

**ORIGIN AND PALAEO-ENVIRONMENTS OF CALCAREOUS
SEDIMENTS IN THE MOSHAWENG DRY VALLEY,
SOUTHEAST BOTSWANA**

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ABSTRACT

Quaternary sedimentation in the Moshaweng dry valley of southeastern Botswana is evaluated on the basis of geomorphological evolution and sedimentological analyses. Stratigraphic evidence reveals an 'upper surface (1095 m) containing abundant sil-calcrete, an intermediate surface (1085 m) in which sil-calcrete underlies nodular calcrete and lower (1075 m) surface in which sil-calcrete and nodular calcrete are interbedded. This subdivision is reflected in the geochemical composition of the sediments which show an overall trend of decreasing SiO₂ content (and increasing CaCO₃ content) with depth from the highest to the lowest surface levels. The calcretes and sil-calcretes represent modifications of pre-existing detrital Kalahari Group sand and basal Kalahari pebbles which thinned over a Karoo bedrock high. Modification took place during wet periods when abundant Ca⁺⁺ -rich groundwater flowed along the structurally aligned valley system. With the onset of drier conditions, water table fluctuations led to the precipitation of nodular calcretes in the phreatic layer to a depth of about 20 m. A major geochemical change resulted in the preferential silicification of the nodular calcrete deposits. Conditions for silica mobilization may be related to drying-induced salinity and *in situ* geochemical differentiation brought about by pebble dissociation towards the top of the sediment pile. As calcretization and valley formation progressed to lower levels, silica release took place on a diminishing scale. Thermoluminescence dating infers a mid-Pleistocene age for sil-calcrete formation suggesting that valley evolution and original calcrete precipitation are much older. Late stage dissolution of CaCO₃ from pre-existing surface calcretes or sil-calcretes led to the formation of pedogenic case-hardened deposits during a time of reduced flow through the Moshaweng system possibly during the upper or late Pleistocene. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: Moshaweng valley; calcretes; sil-calcretes; geochemical-XRD analysis; mid-Pleistocene

INTRODUCTION

Palaeoenvironmental studies are useful in developing scenarios for past environmental conditions which are critical to the understanding of change in a given area (e.g. Houghton, 1997). Environmental change work in Botswana both in historic and geological contexts has been relatively limited partly because of the lack of systematic records and because of the absence of exposures in the characteristically flat terrain (Thomas and Shaw, 1991). Hence work tends to occur where exposures are prevalent, such as in the Moshaweng dry valley (alternatively referred to as the Meratswe or Mmone mokgacha). This valley formed part of an early drainage system in central Botswana rising along the Bakalahari Schwelle and flowing northwards towards the early Makgadigadi basin (Thomas and Shaw, 1993; Nash *et al.*,

1994a,b; Ringrose *et al.*, 1999). This ancient 'fluvial' network of endoreic drainage referred to as the Mmone-Okwa system in Thomas and Shaw (1991) has a potential catchment of 90000 km². It partly corresponds to NS, ESE and WSW trending faults affecting the Archaean Basement complex and Karoo sequences (Shaw and De Vries, 1988; Nijsten and Beekman, 1997; Ringrose *et al.*, 1997). Duricrust development associated with these dry valleys. Correspondence to: S. Ringrose, Harry Oppenheimer Okavango Research Centre, University of Botswana, Private Bag 285, Maun, Botswana.

is assumed to be ancient (the Pliocene or older calcretes of Thomas and Shaw, 1991) and to have been influenced by neotectonic and climatic events over millions of years (Shaw *et al.*, 1997). Supporting evidence for the antiquity of the Moshaweng valley calcretes is that they lie stratigraphically between underlying Karoo sediments and overlying Kalahari sands (Mallick *et al.*, 1981).

Much work on the Tertiary and early Quaternary history of the Moshaweng-Okwa basin remains speculative (e.g. Cooke, 1979). Although earlier wet periods in the Tertiary are acknowledged (Butzer, 1984), archaeological studies reveal that palaeolake Makgadikgadi may have been at its maximum extent around 200000 years BP in the later part of the Middle Pleistocene or the Early Stone Age (Helgren, 1984). Studies around the recipient Makgadikgadi basin suggest that humid conditions were prevalent between 40 and 35 ka BP (Cooke and Verstappen, 1984; Thomas and Shaw, 1991; Nash 1992; Ringrose *et al.*, 1999). The palaeoclimate changed to drier conditions between 35 and 25 ka BP as deduced from lower lake levels (Rust *et al.*, 1984; Nash, 1992; Shaw *et al.*, 1992). The interval 22-10 ka is described as being characterized by alternating moist and dry periods after which more consistent drying took place (e.g. Scott, 1993). While arid conditions have been prevalent throughout the region since about 8 ka BP, localized evidence suggests periods of limited increased precipitation, for instance in the southern Okavango basin (Shaw and Cooke, 1986; Ringrose *et al.*, 1999). However, despite the probable integration of the Moshaweng-Okwa basin with palaeolake Makgadikgadi, humid and drier phases may not be synchronous over the entire Kalahari basin and little specific data on the palaeoclimatic reconstruction in the Moshaweng dry valley are presently available (Nash *et al.*, 1994b; Nijsten and Beekman, 1997; De Vries *et al.*, 2000).

Calcrete and silcrete deposition has received much attention in the literature and typically a number of forms are recognized. Calcretes vary from dispersed powder calcrete, through nodular to hardpan calcrete which may comprise relatively pure CaCO₃ (with or without Mg) and which may grade laterally or vertically into silcrete (Goudie, 1973, 1983; Netterburg, 1980; Watts, 1980; Netterburg and Caiger, 1983; Summerfield, 1983a; Nash and Shaw, 1998). Silcretes have been described mainly on the basis of chemical and micromorphological characteristics, especially fabric morphology (Summerfield, 1982, 1983b). The same fabric morphology is generally applicable to calcretes (cf. Thomas and Shaw, 1991). Calcretes have been defined as occurring within critical climatic boundaries and are normally subdivided into groundwater (non-pedogenic) or pedogenic types (Goudie, 1973, 1983). Vadose calcretes are developed when carbonate is precipitated in the capillary fringe of a fluctuating water table whereas phreatic calcretes form along alluvially filled drainage lines (Mann and Horwitz, 1979; Arakel, 1986; Ringrose, 1996; Nash, 1997). Calcretization is also reported to be related to high evapotranspiration rates both in southern Botswana (Ringrose *et al.*, 1998) and the Okavango/Makgadikgadi Pans complex (McCarthy and Ellery, 1995; Ringrose *et al.*, 1999). E Nash and Shaw (1998) have proposed definitions for silcrete and calcrete duricrusts which are relatively common in the Kalahari of Namibia and Botswana. After Summerfield (1983a), they propose that silcrete is defined as having >85 per cent SiO₂ and calcrete >50 per cent CaCO₃ from whole-rock chemical analysis. Intermediate (intergrade) types (CaCO₃ <50 per cent; SiO₂ <85 per cent) require thin-section analysis to determine their designation. They are defined as either cal-silcretes involving the matrix replacement (epigenesis) of an original silcrete with calcite or CaCO₃ precipitation (Walker, 1960; Watts, 1980) or as sil-calcretes wherein an original calcrete is replaced with silica or SiO₂ precipitation often in voids or along veins (Nash and Shaw, 1998). Matrix replacement, however, may not be the only source of SiO₂ so intergrade deposits with detrital quartz grains in a friable calcareous matrix have been described in the western Makgadikgadi

littoral zone as calcareous sandstones (Ringrose *et al.*, 1999). Preliminary work on the depositional history of the Moshaweng dry valley duricrusts has been undertaken by Shaw and DeVries (1988) and Nash *et al.* (1994a). The present work extends previous studies by identifying lower (sub-rim) valley surfaces, whose stratigraphy is described and components analysed using both X-ray diffraction (XRD) and chemical techniques (cf. Gwosdz and Modisi, 1983). Specific aims are to propose new interpretations for topographic ally lower features in the Moshaweng valley using petrographic, XRD and geochemical techniques. An additional aim is to enhance palaeoenvironmental information and provide tentative dating relating to valley formation. This is taking place to assist in the determination of palaeoenvironments in Botswana under a southern African environmental change project referred to as SAFARI2000.

STUDY AREA

The study area lies within the southern limit of the Moshaweng-Okwa basin comprising an ephemeral-dry valley system in southeastern Botswana between latitude 24°00' to 24°07' south and longitude 25°00' to 25°05' east, covering approximately 28 km² (Figures 1 and 2). To the south, the Moshaweng system rises in an area of exposed Archaean granites and progresses northward through Palaeoproterozoic Waterberg quartzcemented conglomerates before reaching Karoo sediments (Buckley, 1984; Timje, 1987; BRGM, 1991). The area is underlain by sediments of the Karoo Supergroup, on the southern margin of the ENE-WSW trending Permo-Triassic central basin, south of the Zoetfontein fault (Nijsten and Beekman, 1997). Specific units include the Bori Shale, Mmamabula Sandstone and Dibete Mudstone Formations of the lower Karoo Supergroup. These are superimposed by varying thicknesses of Kalahari Group sediments comprising basal conglomerates and sands which thin towards the duricrust-dominated Moshaweng valley (Beekman *et al.*, 1996). Bedrock from the Karoo Supergroup (mainly Mmamabula Sandstone) lies close to the surface and crops out intermittently north and south of the study area. The pebble unit which is described in Shaw and De Vries (1988) as originating from the Waterberg conglomerates, is evident as a series of gravel trains (Figure 3). Piezometric maps indicate that the groundwater level is relatively low in the Moshaweng valley compared to the surroundings, indicating a flow gradient towards the valley floor which is believed to be induced by evapo(transpiration) (Nijsten and Beekman, 1997). Results from piezometric analyses show a low gradient, consistent head decline from southeast to northwest along the length of the Moshaweng valley. Saturation of Kalahari sands during earlier more humid periods led to the introduction of Ca⁺⁺ from the underlying Karoo beds, which precipitated to form calcretes and sil-calcretes during later, drier periods (Watts, 1980; Nash *et al.*, 1994a; Ringrose, 1996). Presently the main aquifer system lies in the Lower Karoo, Mmamabula Sandstone Formation within which groundwater flows northwards along the hydraulic gradient after converging on the Moshaweng dry valley (Nijsten and Beekman, 1997). Hydrochemical and isotope data from borehole water samples in the Mmamabula sandstone evolve from Ca/Mg-HCO₃ waters in the study area to Na-HCO₃ down gradient with Na-HCO₃/Na-Cl in the outflow area to the north (BRGM, 1991; Beekman and Selaolo, 1997). Radiocarbon ¹⁴C and ¹³C data show overall ageing from southeast to northwest with an average residence time along the upper Moshaweng valley of 3500 years (BRGM, 1991; Beekman *et al.*, 1996; Beekman and Selaolo, 1994).

Duricrusts have developed to considerable depth (18 m; Gwosdz and Modisi, 1983) in the study area, apparently over older Kalahari Group sands (Mallick *et al.*, 1981). The duricrust is particularly thick at the confluence of a number of ephemeral, dry valleys which converge on the Moshaweng system over a bedrock high in the vicinity of Letlakeng (Figure 2). These are unnamed (except the Goathlabogwe or G-valley; Masedi *et al.*, 2000), and are referred to here as the K and Q valleys. Mallick *et al.* (1981) and Shaw and De Vries (1988) suggest that calcretes are rare below the main valley rims. However Nash *et al.* (1994a) describe a range of duricrusts from the G and K valley tributaries incorporating borehole and geochemical data from Gwosdz and Modisi (1984). Conclusions are that the mainly grain-supported (GS) duricrusts resulted from groundwater flow through the Kalahari sands during a period of significantly higher (than present) groundwater levels. Fluctuations in the piezometric head during a subsequent drying interval led to the precipitation of calcrete or silcrete depending on the chemical composition of

porewater. Nash *et al.* (1994a) further conclude that while the lack of stratigraphy infers that the duricrusts were formed after valley incision, fining-upward sequences suggest that earlier duricrusts existed prior to valley development. Duricrusts on the opposite valley side may have precipitated later due to diverted flow patterns resulting from initial deposition (Arakel, 1986).

ANALYTICAL METHODS

The Republic of Botswana 1 : 50000 topographic map and panchromatic aerial photography show that the area has gentle relief. Ground level varies from 1100 to 1150 m a.s.l. on the upper rim of the Kalahari plateau surface to about 1070 m in the valley floor. The inner valley including the confluence of the main Moshaweng system with the G, K and Q tributaries, is characterized by three distinct surfaces which initially occur about 10 m below the valley rim which rises to the upper plateau surface (Figure 2). The three surfaces which are

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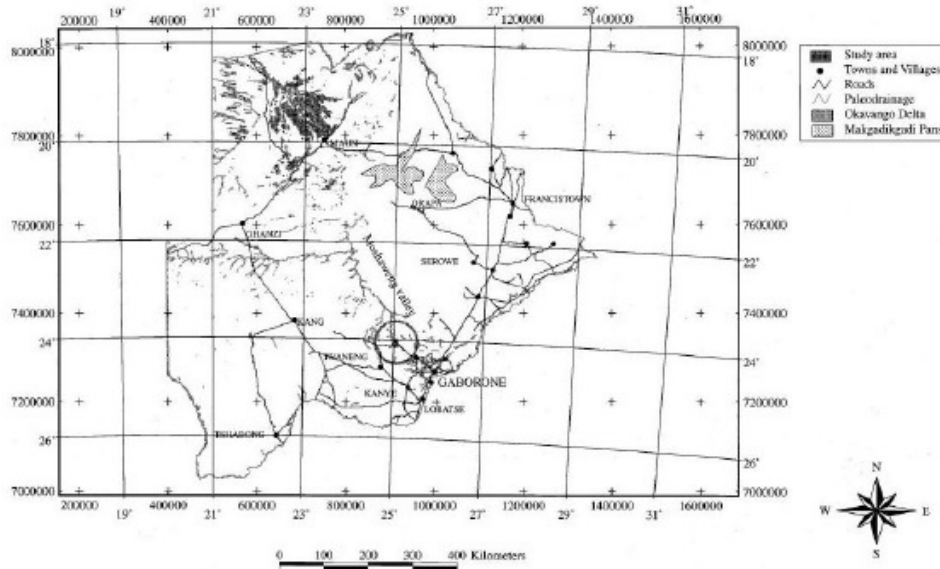


Figure 1. Location of Moshaweng valley area in Botswana (rainfall 400 mm a⁻¹)

500-2000 m wide, occur approximately at 1095 m, 1085 m and 1075 m above mean sea level. The 1075 m level is succeeded by a discontinuous ephemeral river channel.

Sediment description took place from 25 profiles and partial profiles in seven borrow pits and natural sections. Detailed profile description and sampling occurred in five 4-10 m deep borrow pits. The sampling pattern was based on NE and SW transects across and along the naturally occurring lower surfaces. Field descriptions revealed a varied pattern of duricrusts and surface gravel. Samples from all the detailed profiles were subjected to thin section, whole-rock major element chemical and XRD analyses. Two samples were dated using thermoluminescence (TL) techniques using equipment available

in Botswana. Twenty duricrust fragments were sent to the Geology Department of the University of Durban-Westville for thin sectioning. These thin sections were later analysed at the University of Botswana on a Leitz Periplan microscope using

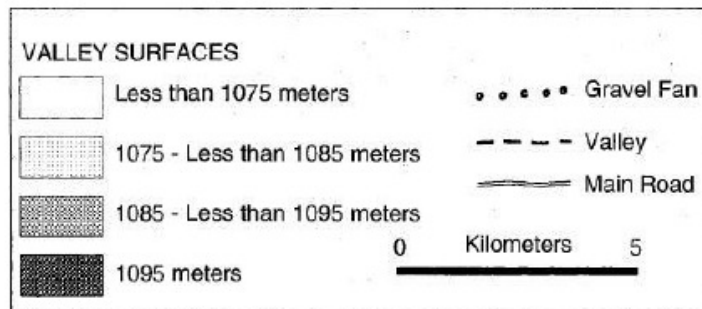
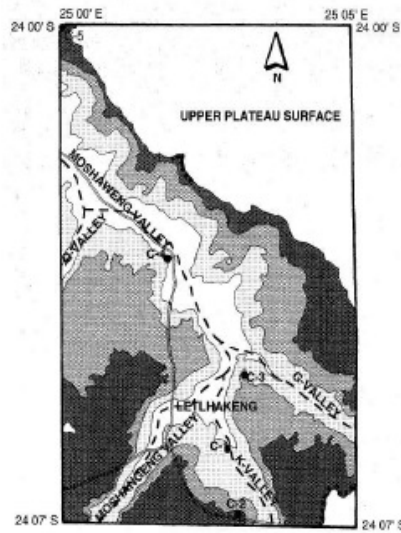


Figure 2. Detail of valley surface features and main sampling locations in the Moshaweng valley



Figure 3. Part of the extensive valley train comprising mainly pebbles derived from the Palaeoproterozoic Waterberg Formation which crop out at the base of the Kalahari Group sediments

Table I Results of thermoluminescence analysis (see text for explanation of units)

Parameter	Unit
U-sediment	ppm
Th-sediment	ppm
K-sediment	per cent
Water content	Wt per cent
Diameter).lm
Layer removed).lm
Density	g cm ⁻³
Cosmic).lCya ⁻¹
Dose	Gy

high resolution objectives and fitted with a Leica MP S52 camera. Twenty bulk samples were subject to XRD powder analysis. The equipment used was a Phillips PW 3710 based XRD unit, operated at 45 kV and 40 mA, employing Cu-K alpha radiation and a graphite monochromator. The samples were generally scanned from 3° to 70° 2θ and their diffractograms recorded. Samples were analysed using software consisting of a data collector with graphics and identify modules which permit control of the

diffractometer, while undertaking storage, identification and graphical presentation functions. After scanning, the bulk samples were leached in a dilute 10 per cent HCl solution. The leached residues were scanned for minor and accessory insoluble silicate phases in the bulk sample.

New whole-rock chemical analyses were performed on 25 samples at Chemex Laboratories, (Canada).

Major element compositions were determined using an ICP-AES with a detection limit of 0.01 wt per cent and precision of ± 1 per cent. Inorganic CO₂ and organic C were determined using a Leco-Gasometric and

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Leco-IR detector with detection limits of 0.2 and 0.01 respectively. Dating of duricrusts from the 1075 m level was undertaken using TL techniques (Aitken, 1985). The samples were obtained from upper and lower units at C-1 (Figure 2) and protected from daylight to prevent bleaching. The calcrete samples were taken from relatively homogeneous horizons regarded as representative of material supplying the environmental dose rate. Alpha counting was carried out on a portion of the whole sample using an Elsec 7286 (low level alpha counter) to determine abundances of uranium and thorium (ppm) and a Coming 410 Flame Photometer to determine potassium weight percentage (Table I). It was assumed that quartz in the sediment had undergone total bleaching in an aeolian or shallow water environment before deposition. Quartz grains in the size range 90-125 μ m were extracted from the raw sediment using a series of treatments. These included removal of carbonates and iron staining using hydrochloric acid and digestion of organic material using hydrogen peroxide. Fluorosilicic acid was used to dissolve feldspars, and heavy minerals were separated using sodium polytungstate. Remaining magnetic minerals were removed using an electromagnetic separator. The purity of the final quartz extract was tested using infrared stimulated luminescence to ensure that no feldspars were present. The clean sample was subjected to a hydrofluoric acid etch for 40 min at 24 QC to remove the outer a-affected skin. The grains were mounted on 10 mm diameter stainless steel discs and fixed using Silkospray silicone oil. Six samples were used for each additive dose step and regenerated bleached samples. The strontium 90 *f3* source was calibrated against a known *f3* source to deliver 2.5 ± 0.1 Gy min⁻¹. The following additive doses in Gy were used for natural and bleached samples:

C6TL N (natural) + *f31* (125 Gy), N + *f32* (417.7 Gy), N + *f33* (750 Gy)

Following the appropriate irradiations the sample was stored for 24 hours and pre-heated at 220 QC for 300 s before TL measurement using a Riso D12 Reader (Botter-Jensen & Duller, 1992). A second glow normalization was performed on the glowed-out discs using a dose of 6 Gy for each sample. The TL glow curves and an excellent temperature plateau over a reasonable temperature range are shown in Figure 4B. Exponential regressions for the additive dose method on the natural and residual TL are shown in Figure 4A.

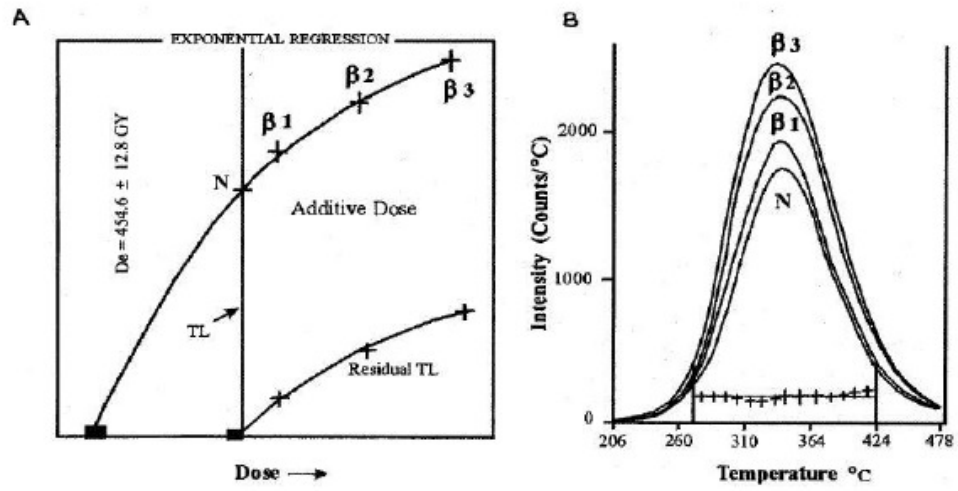


Figure 4. Thermoluminescence analysis. (A) Exponential regressions for the additive dose method on both natural and residual TL. (B) Well defined temperature plateaux for the TL glow curves

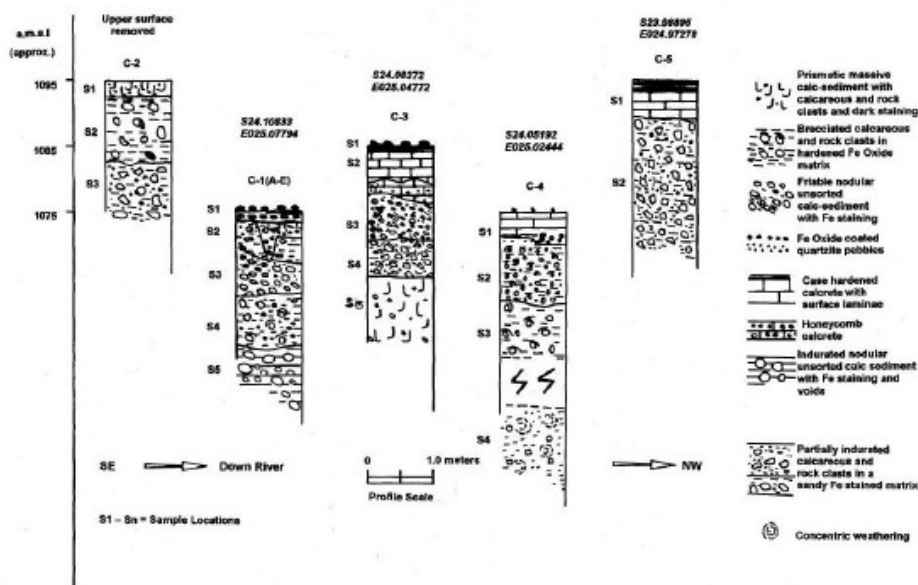


Figure 5. Schematic stratigraphic profiles showing main lithological groupings of the Moshaweng duricrusts

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The curves are of an acceptably similar shape and the D_e (equivalent dose) is also depicted. The residual TL was determined after exposing natural samples to 50 hours of sunlight and the bleached samples were given the same doses as the natural samples. The age determined is that of the sedimentation of the quartz-rich sediment and hence represents the earliest time for calcrete formation and valley development.

STRATIGRAPHIC AND PETROGRAPHIC DATA

The 1095 m surface

The 1095 m surface was examined at five locations and in detail at C-2 and C-5. C-2 is situated at the confluence of the K valley with the main Moshaweng valley (Figure 2). The upper exposed horizon (S1) consists of massive, jointed sil-calcrete with evidence of recrystallization developing into a massive, prismatic structure. The well indurated horizon contains small (< 1 cm) Fe-enriched pebble pseudomorphs and larger 1-3 cm lithoclasts containing carbonate granules showing evidence of radial cracking and fine dark rock clasts (Figure 5). The intermediate unit (S2) is coarser and more friable comprising coarse lithoclasts and fine rock clasts with numerous voids in a FeO stained sandy matrix. The enclosed carbonate granules are larger than in S1 with marked alteration haloes. The lower unit (S3) is similar to S2 with larger, disjointed angular lithoclasts and minor rock fragments in an iron oxide stained sandy matrix. Section C-5 was located at about 7 km from the main confluence area and below the confluence with the

Q valley (Figure 2). The uppermost case-hardened calcrete at this location is 0.5 m thick (S 1) and uniformly overlies the bed below with no intermediate honeycomb calcrete. This underlying unit is a relatively deep (2-3 m) coarse sil-calcrete (S2) comprising large angular lithoclasts (2-3 m) with radially cracked calcareous pebbles in an iron oxide stained sandy matrix. The entire bed is partially indurated and contains small (0.3 cm) weathered Fe-rich pseudomorphs. Thin sections of the lithoclasts show fine, angular quartz grains and Fe-rich pseudomorphs floating (Fm fabric) in a mainly siliceous matrix. The quartz grains show no brecciation and are characterized by partial or total replacement by calcite (earlier calcretization) with later matrix silicification (cf. Wright and Tucker, 1991; Nash *et al.*, 1994a).

The 1085 m surface

C-3 is an exposure in the intermediate 1085 m surface which occurs at the confluence of the G and K valleys (Figure 2). This section is overlain by a series of loose Fe oxide coated quartzite and conglomerate clasts (SI) which form part of the gravel train (Figure 3). The clasts are of pebble-granule size (1.5-4 cm) and although once rounded are now fragmented due to weathering. The clasts overlie a relatively thin (0.3 m) irregular surface layer of non-conglomeratic, case-hardened calcrete (S2) which is extremely pure, shows signs of surface lamination and changes vertically into honeycomb calcrete (Figure 5). This is succeeded by a partially indurated nodular calcrete (S3) in which the nodules have formed mainly around small rock fragments. The nodules are 0.25-2.0 cm in diameter in a partly indurated calcareous matrix which comprises 87 per cent calcite. S3 changes vertically downwards to a cal-silcrete bed of mainly sub angular quartzrich lithoclasts in a sandy matrix (S4). Below, a relatively massive, jointed sil-calcrete contains brecciated lithoclasts and rock fragments (S5). Thin sections from an indurated portion of S5 show two or three phases of cementation throughout the matrix which encloses both coarse, conglomeratic rock clasts and fine quartz grains. The siliceous matrix of the pebble conglomerate clasts was initially replaced by calcite which caused the larger quartz particles to brecciate and the finer quartz clasts to disperse into the matrix (Figure 6). This has led to a bimodal population of Fm grains comprising larger (>0.1 mm) brecciated quartz grains and smaller (c. 0.01 mm) angular, partially replaced grains. Later the initial calcite cement was replaced by a siliceous cement which incorporates the finer quartz grains leaving only the >0.1 mm grains and some fine conglomeratic clasts intact. Minor evidence of (remnant) calcretization is observed around both the larger quartz grains and conglomeratic clasts which form an Fm displacive fabric. No voids or cavities were observed in the thin sections examined (Figure 7).

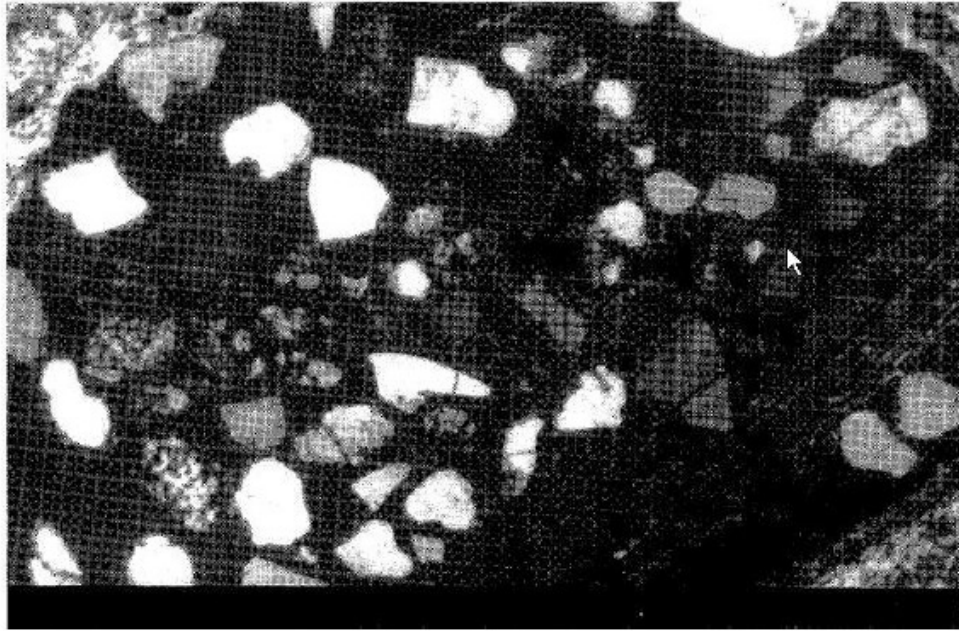


Figure 6. Conglomeratic pebble showing matrix replacement and development of Fm displacive fabric (C3-S5). Scale bar, 0.2 mm

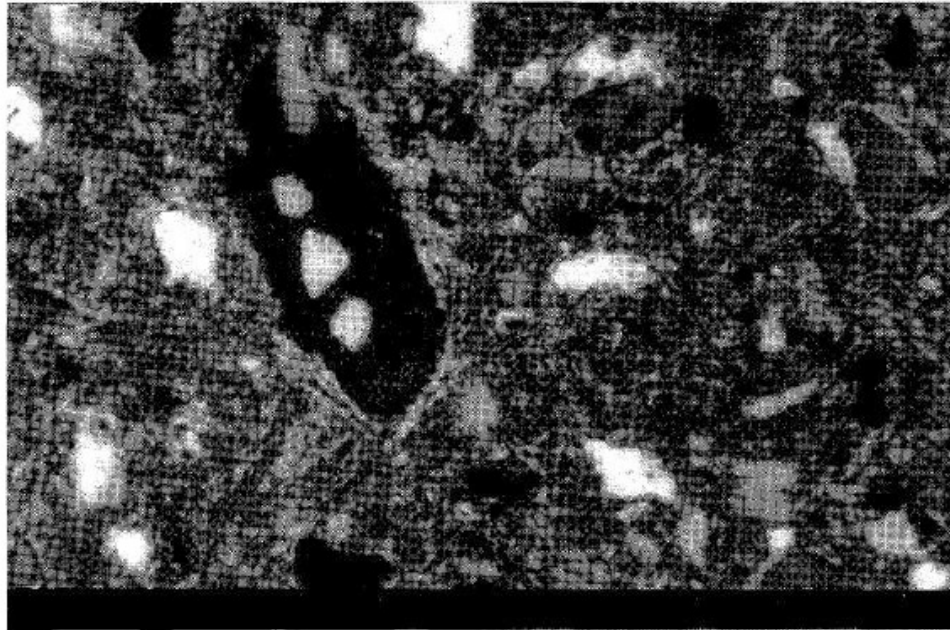


Figure 7. Dominant siliceous matrix enclosing larger rock fragments and partially replaced quartz clasts showing remnant calcite haloes (C3-S5). Scale bar, 0.2 mm

The J 075 m surface: Site C-J

C-1 is located close to the confluence of K valley and the main Moshaweng valley. The site comprises a linear borrow pit from which five composite profiles (A-E) were described and sampled (SE-NW over 200 m) subparallel to the direction of flow in the K valley. The C-1B profile is taken as being representative of

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this exposure which varies little throughout the 200 m length. The uppermost part of the section is capped by loose iron oxide coated conglomerate and quartzite pebbles from the basal Kalahari conglomerate sequence (Figure 3). The conglomerates show evidence of earlier rounding but presently exhibit numerous fracture surfaces and are hence sub-angular. This is succeeded by a case-hardened conglomeratic calccrete which is irregularly deposited into enlarged joints in the bed below (Figure 8). The clasts (2-2.5 cm) are from the basal Kalahari conglomerate, recemented in a case-hardened calccrete matrix (cf. Watts, 1977). The unit (SI) shows several phases of case hardening with a reduction in clast size (and increasing number of voids) towards the surface. The surface layer comprises several subparallel laminae, 0.5 mm thick. This unit varies in thickness throughout site C-1 dipping into joint and fault structures

below causing minor folding and mixing of carbonate coated conglomeratic clasts (Figure 8). Where joint or fault structures are absent the case-hardened unit changes vertically into nodular honeycomb calcrete.

CIB-S2 consists of friable, partially indurated, lithoclastic sil-calcrete which is loosely folded by the lateral swelling of joint fills. The lithoclasts consist of sub angular calcareous concretions, with evidence of discrete quartz particles and fine rock clasts with carbonate coatings. Thin-section evidence is similar to that found in C3-S5 in which it appears that an initial calcite matrix was replaced by siliceous cement which seems to have incorporated (dissolved) the finer quartz grains leaving only larger (>0.1 mm) grains intact with evidence of halo calcretization. The quartz clasts form a Fm displacive matrix fabric. In the succeeding, more friable S3 calcrete unit, calcareous nodules are evident with mainly matrix calcite which incorporates a substantial amount of detrital quartz. Thin-section evidence shows older calcrete forming concretions around relatively large quartz grains with later stage calcretization forming in previous cracks and voids.

The lower units initially form a fractured but otherwise massive sil-calcrete (S4) comprising lithoclasts with angular brecciated calcareous and rock clast fragments in an amorphous matrix with numerous voids and cavities. The matrix is recemented with secondary solutions (mainly silica over calcite) which infill cavities, fracture lines (desiccation cracks) and voids. Thin-section analysis confirms the complex nature of this unit inferring that an earlier calcite cement was replaced by a later siliceous cement which incorporates finer quartz grains. Some of the sections, however, comprise major voids and cavities into which calcite

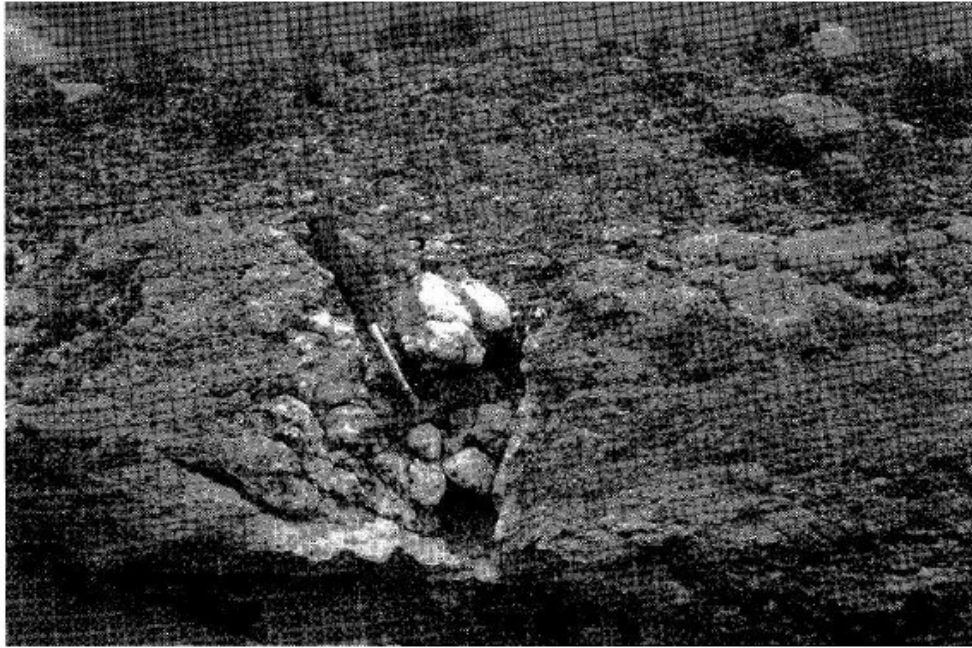


Figure 8. Case-hardened conglomerate (S1) dipping into faulted S2 lithoclastic sil-calcrete unit below, C3-1085 surface. Hammer, 30 cm

crystals have intermittently developed. The larger quartz clasts form a partial GS matrix fabric with less evidence of displacive expansion than the sil-calcretes from the higher valley surfaces. In the lowest S5 unit, the sediment changes back into indurated nodular calcrete. The relatively coarse nodules consist of subrounded to sub angular calcareous concretions, with evidence of discrete quartz and minor rock clasts coated with and largely cemented by carbonate. Thin-section evidence indicates an older fractured carbonate and rock clasts (0.2-0.01 mm in diameter) embedded in a later stage crystalline carbonate with evidence of voids (Figure 9). Some larger carbonate fragments show evidence of radial brecciation and cracking, suggesting that this type of sediment may have been a precursor to much of the sil-calcrete formation in the vicinity.

The 1075 m surface: Site C-4

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A second profile was examined at C-4 about 2 km downstream from the confluence area of C-1. Here the presence of surface iron oxide coated pebbles is less pronounced and the upper case-hardened calcrete (S1) is massive and comprises a basal nodular honeycomb structure. This overlies a massive, partially indurated nodular calcrete (S2) containing elongate nodules 2-5 mm in diameter which shows minor evidence of radial cracking and contains abundant quartz. Below, a more massive, partially indurated sil-calcrete (S3) comprises 1-3 cm lithoclasts within which calcareous clasts show evidence of cracking and Fe oxide staining. The lowest unit of this section (S4) (to 8 m) comprises a massive, calcareous sand-filled sil-calcrete with significant I- circular/spheroidal lithoclasts and calcareous nodules, in addition to voids and cavities. This unit also contains a relatively high proportion of clay minerals. Thin sections show a densely packed rock unit containing numerous subangular quartz grains with a GS fabric. While the quartz shows evidence of brecciation, there is also evidence of a discontinuous carbonate coating around the quartz clasts which lie in a partly silcretized matrix. Hence in this unit there is evidence of partial silicification of an original calcrete. The partially formed lithoclasts have become rounded and desiccated developing an onion skin cracking structure during the silicification phase.

The C1 sedimentary succession is therefore characterized by an alternating sequence of calcretes and silcalcretes with no definite trends in CaCO₃ or SiO₂ content either upwards or downwards through the profiles. A

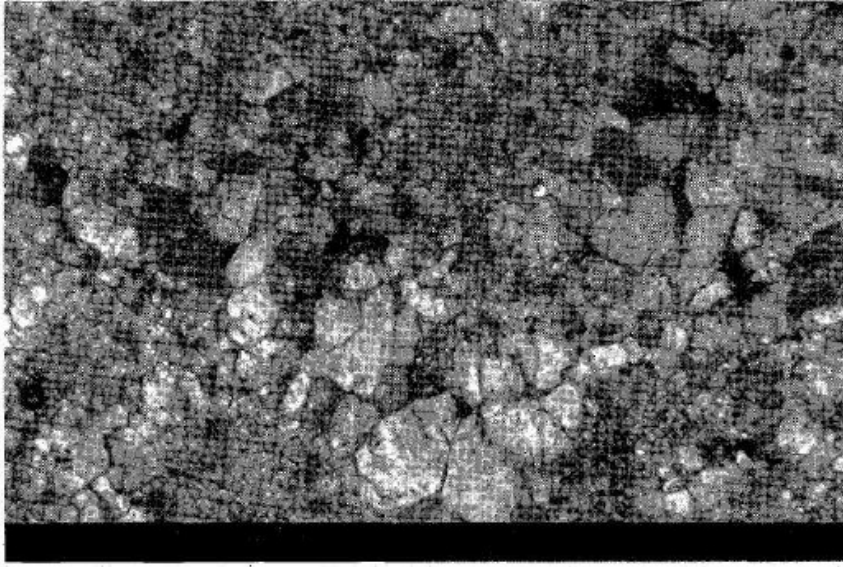


Figure 9. Older coarser calccrete concretions showing radial cracking forming in a recrystallized calccrete cement (C-IB SS). Scale bar, 0.2 mm

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well developed case-hardened pedogenic horizon (cf. Klappa, 1983) overlie non-pedogenic duricrusts. These form an upper brecciated, partially indurated lithoclastic sil-calcrete which has locally undergone shallow folding and jointing and which was selected for dating using TL techniques. Below an intermediate nodular calcrete is succeeded by a brecciated lithoclastic sil-calcrete which was also selected for dating. This bed is succeeded by a lower partially indurated nodular calcrete. In C4 downstream the lower nodular calcrete is missing and replaced by a partially formed clay-rich sil-calcrete.

THERMOLUMINESCENCE DATING

Two sil-calcrete samples from CI-B in the 1075 m level were subject to TL dating. The TL data were fitted by exponential regression over the best temperature plateau range for both the additive dose and bleached regenerated data and a comparison made of the respective curve forms. In this case the R-square regenerated TL growth curve coefficient was in excess of 0.99. The equivalent dose (D_e) was determined after subtraction of the residual signal. The environmental dose rate was determined by a low level alpha counter (Elspec 7286) using a 42 mm ZnS screen (Zoller and Pernicka, 1989). The values shown assume secular equilibrium for both U and Th chains (Carl, 1987). The uncertainty levels represent one standard deviation. The potassium content was determined using a Corning 410 flame photometer. The moisture value used in the age equation determination of this sample is 10 ± 5 per cent. The TL age in years BP for the upper sample CI-B S2 is 254442 ± 19682 . Despite the error bars, it appears that the lower surface at a depth of 25 m below the main incision (rim) in the Moshaweng valley evolved between 235000 and 275000 years BP in the mid-Pleistocene. A TL age for the second sample led to the sil-calcrete being undatable as the sample was saturated. The inference here is that the lower S4 sample is much older than the upper S2 sample and is estimated to be more than 275 000 years old.

X-RAY DIFFRACTION AND GEOCHEMICAL RESULTS

The units are mainly divided into the uppermost pebble conglomerates (P) and case-hardened units (H) and lower nodular (N) and lithoclastic units (L). Results of XRD analyses show that the duricrusts can be subdivided into calcite- or quartz-dominated types, while the basal Kalahari Group pebble conglomerates are predominantly quartz-rich (Table II). The calcite-dominant sediments were identified from each level with calcite being particularly abundant in the nodular (N) units and predominating in the case-hardened (H) units. The N units were found to contain between 59 and 87 vol. per cent calcite and 11-37 vol. per cent quartz while the H units contained between 69 and 92 vol. per cent calcite and 7 - 24 vol. per cent quartz. Other minerals are subsidiary and include dolomite «2), and hematite «2). Nodular samples contain up to 6 vol. per cent clay minerals and <3 vol. per cent feldspars while individual H units contain 1-2 vol. per cent dolomite and <2 vol. per cent feldspars and clay minerals. In contrast the silica-dominant types mainly prevail as brecciated lithoclast (L) units which also occur on all three levels. These show a broader variation of modal composition comprising 1-30 vol. per cent calcite and 57 -80 vol. per cent quartz in addition to clay minerals (1-38 vol. per cent), detrital micas «2 per cent) and feldspars «23 per cent). The clay minerals are mainly neofomed palygorskite along with detrital montmorillonite, illite and hydrobiotite (cf. Watts, 1980). The absence of sepiolite is noteworthy and may be due to the relative absence of Mg in most profiles. The basal Kalahari Group pebble conglomerates (P) are composed mainly of quartz (91 vol. per cent) with detrital micas (3 vol. per cent) and a hematite (6 vol. per cent) coating. The results of bulk geochemical analyses show that the CaO content of the nodular and case-hardened calcretes is highly variable in the range of 29-50 wt per cent (Tables III - V). This results in CaCO₃ values between 69-93 wt per cent for H units and 56-89 wt per cent for N units. Subsidiary elements in the H unit include Al₂O₃ concentrations in the range 0.46-1.46 wt per cent whereas MgO is between 0.34 and 0.66 wt per cent and Fe₂O₃ contents between 0.22 and 1.15 wt per cent. Except for the Fe₂O₃ content

these values are usually lower than those reported for the N units which contain Al₂O₃ concentrations in range 0.85-2.05 wt per cent and MgO concentrations between 0.78 and 2.18 wt per cent. The silica content of both N and H calcretes is highly variable, in the range of 7 -30 wt per cent and the TiO₂ content is low,

Table I. Results of thermoluminescence analysis (see text for explanation of units)

Parameter	Unit	Value
U-sediment	ppm	2.99 ± 0.19
Th-sediment	ppm	3.96 ± 0.24
K-sediment	per cent	0.53 ± 0.03
Water content	Wt per cent	5.00 ± 5.00
Diameter).lm	107.00 ± 17.00
Layer removed).lm	10.00 ± 0.00
Density	g cm ⁻³	2.65 ± 0.00
Cosmic).lGya ⁻¹	170.00 ± 10.00
Dose	Gy	454.60 ± 12.80

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Calcrete - silcrete chemical link

A number of variation diagrams (e.g. Ah03 versus Ti02, Fe203, Na20 and MgO) show that most of the lower Moshaweng valley sediments form a single group defining a continuum of composition (Figure 10). The two Fe203 outliers are from the coatings of the basal Kalahari Group pebble unit which formed separately from the duricrust Fe203. The minor correlation of Ti02 with Ah03 may be indicative of formational processes. Summerfield (1983a) divided silcretes into weathering profile and non-weathering profile types on the basis of Ti02 content. More than 1.2 wt per cent Ti02 is considered to be indicative of prolonged leaching and progressive enrichment, while less than 1.2 wt per cent is indicative of silicification of a pre-existing sediment. While this has been reexamined by Nash *et al.* (1994b) the L units do show higher Ti02 contents (than the Hand N units) while also containing more Ah03, Fe203 and MgO. This may suggest that while silicification of a pre-existing sediment was the predominant process, this may have taken place in conjunction with mineralogical change in the sediment, leading to neoformed clay minerals. The calcretes and sil-calcretes form two distinct groupings defining chemical evolution trends which do not correlate with the previous group with respect to three important oxides (Si02, CaO and CO2) (Figure 11).

Table IV. Representative whole-rock major element compositions (wt per cent) shown in morphostratigraphic sequence (C1B and C1C) from the 1075 m level

The upper group includes both conglomerate pebbles and brecciated sil-calcretes which appear to form a continuum. The second grouping (lower left) defines a different correlation line suggesting a separate origin for the silica found in the nodular calcretes. The CaO and CO₂ plot also defines two distinct groups with a major gap between the low-carbonate fields (pebbles and brecciated sil-calcretes) and the carbonate-dominated calcretes (nodular and hardpans calcretes). This differentiation would suggest a variable source for the CaCO₃ and SiO₂ in the Hand N units compared to the L units and therefore a different origin for both these units is proposed. A possible explanation is that the SiO₂ from the calcrete units is mainly derived from the Kalahari sands while that in the lithoclastic units is derived either from the reworked Palaeoproterozoic Waterberg quartzite (basal Kalahari Group unit) or from remobilized SiO₂ from that same source.

Table V. Representative whole-rock major element compositions (wt per cent) shown in morphostratigraphic sequence (C1E and C4) from the 1075 m level

Element	Quartzite pebbles (C1E-S1)	Calcrete (C1E-S2)	Calcrete (C1E-S3)	Clay-rich silcrete (C4-S3)	Clay-rich silcrete (C4-S4)
SiO ₂	91.21	18.46	28.5	81	84.7
TiO ₂	0.19	0.1	0.08	0.25	0.27
Al ₂ O ₃	1.09	0.8	1.32	4.81	4.07
Fe ₂ O ₃	4.35	0.43	0.58	1.66	1.54
MnO	<0.01	0.01	0.01	0.01	0.01
MgO	0.06	0.57	1.07	2.6	1.74
CaO	0.53	42	36	0.25	0.33
CaCO ₃	0.99	78.13	66.97	0.47	0.61
Na ₂ O	0.05	0.1	0.08	0.12	0.17
K ₂ O	0.16	0.17	0.16	0.78	0.81
P ₂ O ₅	0.01	0.07	0.01	<0.01	0.01
LOI	0.95	37.41	32.01	7.17	5.72
CO ₂ inorg.	<0.2	32.8	28.2	<0.2	<0.2
C	0.16	9.84	8.25	0.11	0.07
TOC	0.15	0.85	0.55	0.1	0.05

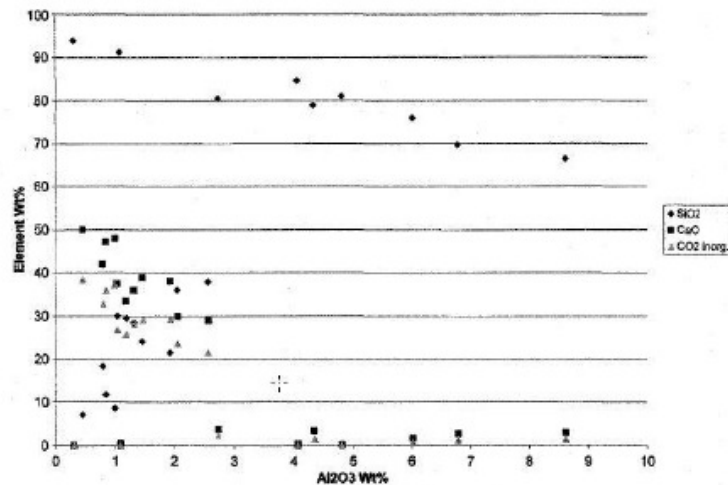


Figure 10. Variation diagram showing a single evolution trend in major elements from the Moshaweng duricrusts

DISCUSSION AND CONCLUSIONS

Stratigraphic evidence pertaining to the Moshaweng duricrusts is derived from three surface levels, namely 1095 m, 1085 m and 1075 m, which occur between the main Kalahari plateau rim and above a valley floor which is now mainly dry. The levels are not regarded as accretionary terrace deposits (Nash *et al.*, 1994a) although fluvial and groundwater flow are both invoked to explain the sequence of duricrust deposition (Shaw *et al.*, 1992). Below a relatively ubiquitous surface case-hardened layer, typical sections reveal an upper level (1095 m) containing abundant sil-calcrete, an intermediate level (1085 m) in which sil-calcrete underlies nodular calcrete. In the lowest (1075 m) level, sil-calcrete and nodular calcrete are interbedded. This tri-partite subdivision is also reflected in the geochemistry of the sediments which shows an overall trend

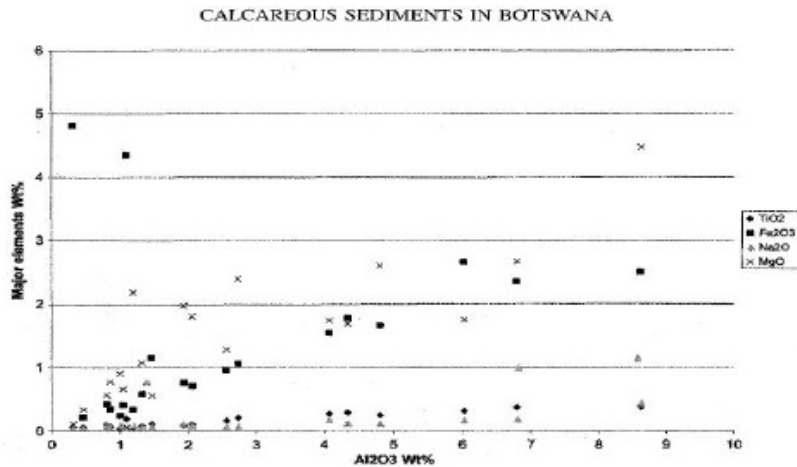


Figure 11. Variation diagram showing the distinctive fields occupied by lithoclastic sil-calcrete units (above) and mainly nodular calcrete units (lower left) based on Al₂O₃ relationships with respect to other major elements

of decreasing SiO₂ content (and increasing CaCO₃ content) with depth, i.e. from the highest to the lowest surface levels.

Sediments occupying the valley prior to modification comprised detrital Kalahari Group sand and iron oxide coated basal Kalahari pebbles. Since these sediments are available locally there appears to be minimal fluvial activity yet large volumes of material have been removed from the valley system which in the study area is 30 m deep and 1-2 km wide. Considerations of initial valley rim development are discussed in Shaw and De Vries (1988), Thomas and Shaw (1993) and Nash *et al.* (1994a). Following rim development, during substantially wetter periods than at present, water continued flowing along the structurally aligned valley system. Hydrochemical data from borehole water samples (Mmamabula sandstone) show high Ca/Mg/HC0₃ contents in the study area (BRGM, 1991; Beekman and Selaolo,

1994). Hence the introduction of Ca^{++} appears to have resulted from throughflow by ground and possibly surface water saturated in Ca^{++} derived from the local bedrock during a time of relatively high humidity (Beekman and Selaolo, 1997). It is possible that the action of ground and possibly surface water running over or through (or adjacent to) the Karoo bedrock high led initially to the formation of a valley-like incision into which basal Kalahari conglomerates were slowly released from the valley walls. As the groundwater was flowing through Kalahari Group sediments which thinned over a Karoo bedrock high, non-pedogenic calcrete precipitation may have initially taken place as the groundwater was periodically exposed to degassing consequent upon evaporation close to the surface. However, with the onset of drier conditions, water table fluctuations through the sand-rich sediment pile led to the precipitation of calcrete within the phreatic layer possibly to a total depth of about 25 m (cf. Arakel, 1986). Assuming that this drying-out sequence was synchronous with valley development, then it is also possible that early drying led to calcrete precipitation immediately below the valley rim, while lower levels of precipitation formed later at lower levels. Whereas the overall calcretization phase or phases may have taken place through a series of discrete stages over a long time period, the geochemical origin of the still prevalent initial nodular calcretes which resulted from this process is relatively constant. This implies that the source of the Ca^{++} was consistently derived from adjacent Ca-rich bedrock sources during the early groundwater phase. Following early calcrete precipitation the geochemistry of the hydraulic system changed and, as indicated in the present groundwater, became increasingly saline (Beekman and Selaolo, 1997). This major geochemical change led to the preferential silicification of the nodular calcrete deposits (Nash *et al.*, 1994a). A source of mobile SiO_2 is believed to stem from the release of silica on the replacement of silicates by calcite (Walker, 1960; Watts, 1980). This is based on inverse solubility relationships between calcite and silica with high pH values (over 9) favouring calcite precipitation and silica solution and low pH values the reverse. Evidence of fluctuating pH conditions is apparent in the present groundwater geochemistry with gradients of concentration and dilution being related to ambient climatic conditions of humidity and aridity (Beekman and Selaolo, 1997). One explanation is that as calcrete precipitation proceeded creating lower pH porewater, much of the available silica should then go into solution and be translocated locally downstream within the valley system. This would be expected to occur mostly where the intergranular SiO_2 content increased resulting from locally favourable geochemical conditions (Watts, 1980). These locally favourable conditions may in turn be related to the geochemical differentiation which has been detected here between detrital silica and associated elements forming the calcrete N units and the remobilized silica in the sil-calcrete L units. The introduction or liberation of Al_2O_3 , MgO and Fe_2O_3 during sil-calcrete formation suggests that complex processes similar to weathering with neoformed mineral development were involved. One possibility is that silica release may be associated with the disintegration of basal Kalahari conglomeratic pebbles which have a different geochemical signature to the detrital silica of the nodular calcretes. Sil-calcrete formation may therefore have preferentially taken place in layers of sediment containing a relatively high proportion of quartz-rich pebbles. The migration of SiO_2 -rich fluids would be expected to take place into areas of high salinity (due to high evaporative loss) or high free CO_2 (decreasing pH) (Summerfield, 1983b). These conditions may have been initially met towards the top of the sediment pile in the partially incised Moshaweng system where some exposure and weathering were simultaneously taking place. However, as calcretization and valley formation progressed to lower levels, this appears to have been followed by preferential silica release and precipitation on a diminishing scale. The precipitation of silica may also have led to differential forces being set up within adjacent sediments causing or reinforcing radial cracking of carbonate clasts and the displacement of quartz grains leading to the formation of a floating fabric. A relatively high proportion of clay minerals including palygorskite and hydrobiotite (21 per cent) which may be neoformed after feldspars (Watts, 1980) were found in the downstream portion of the study area. This also suggests that some internal transformation, akin to weathering processes, was ongoing throughout the sediment pile and that the downstream translocation of the weathering products was an ongoing process.

Hence incipient valley surfaces were formed as a result of calcretization taking place contemporaneously with valley widening (cf. Cooke *et al.*, 1993). These laterally extensive surfaces with variable microrelief

were subject to weathering and repeated wetting and drying. The effects of this process are particularly evident on the 1075 m level, leading to the development of jointing and surface swelling. As the chemical composition of impounded water was initially acidic, the uppermost exposed nodular calcrete and sil-calcrete units appear to have dissolved thereby enriching the porewater with Ca⁺⁺. During subsequent dry periods the enriched waters precipitated CaCO₃ as a series of laminae forming hardpan calcrete. Over a number of years, case-hardened laminae accumulated vertically on top of the sediment pile as a pedogenic deposit overlying the essentially non-pedogenic beds below (cf. Nash and Smith, 1998). At the 1075 m surface, the enriched solution flowed downwards into pre-existing joints and subsequently precipitated causing their enlargement and fossilization (Watts, 1977). This later phase may also have led to Ca⁺⁺ precipitation in voids and cavities within the duricrusts as Ca⁺⁺ moisture seeped down into the sediment pile suggesting multiphase precipitation in a pedogenic environment. During the case-hardening phase, part of the mid-valley also appears to have been subject to either fluvial (cf. Nash *et al.*, 1994a) or colluvial action as the basal Kalahari pebbles were distributed over the surfaces between the 1085 m and 1075 m levels. The relative contemporaneity of these processes is evident in the C1 hardpan within which a fining-upward sequence of pebbles has developed. Although Goudie (1973) and Watts (1977) record Quaternary calcretes from Botswana, it is possible that calcrete formation has been taking place episodically since the Pliocene (Watts, 1980). Netterburg (1980) provided a detailed evaluation of the late Cainozoic climatic history of southern Africa suggesting four major episodes of calcrete formation. The first occurred during Pliocene times, including the Mid-Pliocene 'Kalahari Limestone'; the second during Acheulean or Mid-Pleistocene times; the third during Upper Pleistocene times; and the fourth during Late Pleistocene to Recent times (Netterburg, 1980). The last two episodes correspond to dates obtained by Cooke (1975).

CALCAREOUS SEDIMENTS IN BOTSWANA

The upper TL date reported here infers an Acheulean or Mid-Pleistocene era of sil-calcrete formation suggesting that valley evolution and original calcrete precipitation may be much older. The earlier precalcrete precipitation throughflow may have contributed to early high levels in palaeolake Makgadikgadi (Cooke, 1980) whose basin represents the ultimate repository for the Moshaweng system. Helgren (1984) has also used tentative evidence from the early Stone Age (Acheulian) to suggest that the highest level of the lake occurred before 200000 years BP, in the early Middle Pleistocene (cf. Butzer, 1984; Partridge *et al.*, 1993). Calcretization and subsequent silicification occurred after the main throughflow phase with a suggested date of sil-calcrete formation indicated as 254442 ± 19682 years BP. Radial desiccation cracking and lithoclast formation of the increasingly exposed remnant calcretes and sil-calcretes may have taken place as the subcontinent was subject to increasing aridity around 115000-95000 years ago. This occurred when mega-Kalahari sand seas were subject to intense hyperaridity expressed as aeolian activity dated by optical dating on dune sands (Stokes *et al.*, 1997). This period appears to have been followed by a more recent calcretization episode involving fluvial activity and the dissolution and precipitation of case-hardened units (Grey and Cooke, 1977; Netterburg, 1980). This is anticipated as occurring during a time of reduced flow through the Moshaweng system, possibly during upper or late Pleistocene times.

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