Calcrete Mapping and Palaeo-Environments in the Qangwa Area, Northwest Botswana

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Abstract

Calcrete deposits of the Qangwa area, northwestern Botswana are evaluated on the basis of satellite imagery and sedimentological analysis. Enhanced Thematic Mapper imagery interpretation combined with field evidence has led to identification of the calcrete. This project aims at making a detailed surficial geology map accompanied by a report as a step in expanding the knowledge of calcretes. It also attempts to develop an understanding of the relationship in the timing of the late Quaternary wetter and drier phases. A digital map using GIS and remote sensing applications was developed from both analysed data and fieldwork. Data analysis revealed five types of calcretes and a calcareous soil. Hardpan calcrete along with brecciated and conglomeratic calcrete dominate the interfluves and are believed to predate the formation of nodular and honeycomb calcrete which occupy the valleys. The older hardpan associated types may have developed following regional wet/warm periods the last of which has been dated elsewhere as occurring c. 120,000. The younger valley calcretes show different mechanisms of formation, and are believed to have been developed following incision and palaeo-lake establishment, c. 25,000 years ago.

Introduction

Kalahari sediments comprise post Karoo sedimentary units of sand, calcretes, silcretes, river alluvium and pan sediments of Cretaceous to Recent ages (Thomas and Shaw, 1991). Calcretes accumulated in the interior continental Kalahari basin that developed during the splitting of Gondwanaland in Mesozoic time. The Kalahari sand represents the accumulation of material derived from *in situ* weathering products from pre-Kalahari lithologies, supplemented by material transported to the interior over relatively short distances in a manner which is consistent with endoreic depositional basin infilling (Cooke, 1980). Calcretes are normally subdivided into non-pedogenic and pedogenic types. Non-pedogenic (groundwater) calcretes are common in present day arid alluvial basins and are kilometers wide, 10 km being the maximum, and approximately 10 m thick (Mann and Horwitz, 1979; Carlisle, 1983; Arakel, *et al*, 1989). They form from mobile carbonate-rich ground waters, which become progressively concentrated during flow. The carbonate is precipitated in the capillary fringe zone and also below the water table (Nash, 1997). Groundwater calcretes also form where drainage systems converge, where flow gradient decreases, where saline waters mix or where permeabilities are low (Wright and Tucker, 1991). These calcretes are typically micritic, densely crystalline, nodular to massive or brecciated. Shrinkage cracks and dissolution features may be abundant (cf. Klappa, 1983). Non-pedogenic calcretes do not usually form mature profiles compared to the pedogenic calcretes. Pedogenic calcretes develop when carbonate precipitates vertically

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within the soil profile after being introduced by rainfall, surface runoff, ground water, dust, bioclasts, vegetation, litter and as a result of rock weathering (Goudie, 1983). These calcretes are normally recognized by their laminar, highly indurated upper zone and by their decrease in carbonate content with depth.

Calcrete occurs as a variety of types from powdery to nodular to highly indurated (Wright and Tucker, 1991), and forms from the replacement, displacement and cementation of calcium carbonate into the soil profile, bedrock and sediments in places where ground water and/or surface water become saturated with calcium carbonate, hence developing a high pH (http://gsa.confex.com/gsa/inqua/finalprogram/abstract_54902.htm). Netterberg (1980) and Goudie (1983) have classified Quaternary and pre-Quaternary types of calcretes based on their maturity. They include calcareous soil, calcified soil, powdered calcrete, pedotubule calcrete, nodular calcrete, honeycomb calcrete, hardpan calcrete, laminar calcrete and boulder/cobble calcrete, with the latter assumed to be the most mature.

Satellite images offer the ability to analyse multispectral bands quantitatively in terms of digital numbers (DNs), which allows the application of computer processing routines to discern and enhance certain compositional properties of earth materials. The process of rock unit identification and mapping involves the examination of images to determine the drainage pattern, image tone and vegetation cover of the area under study. The distribution of vegetation may often be used as an indirect indicator of the composition of the underlying soil or rock material (Lillesand and Kiefer, 1999). Remote sensing techniques are increasingly being used in geomorphological research. Ringrose (1996) achieved results in Northern Territory, Australia by using a combination of topographic map data (Alroy Sheet) and Landsat Multispectral Scanner (MSS) print imagery along with supplementary panchromatic aerial photographs. Mapping indicated micro-dunes, which were only visible using aerial photographs or Landsat imagery rather than being observed from the ground (Ringrose, 1996). The map also showed the dune orientation and major aeolian features that extended to other parts of Australia as a result of seasonal winds blowing outward from sub-tropical highs (Wasson, 1986). The Australian area consisted of exposed unconsolidated nodular calcretes with discrete siliceous nodules. In some areas packed nodular calcrete is relatively common within a finer matrix of disseminated calcium carbonate, or the matrix may be comprised of partially cemented calcium carbonate (Ringrose, 1996). On that note it is evident that calcretes occur within critical climatic boundaries in semi-arid terrains with high evapo-transpiration rates and may be defined in terms of past or present depositional environments. (Goudie, 1983; Ringrose *et al*, 2005).

The aims of this present work are preliminary in nature. They are:

- To map and characterize the calcrete deposits in the Qangwa area;
- To suggest mechanisms for calcrete formation; and
- To provide a suggested palaeo-environmental history of the area.

It is envisaged that the map might be useful for the construction industry as there is a shortage of aggregate in the vicinity of Qangwa.

Study Area

The Qangwa area is situated in the northwestern part of Botswana between S19.67299° and E21.04720o and S19.53237° and E21.19014° (WGS84). The distance from Maun to Qangwa is approximately 300 km and the mapped area is approximately 360 km^2 in size and lies adjacent to the Namibian border (Figure 1). Granitic gneiss and local pegmatites are the basement rocks of the study area (Machacha, 1980). Overlying these rocks are Kalahari beds comprising sand and calcrete. The basement complex in the Qangwa valley occurs as sporadic outcrops over a stretch of 10 km being extensively covered by sil-calcrete, younger calcretes and river alluvium. The Damaran basement complex comprises gneisses consisting of quartz, muscovite, epidote and sphene with mineralogical foliation defined by mafic and quartzo-feldspathic layers; microgranitic and aplitic veins cut the gneisses in some places (Calteux *et al*, 1995).

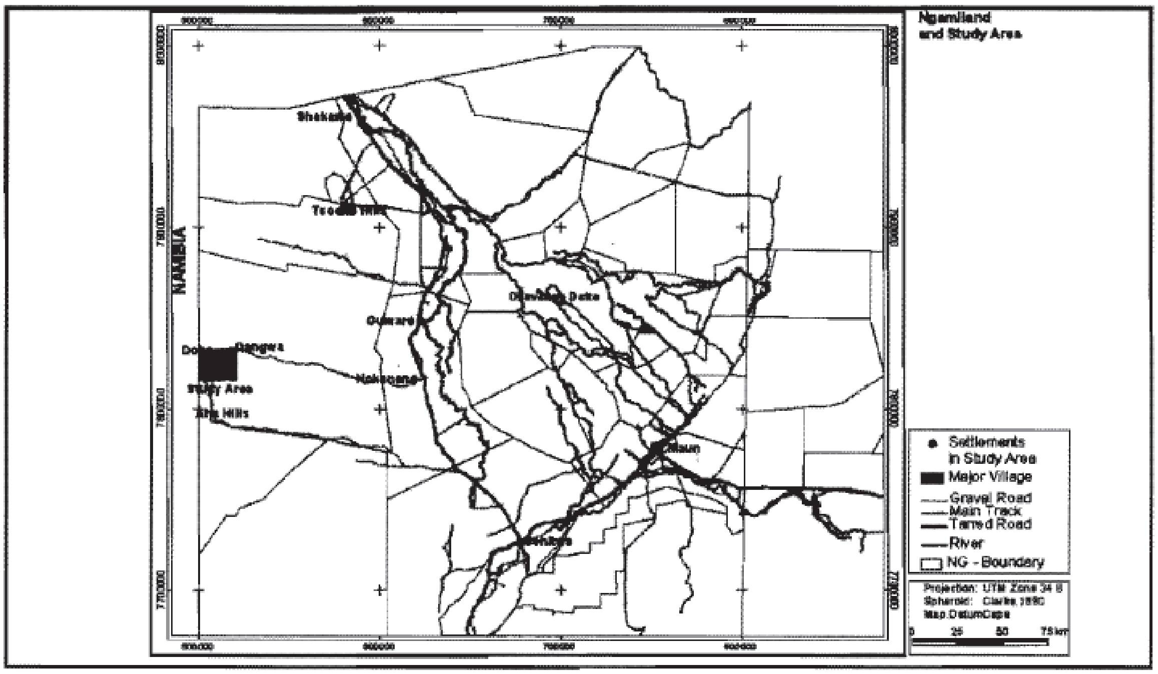

Figure 1. Ngamiland in north-west Botswana showing the location of the Qangwa study area.

Key and Rundle (1981) describe the Qanqua granite as a medium grained rock that consists of quartz, sericitized orthoclase, minor sodic plagioclase, microcline, muscovite, biotite and apatite. The green chlorite shows evidence of replacement to biotite. The rocks have been affected by shearing, cataclasis and a greenschist facies metamorphism (Billton Botswana, 1982). The shear zones affected the granite parallel to the foliations in the marginal gneisses. East of the Qangwa gneisses is the Qangwa adamellite, which consists of equal amount of K-feldspars and sericitised sodic plagioclase. Muscovite is rare and there is titanite, iron oxide, apatite and epidote in minor quantities. Rb-Sr age determinations have yielded an age of 890+/-25 Ma. ($^{87}Sr/^{86}Sr_i$ = 0.7293 + / -3; MSWD: 4.3) for the Qangwa adamellite and 895+/- 195 Ma ($^{87}Sr/^{86}Sr_i$ = 0.73 + / -3; MSWD: 3.5) for the Qangwa granite (Key and Rundle, 1981). The Neoprotezoic age has been used to support the correlation of this basement complex with the Damaran belt. The Aha Hills on the western margin of the study area extend to Namibia and are composed of dolomite marble, showing the basement rocks of the areas around them. The area lies to the west of the faulted MOZ (Makgadikgadi-Okavango-Zambezi) rift depression which is a southeastward extension of the East African rift, believed to have opened during the Tertiary (Modisi *et al*, 2000; Le Gall, 2002). There is no surface water in the area today except during heavy rains, but there is intermittent evidence of drainage eastwards into the Okavango basin.

According to the soil map (Government of Botswana, 1990) the soils in the study area are dominated by ferralic arenosols on the degraded dune surface and calcisols in the area. The study area is characterized by low precipitation (350 mm to 450 mm), low humidity, high evaporation, warm summers and cold winters. Percolation, plant growth and soil organisms are strongly correlated with soil type. Because of low precipitation and high evaporation, leaching of soluble soil substances is insignificant. Soils are often calcic up to their surface and marked by a high base-saturation. The prevailing parts of these soil types have A-C, A-CaC-C or A-B-C profiles.

The study area is covered with typical Kalahari sandveld vegetation (Jellema *et al*, 2002). Plants growing in this vegetation grouping thrive in deep, loose sand. The vegetation cover is mainly comprised of mixed trees and bushes 5-10 metres high with a vegetation density showing a high variety ranging from open shrubland to thick bushes. The plant species present are related to the soil type including both broad-leaved and microphyllous bushes often forming small thickets. The herbaceous layer is sparse, ground coverage is mostly below 50%, and is dominated by grass species like *Digitaria eriantha, Cyanodon dactylon, Aristida spp, Eragrostis spp*, and *Sporobolus spp*. The dominant woody vegetation consists of *Terminalia sericea, Colophospermum mopane, Acacia erioloba, Acacia tortilis* and *Dichrostachys cinera.* Other woody species found in these habitats are *Combretum collinum, Rhus spp., Lonchocarpus nelsii* and *Grewia spp.* The woody vegetation within the study area seldom exceeds 3.5 metres in height.

Methodology

Since there are no detailed maps available satellite imagery was used to provide basic information about the area. Remote sensing techniques have the advantage of regional coverage at adequate mapping resolutions; moreover the multiple spectral nature of remote sensing data allows image-processing applications. In most instances remotely sensed data provide the most current information on an area available (Lillesand and Kiefer, 1999). For this work a Landsat 7 ETM+ image was used based on scene ID: 176-0-074Q2, Date: 02/05/2002. Analysis took place using ERDAS Imagine ver8.6 and ARC GIS on Silicon Graphics computers at Harry Oppenheimer Okavango Research Centre (HOORC). Steps included geometric correction which took place in relation to fixed map locations. The Qangwa valley area (18 x 20 km) was cropped out. An unsupervised 30 class classification was applied using band 3, 4 and 5 to divide the study area into calcrete and non-calcrete formations. Using the nearest neighborhood method (5 x 5 pixel) the classified image was reformed into clusters. The cluster image was converted into a grid using ArcView 3.2. The various grid cells were then sub-divided into calcrete and non-calcrete areas. Field data were overlain to identify the various types of calcrete. Areas of different calcrete types were digitized manually on the processed satellite image (Gobagoba *et al*, 2004).

Field data collection was undertaken along roads, rivers valleys, through cut lines, and at times following the outcrop deep into the bushes. Much of this work was based on earlier work by Mafa (1996) although new sampling areas were identified. Well-defined calcrete exposures tended to follow former drainage channels. Other surface calcrete exposures occurred along or within the sand tracks. The exposures were named and locations noted using a Garmin 12 XL GPS. Taking GPS coordinates and photographs was essential as it improved the accuracy of the map and data analysis. Field procedures included the clearing of the exposure to remove debris. Lithologies were identified in terms of colour, composition, grain size, texture, structure and fossil content. The depth and profiles of the exposed calcrete were noted while descriptions were made of specific lithological types using terminology from Wright and Tucker (1991). All units described were sampled from the centre of a given unit. Approximately 35 samples were taken for further analysis.

Calcrete analysis in the laboratory comprised hand specimen and microscope descriptions. The indurated calcretes were cut to reveal sedimentary structures. The unconsolidated samples readily enabled the measurement of grains or clasts. In the laboratory the colour, shape, orientation and sorting of the calcretes were described and measured. Five mol hydrochloric acid (HCl) was used to differentiate the strength of the calcium carbonate in the calcretes, based on the degree of the effervescence. Microscope analysis was undertaken on all samples to determine sedimentological details. The type of microscope used was the Stereomicroscope Stemi DV4/DR. DV4 stands for Double lens Vario with zoom factor 4 while DR stands for Double lens Revolver and means that the microscope uses two fixed magnifications which can be switched interactively. A Philips 6000 Environmental Scanning Electron Microscope (ESEM) was used (in the Department of Physics, University of Botswana) to obtain preliminary micro-textural information on one brecciated surface sample (LS028), to determine whether micro-organisms were present, to obtain information with respect to micro-structures and their inter-relationships, and to provide quasi-qualitative elemental data using EDAX techniques. Naturally occurring surfaces were examined without preparatory polishing to preserve the micro-textures intact (McFarlane, 1991).

Results

The Landsat ETM+ imagery indicated sand dunes running on a northwest-southeast trend crossed by dry valleys (including the Qangwa valley), which stand out because of the proximity of calcrete to the surface and relative paucity of vegetation cover (Figure 2). The main fossil river in the area runs from southwest to northeast passing through Qangwa village. Towards

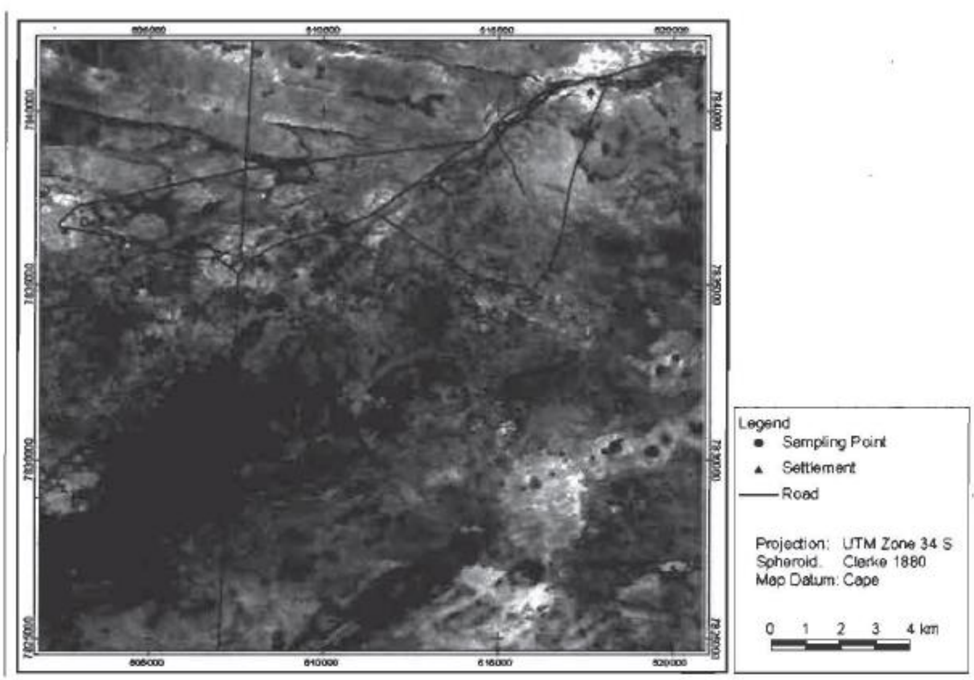

Figure 2. ETM+ satellite image of the Qangwa area.

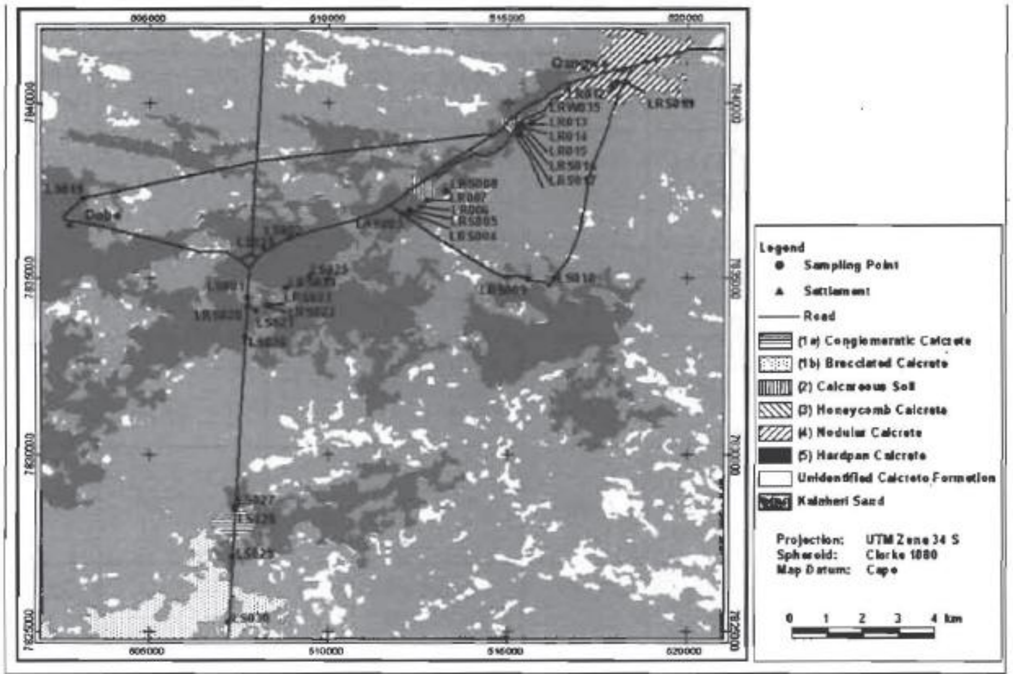

Figure 3. Identification and spatial distribution of the main calcrete types in the Qangwa area.

Dobe three palaeo-channel features appear to coalesce into the main Qanqwa valley. Visual classification of the 35 calcrete samples was based mainly on their clasts size and the cementation of matrix. This resulted in the identification of the five calcrete types, some of which were also observed by Mafa (1996) but classified differently according to the structure. However, this project follows the classification by Goudie (1983) in that the classification is based mainly on texture. Most calcrete in this area is highly silicified and finely crystalline. These consist of a more or less continuous secondary matrix of micrite or sparite carbonate. Their fabric differs from simple cementation, which is more coarsely crystalline in a grain/clasts supported fabric.

The spatial extent of the five calcrete types is shown on Figure 3. The map shows the distribution of conglomeratic and brecciated calcrete (Type 1) towards the southwest, calcareous soil (Type 2) and honeycomb calcrete (Type 3) adjacent to the main Qanqua valley in the northeast (Table 1). The most extensive calcrete type is the hardpan calcrete (Type 4) which is prevalent in the palaeo-valleys and inter-dunes. Nodular calcrete (Type 5) occurs mainly in the downstream Qanqua valley area, adjacent to the village. In general there was little observable stratigraphy except in specific locations in the main Qanqua valley. Conglomeratic calcrete (Type 1a) was found on interfluve exposures and is mainly a consolidated carbonate, similar to hardpan but with an accumulation of pebbles. A typical exposure (LS 030) possesses subrounded carbonate litho-clasts in addition to igneous and metamorphic rock clasts which range in size from 1 mm to 20 mm (Figure 4). The pebbles show a slight orientation and moderate sorting, suggesting transportation of pebbles from their source rock before diagenesis. Looking under the microscope the matrix comprises a light grey, silica rich sil-calcrete with numerous voids and no fossils. The adjacent brecciated calcrete differs from the conglomeratic calcrete as the clasts are either angular or sub angular (Figure 5), as exemplified by LS 028. The clasts have no preferred orientation and are poorly sorted with wide rims of iron oxide. The size range of the clasts is from 0.8 mm to 17 mm and there is no effervescence with hydrochloric acid on the clasts, although it is weak on the matrix.

Table 1. Differentiation of the main calcrete types in the Qangwa area.

Types	Texture	Matrix	Main structure	Presence of clasts	Effervescence With HCl
Conglomeratic calcrete (Type 1)	Indurated with clasts	Micritic	Slightly orientated and moderate sorting	No	Strong
Brecciated calcrete (Type 2)	Indurated with clasts	Micritic	No orientation and poor sorting	0.8- 17mm	Weak
Honeycomb calcrete (Type 3)	Partly consolidated	Clastic	Partly joint nodules with voids	0.5- 40 mm	Very Strong
Nodular calcrete(Type 4)	Carbonate concretions consolidated	Clastic	Laminated	1- 32 mm	Very Strong
Hardpan calcrete (Type 5)	Completely indurated	Micritic	Voided with Shrinkage cracks	No	Strong

Calcareous soil (Type 2) is a weakly cemented carbonate accumulation mainly in sand samples which contain patches of powdery carbonate or small carbonate nodules. Exposures are found extending from the dry valleys, commonly at LR 007, LR 013 and LR 014. The grey sand is characterised by a high organic matter content. Small nodules comprise quartz grains, some with accreted calcrete as indicated by a strong effervescence with hydrochloric acid. Honeycomb calcrete (Type 3) is found in dry valley profiles often under an intermittent cap of hardpan calcrete (Figure 6). This type comprises partially consolidated nodules in a more friable

Figure 4. Conglomeratic calcrete with subrounded carbonate litho-clasts with bedrock clasts (LS030).

Figure 5. Brecciated calcrete with angular to sub angular clasts (LS028).

matrix, for example at LR 015. The honeycomb calcrete is mainly cream white and has sub-rounded clasts forming a clast supported fabric. It is characterized by numerous voids, some of which are infilled. The matrix is light grey and does not have fossils. It produces strong effervescence with hydrochloric acid, thereby showing a high carbonate content. The nodular calcrete (Type 4) comprises a semi-indurated carbonate matrix with subrounded calcareous nodules and quartz clasts and is found mainly in profiles along the dry river valley near Qanqua (e.g. LR 012). This type of calcrete is light grey in colour, shows some evidence of lamination

Figure 6. Honeycomb calcrete with enlarged nodules in a calcareous matrix.

Figure 7. Nodular calcrete in a friable matrix under a 50 cm hardpan.

(Figure 7) and reacts very strongly with hydrochloric acid. There is no evidence of fossils in the calcrete samples collected.

Hardpan calcrete (Type 5) is the most extensive of all the calcrete and occurs exclusively on the surface of the mapped area. It is completely indurated with a complex internal fabric (Figure 8). The colour range is from light brown to white, and on some parts it appears to have black patches suspected to be manganese oxide. This hardpan calcrete either consists of sub-angular or sub-rounded concretions although most contained quartz clasts of 1 mm to 13 mm. Most of the clasts and concretions were poorly sorted with no preferred orientation. Some clasts were surrounded with rims of red to orange iron oxide. This unit has voids and shrinkage cracks with minor shell fossils at LS 021 and LS 010.

Environmental Scanning Electron Microscope Results

ESEM analyses were undertaken on both the matrix and the clasts from the brecciated calcrete (Type 1b). The matrix was analysed to determine how many phases of crystallization were evident, while the clasts were analysed to determine whether these were originally incorporated pebbles from the Damara bedrock or altered litho-clasts from a previous phase of calcretisation (or Fe pebbles from a phase of laterisation). Evidence from hand specimens had indicated

Figure 8. Hardpan calcrete showing lithoclasts and dessication cracks.

evidence for silica re-mobilisation in addition to the mobilization from Fe rich clasts into the matrix. Results from the matrix indicated that it consists of both Ca and Si rich sections with the Fe rich clasts occurring mainly in the Si rich section. The Si rich matrix also comprises zones, which contain both Si and Ca (Figure 9). The Ca rich matrix contains approximately

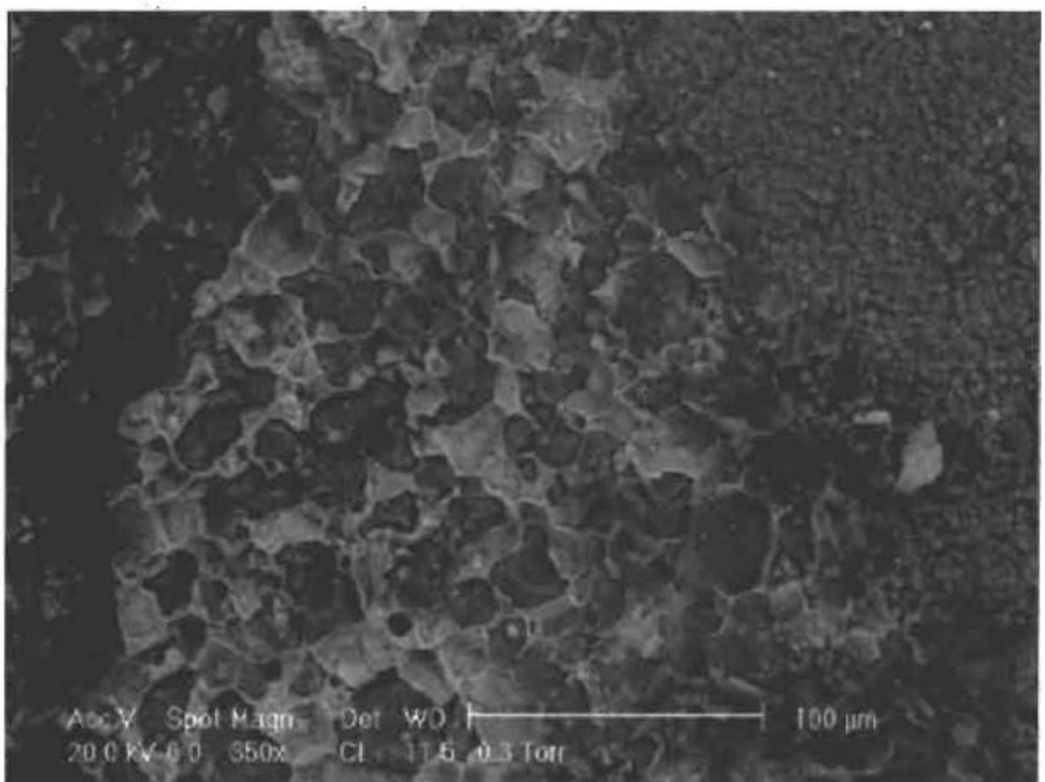

Figure 9. ESEM micrograph showing Fe clast disintegration as a result of calcite penetration and recrystallisation.

37.4% calcium while the Si rich matrix contains 49.6% silica, so while both are relatively high proportions, the Si rich matrix is relatively dominant (Table 2). However, a number of additional inclusions are apparent in the Si matrix. These comprise the Fe particles which appear to be disaggregating but contain 55.8% Fe, and a thin layer comprising Mn and Ca suggesting the liberation (re-mobilisation) of compounds from clastic material and its incorporation into the matrix (Table 2). Detailed observations on the Ca-Si section (in the Si rich matrix) show re-crystallised Si crystals (17.9%) in a Ca matrix (35.1%).

Table 2. Results of EDAX analysis on brecciated type 2 calcrete (LS 028).

	Mg	Al	Si	K	Ca	Fe	Ba	Mn
Ca rich matrix	0.6	1.0	2.7	0.2	37.4	5.6		
Si rich matrix	-	0.5	49.6	-	1.4	-		
Fe fragment	0.4	1.8	8.4	-	3.3	55.8		
Mn-Ca layer	0.4	0.5	8.9	-	29.0	3.5	4.2	15.2
Ca-Si layer	0.4	0.5	17.9	-	35.1	1.8	-	1.1
Inner rock clast	0.3	0.5	36.4		15.1			
Outer rock clast	0.6	0.4	2.5		47.6	0.5		

Further analysis was undertaken on the rock clasts. One rock clast comprised small (25 μm) quartz pebbles in a local matrix of Fe, Ca and Si indicating that the clasts have undergone several phases of re-crystallisation prior to incorporation into the later calcrete cement. Outside the clast the Ca rich matrix prevails with the matrix penetrating into the rock clast, which appears to be disintegrating and shedding small Si clastic fragments into the otherwise Ca rich matrix. Hence the areas of re-crystallised Si in the otherwise Ca rich matrix may be derived from the disaggregation of quartz rich rock clasts. The analysis of further rock-clasts (grain 01) confirmed the presence of intact quartz grains within the predominantly calcareous matrix (Figure 10). Further observations indicate that the original (Si rich) rock clasts are covered by a Fe layer and that the Fe is migrating down into the interstices of the quartz grains, while quartz crystals appear to be migrating through the Fe shell into the Ca rich matrix beyond.

Palaeoenvironmental Evidence

Analysis of calcrete deposits was undertaken to provide insight into the palaeo-envionments of the Quanqwa area of northern Botswana. Previous work includes that of Wright (1958) and Mafa (1996). In the western part of the Makgadikgadi basin in Botswana, work on aspects of palaeo-environmental change has been undertaken using a combination of remote sensing data analysis and sedimentological techniques (Ringrose *et al*, 1999). $CaCO_3$ precipitation may have taken place mainly in an early Kalahari dune sand environment after initial down warping of the Makgadikgadi basin (Thomas and Shaw, 1991). This basin may have developed during pre-Pleistocene times when large palaeo lakes formed as a result of moist conditions and inflow from the proto Zambezi, Kwando and Okavango Rivers (Ringrose *et al*, 2005). The alluvial fan Okavango Delta also tends to add to the evidence that water levels fluctuated during the late Pleistocene (Ringrose, 1999). Consistent with palaeo-lake development, it is believed that calcrete formation has been taking place episodically since Pliocene (Watts, 1980). Netterburg (1980) provided a detailed evaluation of the late Cenozoic climatic history of southern Africa,

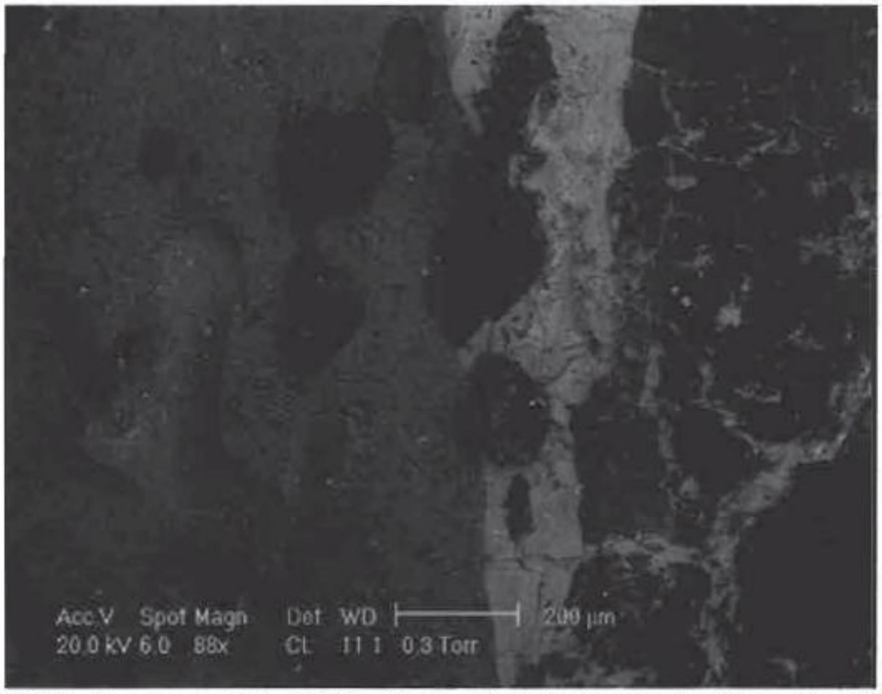

Figure 10. ESEM micrograph of a clast in the brecciated calcrete showing a Fe rich clast being penetrated by calcite (right) and Fe rich fragment in the adjacent matrix (left).

suggesting four episodes of calcrete formation. The first occurred during Pliocene times, the second during the mid-Pleistocene, the third during the upper Pleistocene and the fourth during the late Pleistocene to recent times (Netterburg, 1980). Palaeolakes and palaeodune data show that the southern African region possesses sedimentary and geomorphic evidence of hydrological changes during the last 100,000 years (Thomas and Shaw, 1991).

Formation of the calcretes of the Qangwa area appears to have taken place during the Quaternary era. Calcrete formation of the Tsodilo Hills is believed to be related to the calcretes of the Qangwa area because of geographic proximity, although their palaeoenvironments may slightly differ (cf. Thomas *et al*, 2003). The major controls on calcrete formation are climatic conditions, particularly the hydrological setting. While the general association of calcretes with the dry valleys is evident, many of the surface calcretes are interfluval suggesting that in the location both pedogenic and non-pedogenic types may prevail. Evidence suggests that extensive hardpan and related brecciated and conglomeratic calcrete development occurred as a

Table 3. Chronology of late Quaternary Tsodilo and Qangwa area palaeo-environment (partly based on Thomas *et al*, 2003).

Time	Climate	Activity
50-40 ka*	Dry/ cool	Dune activity
40-32 ka	Warm/ wet	Lake Tsodilo and Lake Qangwa
32-27 ka	Dry/ cool	Arid dune construction
27-22 ka	Warm/ wet	Lake Tsodilo and Lake Qangwa
20-18 ka	Dry/ cool	Last Glacial maximum
19-14 ka	Warm/ wet	Lake Tsodilo and Lake Qangwa

* Ka = 000 years

result of regional drying following a major wet interval (Table 3). While the literature suggests a number of warm, wet intervals, the most extensive appears to have developed c. 120,000 years ago as indicated by TL dates which correspond to regionally identifiable Milankovich cycles (Tyson *et al*, 2002; Ringrose *et al*, 2005; Huntsman-Mapila *et al*, 2005). It is thought that extensive wetlands developed in the MOZ basin at this time. The antiquity of the hardpans is based on their extensive coverage, their degree of induration and several phases of recrystallisation, although more work including dating is required. The hardpans are believed to be pedogenic in origin and owe their characteristics from the bedrock over which they lie. However, there is an absence of diverse clasts types (predominant quartz) suggesting a degree of reworking on the original African surface. The African surface may have been laterised thereby introducing Fe into the interfluval hardpans.

The hardpan calcrete are locally modified therefore where the underlying bedrock differs in the southern part of the study area. For instance the conglomeratic types show more evidence of original reworking and the brecciated type appears older and more modified *in situ*. SEM analyses on a hardpan brecciated sample shows that the matrix is essentially complex consisting of both Ca and Si phases with inclusions of K, Fe and Mn, suggesting that the original material was derived from the adjacent Damara bedrock. A particular bedrock component appears to be Fe which has mobilized in the form of Fe rich clasts resembling lateritic nodules, which may have developed on the original African surface. The original 'lateritic' nodules may have provided a source for mobilized Fe-oxides, which also coated some quartz particles. However, not all the clasts are Fe rich, as others have formed later of very small angular quartz clasts, cemented together in a Ca, Fe, Si matrix. This suggests an intermediate stage of duricrust development during which time a number of elements were mobilized, and infers a change from high pH alkaline conditions (leading to the precipitation of calcite and mobilization of silica) followed by freshwater incursions and the lowering of the pH, leading to Si precipitation, and leading to the formation of matrix silica in the sample. The intermediate phase appears to have been followed by late stage calcretisation, suggesting a second phase of high pH conditions without the later, freshwater incursion phase. However, the later calcretisation appears to have been relatively aggressive with calcite penetrating the fractured edges of pre-existing clasts, causing modifications to the matrix and the Fe layers leading to the incorporation of Si fragments into the calcium rich matrix.

The younger nodular and honeycomb calcretes appear to correspond to the development of the main Qanqua valley and its immediate tributaries. These calcretes may be non-pedogenic as suggested by their locations associated with surface/sub-surface water drainage. Deep permanent water bodies in the Qangwa area occurred during wetter periods, which based on 14C dating in the similar Tsodilo area ranged from 40,000 years ago to 32,000 years ago (Thomas *et al*, 2003). The surface water may have dissolved carbonate ions (from the earlier hardpans) which infiltrated into the soil and precipitated upon drying (Goudie, 1983). The different types and/or stages of calcrete formation may therefore have been caused by *in situ* dissolution and reprecipitation. Field relationships suggest that the nodular calcrete precipitated first, possibly using enlarged quartz grains as a locus of deposition. Further groundwater saturation with Ca++ ions led to the consolidation of matrix around the nodules, leading to the development of honeycomb calcrete (Wright and Tucker, 1991). Further compilation of geochemical data is required and will determine the origin of the sediments. The calcrete likely formed during drying when H_2O evaporates and the sediment looses CO_2 by degassing, thereby triggering the calcite precipitation (Watts, 1980; Ringrose *et al*, 2000). Along with silicate dissolution (1) the Ca^{2+} increases, (2) HCO_{-3} increases, (3) $H^+(H_2\,CO^o_3)$ is consumed and (4) the pH increases. This calcrete develops mainly as scattered to packed nodules which through time have become partially consolidated.

Conclusions

1. Analysis of satellite imagery and fieldwork led to the identification of five main calcrete types and calcareous soil in the Qangwa area, northwestern Botswana.
2. Preliminary analyses suggest two distinct phases of calcrete formation in the Qanqwa area - an earlier more indurated hardpan/conglomeratic/brecciated phase which occurs extensively over the interfluve and a later unconsolidated nodular/honeycomb calcrete phase which is confined mainly to the dry valleys.
3. The earlier indurated hardpan/conglomeratic/brecciated phase may have developed over dune sands on the original African surface following a regional wet period and therefore may be extremely old, possibly dating from the inception of drainage since the late Cretaceous (Goudie, 2005).
4. ESEM analyses suggested the inclusion of Fe clasts and several stages of recrystallisation, which tends to confirm the antiquity of the interfluval hardpans.
5. The valley nodular and honeycomb calcretes likely formed during the later Quaternary era between 40,000 and 32,000 years ago, possibly during the drying phase of an extensive, quasi-lacustrine environment.

In terms of the construction industry, the later stage calcretes are relatively friable so are more immediately suitable as aggregates relative to the ubiquitous hardpans.

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