Mineralogical Appraisal of Sediments of Duricrust Suites and Pans around Jwaneng Area, Botswana

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ABSTRACT: A mineralogical investigation of duricrust suites in Lethakeng valley, and five pans around Jwaneng in Botswana was undertaken in order to know the mineral assemblages and infer on their landscape formation. In Lethakeng, duricrusts comprised calcrites, silcrete and ferricretes. Calcrites were dominated by the minerals: calcite, quartz and to a lesser extent dolomite. Silcrete mineralogy was dominated by quartz, opal, and some occurrences of polygenite, microcline and mullite. The intermediate forms of cal-silicates yielded quartz, muscovite, and kaolinite. Ferricretes occurred on an area of the valley capping with minerals dominated by goethite and haematite. The inclusions are believed to have been formed through groundwater mechanisms. The general lowering of the valley, led to precipitation of the duricrusts. The pans were dominated by calcrite and silcrete only. The calcrites mineralogy was mainly calcite, dolomite and quartz. Illite-muscovillite and sepiolite were also present. Samples of pan clay floor, other than being dominated by calcite, dolomite and quartz, also had sepiolite ferricrete. Pans and valleys are accumulation sites, with polygenetic modes of genesis. The duricrusts have undergone several alterations throughout time.

Calcrites, silcretes and ferricretes are principal materials constituting duricrust suites and pans. They are distinguished from one another by their mineralogy and modes of formation, and could sometimes have economic bearings. Most of the minerals are secondary and do affect landscape topography. Calcrites are found on the near surfaces and composed of CaCO₃ varying from powdery to nodular highly indurated form (Wright and Tucker, 1991). It could be formed from either groundwater or pedogenetic activities. The non-pedogenetic calcrite may be known as groundwater, phreatic, valley or channel calcrites, with all of them relating to movement of sub-surface water, which could be lacustrine (pans) riverine or from water table. The processes often overlap in the natural environment. Silcretes may form predominantly from either surface or groundwater sources (Ollier, 1978). The silcrete may form as monosilicic acid, a colloid in pervious sediment or in weathered rock. Thus chemical weathering of silicate rocks is an important source of silcrete formation, so can solution of quartz dust. The cementing agent (silica) may be transported either laterally or vertically in groundwater, pore water and surface water. In arid environments, silica dissolved in water probably originated as quartz or silicates, mainly clays.

Fig 1: Map of Botswana showing sampling areas
Ferricretes, having the minerals goethite, haematite, ferricyanide, lepidocrocite and maghemite occur in nature, under varying environmental conditions. Fe mobilization is normally associated with wetter conditions than calcrete or salcrete. The formation of ferricretes may be related to landscape dynamics e.g. etching, downwasting and relief inversion. As such ferricretes have been used as morphotectonic markers (relative dating) – as has been for calcretes and silcretes (Young et al. 1996; Twidale and Bouma, 1996; Taylor and Howard, 1999; Twidale, 2002; Watchman and Twidale, 2002). All the three duricrust suites formations may be aided by microorganisms. In ferricrete formation the microbes may rework (dissolution and reprecipitation) indurates resulting in a younger isotopic age of the Fe suites (Yapp, 2000).

In Botswana, due to its arid to semi arid climate, duricrusts dominate the topography especially close to the hinges of the Kalahari Desert. Although several duricrust suites and pans exist in Botswana, no known mineralogical investigation has been carried out on them. This study therefore attempts to use mineralogy of sediments of duricrusts suites and pans close to the country’s well known Kalahari Desert to infer on their formation.

MATERIALS AND METHODS

Sediment samples were obtained from fossil valleys and pans around the Jwaneng area, Botswana (Figures 1 and 2). The pans had variable associated landforms, namely lunette dunes. The location of the dunes tended to be on the south to south-west, inferring formative wind was from north to north-east. Ten samples were from Letlhakeng Fossil Valley one (S24° 07.132; E25° 08.166; E25° 09.005") and two samples from Letlhakeng Fossil Valley two (S24° 09.011; E25° 04.878") Eleven samples were obtained from the Sese pan (S24° 38.997; E 24° 48.825°), nine samples from Sekoma pan (S24° 30.814; E23° 33.908°), two samples from Keng pan (S24° 35.240; E23° 44.918°), two samples from Klongkwa pan (S24° 33.724; E23° 51.080°) and two samples from 1khakha pan (S24° 41.937; E25° 29.357°).

![Fig 2: Base geomorphological map of the study area](image)

X-ray powder diffractometry was the technique employed in identifying the sampled sediments. Samples for X-ray powder diffractometry tests were mounted on the sample holder with very little pressure, and later scanned in the XRPD equipment. Prior to mounting of the samples, they were pulverized in a Seib Mill to change their physical state from indurated hard material to fine powdery texture.
substance. The minerals in the samples were identified using a Philips PW 3710 XRPD X-ray diffractometer system, operated at 40 kV and 45 mA, having a Cu-Kα radiation and a graphite monochromator. A PW 1877 Automated Powder Diffraction, XPERT Data Collector software package was used for the capturing of raw data, and a Philips XPERT Graphics & Identify software package for qualitative identification of the minerals from both the data and patterns obtained by scanning at a speed of 1° 2θ/min. Samples were scanned from 10° 2θ to 70° 2θ. The interpreted results were compared with data and patterns available in the Mineral Powder Diffraction File, data book (International Center for Diffraction Data (ICDD) 2001).

RESULTS AND DISCUSSION

Minerals identification: The results obtained by XRPD analyses are briefly presented in accordance with the different areas from which the samples were obtained. Representative diffractograms from Ses and Sekoma samples are given in Figures 3 and 4 respectively. The samples from the Leihakeng Fossil valley one were identified as calcite, nodular silcrete, siliceous conglomerate, hard floor pan calcite, and fissurecalcite. The silcrete consisted of quartz (SiO₂), calcite (CaCO₃), Ca rich albite ((Na,Ca)Al(Si₂Al)O₈) and montmorillonite-15A (Ca₃Al₂(Al,Mg)₂Si₄O₁₀(OH)₂·3H₂O). Quartz, opal (SiO₂·nH₂O), and polygorskite (Mg₆(Si₄Al₂)O₂(OH)₂·8H₂O) were formed the nodular silcrete. The siliceous conglomerate comprised quartz, opal, calcite dolomite (CaMg(CO₃)₂), and rutile (TiO₂). The hard floor pan calcite was composed of calcite and quartz; and the fissurecalcite consisted of goethite (Fe₂O₃(OH)), hematite (Fe₂O₃), quartz and microcline (KAlSi₃O₈). The Leihakeng Fossil valley two samples were silcrete and calcite. The silcrete was made of quartz, kaolinite (Al₂Si₂O₅(OH)₄) and muscovite (K₂Al₂Si₃O₁₀(OH)₂), and the calcite consisted of calcite and quartz.

![Fig 3: X-ray diffractogram of representative sample from Ses Pa (Q = quartz, A = ankerite and C = calcite)](image)

The Ses Pa Pan samples were principally calcite and they all contained calcite and quartz. Samples 7, 8 and 9 also had ankerite (Ca(Fe²⁺,Mg)(CO₃)₂). The Sekoma Pan samples were calcite with calcite being dominant in all the samples except for one sample (SEK 2), and quartz was present in all the samples except sample SEK 9. Dolomite was a major mineral constituent in sample SEK 2, and a minor mineral constituent in samples SEK 4 and SEK 6. Illite-montmorillonite (KAl(Si₂Al)O₂(OH)₂·4H₂O) was identified in samples SEK 1, SEK 4, SEK 5 and SEK 6. The pan calcite and clayey material from the pan floor were the two types of samples from the Kong Pan, Khonkhwo Pan and Khikhe Pan. The calcite sample from Kong Pan had calcite, quartz and sepiolite (Mg₅Si₈O₂₅(OH)₇·8H₂O); and the clayey material consisted of calcite, dolomite, quartz and sepiolite. Both the calcite and clayey material from the Khonkhwo pan consisted of calcite, dolomite, quartz and sepiolite. Calcite from Khikhe Pan comprised calcite and dolomite; and the clayey material had calcite, quartz and montmorillonite.

Calcrete formations of the karroo carbonates: and pans: Calcrite is dominantly present in the study area. The occurrence of calcrite and its associated landforms has been discussed in relation to fossil valleys (Nash et al., 1994) and also in pans (Netterberg 1978). The polygenetic nature of calcrite is best appreciated when erosion, dissolution and re-crystallization are noted to be at the core of the calcrite formations. Calcrite is typified by calcite minerals, and the ubiquitous quartz. Some of the material suspected to be calcrite, also has dolomite.
which is better explained in terms of more evaporative conditions.

Calcrites may vary in chemical composition from those with dolomite; the presence of clays and may be polygenetic, resulting in admixture of calcrite types as well as with silica. Those with silica admixtures tend to be regarded as sil-calcrites (Watson and Nash, 1997). Calcrites could be mobilized and precipitated, and affect landscape evolution. The carbonate source (dissolved) may be derived from topographic highs and precipitate out in the low ends. With time, this indurate would prove resistant to erosion, and possibly end up as a capping, hence the relief inversion. The mobilization of carbonate by groundwater or valley side processes, as resistant blocks may also lead to the same. The etching of the subterranean relief, with the area covered by duricrust, resting as a capping, may aid the same process, of having calcrite mass as cappings.

![Graph](Image)

**Fig 4:** X-ray diffractogram of representative sample from Sedona Pan (Q = quartz and C = calcite)

Silcretisation of sediments of the duricrust suites and pans: The analysed silcretes had quartz and opal. The latter may form in more mature silcretes, hence older. Silcrete formation results from silica precipitating as a result of pH drop, evaporation, as well as cooling and organic processes. Silcretes may also form under alkaline oxidising conditions by the cryo-elastic-elastic silica cement. At a micro scale four types of silcretes may be identified: grain supported fabric (quartzitic and conglomeratic silcretes) or fabrics with more than 40% silica cement and either quartzose, chaledonite or opaline (porcellanite and terrazzo silcretes). Silcretes tend to form through a variety of mechanisms; hence no single model is universally acceptable (Watson and Nash, 1997). Thiry (1997) outlines details in climate, landscape dynamics, geochemistry and crystal growth as pivotal to understanding of silcretes. Three silification processes were outlined: pedogenic (climates alternate between humid and dry, and Si in solution when wet and precipitates when dry); groundwater silifications (develop at depth, away from climatic influences, Si moved in groundwater, silcretes arise due to groundwater lowering after landscape dissection, hence the silifications are diagnostic of dissected terrain); and evaporate silifications (due to mixtures of brine and fresh waters containing Si, brines greatly reduce Si solubility, silcretes diagnostic of restricted environments and arid climates) (Thiry, 1997).

Ferricretisation of sediments of the duricrust suites and pans: Ferricretes are the least abundant of the duricrusts in Botswana. They may be mainly found in the eastern fringes of the country (Garney et al., 1994). Despite their limited occurrence in the Kgalagadi region, these occur on Lethlakeng valley 1. Another occurrence has been noted at Lekwatsi Pan (NE of Mochudi), Thomas and Shaw (1991). Ferricretes in the Lethlakeng valley were dominated by goethite and hematite minerals, as well as the quartz from the sandy host material. Iron may have migrated downslope in former wetter and probably cooler conditions than the present. The reverse relief model of landscape evolution would explain the ferricretes. Calcrite and silcrete both believed to have evolved through groundwater mechanisms (Nash et al., 1994) and the general valley and Kalahari development considered to be depositional rather than erosional (Thomas and Shaw 1991), the groundwater lowering model of ferricrete formation at Lethlakeng may be favoured. Landscape lowering of valley must have led to Fe precipitating out, as groundwater subsided. Fe oxide movement in soils or landscape may be due

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to clay migration or surface erosion; reduced or re-dissolved by complexation with organic compounds (Cornell and Schwertmann, 1996).

The goethite tends to form in aerobic and anaerobic soils of all regions, while hematite is favored in aerobic soils of sub-tropical, Mediterranean and humid sub-humid tropical regions. To form goethite, Fe may be derived from several Fe compounds including silicates, carbonates and sulphides, after which oxidation occurs. Goethite may also form from the precursor mineral, ferrihydrite (metastable). The high thermodynamic stability of goethite makes it one of the commonest Fe oxide minerals in soils (Cornell and Schwertmann, 1996). Hematite has similar thermodynamic stability as goethite, but favors warmer climates. Hematite rarely occurs alone, but is associated with goethite (Cornell and Schwertmann, 1996).

Environmental issues in the formation of sediments of the duricrust suites and pans: Field relations of these indurated materials, was also sought, so as to establish their chronologial sequence of formation. Mineralogical determinations of the valleys and pans have shown quartz to be the most abundant mineral. The most occurring duricrust is calcite. Silcrete tended to underlay the calcite, and the predominant mineral being quartz, with some opal occurring only in the Lethakeng valley. Ferricretes were encountered only in Lethakeng. The floor pan clay samples had occasional occurrences of clay minerals.

The Kalahari setting duricrust formation is more of the accumulation (e.g. sub-aerial processes), rather than erosional (Thomas and Shaw, 1991). The duricrusts may follow precipitation gradient – ferricretes in northern, with calcrites and silcretes in the Kalahari core. Indurates may also be associated with landforms e.g. pans and drainage lines. The duricrusts may form through surface water ponding and groundwater systems; deep weathering mechanisms; salts and organics. Several of the lateral transfer models e.g. lacustrine–pan (high evaporation, alternating pH within a pan or lake) and groundwater models (dissolution of water table, capillary fringe evaporation, and lateral throughflow) may result in indurates forming (Nash et al., 1994). In Lethakeng valley, the duricrust formation has been linked to groundwater flow beneath valley floors, in former times of high water tables.

According to Nash et al. (1994) silcretes in Lethakeng are a result of direct silica precipitation and cementation on a quartz host material, and not passive replacement of pre-existing bedrock; and the calcrites have an authigenic nodular to massive micromorphology typical of groundwater calcrites. The groundwater may be fresh, as indicated by freshwater bivalves in Lethakeng (Nash et al., 1994) and in the Kalahari beds of Matsheng due to meteoric water recharge (Molwalefe, 2001). The calcrites and silcretes, may accumulate through void filling (Nash et al., 1994) and the model of Molwalefe (2001) advances scavenging of calcite, SiO₂, N₂ gas, and the exchange site of Ca²⁺/Na⁺ (release of Na⁺ to solution) and Na⁺/Mg⁺ (Na⁺ uptake by exchange complex) to be associate with calcitisation. The real environmental setting is complex due to several geochronological pathways, changing endogenic and exogenic conditions, which could lead to geomorphical evolution of the duricrusts.

In concluding, field relations of the various duricrusts are noteworthy. The order of duricrust sequences is that of calcrite, overlying silcrete, in most of the pans investigated. The various pans have similar mineralogy — they are dominated by calcite, quartz and dolomite. The latter would indicate evaporative conditions under warm standing water environment (Holmgren and Shaw, 1995). Calcrite rims, typical of the pans, tend to be dominated by the three minerals. The silcrete layer is mainly quartz. Samples from Khakhles, Khokhwa, and Keng pans yielded mainly calcite, quartz and/or dolomite, with the clayey material consisting of either montmorillonite-1:1A or sepiolite. Usually pans are assumed to contain a lot of clay. The results here support those of Holmgren and Shaw (1995) that what may be taken as pan floor clay, could in reality be clay size material like very fine quartz and calcite.

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