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# Morphological and micromorphological aspects of the sandstone karst of eastern Niger

by

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with 5 figures and 10 photos

**Zusammenfassung.** Die Arbeit beschreibt im ersten Teil die Auswirkung der Sandstein- und Eisenkrustenverkarstung auf das Plateaurelief des östlichen Niger. Angesprochen werden die abflußlosen Karstdepressionen auf den Plateaudachflächen, die Rolle intensiver Verkarstung bei der Herauspräparierung von Sandsteinsäulen an Hängen, von Plateauspornen und Inselbergen, die Mitwirkung bei der Talbildung sowie Einsturzdolinen an Hängen. Im zweiten Teil wird die Mikromorphologie von Karsthöhlenüberzügen aus der Endphase der phreatischen Karstlösung beschrieben. Oberflächennahe Körner weisen starke Korrosion auf. Phosphor in der wiederausgefällten Matrix und eingekieselte Bakterien deuten auf eine organische Komponente bei der Ausbildung des tertiären Silikatkarsts.

**Summary.** In its first part the paper describes the morphological effects of silicate karstification on the plateau landscape of eastern Niger. The description centers on the endorheic depressions dotting the plateau surfaces, the role of intensive karstification in the formation of slope pillars, plateau spurs and inselbergs, its contribution to valley formation, as well as on collapse structures on slopes. The second part describes the micromorphology of the lining of cave walls. Near-surface grains are heavily corroded. Reprecipitated matrix containing phosphorous and silicified bacteria on quartz grains point towards an organic element in the Tertiary formation of the silicate karst.

**Résumé.** Dans la première partie on décrit des éffets morphologiques de karstifiction des grés et des roches ferrugineuses sur le paysage des plateaux de l'ést désertique du Niger. La déscription se concentre sur des dépressions endorhéiques des plateaux, sur le rôle de la karstification intense dans la formation des tours sur les pentes, des éperons des plateaux, des inselbergs et de certaines vallées. Dans la deuxième partie on discute la micromorphologie des surfaces des tuyaux et grottes karstiques datant de la dernière période de karstification. Des grains proche à la surface sont fortement carieux par la solution. Le silice de réprécipitation entre les grains contenant du phosphore ainsi que des microbes silicifiées sur certains grains indiquent une contribution organique à la karstification des roches silicieuses.

## 1 *Introduction*

This is the joint publication of two papers that were read at the 2nd International Conference on Geomorphology at Frankfurt: the first one by Busche, on the effects that the subterranean sandstone karst has had on the geomorphology of the desert escarpment landscape of east-

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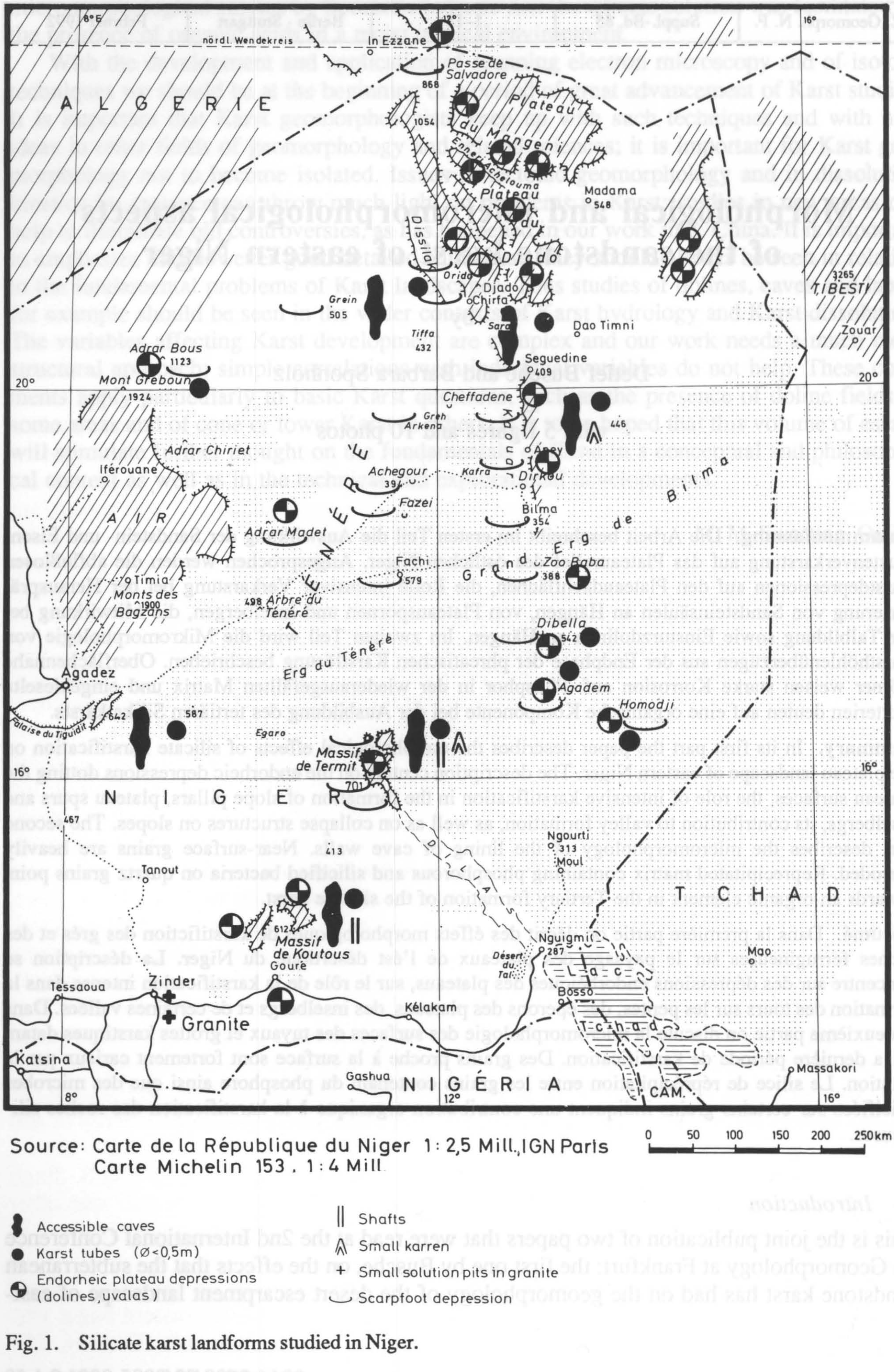


Fig. 1. Silicate karst landforms studied in Niger.

ern Niger, and the second one, by Sponholz, on the micromorphological aspects of it, mainly with respect to the formative conditions of silicate karst.

An earlier paper on the silicate karst landforms of the southern Sahara was read at the 1st International Conference on Geomorphology at Manchester 1985 and subsequently published in the conference proceedings (Busche & Erbe 1987). It will therefore not be necessary to present the evidence once more that surficial and subsurface solution forms do exist in non-calcareous sandstones and pisolithic iron crusts, and that they have to be regarded as true karst features. A full-length description of this variety of karst has recently been published by Sponholz (1989). Aside from a brief introductory description of the silicate karst morphology of eastern Niger this paper will concentrate on some indirect effects of karstification on the morphology of the isolated plateaus and, in its second part, on the information gained from micromorphological studies on the environmental conditions that enabled the intensive solution of silicates.

As described in several publications by now (Busche 1988, Busche & Sponholz 1988, Baumhauer et al. 1989, in addition to the titles already referred to), silicate karst is a rather ubiquitous element of the plateau landscapes of the Saharan desert and the Sahel to the south of it. It has been observed in areas from southern Morocco to southern Egypt, and it has been studied in some detail first on the Messak Plateau along the Libyan/Algerian border and the adjoining Djado Plateau of northeastern Niger (Busche 1982), and then in various other regions of eastern Niger, with emphasis on the Kawar depression and its escarpment, the plateau of Termit and the sahelian mesa landscape of the Koutous (Fig. 1).

All the areas have in common that they lay close to an ocean or lagoonal shoreline in a moist tropical environment during the early and middle Tertiary when most of the karst formation appears to have taken place. Karstification occured on and below an etchplain (the Miocene Surface of South African terminology) that was still undissected. In the study area it mainly affected the sandstones of the Cambrian and Upper Cretaceous, the sandstones of the largely Upper Oligocene *Continental Terminal* with its iron crusts, and the silcrete of probably Early Miocene age capping most of the plateaus (for the geology cf. Faure 1966, Sponholz 1989 or Baumhauer & Hagedorn 1989). Two principal periods of karst-formation have been identified: the first one in the early Tertiary prior to the deposition of the *Continental Terminal*, as sediment believed to be of this age was found in karst vessels, and the second period after deposition of the *Continental Terminal* and after silcrete formation, as subaerial karst landforms, up to large uvalas and poljes, have been found within them or cutting through them. Large-scale karstification came to an end with the onset of scarpland and plateau formation, due to general uplift, incision and improved drainage as well as to decreasing humidity. It lead to the dismemberment and consequently the drainage of an increasing number of subterranean karst vessels that had developed under phreatic conditions. Where suitable conditions of high water supply and poor drainage prevailed, however, silicate karst processes above and below the surface continued until about the end of the Pliocene with the formation of scarpfoot depressions (Busche & Erbe 1987). Underground solution processes in groundwater bodies are obviously still at work today, as can be seen from $SiO_2$-contents as high as 10,000 ppm in the groundwater of the Kawar (Faure 1963, Annexe 2-X, Baumhauer 1986: 27, Baumhauer & Hagedorn 1989).

## 2 *Morphological effects of subterranean sandstone karst*

### 2.1 *Solution sinkholes and uvalas*

The most salient feature of the sandstone karst is the occurrence of innumerable flat-floored solution sinkholes on all the plateau surfaces, indicating that the the principal phase of

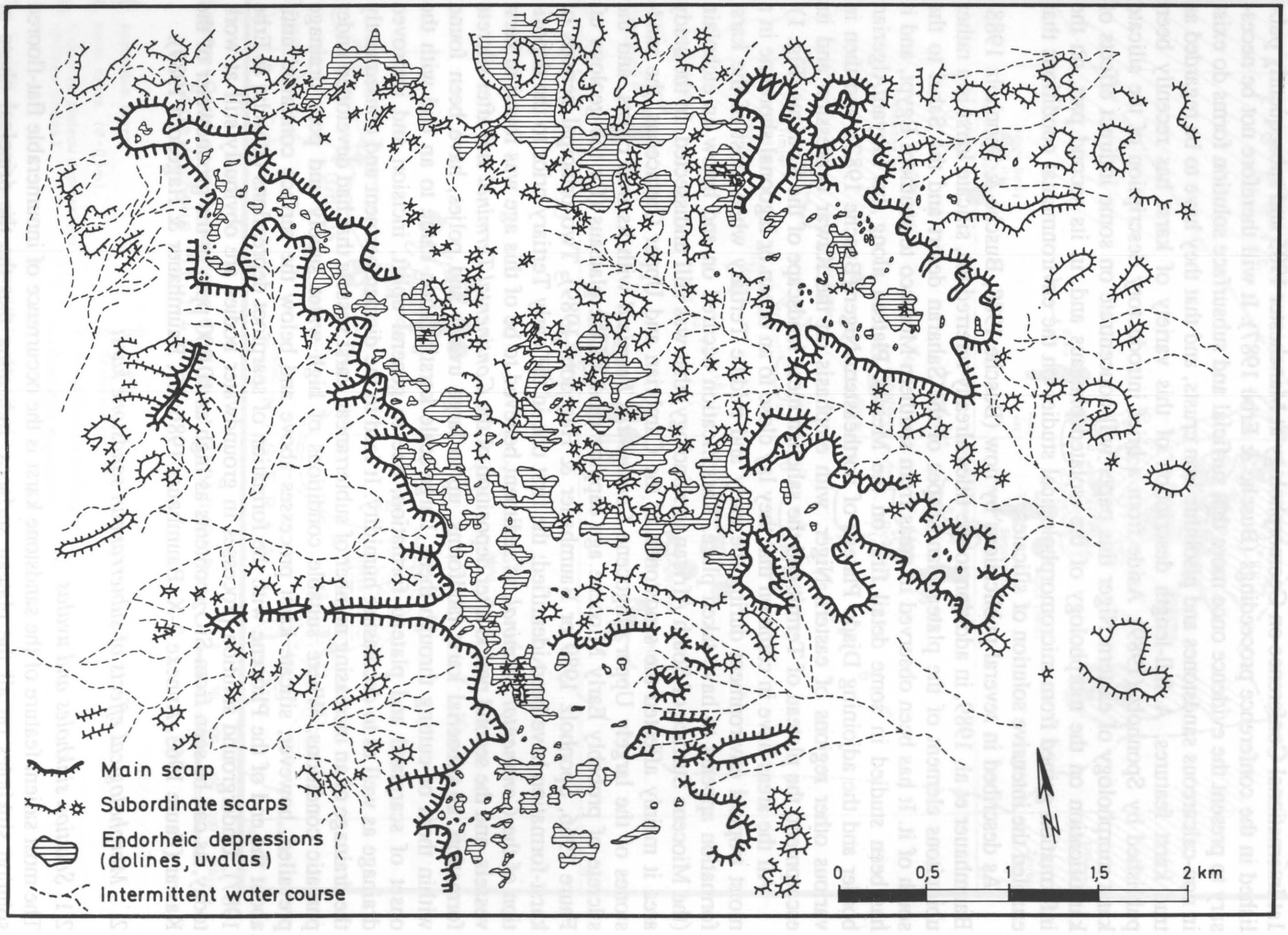


Fig. 2. Map of endorheic depressions on the plateau surface of the Massif de Termit, E of Dougoulé, mapped from air photographs 1:50,000. From: Sponholz 1989.

Photo 1. Endorheic depressions on the Termit Plateau, center of Fig. 2. Small silt-filled swallow holes in a shallow doline in the foreground; irregular uvalas with steep walls and a thin silt cover on the sandstone floor in the background. Busche 1986, Ni-86-768.

karstification took place prior to the dissection of the etchplain. Wherever silcrete is still preserved on the plateau surfaces (Busche 1983) the depressions of all sizes, ranging from a few square meters to more than a square kilometer, have been sunk through it. The original latosol cover of the region had already been removed by then, to be deposited in the south as part of the *Continental Terminal* already referred to (cf. Faure 1966). There are regional differences of the karst depression patterns the significance of which is not clear yet. Photo 1 and Fig. 2 show an impressive complex of depressions from small doline to uvala and polje size on the Termit Plateau, up to several meters deep, with steep to vertical rims and with many joint-oriented solution fissures with round shoulders tens of meters long each, cut into their level rock floors and swallowing the water from the occasional rains (Photo 2).

Obviously there must have been some kind of water-logged soil cover in the areas where the depressions were being formed by solution, as neither the steep surrounding walls with their sharp knickpoints nor the rock floors could have been developed by subaerial processes. Further evidence comes from occasional subvertical tubes in silcrete a few tens of centimeters in diameter that start abruptly at full width at the surface, as well as from some quite spectacular concentrations of hundreds of tubes of smaller diameter on the iron crust floors of large depressions farther to the south. They lie right next to each other (Photo 3), giving a sponge-like impression to the surface, and again their diameters are about the same size where the tubes are cut by the horizontal surface as they are farther down in the ground. If there ever was a higher funnel-shaped opening at the surface, it must have disappeared with the stripping of the unconsolidated cover. This type of sinkhole assemblage seems to be restricted to iron crusts, but was found in widely separated areas, such as the plateau of Termit and that of Agadem.

**Photo 2. Fissure-shaped swallow holes in an endorheic depression on the Termit Plateau, center of Photo 1. Busche 1986, 763.**

**Photo 3. Silt-filled mouths of densely spaced subvertical karst tubes in an oolithic iron crust, floor of a large endorheic depression, Termit Kaoboul. A number of the tubes were later excavated to some depth. There are links between them below the surface. Busche 1986, 1311.**

## 2.2 *Slope wash from karst tubes*

The close spacing of holes on the surface reflects the three-dimensional maze of small-diameter tubes perforating the sandstone in some areas, fully comparable to the mazes found in the karstic Eocene limestone of southern Egypt. Where such a tube-riddled sandstone complex has been cut by a slope during escarpment formation, as in some areas of southern Termit, its present morphology is affected by it. As a rule all slopes below the free face are covered by a sheet of downslope-oriented angular slope debris frequently about 1 m thick (cf. Photo 8). Larger vertical tube segments have been debris-filled, but where there are many small subhorizontal karst tubes, often only a few centimeters in diameter, that have been truncated at the slope, water gushing from them after heavy rains either has removed most of the late Pleistocene to early Holocene debris blanket or has perhaps never allowed its formation there.

## 2.3 *Slope pillars, plateau spurs and inselbergs*

In the southern part of Termit, where the highest density of small-diameter karst vessels was found, karstification has affected slope processes in yet another way. In a number of places tor-like pillars and small ridges several meters high, shaped from the same sandstone as their surroundings, stand out on the plateau and, more conspicuously, on the front slopes of the escarpment (Photo 4a). Close-up examination in each case showed that they are riddled with karst tubes, lined with a thin coating and sometimes globular or stalactitic precipitation forms of iron-containing silica (Photo 4b). As it is only the extreme viability for water and possibly an increased stability of the sandstone due to the coating that distinguishes these forms from the rock surrounding them, the latter must be credited for their preservation during slope and plateau denudation. On one hand water for chemical weathering could drain faster than in less karstic areas and, once an initial separation had taken place, runoff, instead of eroding on the outside, would flow through the numerous passages protected by their coating, removing particles at a lesser rate than on the surrounding slope.

These forms are certainly not more than arabesques on the slopes, but they may serve as a model for the influence karstification had on differential denudation at a larger scale. In our search for caves and related karst forms two types of relief were found to have the highest density of subterranean passages. The first one is a number of spurs jutting from the plateau towards the foreland, especially along the Kawar escarpment, that contain a host of caves large enough to be entered, whereas the back walls of the amphitheaters, although equally accessible, show much less to hardly any subterranean karst forms. Very good examples are the spur of Chemidur (near Dirkou), with more than a dozen accessible caves over a distance of a few hundred meters, and, farther to the north, the spur south of the medieval fortress of Aney (for location cf. Fig. 1).

The second type of relief with extreme subsurface karstification are the inselbergs of the region, regardless of their stratigraphy and size. The most important ones are the Cambrian sandstone towers along the southwestern rim of the Djado Plateau that are up to 300 m high. Most of the large caves were discovered within them, including the one with a portal 30 m high in Ehi (= Mt.) Ouarek (Photo 5) that was first described by Renault (1953). Almost each dark shadow on the inselberg stands for a cave entrance, although their mouths have often been widened by tafonization. Sponholz's (1989) estimate of the karst volume of this inselberg is around 3%. It may be much higher in a small inselberg north of the village of Aney (Fig. 3) about 50 × 10 × 20 m with about 100 large and small openings along its flanks and on its top. A large number of karst caves also exist in the rock of comparable size in the village of Aney, as well as is the severed plateau spur bearing the old fortress of Aney.

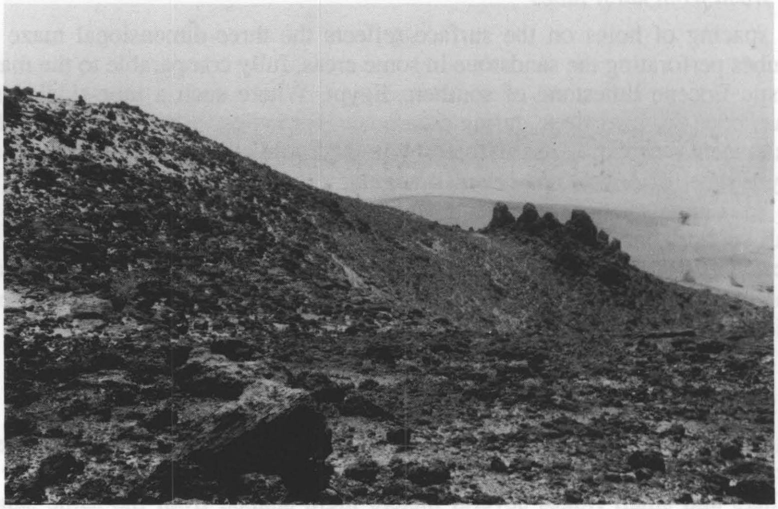

Photo 4a. Sandstone pillars on a slope preserved because of intensive karstification, Termit Kaoboul, Busche 1986, 1337.

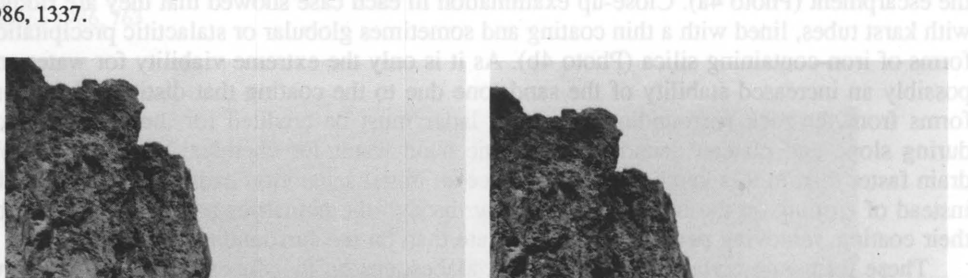

Photo 4b. Stereogram of part of one of the pillars. Note the lining of the tubes cut open and another pillar in the background. Busche 1986, 1341, 1342.

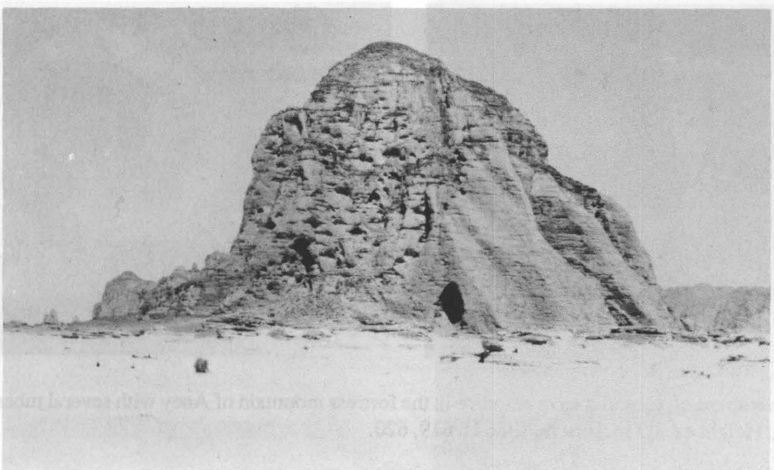

Photo 5. Ehi Ouarek, severely karstified Inselberg ca. 300 m high in a scarp-foot depression, southwestern rim of the Djado Plateau. The large portal is ca. 30 m high. Almost each shadow on the flank marks a cave entrance. Busche 1986 H, 1128.

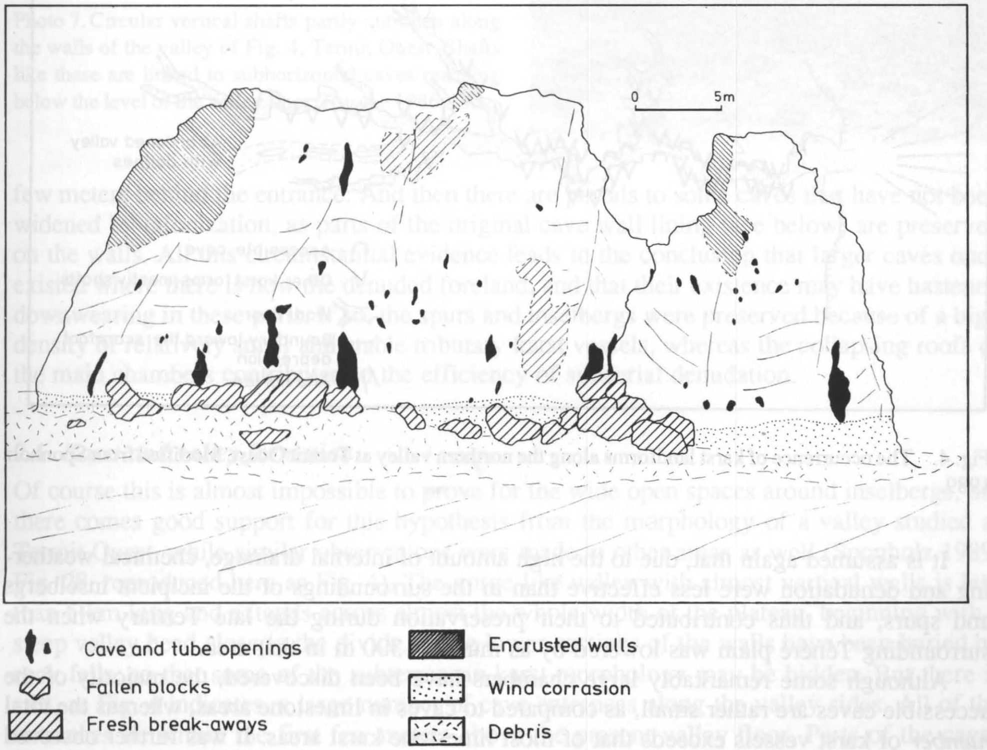


Fig. 3. Severely karstified sandstone inselberg (ca. 50 × 10 × 20 m) N of Aney, northern Kawar. The rock is riddled by numerous karst tubes and caves. At A and B passages cross it. Ca. 100 karst holes have been counted. Drawing by Sponholz 1989.

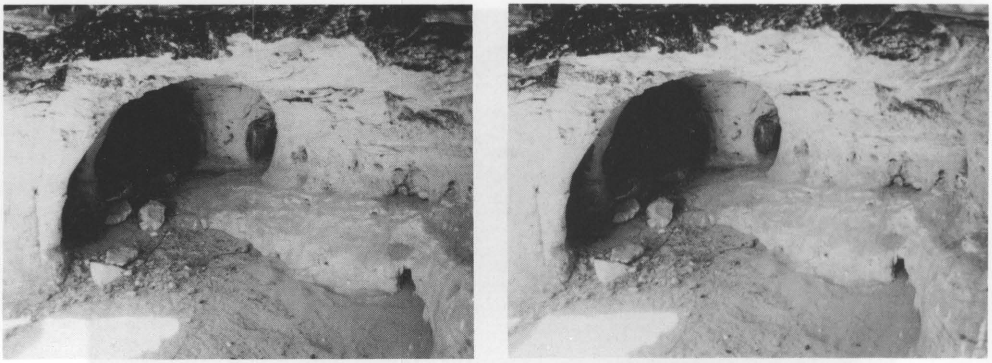

Photo 6. Stereogram of a circular cave entrance in the fortress mountain of Aney with several tubes coverging towards it. Height ca. 1.3 m. Busche 1986 H, 619, 620.

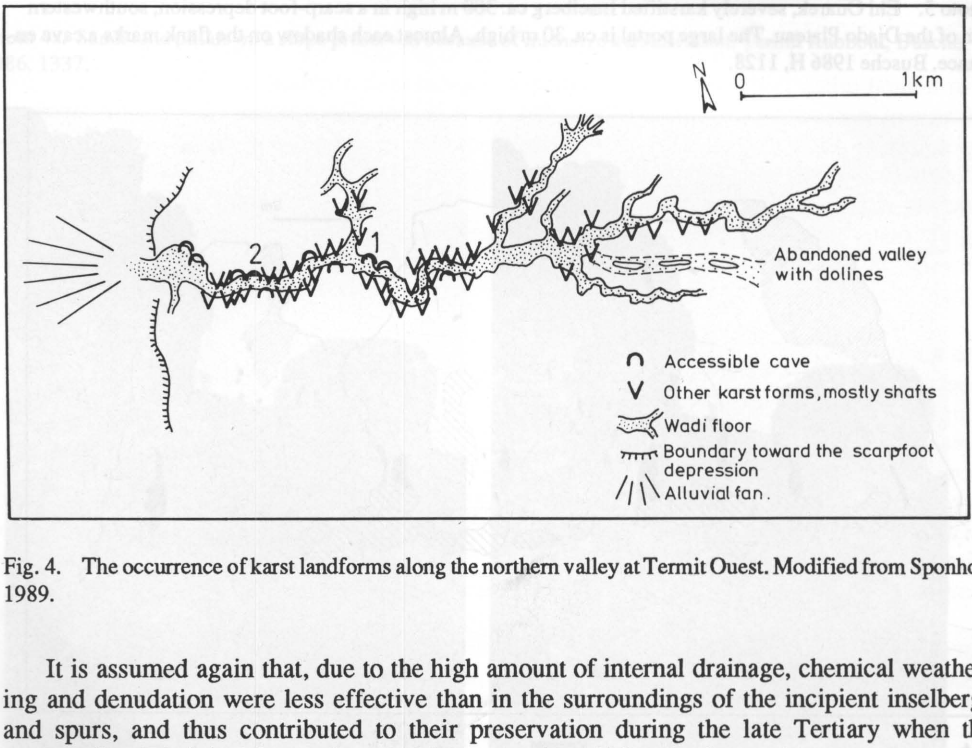


Fig. 4. The occurrence of karst landforms along the northern valley at Termit Ouest. Modified from Sponholz 1989.

It is assumed again that, due to the high amount of internal drainage, chemical weathering and denudation were less effective than in the surroundings of the incipient inselbergs and spurs, and thus contributed to their preservation during the late Tertiary when the surrounding Ténéré plain was lowered by as much as 300 m in that area.

Although some remarkably large chambers have been discovered, the majority of the accessible caves are rather small, as compared to caves in limestone areas, whereas the total *number* of karst vessels exceeds that of most limestone karst areas. It was further observed that a large number of caves, especially in the spurs, today begin with a large, sometimes bubble-shaped room right behind the entrance towards which a number of vessels converge (Photo 6). Even the wider passages narrow quite soon, so that access is restricted to the first

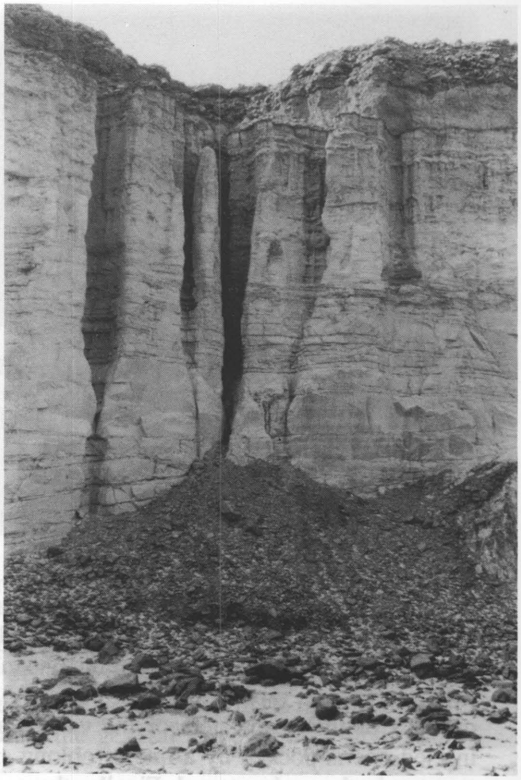

Photo 7. Circular vertical shafts partly cut open along the walls of the valley of Fig. 4, Termit Ouest. Shafts like these are linked to subhorizontal caves reaching below the level of the valley floor. Busche 1986, 573.

few meters behind the entrance. And then there are portals to some caves that have not been widened by tafonization, as parts of the original cave wall lining (see below) are preserved on the walls. All this circumstantial evidence leads to the conclusion that larger caves once existed where there is now the denuded foreland, and that their existence may have hastened downwearing in these parts. If so, the spurs and inselbergs were preserved because of a high density of relatively small and stable tributary karst vessels, whereas the collapsing roofs of the main chambers contributed to the efficiency of subaerial denudation.

## 2.4 *Karst and valley formation*

Of course this is almost impossible to prove for the wide open spaces around inselbergs, but there comes good support for this hypothesis from the morphology of a valley studied at Termit Ouest, while similar observations were made in other areas as well (Sponholz 1989, Fig. 28, reproduced here as Fig. 4). The gorge-like valley with almost vertical walls is less than 5 km long and extends across almost the whole width of the plateau, beginning with a steep valley head close to the divide. Some lower sections of the walls have been buried by rock falls, so that some of the subterranean karst morphology may be hidden. But there is still, as Fig. 4 indicates, a large number of cave entrances along the valley sides. All of the entrances lie within the first few meters above the present valley floor. Parts of the caves extend well below it, however. None of them extends very far from the valley wall. Again there are caves where the chamber size decreases away from the entrance, and there are numerous dead ends converging towards the entrance.

Photo 8. Stereogram of one of the largest collapse depressions on the flanks of a slope, Termit Chéguélenga. Scars of another collapse form are visible uphill, and karst openings on the fresh back wall. Note the rim of the slope debris blanket cut by the collapse. Busche 1986, 813, 814.

The caves are supplemented by a number of vertical shafts (Photo 7), generally occurring in groups, leading 10 and more meters down from the surrounding plateau level. Their round profiles can easily be studied as the rock falls have cut open a number of them. In some places, their link with the subhorizontal part of the cave system is clearly visible. Shaft entrances, either open or sediment-filled, only occur just along the rim of the wadi, where there is also a concentration of sinkholes. The degree of karstification along the tributary valleys rapidly decreases at some distance from the main valley. On the plateau itself, S of the headwaters of the valley, a higher abandoned valley floor parallel to the incised one is pocked by a line of oblong silt-filled dolines pointing towards a major karst passage in the underground. Finally, there were several fresh collapse features upstream of the type to be discussed below.

Taking all the evidence together, it is likely that the rather straight box-shaped valley came into existence when roof segments of a major cave system along the trace of the present valley collapsed. The higher dry valley mentioned above may be a still preserved part of the shallow precursor to the present valley. It is highly improbable that the caves on both sides of the valey sides formed with the valley floor as the local base level. For once, a number of the caves, as stated above, extend below the level of the valley floor, and the shafts could hardly be explained that way.

## 2.5 *Collapse sinkholes*

Sinkholes on the plateaus everywhere in eastern Niger are solution features, regardless of their size and depth. From the central region of Termit southward to the end of the plateau, however, there are occurences of collapse sinkholes, all of them at various heights on the debris-covered plateau slopes. They are well visible from the distance as crescent-shaped scars of fresh rock colour, their ends facing downslope, within the black-brown desert varnish of the debris blanket of the slopes (Photo 8).

Their diameter parallel to the contour line lies below 10 to more than 20 m. The vertical to overhanging back slopes are several meters high, and there may be more than one scar in a row upslope. The floor frequently rises towards the center, and even where this heap has been washed off, there is a ramp towards the back wall sloping into a sediment-filled chamber beneath it. Each crescent floor is the top of a debris cone formed when an under-

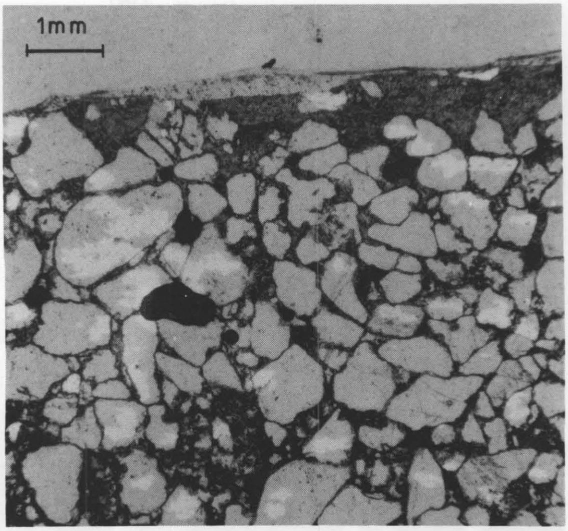


Photo 9. Thin section of the transition from severely corroded quartz grains close to the cave wall (top) to the fresher sandstone (bottom). The cave wall is lined by a thin coating of water-rich amorphous silica with a greenish colour. The matrix between the corraded grains contains Al and P (from Sponholz 1989, Abb. 13).

ground chamber collapsed. Small karst vessels truncated by the back and side walls further support the karst-related origin of these features. Fresh drainage marks indicate that some of the crescents act as swallow holes today; others temporarily act as karst springs, or they may serve both purposes at various times. An origin of these forms by slope erosion or spring sapping can definitely be excluded. In most cases there are not even drainage lines on the slope uphill of the scars, and in some of the forms the general slope of their floors only allows drainage towards, not from the back wall.

All the scars are very fresh in colour and have been little modified by erosion since their formation. Unlike the inferred collapse-form of the valley described above they are very young, and they are all of about the same Holocene age. This can be read from the fact that all of them cut through the same slope debris blanket that was deposited during the last major pluvial (late Pleistocene to early Holocene). Not a single older collapse form has been found so far. Therefore a common cause has to be assumed for their simultaneous formation.

Two explanations seem possible. At the time of collapse, the chambers can no longer have been filled with water, as this would have supported the roofs. As the collapse forms are all younger than the last major pluvial, and, reckoning from the freshness of the walls, also younger than the neolithic pluvial, it could be assumed that the recent past has been the first period in Saharan history where excessive aridity had caused the disappearance of the karst water bodies. It is problematic, however, that so far almost all of the collapse sinkholes have been found in Termit and not in other, even drier areas (a form of possibly the same origin was identified at the southern end of the plateau of Agadem to the east). Termit lies at the northern end of the west-African rift, and although there is no other evidence of young tectonic movements, it cannot be excluded that the roofs of the dry karst chambers collapsed during a major earthquake. Further obervations in other sandstone karst areas of the central Sahara are clearly necessary.

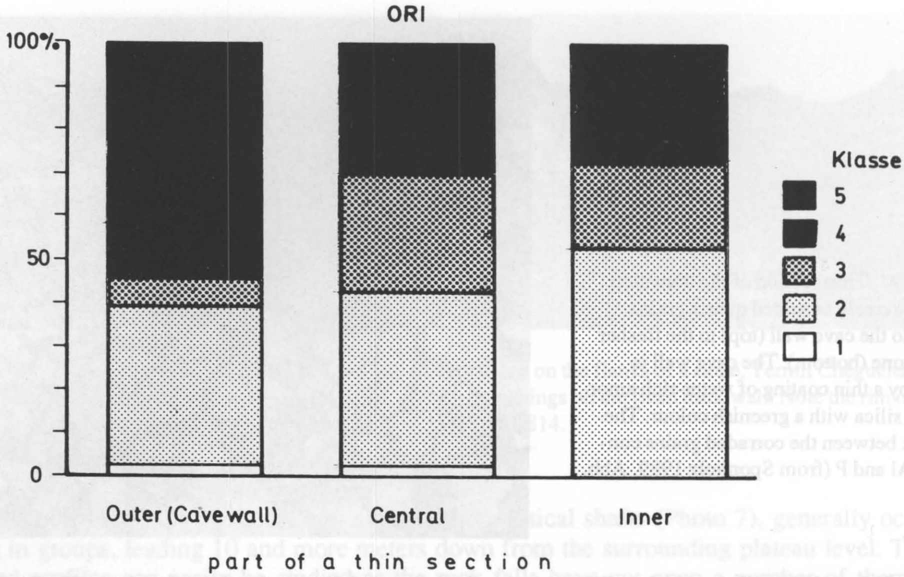


Fig. 5. Degree of corrosion of quartz grains at a cave wall in Orida, Djado Plateau, determined from a thin section. Corrosion classes after Burger & Landmann 1988: from 1 = not corroded to 5 = heavily corroded. Distance from outer to middle to inner sampling position ca. 10 mm. Note the strong increase of class 4 and 5 grains towards the cave wall. (Fig. 37 from Sponholz 1979.)

## 3 *Micromorphological aspects of karst formation in silcate rocks*

Further evidence for the solutional nature of the landforms described above as well as for the palaeoclimatic conditions under which they could have developed was obtained from micromorphological studies by B. Sponholz. The samples studied were taken from those parts of cave and tube walls where the original lining of silica mentioned above had been preserved. As the forms under discussion are solution forms, the lining is likely to reflect a final phase of deposition along the walls of the karst vessels just before they fell dry for reasons of climate or, more likely, dissection of the karst water system. As relics of the lining were found in all positions of karst vessels, it must have been formed at a time when they were still completely filled with slowly circulating water. For comparison rock samples were taken at some distance from the karst-affected surfaces.

The crusts studied so far are usually thinner than 2 mm, consisting almost exclusively of pure silica. As it is always amorphous, it must have been precipitated from a saturated solution (at a saturation below ca. 10 ppm crystalline quartz would have been formed; Roose 1981). The lining also contains no oriented clastic material, as would be expected if precipitation had occurred from water dripping down the cave walls. This supports the assumption that the lining represents the first documented period of processes affecting the walls of karst vessels at the end of solution activity.

Samples were analyzed as thin sections under the microscope and the scanning electron microscope. All the samples analyzed show a high degree of silica mobilization, either as solution or as precipitation features. The thin sections clearly show that corrosion proceeded from the walls towards the interior (Fig. 5, Photo 9). In contact with the wall, more than


Photo 10. SEM photograph of a silicified bacterium, together with globules of amorphous silica, both attached to a quartz grain. From Sponholz 1989, Fig. 17, sample Kou 8.

50% o the quartz grains may be heavily corroded. Corrosion sharply decreases at about 2–3 mm below the surface.

Quartz grains extracted from the lining by HCl and oxalic acid treatment and studied under the SEM, at magnifications up to 30,000 ×, show an enormous amount of silica mobilization on their surfaces, following the interpretation of those features by Krinsley & Doornkamp (1973: 9). Precipitates of crystallized quartz and amorphous silica coatings were identified. As even the most delicate features have been preserved undisturbed, the grains cannot have been moved after their formation. The forms are therefore those of the final phase of chemical mobilization of silica in the context of silicate karst formation.

From the SEM studies there appears a regional pattern of silica precipitation. In the north of the study region (Djado and the Kawar escarpment) precipitation in the form of well-crystallized quartz platelets prevails, forming large and flat crystal surfaces only interrupted in places by triangular hollows or small quartz scales described as saccharoid precipitation (Leneuf 1973). The crystallized precipitates either indicate a very slow development or growth from a poorly concentrated solution, following the interpretation by Roose (1981) referred to above. As the area where these forms are found is that of the oldest rocks of the region (Cambrian and Cretaceous), time cannot be ruled out as the decisive factor.

The karstified sandstones of the southern part of the study region, of Cretacous to early Tertiary age as described above, are characterized by higher contents of iron and aluminum. In that area all silica precipitation has been amorphous, mostly in the form of little spheroids of $H_4SiO_4$. Given the high contents of Fe and Al in the rock, and therefore in the circulating ground water as well, the metal ions may be responsible for the lack of neocrystallization of quartz. On the other hand, a short-term development could have lead to the same result.

As stated in the introduction, silica solution is still very important today in the ground-water-saturated zone (Baumhauer & Hagedorn 1989) of the region, with $SiO_2$-contents of about 10,000 ppm measured, and there are also pedological indicators pointing in the same direction (Völkel 1989: 91). Whereas the interpretation from chemical evidence is somewhat equivocal, it appears certain that the solution processes took place in a groundwater-saturated environment. This does not necessarily imply high precipitation in the region, however, especially towards the end of karstification, but only the presence of a groundwater body. The north-south differences of silica precipitation towards the end of the karstification period may, in addition to the possibilities already mentioned, also be due to climatic differences or to different independent groundwater systems.

Work with the electron microprobe, however, has yielded some rather unequivocal evidence concerning the environment at the time of karstification. In various layers of the matrix a phosphorous content of as much as 20% was measured, below the final lining that appears to be free of it.

On quartz grains from the same samples, mostly from the southern part of the study region, silicified microorganisms have been identified. Their organic substance has been fully replaced by amorphous silica (Photo 10). Various types of spores and bacteria thus preserved were found. Again the surface structure shows that no relocation of the grains occured after the organisms had been silicified on their surface.

## 4 *Conclusion*

Both the phosphorous content and the pseudomorphoses of the microorganisms make it likely that it was not merely a specific acidity level of the ground water that enabled the development of important surficial and underground forms of silicate karst, but that solution was facilitated and accelerated by various organic acids. As stated in the introduction, the region affected by silicate karstification at the time when the solution sinkholes and uvalas developed, was an etchplain still undissected or in its first stages of dissection. The karst area to the north, which is underlain by rocks of Cambrian to Cretaceous age, lay close to to the sea. Karstification within the deposits of the Continental Terminal equally took place in a level landscape close to the regional base level of the Tchad basin. The phosphorous and and the microorganisms, together with the evidence for a near-coastal to basin position, point towards a poorly drained, swampy or humid vegetation environment with slow groundwater movement. Both the silcrete formation preceeding the final phase of surficial karst formation and the densely spaced vertical tubes in the iron crusts support this hypothesis.

Further support comes from the fact that all surficial sinkhole and uvala formation came to an end during the first stages of dissection of the original "Miocene" etchplain. Not a single solution sinkhole of the type dotting the plateau surfaces by the thousands has been found on intermediate levels or on the foreland level of the late Pliocene Ténéré level. Wherever there was sufficient water available, the sub-surface karstification seems to have continued, however, and may still be in progress today within the groundwater-saturated zone of the region. As the organic element of silicate solution, first in a well-drained environment with scarpland formation, then under conditions of increasing aridity towards the present, can more or less be ruled out for the younger subterranean part of the solutional history, it has either to be assumed that most of the karst system, even that reaching below the floor of the scarpfoot depressions of Djado, more than 300 m below the original etchplain surface, had already come into existence before the dissection of the etchplain, or that the conditions of the principal phase(s) of karstification were different from the later ones. As for the endorheic scarpfoot depressions (cf. Fig. 1), which have not been discussed in the context of this paper (cf. Busche & Erbe 1987: 68ff) and which appear to be the youngest large surficial karst forms of the region formed perhaps as late as the earliest Pleistocene, they may have developed under special edaphic conditions of high moisture and dense vegetation cover at a time when etchplain formation on the Ténéré plain had already come to an end for lack of humidity and sufficient chemical weathering.

Obviously silicate karstification has not been just a minor element of landscape formation of this part of today's hyper-arid Saharan desert, although it has been almost completely overlooked until recently; and it may have been important for other regions with a similar palaeoenvironment as well. The most obvious surficial expression of it are the multitude of endorheic depressions on all the plateaus of the region. The intensive subterranean karstification had a number of less obvious indirect effects on the shaping of the present landscape, from affecting the pattern of inselbergs, plateau spurs and certain valleys during the late Tertiary and Pleistocene, to the Holocene occurence of the only, but numerous, collapse sinkholes on the slopes of Termit.

Obviously there is still a host of open questions, from the nature of the solution processes to the better temporal resolution of the karstification history, or to details of the development of individual karst or karst-related landforms. Work on these problems will continue during a further expedition to the region in the spring of 1990.

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