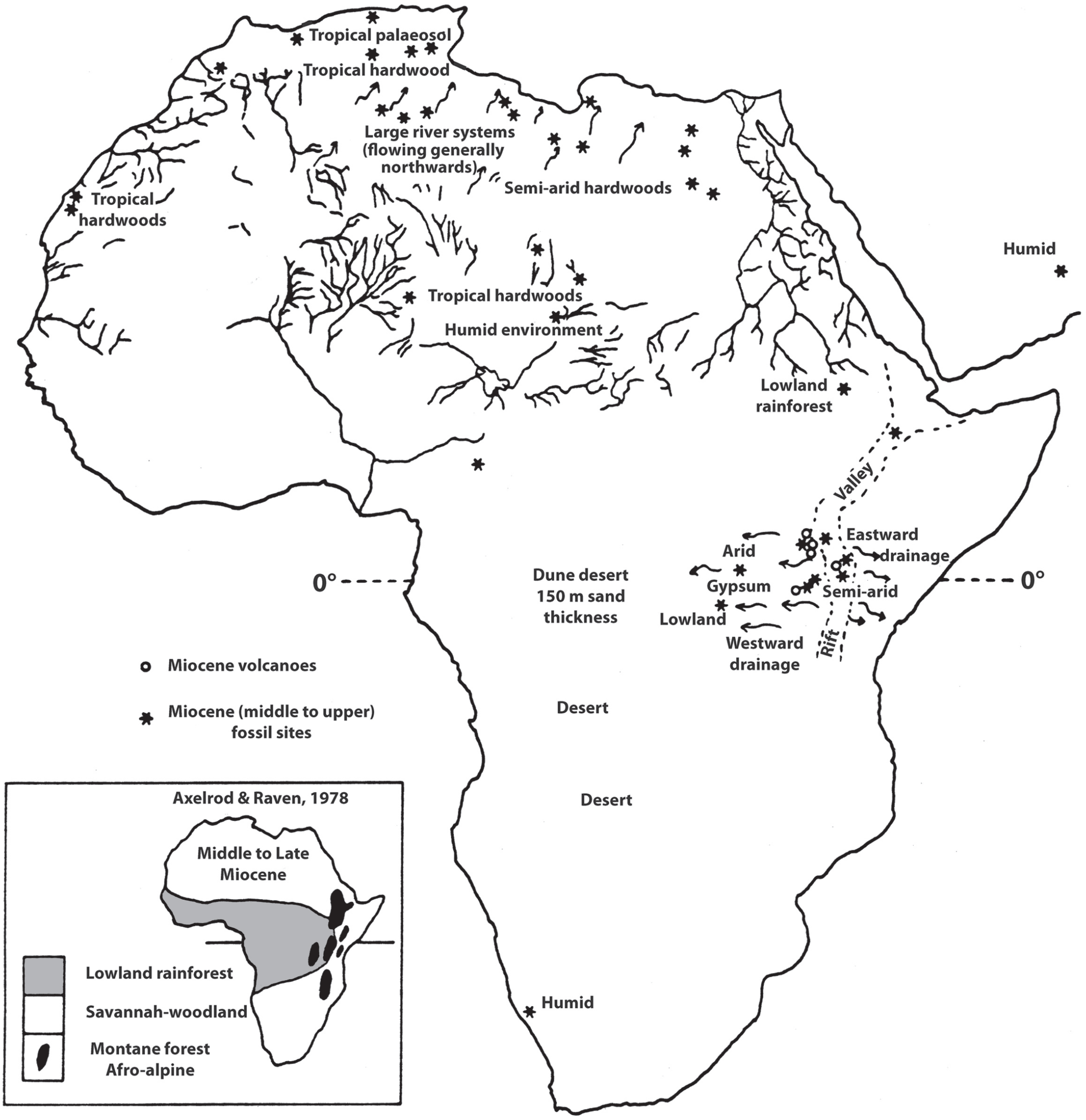

Figure 28. The distribution of aeolianites and fluvial drainage networks reveals that African palaeoclimate changed radically during the Miocene. What is now tropical forest in Angola, Congo and Gabon, was desert, and what is now desert in the Sahara and parts of Namibia, used to be humid.

the CNRS, the Société des Amis du Musée de l'Homme (Mme J. de Beaumarchais, Mme Nancy Wise) and their Antenne Marseille (M. A Martin) and the Mission de Co-operation Culturelle, Scientifique et Technique (M. Yves Maire, Mme Nicole Weil, M. J.-M. Langlais, M. P.-J. Lahaye). On the Namibian side, support was kindly supplied by the Geological Survey of Namibia (Dr R. McG. Miller, Dr B. Hoal, Dr G. Schneider).

Authorisation to carry out research in Namibia was granted by the National Monuments Council (Mrs Vera Freyer, Mr G. Hoveka, Mr Andreas Vogt,) and its successor organisation, the National Heritage Council (Mme Erica Ndalekokule). Access to the Berg Aukas and other areas in Otavi was granted by Goldfields Namibia, Tsumeb Corporation Ltd (Dr L. Kruger, Dr C. King) and the Development Brigade Corporation.

Many people helped both in Windhoek and the field. The following were of particular assistance directly related to the success of the expedition, and we thank all of them. Dr R. McG. Miller, Dr B. Hoal, Dr G. Schneider, Dr W. Hegenberger, Dr R. Swart, Dr H. Roessner, Mrs M. Dunaiski, Mr D. Richards, Mr S. Cloete, Miss B. Allison, Mrs U. Kutzner, Mr G. Brooker-Smith, Mr A. Ipinge, all of the Geological Survey of Namibia. We also thank Prof. P. Katjavivi, Dr J. Mendelson, Dr J. Kinahan, Dr E. Marais, Mr A. Palfi, Mr T. Cooper, Mr E. Freyer, Dr B. Sandelowsky, Mr R. Camby, Mr

F. Endler, Mr M. Abolivier, Mrs S. Potgieter, Miss G. Bessinger, Miss F. Dealie. The French ambassadors and their staff were of great help (M. A. Dementhon, M. F. Baleine de Laurens).

Farmers and other inhabitants of the Otavi region are thanked for allowing us access to their land to look for fossils or for information concerning Otavi natural history, geology and history. We treasure the memories we have of your land and of the hospitality extended to us - the many cups of much appreciated tea or glasses of beer, always accompanied by lively and interesting conversations. Dr J. Richter, Mr Stritter, Mrs Putsch, Mr D. Dieckmann, Mr and Mrs L. Pretorius, Mr Hellwig, Mr Bauer, Mr Esterhuizen, Mr Kuele, Mr and Mrs Schiedelowski, Mr Boschoff, Dr Boschoff, Mr Hoch, Mr Otto, Mr and Mrs P. Liebenberg, Mr and Mrs Schickerling, Dr and Mrs Eggers, Mr and Mrs Beddies, Mr Frenzel, Mr Beckers, Mr Van Biljon, Mrs Hellinghausen, Dr Vermeulen, Mr Syversten, Mr P. Von Vrede, Mr F. Schultz, Mr J. Van Zyl, Mr M.P. Cronie.

In Kaokoveld, we were offered kind hospitality at Ombarundu Lodge (E.M.E.C.): we wish to thank Eckardt and Vera Freyer, Tim Williams, Paul Howe, Iain Reid and Rosanna Marzi.

Finally, we thank Pierre Mein, Yannicke Dauphin, and Dominique Gommery for identification of fossils.

References

Chadwick, P.J. 1993. *A Study of the Berg Aukas-type Pb-Zn-V Deposits in the Otavi Mountainland, Namibia*. MSc Thesis, Univ. Cape Town, South Africa.

Begun, D. 2001. European hominoids. *In*: W.C. Hartwig (ed.) *The Primate Fossil Record*. pp. 339-368, Cambridge, Cambridge University Press.

Conroy, G., Pickford, M., Senut, B. and Mein, P. 1993. Additional Miocene Primates from the Otavi Mountains, Namibia. *C. R. Acad. Sci. Paris, Sér. 2*, **317**, 978-990.

Conroy, G., Pickford, M., Senut, B., Van Couvering, J.A. and Mein, P. 1992a. *Otavipithecus namibiensis*, first Miocene hominoid from Southern Africa (Berg Aukas, Namibia). *Nature*, **356**, 144-148.

Conroy, G., Pickford, M., Senut, B., Van Couvering, J. and Mein, P. 1992b. The Otavi Mountain Land of Namibia yields Southern Africa's first Miocene hominoid. *Research and Exploration Natl Geog. Soc*., **8(4)**, 492-494.

Conroy, G., Senut, B., Gommery, D., Pickford, M. and Mein, P. 1996. New primate remains from the Miocene of Namibia, Southern Africa. *Am. Journal Phys. Anthropol.*, **99**, 487-492.

Deane, J.G. 1993. *The Controls on "Contact Type" Cu-Pb (Ag) Mineralization within the Tsumeb Subgroup of the Otavi Valley Syncline, Northern Namibia*. MSc Thesis, University of Cape Town, S. Afr.

De Bonis, L., Johanson, D., Melentis, J. and White, T. 1981. Variations métriques de la denture chez les Hominidés primitifs: comparaison entre *Australopithecus afarensis* et *Ouranopithecus macedoniensis*. *C. R. Acad. Sci. Paris*, **292**, 373-376.

Emslie, D.P. 1979. *The Mineralogy and Geochemistry of the Copper, Lead and Zinc Sulphides of the Otavi Mountainland, South West Africa*. PhD Thesis, Univ. Orange Free State, Bloemfontein.

Gommery, D., Senut, B. and Pickford, M. 1998. Nouveaux restes postcrâniens d'Hominoidea du Miocène inférieur de Napak, Ouganda. *Ann. Paléont.*, **84**, 287-306.

Grobler, N.J. 1961. *The Geology of the Western Otavi Mountainland, South West Africa*. MSc Thesis, Univ. Orange Free State.

Hoffman, K.H. 1990. Sedimentary depositional history of the Damara Belt related to continental breakup, passive to active margin transition and foreland basin development. *Abstr. Geocongress Geol. Soc. South Africa*, **90**, 250-253.

Hughes, M.J. 1982. The Owambo basin-type ore association: karst control of complex Cu-Pb-Zn mineralization. *Abstr. Int. Conf. on Mississippi Valley Type Lead-Zinc Deposits*, pp. 11-14.

Hughes, M.J. 1987. *The Tsumeb Orebody, Namibia, and Related Dolostone-hosted Base Metal Ore Deposits of Central Africa*. PhD Thesis, Univ. Witwatersrand.

King, C.H.M. 1990. *The Geology of the Tsumeb Carbonate Sequence and Associated Lead-Zinc Occurrences on the Farm Olifantsfontein, Otavi Mountainland, Namibia*. MSc Thesis, Rand Afrikaans Univ.

Kräusel, R. 1965. Stromatolithe von Tsumeb. *Journal of the South West Africa Scientific Society*, **18-19**, 85-93.

Kröner, A. and Correia, H. 1980. Continuation of the Pan African Damara Belt into Angola: A proposed correlation of the Chela Group in Southern Angola with the Nosib Group in Northern Namibia/SWA. *Trans. Geol. Soc. South Africa*, **83**, 5-16.

Krüger, L. 1969. Stromatolites and oncolites in the Otavi Series, South West Africa. *Journal of Sedim. Petrol.*, **39(3)**, 1046-1056.

Le Roex, H.D. 1942. *The Geology of a Portion of the Otavi Mountainland, South West Africa*. MSc Thesis, University College of the Orange Free State.

Malan, M. 1975. Thigh bone discovery excites the experts. *The Johannesburg Star*, 7th Feb. 1975.

Martin, H. 1965. The Precambrian Geology of South West Africa and Namaqualand. *PreCambr. Res. Unit. Univ. Cape Town*, 159pp.

Mason, R. 1976. Exploration archaeology of the Kaokoveld and Southern Angola and the potential australopithecine sites in the Serra de Chela Massif, Southern Angola. *Ann. South African Mus*., **71**, 215-223.

Misiewicz, J.E. 1988. *The Geology and Metallogeny of the Otavi Mountainland, Damara Orogen, SWA/Na-*

mibia, with Particular Reference to the Berg Aukas Zn-Pb-V Deposit - A Model of Ore Genesis. MSc Thesis, Rhodes University, Grahamstown.

Pia, J. 1930. Eine neue quartäre Wartzenschwein art aus Südwest Afrika. *Zentralbl. min. Geol. Pal., Stuttgart*, **B(2)**, 76-83.

Pickford, M. 1990. Some fossiliferous Plio-Pleistocene cave systems of Ngamiland, Botswana. *Botswana Notes and Records*, **22**, 1-15.

Pickford, M. 1993. Age of supergene ore bodies at Berg Aukas and Harasib 3a, Namibia. *Communs Geol. Surv. Namibia*, **8**, 147-150.

Pickford, M. 1994. A new field for vertebrate palaeontology in Africa. *Roan News, Wildlife Soc. Namibia, Windhoek, Spring*, **1994**, 10-11.

Pickford, M. 1996. Pliohyracids (Mammalia, Hyracoidea) from the upper Middle Miocene at Berg Aukas, Namibia. *C. R. Acad. Sci. Paris*, **322**, 501-505.

Pickford, M., Fernandes, T. and Aço, S. 1990. Nouvelles découvertes de remplissages de fissures à primates dans le "Planalto da Humpata", Huila, Sud de l'Angola. *C. R. Acad. Sci. Paris, Sér. 2*, **310**, 843-848.

Pickford, M. and Mein, P. 1988. The discovery of fossiliferous Plio-Pleistocene cave fillings in Ngamiland, Botswana. *C. R. Acad. Sci. Paris, Sér. 2*, **307**, 1681-1686.

Pickford, M., Moya Sola, S. and Köhler, M. 1997. Phylogenetic implications of the first African Middle Miocene hominoid frontal bone from Otavi, Namibia. *C. R. Acad. Sci. Paris*, **325**, 459-466.

Pickford, M. and Senut, B. 2005. Hominoid teeth with chimpanzee- and gorilla-like features from the Miocene of Kenya : Implications for the chronology of the ape-human divergence and biogeography of Miocene hominoids. *Anthropological Science*, **113**, 95-102.

Pickford, M., Senut, B., Conroy, G. and Mein, P. 1994. Phylogenetic position of *Otavipithecus* : Questions of methodology and approach. *In*: B. Thierry, J. R. Anderson, J. J. Roeder, and N. Herrenschmidt, (eds) *Current Primatology*, **1**, 265-272. Ecology and Evolution, Université Louis Pasteur, Strasbourg.

Pickford, M., Senut, B., Mein, P. and Conroy, G. 1993. Premiers gisements fossilifères post-miocènes dans le Kaokoland, nord-ouest de la Namibie. *C. R. Acad. Sci. Paris, Sér. 2*, **317**, 719-720.

Pirajno, F., Kinnaird, J.A., Fallick, A.E., Boyce, A.J. and Petzel, V.W.F. 1993. A preliminary regional sulphur isotope study of selected samples from mineralised deposits of the Damara Orogen, Namibia. *Communs Geol. Surv. Namibia*, **8**, 81-97.

Pirajno, F. and Joubert, B.D. 1993. An overview of carbonate-hosted mineral deposits in the Otavi Mountainland, Namibia: implications for ore genesis. *Journal of African Earth Science*, **16**, 265-272.

Porada, H. 1983. *Die Geosynklinalentwicklung des Damara-Orogens in Namibia und ihr Geodynamischer Rahmen*. Habilitationsschrift, Univ. Göttingen, 209 pp.

Rasmussen, T., Pickford, M., Mein, P., Senut, B. and Conroy, G. 1996. Earliest known procaviid hyracoid from the late Miocene of Namibia. *Journal of Mammalogy*, **77**, 745-754.

Robinson, J.T. 1959. The occurrence of fossils on the Otavi Plateau. *Der Kreis: Afrikanische Monatshefte für Pflege des Heimatgedankens und deutsche Kultur*, **2**, 224-226.

Schlenter, K. 1987. Primary Atlas for Namibia. *Collins-Longman Atlases 1987*, Windhoek.

Schneiderhöhn, H. 1920. Beiträge zur Kenntnis der Erzlagerstätten und der geologischen Verhältnisse des Otaviberglandes, Deutsch-Südwestafrika. *Abh. Senckenb. naturf. Ges*., **37(3)**, 219-318.

Schneiderhöhn, H. 1929. Das Otavibergland und seine Erzlagerstätten. *Z. Prakt. Geol. Halle*, **37**, 85-116.

Schwellnus, C.M. 1946. Vanadium deposits in the Otavi Mountains, South-West Africa. *Trans. Geol. Soc. South Africa*, **48**, 49-73.

Schwellnus, C.M. and Le Roex, H.D. 1944. Columnar, conical and other growths in the dolomites of the Otavi System, S.W. Africa. *Trans. Geol. Soc. South Africa*, **47**, 93-104.

Senut, B., Pickford, M., Mein, P., Conroy, G. and Van Couvering, J.A. 1992. Discovery of 12 new Late Cainozoic fossiliferous sites in palaeokarsts of the Otavi Mountains, Namibia. *C. R. Acad. Sci. Paris, Sér. 2*, **314**, 727-733.

Smit, J.M. 1959. *The Geology of the Southern Part of the Otavi Mountainland*. MSc Thesis, Univ. Pretoria.

Söhnge, P.G. 1954. *Geology of the Otavi Mountainland, S.W.A., Tsumeb Corporation Ltd.*, Unpub. Rept.

Söhnge, P.G. 1957. *Revision of the geology of the Otavi Mountainland, S.W.A. Tsumeb Corporation Ltd.*, Unpub. Rept.

Sönghe, P.G. 1958. The environment of copper deposits in South-West Africa. *Comm. Reg. Centre-Est, Centre-Ouest et Sud, Léopoldville, CCTA*, **44**, 231-248.

Spencer, L.T. 1929 (unpubl.). *Label with breccia block from Berg Aukas, dated 1929*.

Stuart, C. and Stuart, H. 1988. Field Guide to the Mammals of Southern Africa. *Cape Town, Struik*, 272 pp.

Van Bruggen, A.C. 1969. Studies on the Land Molluscs of Zululand with notes on the distribution of land molluscs in southern Africa. *Zool. Verh*., **103**, 3-116.

Van der Westhuizen, W.A. 1984. *The Nature, Genesis and Geochemistry of the Supergene Vanadium Ores of the Otavi Mountainland*. PhD Thesis, Univ. Orange Free State, Bloemfontein. 196 pp.

Van Zijl, P.J. 1964. Stromatolite and onkolite beds in the Otavi Series of the Otavi Mountainland. *Journal of the South West Africa Scientific Society*, **5**, 9-11.

Veldsman, J.H. 1977. *Die geologie van 'n gedeelte van* *die Tsumeb-sinclinorium met spesiale verwysing na litostratigrafie, struktuur en diagenese*. MSc. Thesis, Univ. Stellenbosch, 169 pp.

Verwoerd, W.J. 1957. The mineralogy and genesis of the lead-zinc-vanadium deposit of Abenab West in the Otavi Mountains, South West Africa. *Ann. Univ. Stellenbosch*, **33**, Sec. A, (1-11), 235-239.

Wartha, R.R. and Schreuder, C.P. 1992. Vanadium. *The Mineral Resources of Namibia, Geological Survey of Namibia, Windhoek*.

White, F. 1986. La végétation de l'Afrique. *Mémoire accompagnant la carte de végétation de l'Afrique. UNESCO/AETFAT/UNSO: Orstom - Unesco*.

Annex 1
Karst References, Namibia

Additional references, notably to newspaper articles, are provided by Jeutter (1995, 1998) and Laumanns (2008).

Avery, D.M. 1984. Micromammals and environmental change at Zebrarivier Cave, Central Namibia. *Journal of the Southwest Africa Scientific Society*, **1983/84**, 76-86. Windhoek.

Blacquière, J. 1968a. Hawusib Cave. *Bull. South African Speleol. Assoc.*, **1968**, 41.

Blacquière, J. 1968b. Plan of Harasib. *Bull. South African Speleol. Assoc.*, **1968**, 16.

Blacquière, J. 1969. The Wondergat, Richtersveld. *Bull. South African Speleol. Assoc.*, **1969**, 23-24.

Breunig, P. 1990. Untersuchung prähistorischer Höhlenmalereien in Namibia. *Mitt. LV für Höhlenkundliche Oberösterreich*, **95**, 27. Linz, Austria.

Burman, V. 1965. Crater Lakes of South West Africa. *Bull. South African Speleol. Assoc.*, **1965**, 11-14.

Burman, J.L. 1968. The Labyrinth of Gaub. *Bull. South African Speleol. Assoc.*, **1968**, 10-13.

Caves, 1976. Verein für Höhlenforschung gegründet. Bericht über eine Exkursion in die Naukluft. *Newsl. Southwest Africa Scientific Society*, **8(2)**, 2, 9-10.

Collins, R.G. 1977. Description of bone breccia and stone implement occurrences on "Ondura Karume (Kamelberg) Mountain" situated on the farm Etaneno N^{o} 44 in the Otjiwarongo District, S.W.A. *Arbeitsber. Ver. Höhlenforsch*, **10**, 1-4.

Duffin, A.C. 1986. Wondergat. *Bull. South African Speleol. Assoc.*, **27**, 82-83.

Ellis, R. and Sefton, M. 1986. Drachenauchloch (Dragonsbreath Cave). *Bull. South African Speleol. Assoc.*, **27**, 66-71.

Fileccia, A., Sitta, E. and Tormene, G. 2005. I Laghi sotterani dela Namibia. *Speleologia SSI*, **52**, 68-72. Bologna.

Gaerdes, J. 1964. Ueber einige Suedwester Karsthoehlen, Felsgravierung, Kultstaetten, und ein "steiners Glockenspiel". *Newsl. Southwest Africa Scientific Society*, **5(3)**, 3-6.

Gow, C. 1968. Aigamas Cave. *Bull. South African Speleol. Assoc.*, **68**, 25-27.

Heine, K. and Geyh, M.A. 1984. Radiocarbon dating of speleothems from the Rössing Cave, Namib Desert, and palaeoclimatic implications. *In*: J.C.Vogel (ed.) *Late Cainozoic Palaeoclimates of the Southern Hemisphere*, 465-470. Rotterdam, Balkema.

Helm, R. 1960. Ausflug zur Märkerhöhle. *Newsl. Southwest Africa Scientific Society*, **1(7)**, 5.

Hugo, H. 2002. Namex 2000. *Bull. South African Speleol. Assoc.*, **37**, 25-30.

Irish, J. 1986. SWEX 86: a SASA expedition to South West Africa - Namibia 1986. *Bull. South African Speleol. Assoc.*, **27**, 60-61.

Irish, J. 1986. Two small SWA Caves. *Bull. South African Speleol. Assoc.*, **27**, 100.

Irish, J. 1988. Ghaub Cave: the CO2 section. *Bull. South African Speleol. Assoc.*, **29**, 4-5.

Irish, J. 1991. Cave investigation in Namibia I: biospeleology, ecology, and conservation of Dragon's Breath Cave. *Cimbebasia*, **13**, 59-67.

Irish, J. 1991. Conservation aspects of karst waters in Namibia. *Madoqua*, **17(2)**, 141-146.

Irish, J., Martini, J.E.J. and Marais, J.C.E. 1992. Cave investigations in Namibia III: some 1992 SWAKNO results. *Bull. South African Speleol. Assoc.*, **32**, 48-71.

Irish, J. and Marais, J.C.E. 1991. Cave investigations in Namibia II: Merker Cave, a possible prehistoric pigment mine. *Cimbebasia*, **13**, 69-74.

Irish, J. and Marais, J.C.E. 2000. Cave investigations in Namibia IV: The desert caves in and around the Namib-Naukluft Park. *Cimbebasia*, **16**, 177-193.

Irish, J., Marais, E., Juberthie, C. and Decu, V. 2001. Namibia. *In*: Juberthie, C. and Decu, V., *Encyclopaedia Biospéologica*, **111**, 1637-1650, Moulis (France).

Jeutter, P.W. 1994. New Drachenhauchloch survey and Windgat Cave. *International Caver*, **11**, 17-24. Swindon.

Jeutter, P.W. 1995. OTAVI 1995. Report of the speleological expedition to the Otavi Mountains in northern Namibia, February 1995. *Bericht der höhlenkundlichen Expedition in die Otavi Berge Nord-Namibias, Februar 1995*, 108 pp. Bad Mittendorf (Austria) (Verein für Höhlenkunde in Obersteier).

Jeutter, P. 1999. Otavi 98. *Bad Mitterndorf, Austria, Herausgeber (Verein für Höhlenkunde in Obersteier)*, 173 pp.

Kruparz, 1966. Einseig in die Karsthöhle auf Farm Harasib bei Grootfontein. *Newsl. Southwest Africa Scientific Society*, **7(7)**, 1-4.

Laumanns, M. 2008. Atlas of the Great Caves and the Karst of Africa: Part 2 : Guinea Bissau - Namibia. *Berliner Höhlenkundliche Berichte (2nd Edition)*, **29**, 159-311.

Magnin, R. 1988. Namibie, Afrique du Sud. *Spelunca*, **29**, 11. Lyon.

Marais, E. 1990. The caves at Gam, Namibia. *Bull. South African Speleol. Assoc.*, **31**, 93-95.

Marais, E., Irish, J. and Martini, J.E.J. 1996. Cave investigations in Namibia V: 1993 SWAKNO results. *Bull. South African Speleol. Assoc.*, **36**, 9-13.

Marais, E., Martini, J. and Irish, J. 1995. Gâuab AS (Namibie occidentale). *Karstologia*, **25**, 51-54.

Martini, J. 1986. Contribution to the geology and speleogenesis of Gaub Cave. *Bull. South African Speleol. Assoc.*, **27**, 62.

Martini, J.E.J. 1988. Swex 87 – a preliminary account. *Bull. South African Speleol. Assoc.*, **28**, 55-56.

Martini, J.E.J. 1988. Afrique du Sud, Namibie. *Spelunca*, **33**, 9. Lyon

Martini, J.E.J. 1989. The 1987 Drachenhauchloch survey. *Bull. South African Speleol. Assoc*., **29**, 24-29.

Martini, J.E.J. 1991. Some data on the chemistry of karst water from the Otavi Mountainland, Namibia. *Bull. South African Speleol. Assoc*., **32**, 74-79.

Martini, J.E.J., Irish, J. and Marais, J.C.E. 1990. Les grottes du sud-ouest Africain. Namibie. *Spelunca*, **38**, 24-29. Lyon.

Martini, J.E.J. and Marais, J.C.E. 1996. Grottes hydrothermales dans le nord-ouest de la Namibie. *Karstologia*, **28**, 13-18. Lyon.

Martini, J.E.J. and Marais, J.C.E. 2002. Cave investigations in Namibia. Kaokoland revisited – VI. *Bull. South African Speleol. Assoc.*, **37**, 37-54.

Martini, J., Marais, J.C.E. and Irish, J. 1990. Kaokoveld Karst, Namibia. *Bull. South African Speleol. Assoc*., **31**, 25-41.

Martini, J.E.J., Marais, J.C.E. and Irish, J. 1999. Contribution à l'étude du karst et des grottes du Kaokoland (Namibie). *Karstologia*, **34**, 1-8, Lyon.

Maxwell, C.D. 1988. Harasib underground lake revisited July, 1988. *Bull. South African Speleol. Assoc*., **29**, 17-19.

Maxwell, C.D. 1989. Underwater exploration of Dragon's breath lake. *Proc. Int. Congr. Speleol. Budapest, 1989*, **1**, 134-136. Budapest.

Penney, A.J. and Maxwell, C.D. 1988. Johan's Cave: a new cave on Aigamas Farm. *Bull. South African Speleol. Assoc.*, **29**, 1-4.

Penney, A.J., Maxwell, C.D. and Roux, D.E. 1988. Guinas lake. *Bull. South African Speleol. Assoc.*, **29**, 6-10.

Pickford, M., Mein, P. and Senut, B. 1994. Fossiliferous Neogene karst fillings in Angola, Botswana and Namibia. *South African Journal of Science*, **90**, 227-230.

Sefton, M. 1986. Conclusion. *Bull. South African Speleol. Assoc*., **27**, 97-99.

Sefton, M. 1986. Prelude. *Bull. South African Speleol. Assoc*., **27**, 53-55.

Sefton, M. 1986. Aigamas. *Bull. South African Speleol. Assoc.*, **27**, 73-75.

Sefton, M., Martini, J. and Ellis, R. 1986. *Cave descriptions. Bull. South African Speleol. Assoc*., **27**, 86-97.

Sefton, M. and Redmayne-Smith, C. 1986. Ghaub Cave. *Bull. South African Speleol. Assoc*., **27**, 55-60.

Skelton, P. 1987. An expedition to the caves and sink holes of South West Africa - Namibia. *Ichthos*, **16**, 22-23.

Smith, K. 1968. South West African expedition, 1967. *Bull. South African Speleol. Assoc*., **1968**, 1-6.

Smith, K. 1968. Harasib! *Bull. South African Speleol. Assoc*., **1968**, 19-24.

Smith, K. 1968. Breccia Cave. *Bull. South African Speleol. Assoc*., **1968**, 31-32.

Strinati, P. 1985. Les grands lacs karstiques de Sud-Ouest Africain. Actes du Séminaire sur les grands volumes souterrains, 1984. *Mémoires S.C., Paris*, 12 pp. Paris.

Strinati, P. 1990. More about Namibian biospeleology. *Bull. South African Speleol. Assoc*., **31**, 96.

Truluck, T. 1998. Namibia, Otavi 98. *International Caver*, **22**, 42, Swindon.

Uhlmann, 1975. Neuentdeckung von Höhlen im Otavi-Bergland. *Newsl. Southwest Africa Scientific Society*, **15(9-10)**, 13-16.

Von Wrede, P. 1969. Die Höhle von Ghaub. *Arbeitsberichte Verein für Höhlenforschung, Windhoek*, **6/7**, Windhoek.

Von Vrede, P. 1970. Höhlenforschung in Südwestafrika. *Laichinger Höhlenfreund*, **5(10)**, 26-27.

Von Vrede, P. 1970. Die Rössing-West-höhle. *Arbeitsberichte Verein für Höhlenforschung SWA Wissenschaftl. Ges.*, **9**, 17-20.

Von Vrede, P. 1977. Die Etanenohöhle. *Arbeitsberichte Verein für Höhlenforschung*, **10**, 5-7.

Von Wrede, P. and Garny, W.H. 1968. Die Höhlen der Farm Nooitgedag. *Arbeitsberichte Verein für Höhlenforschung Windhoek*, **4**, 1-6.

Wolf, A. 1991. Eine Dokumentation über die beiden bedeutendsten Höhlen auf der Harasibfarm in den Otavibergen in Namibia. *Der Schlaz*, **65**, 23-54. München.

Wolf, A. 1992. Eine Dokumentation über die zwei bedeutendsten Höhlen auf der Harasibfarm in den Otavibergen in Namibia. *Mitt. Verb. Dt. Höhlen- und Karstforscher*, **38(2)**, 26-32, München.

Annex 2
Glossary

There are few people in Namibia familiar with karst teminology. For this reason, we have prepared a glossary of terms that are often encountered in the literature on karst.

Glossary of terms with examples from the Otavi Mountains

(with definitions based on the Glossary of Geology, 3rd edition, Bates and Jackson (eds), 1987)

Active karst : Said of a karst feature that contains moving water, or that is being developed by the action of moving water. It is clear that during the middle Miocene, Berg Aukas was an active cave. Evidence is provided by fossiliferous speleothems, such as masses of sunken crystal rafts, stalagmites, calcite linings in spelean sediments, and by cut and fill structures in the sediments.

Active cave : A live cave in which there is moisture and growth of speleothems associated with the presence of moisture (see active karst).

Alluvial ore : Said of a placer formed by the action of running water, as in a stream channel or alluvial fan. Some of the Otavi descloisite ores are spelean placers, derived from primary deposits formed in subsoil rundkarren settings which were eroded, reworked and concentrated in caves and fissures by running water. The best examples are at Berg Aukas and Harasib 3a, but it should be noted that not all the descloisite at these mines is alluvial. The highest grade ores were in fact developed autochthonously within cave sediments.

Aven : A vertical shaft open to the surface. The most spectacular example in the Otavi Mountainland occurs on Farm Harasib. Palaeo-avens are known at Harasib 3a and Berg Aukas.

Bare karst : Karst that is developed in a region without soil cover, so that its topographic features are well exposed. Even though the Otavi Mountains are well vegetated, there are many fine exposures of bare (or naked) karst. Good examples occur at Friesenberg, a few kilometres south of Tsumeb.

Bone breccia : An accumulation of bones or bone fragments and teeth, often mixed with earth, sand and rock fragments, and cemented with calcium carbonate, especially those examples formed in limestone caves and fissures. The Otavi region is extremely well endowed

Plate 28. Lapiaz (foreground) and patches of bare karst (in the background) near Friesenberg, Otavi Mountains, Namibia.

with bone breccia deposits ranging in age from middle Miocene (ca 12 Ma) at Berg Aukas, through the upper Miocene (ca 10-9 Ma) at Harasib 3a, to the Plio-Pleistocene (ca 2 Ma) at Jägersquelle, Nosib Palaeocave, Aigamas, Berg Aukas, Friesenberg and Rietfontein, and to Holocene (less than 10,000 years) in a small cave near the summit of Berg Aukas.

Bone cave : Said of a cave in which bones are found (see bone breccia).

Boxwork : In mineral deposits, a network of intersecting blades or plates of limonite or other iron oxide, deposited in cavities and along fracture planes from which sulphides have been dissolved by processes associated with the oxidation and leaching of sulphide ores. In karst terrains, this term is sometimes used by analogy, in which the boxwork is comprised of siliceous blades or plates, often of chert, in which the cavities have been formed by the dissolution of limestone or dolostone (see also spongework). In the Otavi mountains, the surfaces of karst boxwork may be lined with crystals, such as dioptase (copper silicate), descloisite (lead vanadate) and mottramite (copper vanadate), or may be devoid of such linings. Crystal-lined boxworks are known from Rodgerberg, Tygerschlucht and Guchas.

Carbonate down wasting : The regional lowering of the upper surface of carbonate bodies, principally by dissolution by waters charged with carbonic acid. A typical production of this process is karst topography. In a region which is undergoing carbonate down wasting, the insoluble residues which often mantle the upper surface of the carbonates, reach lower topographic levels by the process of letdown, as a result of the down wasting of the carbonate body on which they respose, the movement of the clasts being predominantly vertical and driven by gravity. In the Otavi Mountains, carbonate down wasting on a regional scale, occurs at a rate of ca 15 metres per million years.

An important element of carbonate down wasting, is that soluble and insoluble rock constituents are not immediately removed from the area, but remain within it for substantial periods, thereby often leading to concentration of such constituents. The Otavi vanadium ores owe their origin largely to carbonate down wasting, with concomitant letdown or solutional subsidence, the vanadium being dissolved from the upper levels and carried downwards in solution until precipitated underground under favourable geochemical conditions as the relatively insoluble minerals descloisite and mottramite. Continued carbonate down wasting then exposes the ores so formed, at the surface (see also eluviation and leachate).

Cave breccia : Angular fragments of limestone and other rock types that have fallen to the floor from the roof and sides of a cave and that are cemented with calcium carbonate or occur in a matrix of cave earth. The best examples of fossil (i.e. indurated) cave breccias occur at Berg Aukas, but others are known at Harasib 3a, Friesenberg Hilltop and Jägersquelle.

Cave earth : Fine-grained, generally unconsolidated detrital material partly filling a cave; also, similar material regardless of grain size. Indurated cave earth is known at Berg Aukas, Nosib Palaeocave, Aigamas Cave and many other places in the Otavi region.

Cave raft : A thin mineral film, usually of calcite, floating on a cave pool. Also termed crystal raft. These sink if they become too large or too thick, or if the surface of the water is agitated, and they thereby form beds of sunken cave rafts, the individual rafts ending up subparallel to each other. Blocks of sunken cave rafts are common in the mine dump at Berg Aukas.

Cave exterior deposits : A class of sedimentary deposits which accumulated subaerially in the vicinity of caves. These include cave rampart deposits, precipitates and evaporites, including laminated and blocky calcretes, as well as superficial fissure deposits. Good examples are known at Rietfontein.

Cave interior deposits : A class of sedimentary deposits which accumulated inside caves or cave systems interior to the drip-line of the cave. There are two broad categories of cave interior deposits **a) autochthonous clastic** deposits which consist of breakdown products such as roof collapse breccias, insoluble residues of limestones and dolomites, reworked breakdown products (spelean fluvial and lacustrine deposits), precipitates and evaporites (well over 100 mineral species are known to crystallise in cave environments) and **b) allochthonous clastic** deposits which comprise fluvially introduced materials, dejecta cones, colluvium, mudflows, filtrates (cones of fine materials from seepage), aeolian sands and silts, and organic matter brought into the caves by fluvial, aeolian or cave using faunas. The latter includes bat guano, owl pellets, and various fossils including pollen, macroplant remains, and vertebrate bones and teeth. Virtually all the palaeokarst in the Otavi region contains interior sediment. Fine examples occur at Abenab, Berg Aukas and Baltika.

Cenote : A vertical shaft in limestone, open to the surface, that contains standing water. Otijkoto and Guinas are the most famous Otavi occurrences of cenotes.

Chimney : In a cave system, a chimney is a rounded vertical passage or opening in the roof of a passage or room. It usually forms by upward dissolution, and when it breaks through to the surface it is known as an aven. The Central Ore Body at Berg Aukas started out as a chimney before becoming an aven through which external sediments entered the cave system, to give rise to the stratified spelean sediments.

Chute : In a cave system, a chute is an inclined passage or channel. Part of the Berg Aukas palaeocave consisted of large chutes, now choked with sediments. Chutes in the Uris palaeocave became choked with speleothems, thereby forming inclined pipe-like masses of travertine.

Clint : A slab of limestone pavement that is separated from adjacent clints by solution fissures, or grikes, along joints. Many examples of clints and grikes occur in the exposed parts of the Otavi Mountains. Good examples occur on barren hills at Friesenberg and Aigamas.

Cockpit karst : A typical karst of the tropics, in which cockpits are separated by steep-walled rounded hills, forming a pattern that resembles a moulded egg box. Cockpit country is not well developed in the Otavi Mountains, mainly because the carbonate horizons have been folded and faulted. However, some areas, such as Hufeisenberge, southwest of Tsumeb, approach the morphology of cockpits (Schneiderhöhn, 1929), but present cockpits which are open on one quadrant.

Collapse breccia : A breccia formed by the collapse of rock overlying an opening or cavity, as by foundering of the roof or upper walls of a cave. Remnants of the cave infilling exposed in the southern face of the Central Ore Body at Berg Aukas, reveal that parts of the roof collapsed at least four times during the Miocene. The fallen blocks of breccia have deformed the underlying bedded silts, indicating that the latter were still soft at the time of collapse.

Collapse sinkhole : A type of sinkhole that is formed by collapse of an underlying cave. The most spectacular examples of this landform in the Otavi Mountains are the cenotes, Guinas Lake and Otjikoto Lake.

Colluvial ore : Any loose heterogeneous, and incoherent mass of soil material and/or rock fragments containing economic minerals, deposited by rainwash, sheetwash, or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides. In the Otavi region, numerous such deposits occur near the break in slope between dolomite hills and alluvial valleys, and these often contain reworked descloisite and mottramite crystals. Many are of sub-economic interest but a few such as Friesenberg yielded profitable grades.

Crackle breccia : An incipient breccia having fragments parted by planes of rupture but showing little or no displacement. There are many exposures of crackle breccia in the Otavi Mountains, but most, if not all of them formed prior to the Palaeozoic or Late Proterozoic. The interstratal breccias of the Otavi area are important because they are often spatially, and probably genetically, associated with massive heavy metal sulphide deposits, the ore-bearing fluids borrowing brecciated pathways as the most accessible porous conduits.

Crevice karst : A karst pattern of deep solution along closely spaced joints. There are fine examples of this geomorphological type in the Otavi Mountains, usually near hilltops such as at Aigamas.

Crystal raft : See *cave raft*.

Cut and fill : A sedimentary structure consisting of a small erosional channel that is subsequently filled with further sediment. The same process occurs in sediment bodies which accumulate within cave systems. Fine examples of spelean cut and fill are known at Berg Aukas, Abenab and Baltika.

Dead cave : A cave in which there is no longer any moisture or any growth of speleothems associated with the presence of moisture. There are several dead caves in the Otavi region, especially on Farm Uisib.

Decalcified soil : A soil which has been leached of its calcium carbonate content. Several blocks of brick-red soil-like sediment were collected at Berg Aukas. They are poorly fossiliferous and react very slowly in acid, suggesting a low tenure in carbonates. These sediments indicate that leaching processes at the surface were strong, suggesting in turn that the climate at the time of their deposition (middle to upper Miocene) was humid sub-tropical to tropical.

Deckenkarren : Rounded solution grooves formed under a cover of vegetation or soil. Many examples of deckenkarren occur in the Otavi region, usually near the edges of flat or slightly inclined, soil-filled valleys. Many of them have yielded economic to sub-economic quantities of vanadium minerals, principally descloisite, for example at Tsumeb West, and at Auros.

Deep phreatic : Said of cave formation at considerable depth below the top of the water-saturated zone. There can be little doubt that some of the palaeocaves in the Otavi Mountains formed in the deep phreatic zone. Tsumeb, for example, is a pipe-like structure which extends well below present sea level. At Berg Aukas, there were large cavities below present day water table levels.

Diagenesis : All the chemical, physical, and biologic changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism. The term has many nuances around the world, but generally includes processes such as compaction, cementation, reworking, authigenesis, replacement, crystallisation, leaching, hydration, bacterial action, and formation of concretions, that occur under conditions of pressure (up to 1 kilobar) and temperature (maximum range of 100° to 300°C) that are normal to the surficial or outer part of the Earth's crust. The spelean sediments of the Otavi region become consolidated by various means, including compaction, calcification, dolomitisation, and permineralisation (replacement of sediments by minerals including descloisite, but in general retaining the structure and fabric of the original sediment). Some insoluble spelean sediments appear to have a high proportion of phosphate in them, the phosphate ions probably originating from bat guano.

Disappearing stream : A sinking stream, often in karst country. Several disappearing streams are known in the Otavi Mountains, usually only active during and immediately after rains. One occurs on Gauss, while another is known on Sommerau, near Kombat.

Doloclast : A lithoclast derived by erosion from an older dolomite rock (see dololithite).

Dololithite : A dolomite rock containing 50% or more of fragments of older dolomitic rocks (doloclasts) that have been eroded and redeposited. In the Otavi region, two kinds of dololithite have been recognised. One is interstratal, and consists of volumetrically important breccia-like beds of Proterozoic age, while a less important variety formed locally during the Tertiary, mainly in spelean settings such as Berg Aukas (see doloclast).

Doline : A sinkhole. Numerous dolines occur in the Otavi Mountainland. A fine example occurs at Rietfontein.

Dolomite : A carbonate sedimentary rock of which more than 50% by weight consists of the mineral dolomite, or a variety of limestone or marble rich in magnesium carbonate. There are variations of this definition, some making the mineral dolomite more important, others less important in volume. Also the mineral $CaMg(CO_3)_2$. Often also called dolostone in order to prevent the sedimentary rock from being confused with the mineral dolomite, but common practice is that both the mineral and the sedimentary rock share the same name. Vast quantities of sedimentary dolomite occur in the Otavi Mountains, intercalated with limestones, conglomerates, sandstones and shales.

Drapery : A thin translucent sheet of travertine formed when drops of water flow down an inclined cave ceiling and leave behind a sinuous trail of calcite. Fine examples of drapery occur in the caves of the Otavi Mountains, especially those on Farm Uisib.

Drip line : Said of a linear feature produced on the floor at the entrance of a cave or overhang produced by water dripping from the outer edge of a cave roof or overhang. This line separates the cave exterior from the cave interior.

Dripstone : A general term for calcite or other mineral deposit formed in caves by dripping water, including stalactites and stalagmites, and also usually including similar deposits formed by flowing water. Fossil dripstone is common at Berg Aukas, Uisib and Aigamas.

Eluvial : Said of an incoherent ore deposit, such as a placer, resulting from the decomposition or disintegration of rock in place. The material may have slumped or washed downslope for a short distance but has not been transported by a stream. Some of the epikarst ore deposits of the Otavi Mountains fall into the category of eluvial placers, especially some of the ores encountered in deckenkarren settings and in solution hollows such as at Harasib 3a and the upper levels of Berg Aukas, Uris and Uisib, in which reworked descloisite, soil, lithic fragments and iron oxide nodules occur as part of regional carbonate downwasting processes. Such deposits, on their own, are rarely of economic interest, but they can indicate the presence of richer ores at depth, including the presence of massive sulphide bodies.

Eluviation : The downward movement of soluble or suspended material in a soil, from the A horizon to the B horizon, by ground-water percolation. The term refers especially but not exclusively to the movements of colloids, whereas the term leaching refers to the complete removal of soluble materials. In the Otavi region, eluviation and leaching possibly played important rôles in releasing vanadium into the groundwater environments, whence it became a wanderer element until precipitated in other environments in which lead and copper were concentrated, whereupon the minerals descloisite and mottramite (and their intermediates) would crystallise. The latter often occurred within the vicinity of massive heavy metal sulphide bodies, such as Berg Aukas, Rietfontein, Uris and Karavatu, often in subsoil enriched in lead and copper (6,000 ppm lead, for example) developed in karst terranes (rundkarren) or in spelean situations such as Berg Aukas and Abenab (see also carbonate downwasting).

Epikarst : Term applicable to features or deposits that occur in the uppermost metre or two of karst terrains. e.g. epikarst breccias, soils and calcrete, as opposed to underground breccias and reworked soils that occur in caves. Thin laminated calcrete occurs in many places in the Otavi Mountains, and often contains fossil terrestrial gastropods, such as *Xerocerastus, Sculptaria*, and *Achatina*, as for example, at Elephantenberg Nord, Dogleg (on Farm Olifantsfontein) and Rodgerberg.

Ferricrete : A term for a conglomerate consisting of superficial sand and gravel cemented into a hard mass by iron oxide derived from the oxidation of percolating solutions of iron salts. The term has been employed (or mis-employed) in the Otavi region for reddish epikarst sedimentary infillings. Most of these are in fact cemented by calcite or dolomitic calcite, albeit with an imporant proportion of ferric oxides.

Geopetal internal sediments : Internal sediments with one or more features that indicate the relation of top to bottom at the time of formation of the rock. e.g. cross-bedding, interlayered calcite laminations formed during pauses in sedimentation, fining-upward sequences etc. The finest examples occur at Abenab, Berg Aukas and Baltika.

Grike : Solution fissure. Grikes are ubiquitous on barren dolomite surfaces in the Otavi region. In some areas, the bottoms of grikes are enriched in insoluble lithic fragments as well as nodules of iron oxide and reworked crystals of descloisite. Examination of these concentrations may yield information concerning the former existence of vanadium mineralisation in the vicinity, and as such are a potential prospecting tool.

Gossan : An iron-bearing weathered product overlying a sulphide deposit. It is formed by the oxidation of sulphides and the leaching-out of sulphur and most metals, leaving hydrated iron oxides and rarely sulphates. There are numerous patches of gossan in the Otavi Mountains which have frequently been the first observed signs of the presence of an underlying sulphide body. As such, most of the gossan occurrences in the region have been intensively prospected. A fine example occurs at Harasib 3a. Gossan should not be confused with iron oxide nodules, which form in soils and are not necessarily associated with underlying sulphide bodies.

Gour : A rimstone pool or rimstone dam. Dead gours occur in caves on Uisib Farm, and palaeogours are inferred to have existed at Berg Aukas on account of the masses of sunken cave rafts that have been found there.

Guano : A phosphate or nitrate deposit formed by the accumulation of bat excrement in caves, and sometimes worked for phosphate or nitrate. Caves in the Otavi Mountains invariably contain guano, sometimes in impressive quantities. Some guano accumulates in dry chambers and remains powdery, while some accumulates in water and forms beds of waterlogged guano. The rôle that the phosphates and nitrates in guano has played in the geochemistry of Otavi caves has not been investigated, although it can be surmised that one effect has been the enlargement of caverns due to the acidic nature of the guano when it is wet. Some minerals known from Tsumeb, such as corkite ($PbFe_3(PO_4)(SO_4)(OH_6)$) and tsumebite ($Pb_2Cu(PO_4)(SO_4)(OH)$) may well have obtained their phosphorous content from bat guano.

Holokarst : Karst that is completely developed, characterised by thick limestone bedrock, little or no surface drainage, and a bare surface with well-formed depressions and caves. Parts of the Otavi Moutainland conforms with the concept of holokarst, but due to the folded and faulted nature of the strata, it is not everywhere well developed. The principal horizons that have developed the best examples of holokarst, are the dolomites of the Otavi Group (see merokarst).

Internal erosion : Erosion effected within a compacting sediment by movement of water through the larger pores. Some examples of internal erosion have been encountered at Berg Aukas. Cavities thus formed are often lined with calcite crystals.

Internal sediment : An accumulation of clastic or chemical sediments derived from the surface of, or within, a more or less consolidated carbonate sediment (mud or silt), and deposited in secondary cavities formed in host rock (after its deposition) by bending of laminae or by internal erosion or solution. The most interesting examples of internal sediment encountered in the Otavi region occur at Berg Aukas, Baltika and Abenab. Some fine examples of small cavities formed by the bending of laminated silty clay sediment occur at Berg Aukas. The resultant cavities so formed often contain euhedral calcite crystals.

Interstratal breccia : A brecciated rock unit that forms at depth below a resistant non-soluble rock, or one that is less soluble than that forming the breccia. Interstratal breccias, probably of Palaeozoic age occur abundantly in the Otavi region. They are of importance because of their associated heavy metal sulphide bodies, many of which are of economic importance.

Interstratal karst : Karst that forms at depth below a resistant nonsoluble rock. Examples of interstratal karst occur in the Otavi Mountains, and are usually represented by various kinds of breccia deposits. Good examples occur at Friesenberg.

Iron oxide nodule : A small, irregular rounded knot, mass, or lump of iron oxide, normally having a warty or knobbly surface and no internal structure, often found in soils, where they are also known as murram nodules. In the Otavi Mountains iron oxide nodules appear to form in soils, from which they can be reworked into eluvial masses, and sometimes find their way into depressions, such as deckenkarren, and caves where they can comprise an important fraction of the sediment infilling such depressions. The presence of iron oxide nodules is often considered to be a guide to the presence of underlying mineral deposits by prospectors, but in the Otavi region, they appear to be too ubiquitous to be of much importance in this respect. They should not be confused with gossan deposits, which are iron-rich, but are generally not nodular in form.

Kamenitza : Solution pan, usually circular in plan, with flat bottoms and rounded edges. Such solution pans occur on exposed limestone surfaces in the Otavi Mountains, but are often sharp-edged.

Karren : In karst topography, karren is a general term for solution grooves ranging in width from a few millimetres to more than a metre, and commonly separated by knifelike ridges. Karren that originate under a soil cover (see rundkarren) are rounded and average about 50 cm wide, whereas those that originate at the surface (see rinnenkarren) are sharp and typically 1 cm wide. Virtually the entire region of the Otavi Mountains is riddled with karren of various kinds and at various scales from millimetric to kilometric (as seen on satellite images).

Karst : A type of topography that is formed on limestone, dolostone, gypsum and other rocks by dissolution, and that is characterised by sinkholes, caves, and underground drainage. The entire Otavi region is a vast karst field.

Karst Base Level : A level below which karstification is presumed to cease. The present day karst base level in the Otavi Mountainland is unknown. The Tsumeb pipe is at least 1500 metres deep, the present deepest mine workings being some 500 metres below sea level. However, the Tsumeb pipe is not strictly speaking a karst feature related to surface phenomena. It may well have a hydrothermal origin, dating from the Palaeozoic.

Karstcrete : A local term employed by geologists and miners in the Otavi Mountainland for near surface indurated reddish karst infillings, often containing vanadium mineralisation, and sometimes fossils (see sand sack).

Karstfeld : A local term employed by farmers in the Otavi Mountains and neighbouring areas for the ensemble of karstified country that typifies the region. There is little or no surface water, vegetation is usually relatively undisturbed on account of the difficulty of exploiting it on a commercial basis, and moving around in it often requires agility and care on account of the loose blocks, the sharp karren of various kinds, and in the Otavi Mountains, the characteristic vegetation of which thorny plants and giant nettles are abundant in patches.

Karst Hydrology : The drainage pattern and features that are characteristic of karst. Understanding of ancient

Plate 29. Karstfeld in the Otavi Mountains, Namibia.

karst hydrology could throw light upon the question of vanadium mineralisation in the Otavi Mountains.

Karstification : The formation of karst features by the solutional, and sometimes mechanical, action of water in a region of limestone, gypsum and other bedrock.

Karst Plain : A plain, usually of limestone, on which karst features are developed.

Laminated flowstone : A general term for any deposit of calcium carbonate or other mineral formed by flowing water on the walls or floor of a cave. Fine examples of flowstone occur in many of the caves of the Otavi region. Fossil examples are known at Jägersquelle, Aigamas, Berg Aukas and Nosib Palaeocave.

Lapiaz : A term from Pyrenean dialect, being a synonym of karren.

Leachate : A solution obtained by leaching; e.g. water that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution (see eluviation and carbonate downwasting). In the Otavi region, an economically important component of leachates has been vanadium, possibly in the form of soluble calcium metavanadate, the vanadium precipitating out in the presence of lead and copper under suitable pH conditions (weakly to strongly alkaline: pH 8 to 10), to form the minerals descloisite and mottramite.

Leaching : The separation, selective removal, or dissolving-out of soluble constituents from a rock or orebody by the natural action of percolating water (see eluviation and leachate).

Letdown : A process during which surficial rocks and soils lose altitude in a more or less vertical sense, usually due to the dissolution of underlying strata, especially in karst settings. In the Otavi Mountains, important quantities of epikarst sediments underwent letdown, sometimes into underground cavities in which they were then trapped, canalised and concentrated. Examples of economically important letdown deposits occur at Berg Aukas, Abenab, Wolkenhaben, Harasib 3a, Uris, Karavatu, Rietfontein and Friesenberg.

Limestone : A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of calcite, with or without magnesium carbonate. Specifically, limestone has less than 5% by weight of dolomite. Limestone occurs in the Otavi Mountains, but is subordinate in volume to dolomite.

Plate 30. Lapiaz with rinnenkarren at Friesenberg, Otavi Mountains, Namibia

Merokarst : Karst that is imperfectly developed, characterised by thin or impure limestone bedrock and by the presence of surface drainage. In the Otavi region there are areas of merokarst, mainly developed in the thin-bedded carbonate rocks of the Mulden Group (see holokarst).

Palaeocave : An ancient cave or part of a cave that is usually no longer cave-like, as in a former cave whose roof and walls have been eroded away, or an ancient cave that has become completely clogged with sediments. Several fine examples occur in the Otavi Mountains, on account of the rapid rate of carbonate mass wasting that typifies the area. At Jägersquelle, Nosib Palaeocave, Karavatu, Rietfontein and Friesenberg Hilltop, all that remains of former caves are the cave floor breccias that accumulated in them. All these deposits, except for Karavatu, are rich in vertebrate remains and speleothems. The term can also be applied to caves which have become completely filled with sediments, thus no longer presenting an open morphology. Examples of filled palaeocaves in which the walls are preserved are Berg Aukas and Harasib 3a.

Palaeokarst : Literally ancient karst, this term covers a rock or area that has been karstified and either buried under sediments, or left exposed at the surface for long periods after karst processes ceased. Buried palaeokarst may be re-exposed at the surface by exhumation, and is known as exhumed karst. Many examples of palaeokarst of Palaeozoic age are known in the Otavi Dolomites. They are of great economic importance on account of the massive heavy metal sulphides that occur in association with them, such as at Tsumeb, Berg Aukas and Kombat. Remnants of Tertiary and possible Mesozoic karsts are also known to occur in the region. The best examples are Abenab and Baltika which are possibly Mesozoic in age, and Berg Aukas and Harasib 3a, which are Miocene in age.

Phreatic solution : The solution action by ground water below the water table. The presence of cavities deep below the water table in the Otavi region, suggests that phreatic solution is an important geomorphological process of the area.

Phreatic water : All water in the zone of saturation (= ground water). Huge reserves of phreatic water occur in the Otavi region, known for its underground lakes. Mines such as Kombat, Berg Aukas and Tsumeb have had to be constantly pumped dry on account of the phreatic water that seeps or pours into them.

Phreatic sediment : A sediment which accumulates in the phreatic zone. It is often comprised of fine-grained, well-bedded silts and clays which usually represent insoluble residues of the dissolving country rock. In the Otavi Mountains, some of the fine-grained, well-bedded sediments which occur at Baltika and Abenab appear to have been deposited by slowly moving water in the phreatic zone.

Phreatophyte : A plant that obtains its water supply from the zone of saturation or through the capillary fringe and is characterised by a deep root system. In dolomite outcrops, tree-roots often dissolve deep vertical cavities in the rock, producing circular doline-like depressions several metres deep and up to 1 metre in diameter. (See Phytokarst).

Phreatic zone : Zone of saturation.

Phytokarst : A type of solution landscape in which the major morphology is produced by the attack of boring algae and/or fungi on limestone. It is charaterised by jagged, grotesque sculpture; it differs from ordinary solution karst by a random orientation of the sculpture with respect to gravity, and a black algal coat. In the Otavi Mountains, various species of lichen produce microphytokarst. Their principal interest lies in the observation that some species are specific to rock types, including mineral deposits. Knowledge of such lichen/mineralisation associations are useful when prospecting for heavy metals, for example, zinc.

Plain with towers : In karst topography, a plain with towers is a flat valley out of which stick vertically sided towers of carbonate rock. In the Otavi Mountains, fine examples of plains with towers occur on Auros and Gauss.

Polje : A large flat-floored closed depression in a karst area. Its drainage is subsurface, its size is measured in kilometres or tens of kilometres, and its floor is commonly covered by alluvium. Poljes (= interior valleys) may become intermittent lakes during periods of heavy rainfall, when the sinking streams that drain them cannot manage the runoff. A good example of a polje is provided by the mealie lands at Farm Gauss.

Pseudo-aplite : A local term employed in Namibian mining circles for a rock resembling aplite in hand specimen that occurs abundantly in the Tsumeb pipe and elsewhere in the Otavi Mountains, but which is a spelean sediment and not of intrusive igneous origins. It consists of well indurated fine sandstone.

Rillenkarren : Downslope solution grooves about 1 cm wide, with sharp intergroove crests. Rillenkarren are ubiquitous on hillslopes of exposed Otavi dolomites.

Rillenstein : Tiny solution grooves about one millimetre or less in width, formed on the surface of a soluble rock. Rillenstein are common features of the Otavi Mountains.

Plate 31. A polje or "through valley" near Kombat, Otavi Mountains, Namibia, here used for accessing the interior of the mountains. Note the heavily karstfied dolomite flanks of the polje.

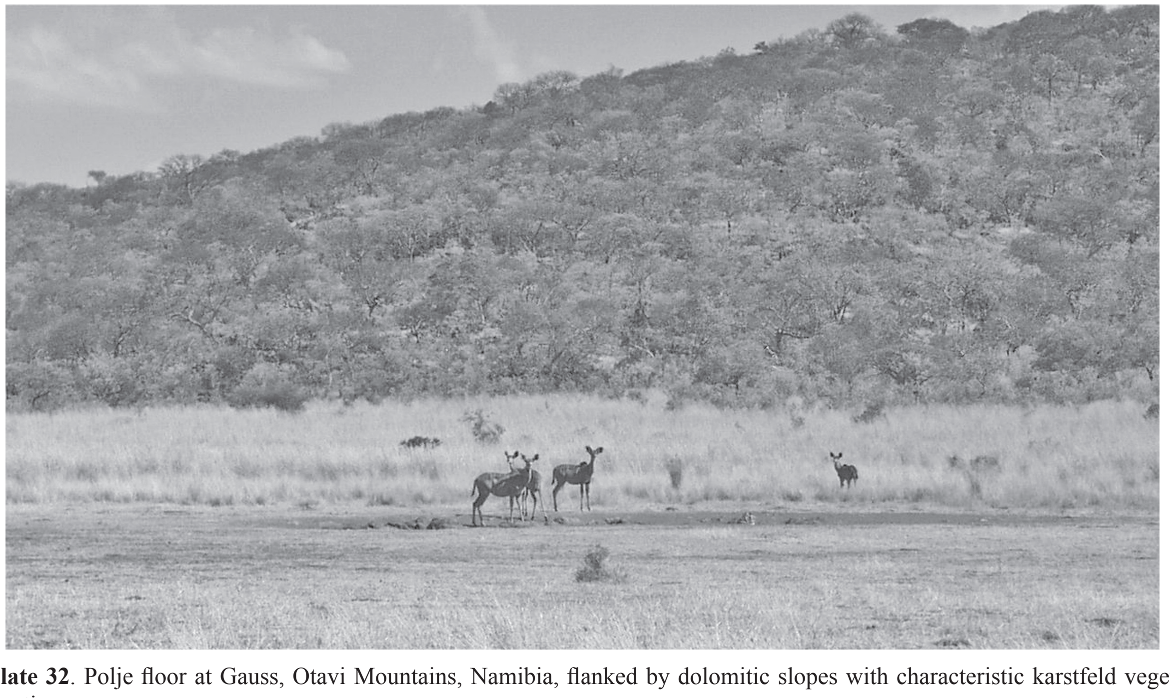

Plate 32. Polje floor at Gauss, Otavi Mountains, Namibia, flanked by dolomitic slopes with characteristic karstfeld vegetation.

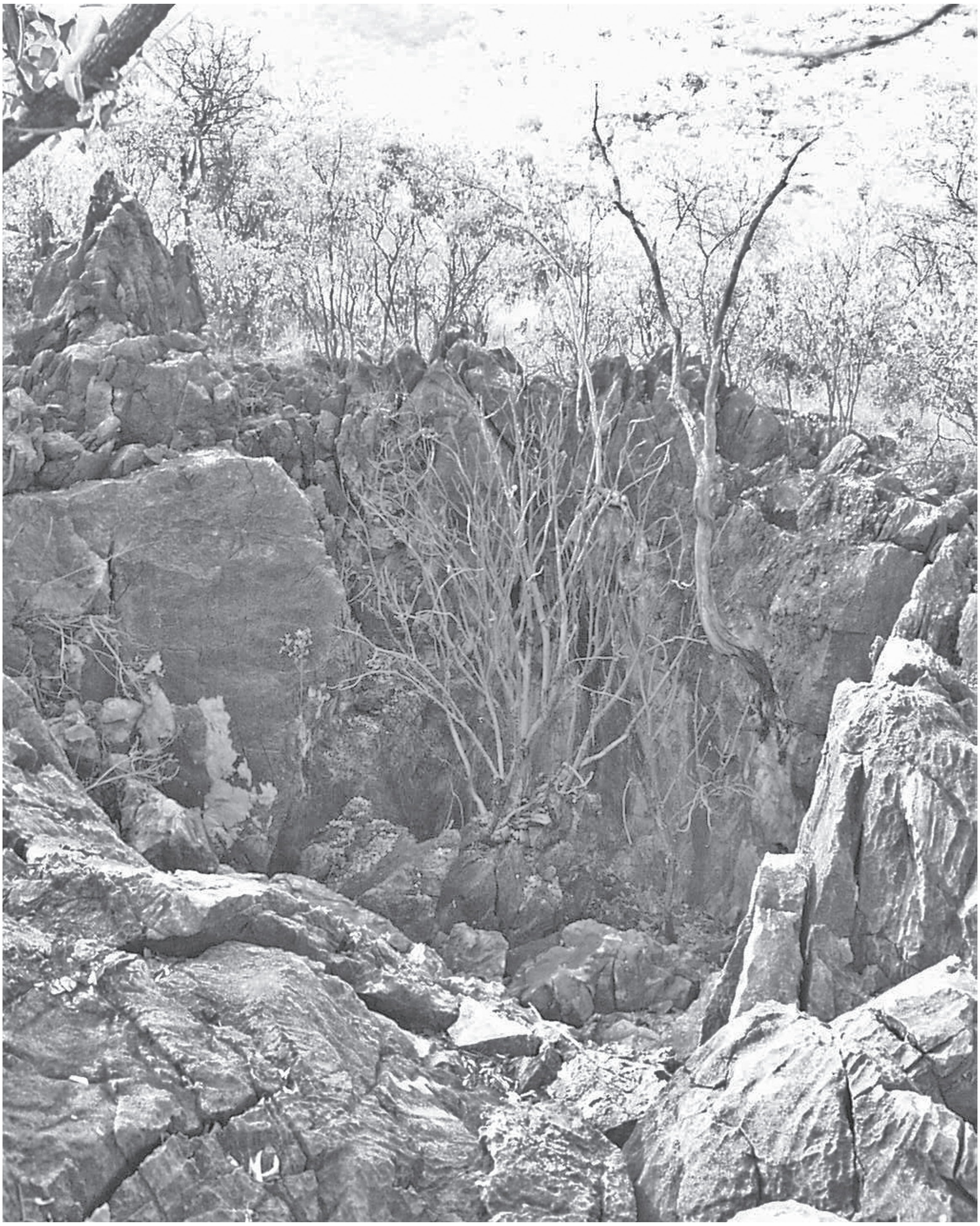

Plate 33. Sinkhole near Rietfontein, Otavi Mountains, Namibia.

Rinnenkarren : Downslope solution grooves about 0.5 metres wide, with sharp intergroove crests. Rinnenkarren are common on barren slopes of dolomite in the Otavi region. They are often associated with loose blocks of jagged and sharp dolomite, which represent detached fragments of interkarren crests.

Sand sack : A local term employed by miners and geologists in the Otavi Mountainland, for reddish sand to clay grade sediments usually found in fissures or cavities in the dolomite country rock. They are comprised of various kinds of karst infillings including reworked soils, concentrations of insoluble residues of the dolomites, cave breccias (often fossiliferous). Some of them are epikarst infillings, while many of the larger sand sacks, such as Berg Aukas and Abenab are spelean sediment bodies (see karstcrete).

Sinkhole : A depression, often circular or oval in outline, in limestone, dolomite or other soluble rocks. Sinkholes are generally choked with loose blocks derived from the surroundings, and when it rains they are the conduits down which water disappears. These depressions are often caused by upward dissolution of soluble rocks, and thus often signal the presence of underground cavities.

Speleothem : Any secondary mineral deposit that is formed in a cave by the action of water. Speleothems are very common in the Otavi Mountainland. Good examples are known at Tsumeb, Berg Aukas, Aigamas Cave, Uris and Baltika. Many speleothems, such as stalactites and stalagmites, are geopetal, and thus indicate the way-up of the rocks in which they occur. Others, such as geode-like cavity linings which occur at Uris and Tsumeb are not geopetal, and probably crystallised onto the walls, floor and roofs of cavities that were entirely filled with water, possibly by hydrothermal fluids.

Spitzkarren : Solution grooves about 0.5 metres apart, separated by rows of sharp-crested pyramidal peaks. Spitzkarren occur frequently near the tops of dolomitic hills in the Otavi region, for example on Farm Aigamas.

Spongework : An entangled net of irregular interconnecting cavities of various sizes produced by solution in the walls of limestone caves and separated by intricate perforated partitions and remnants of partitions. The best examples of spongework seen in the Otavi Mountains are at Tygerschlucht, Wolkenhaben, Guchas and Rodgerberg, where the cavities are often lined with crystals of descloisite and/or dioptase.

Travertine : A dense, finely crystalline massive or concretionary limestone, of white, tan, or cream colour, often having a fibrous or concentric structure and splintery fracture, formed by rapid chemical precipitation of calcium carbonate from solution in surface and ground waters, as by agitation of stream water or by evaporation around the mouth or in the conduit of a spring, especially a hot spring. It also occurs in limestone caves, where it forms stalactites, stalagmites, and other deposits; and as a vein filling, along faults and in soil crusts. The spongy or less compact variety is tufa. Travertine is common at Tsumeb, Berg Aukas, Nosib Palaeocave and Jägersquelle. A superbly developed subaerial tufa field rich in plant impressions has formed at Ghaub.

Terra rossa : A reddish-brown residual soil found as a mantle over limestone bedrock, typically in karst areas around the Adriatic Sea, under conditions of Mediterranean-type climate. This term is often employed more widely to include reddish residual soils formed in karst areas under other climatic regimes as well, in particular in tropical climates. Reworked terra rossa has been found at Berg Aukas, where it is usually poorly calcified.

Trace fossil : A sedimentary structure consisting of a fossilised track, trail, burrow, tube, boring, or tunnel resulting from the life activities (other than growth) of an animal. In the epikarst sediments of the Otavi Mountains, trace fossils are common, the most abundant being calcite lined tubes in silty to sandy sediments probably excavated by termites and ants. Some of the breccia blocks at Berg Aukas contain such meandering and branching tubes, meaning that the sediments accumulated at relatively shallow depths and above the water table, because termites and ants are restricted to the epikarst zone above the water table. Similar examples of trace fossils are known at Gabus and Elefantenberg Nord.

Trittkarren : Crescentic solution pockets about 30 cm in diameter on limestone surfaces. Trittkarren are asymmetrical in vertical section with a flat tread and a vertical riser and are often laterally coalescent. Trittkarren are common in the Otavi Mountains.

Vadose sediment : A sedimentary rock which accumulates in cavities within the vadose zone. Examples of indurated vadose sediment are known from Berg Aukas, where they are often richly fossiliferous, and at Baltika and Abenab.

Vadose solution : Solution action by vadose water above the level of the water table. Many of the caves and palaeocaves in the Otavi Mountainland formed by vadose solution of dolomite and limestone.

Vadose water : Water of the zone of aeration.

Vadose zone : Zone of aeration.