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GEOLOGY OF SOUTHERN AFRICAN CALCRETES: 1. TERMINOLOGY, DESCRIPTION, MACROFEATURES, AND CLASSIFICATION*

by

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ABSTRACT

Calcretes and other authigenic carbonate accumulations in the regolith in southern Africa are described in relation to their occurrence in the profile and their sequence of development. On the basis of secondary (chemical) structure, such materials can be classified in the field into calcareous soils, calcified soils, powder calcretes, glaebular calcretes, cutans, pedotubules, honeycomb calcretes, hardpan calcretes, calcrete boulders and calcrete cobbles. Each of the major varieties possesses a significantly different range of geotechnical properties as well as representing a particular stage of calcrete development. Several variants of some of these varieties are also recognised on the basis of morphology, mineralogy, origin, and other properties. With simplification and addition of standard descriptors the classification is also suitable for geotechnical and other uses.

CONTENTS

I. INTRODUCTION

Calcretes are common in warm arid and semi-arid lands everywhere, including southern Africa, where they are familiar features of the western two-thirds of the subcontinent south of latitude 17°S.

In spite of their widespread occurrence, the calcretes of southern Africa have until recently remained comparatively unknown, their limited economic significance having caused them to attract little attention since the pioneering studies of early workers. Within the last 15 years, however, the increasing demand for roadbuilding materials, cement, lime, limestone, uranium, and agricultural development has brought about a renewed interest in these materials. In particular, the development of the arid and semi-arid zones has led to the use of a number of non-traditional geological materials in construction, of which calcretes are the most important. At present they probably constitute the most widely used class of road material in southern Africa and, aeolian sands excepted, are often the only material available in the vast area underlain by the Kalahari Beds. It is this which has led to the present study.

Materials which have been called calcretes or surface limestones have varied from loose soils containing only a small percentage of carbonate to hard limestones requiring blasting for excavation and which may crop out or oc-

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cur at depth. Some "calcretes" investigated contained no carbonate at all. Classification of these materials by the classical methods of soil mechanics developed for the soils of the temperate zone is also often both misleading and inadequate. It is the purpose of this paper to define terminology, to describe the macrofeatures of calcrete profiles, to present a simple classification based upon secondary (chemical) structure and sequence of development, and to serve as a basis for a series of subsequent papers on the geology and geotechnical properties of these materials in this journal and others.

Preliminary work on ferricretes and silcretes indicates that much of what will be outlined in this paper is also applicable to these materials.

The work upon which this paper is based (Netterberg, 1969a) was carried out largely in South West Africa, the Republic of South Africa and, to a lesser extent, in Botswana. However, superficial examination of calcretes in parts of Israel, Swaziland, Texas, Zambia and Zimbabwe, together with a survey of published work and field trips with workers with experience elsewhere, suggests that the observations and classification reported here should be applicable to calcretes everywhere.

The term "soil" is used throughout this paper in its wide engineering sense for practically any geological or pedological material which the engineer does not classify as rock, which latter requires blasting for excavation. While this concept of soil is similar to the geological term "regolith" it is in strong contrast to the pedological concept of soil.

The sample numbers referred to are those of the Soil Engineering Group of the National Institute for Transport and Road Research (NITRR).

II. PREVIOUS WORK

A. Definition

The term "calcrete" was coined by Lamplugh (1902, 1907) to describe the material formed when "sand-and-gravel beds are cemented sporadically into hard masses by solution and redeposition of lime through the agency of infiltrating waters" (Lamplugh, 1902). Subsequent usage (Du Toit, 1939, 1954; Netterberg, 1967, 1969a, b, c; Goudie, 1972, 1973) has formally or informally extended the term to include almost any material of almost any consistency and carbonate content formed within the regolith by the *in situ* cementation and/or replacement of a pre-existing material by carbonate precipitated from the soil water or groundwater. Although they may be formed in a related fashion, materials like certain speleothems, spring tufas, aeolianites and beachrocks are usually excluded partly for the sake of convention. For example, carbonate-cemented cave deposits "are essentially a special case of vadose caliche . . . and have been shown to share many of the textural features of caliche deposits" (Scholle and Kinsman, 1974). "The mechanism of calcification is not restricted and calcretes may be of pedogenic or non-pedogenic origin, or both" (Netterberg, 1969c).

Calcretes represent different things in different disciplines: to a sedimentologist they may be secondary (chemical) structures, diagenetic segregations, or simply chemical sediments; to a pedologist either pedological or geological horizons according to their origin, age, relative position in the pedological soil profile, and his individual outlook; while to most geologists they are simply superficial deposits which obscure the real geology, and the less there is of them the better. To the civil engineer, geological materials can be broadly classified as rock, residual soil, transported soil, or pedogenic material (Brink and Williams, 1964). Pedogenic materials, which vary in consistency from soil to rock, include materials such as calcrete, ferricrete, silcrete, gypcrete, phoscrete, laterite, etc. The term "pedocrete" has recently been suggested (C.N. Macvicar, 1977, pers. comm.) as a synonym for "pedogenic material" which should be acceptable to workers in all disciplines. This term, restricted to the "cretes", will be used in this and subsequent papers. Another synonym for such materials is "duricrust" (e.g. see Goudie, 1973).

B. Classification

Variability, both lateral and vertical, is a feature of most calcrete occurrences, and a variety of forms of calcrete has been recognised by many workers from Newbold (1844) and Abbott (1845) onwards. Several classifications have been proposed, most of which "are based on genetic factors, mineralogy, and soil fabric changes", their usefulness for a specific purpose varying according to the discipline of the worker (Reeves, 1976), which includes pedology, geology, geography, and civil engineering. Some of these classifications will be considered here.

One of the earlier classifications was that of Price (1933), who divided United States caliches (calcretes) according to their degree of maturity into:

1. young caliche: grains, flakes, nodules, irregular aggregates, and unconsolidated beds of soil carbonates;
2. mature caliche: consolidated beds of calcium carbonate;
3. old caliche: hard caliches.

A related classification was followed by Reeves (1970, 1976), working in the same area, although, recognising that certain hard crusts may also be young caliches, he was careful to distinguish between age and maturity. Maturity has also been used as a basis for classification by Chapman (1974, *in* Reeves, 1976) and others.

Gillette (1934) classified the Texas caliches used in highway construction according to their hardness as follows:

1. flourlike caliche: fine, powdery, loosely cemented sand composed mainly of silica or calcium carbonate, which can be excavated by hand or excavator without ripping;
2. semihard caliche: cemented areas interspersed with flourlike caliche; has to be ripped and loaded by an excavator;
3. hard caliche: well-cemented caliche, sometimes conglomerate-like, which has to be blasted and crushed before use.

A similar threefold classification of calcretes suitable for use in road construction (apparently those with more than 70 per cent $CaCO_3$ in the fraction passing 0.425 mm) has been used by Horta (1980) in Algeria:

1. hard pavement calcrete: a gravel with a maximum Los Angeles Abrasion (LAA) ("A" grading prepared by wet sieving) of 35 per cent resulting in no change in grading during compaction;
2. friable pavement calcrete: a gravel with an LAA of 35–50 per cent, but with degradation during compaction insufficient to result in reclassification as a sand;
3. soft pavement calcrete: a gravel with an LAA of more than 50 per cent which degrades to a sand during compaction.

In pedological work in the United States and most other countries, most of whose methods of soil description are based upon the Soil Survey Manual (Soil Survey Staff, 1951) (Hodgson, 1978), authigenic soil carbonate accumulations are usually referred to as "calcic" or "ca horizons", the suffix "ca" being attached to the master horizon, e.g. Cca, Bca. Continuously indurated calcic horizons may be referred to as "petrocalcic horizons" (Soil Survey Staff, 1975), or "calcretes" (abbreviated "ka") (Macvicar *et al.*, 1977). Gile *et al.* (1965) proposed the "K horizon" as a new master horizon for soil profiles containing much carbonate. The K horizon was subdivided into three subhorizons on the basis of K-fabric. Horizons with less than 50 per cent K-fabric were denoted by the ca suffix in the usual way. K-fabric was defined as a "fabric in which fine grained authigenic carbonate occurs as an essentially continuous medium" (Gile *et al.*, 1965).

A useful classification of the ca horizons in Dona Ana County, New Mexico has been devised by Gile (1961). In cases where carbonate was more or less evenly distributed throughout the horizon, he described it as liminar, platy, blocky, bedded or massive. Carbonate segregations within the horizon were described as nodular, cylindrical, concretionary, filamentary, veined or flaky. He also divided the horizons according to their degree of calcification into weak, moderate, strong and very strong ca horizons. Some properties of Gile's (1961) horizon classification are shown in Table I.

(Unfortunately, comparison of the consistency part of the latter system with that of Gile (1961) shows a poor correlation, which varies with the criteria used for comparison.) Soil description for pedological purposes uses a not dissimilar set of parameters, Hodgson (1978) listing colour, organic matter, particle size, distribution, stoniness, soil-water state, structure, consistence, calcium carbonate and dolomite, roots, other soil flora, other features of pedogenic origin (concretions, nodules, cutans, pans, crusts, etc.), fauna, unusual features, and horizon boundary.

In an important paper, Gile *et al.* (1966) described distinct sequences of calcrete development in desert soils in New Mexico, emphasising the importance of the gravelly or non-gravelly texture of the host material. This work, together with that of Netterberg (1967, 1969a, b), forms the genetic basis for the morphogenetic classification to be described in this paper.

TABLE I
Classification of ca Horizons After Gile (1961)

Horizon Class	Induration Grade	Range of Properties[2]							
		Carbonate Contents[1] % by mass	Infiltration Rate		Uniaxial Compressive Strength				Bulk Density[1] g/cm³
					Air-Dry		Moist[3]		
			in/h	mm/h	psi	MPa	psi	MPa	
Very strong	Very strong	75–95	<0,1	<2,5	3 000–8 000	21–55	2 000–6 000	14–41	1,90–2,25
	Strong	50–75	0,1–0,6	2,5–5	750–3 000	5–21	250–2 000	1,7–14	1,60–1,90
Strong	Moderate	30–50	0,6–1,5	5–40	150–750	1–5	50–250	0,3–1,7	1,60–1,85
	Nonindurated	30–50	0,6–1,5	5–40	400–800	3–5,5	<25	<0,2	1,60–1,85
Moderate	Slight	10–30	1,5–4,0	40–100	<150	<1	<50	<0,3	1,60–1,85
	Indurated	10–30	1,5–4,0	40–100	<400	<3	<25	<0,2	1,60–1,85
Weak	Nonindurated	<10	1,5–5,0	40–130	<200	<1,5	<10	<0,1	1,30–1,75

1 Based on <2 mm fraction
2 Metric equivalents are approximate
3 100 mm moisture tension

His grades of induration were defined as follows:

1. very strongly indurated: dry consistency extremely hard (following the Soil Survey Staff (1951) convention), picked with great difficulty, broken with difficulty with a hammer, scratched with difficulty by a knife or not scratched at all, does not soften noticeably on wetting and does not slake, air-dry uniaxial compressive strength 3 000–8 000 psi (21–55 MPa);
2. strongly indurated: dry consistency very hard, picked with difficulty, but when removed, easily broken with a hammer, scratched easily by a knife and softens slightly when wet, but does not slake, air-dry compressive strength 750–3 000 psi (5,2–21 MPa);
3. moderately indurated: dry consistency hard, readily picked, broken with a hammer and scratched with a knife, softens when wet but does not slake, air-dry compressive strength 150–750 psi (1,0–5,2 MPa);
4. slightly indurated: dry consistency hard, easily shovelled, broken with a hammer and scratched with a knife, softens slightly when wet, but does not slake, air-dry compressive strengths less than 150 psi (1,0 MPa);
5. non-indurated: dry consistency loose to very hard, but slakes when wet. Ranges from loose material to that which is only picked with difficulty. Scratched easily by a knife and broken easily with a hammer, air-dry compressive strengths 0–800 psi (0–5,5 MPa), but moist strengths are less than 25 psi (170 kPa).

In South Africa the most widely used general method of soil description for civil engineering purposes is that of Jennings and Brink (1961), revised by Jennings *et al.* (1973). In this method each stratum is described according to standard descriptors of moisture condition, colour, consistency, structure, soil type, inclusions, and origin.

Gile's (1961) classification is a well-defined, relatively detailed and complicated system developed for scientific study and general pedological purposes. In contrast, simple descriptive terms without definition such as (translated) "nodules", "farinaceous powdering", "veinlets", "spots", "mycelium", "continuous impregnation", and "efflorescence" were used by Russian pedologists in Ivanova (1966) for describing the carbonate "separations" in the soils of the Caspian area. Similar simple terms such as the "cappings", "concretionary nodules" and "powdery calcareous earths" of Sofoulis (1963) and the "sheet", "nodular", "powdery" and "boulder" calcrete of Caiger (1964; pers. comm., 1965) have been used by geologists and civil engineers. Influenced by Caiger, calcretes in South and South West Africa were briefly defined and described on a basis of secondary structure by Netterberg (1967), who divided them into calcified soils and powder, glaebular (or nodular or accretionary), honeycomb, hardpan, and boulder calcretes, and listed some of their engineering properties. This morphogenetic classification subsequently underwent slight modifications (Netterberg, 1969a, 1971) after several years of use and its application to over 600 calcrete profiles in South and South West Africa. The current version is here described in full for the first time after a further ten years of use and application in southern Africa and elsewhere. In comparison with the classifications of other workers it is closest to that of Ruellan (1971, p. 46) and Goudie (1973, p. 13), the latter being clearly based upon that of Netterberg (1969a, b).

Calcrete occurs extensively in North Africa, Durand (1963), for example, classifying that of Algeria into (translated) stratified crusts, pulverulent lime, incrustations, petrified roots, and nodules, and Ruellan (1967,

1971) that of Morocco into diffused accumulations with or without pseudo mycelium, friable lumps, concretions (granules and "kidneys"), encrustment hardpans, crust hardpans grading downwards into encrustment hardpans, ribboned films, and compact slabs. Durand's (1963) work represents the only comprehensive North African study

TABLE II
Genetic Classification of Calcrete After Van Zuidam (1976)

Calcrete forming process	Calcrete types
I. Mono-genetic	
1. Spherical calcrete concentration, by	
1.1 pedogenic processes	— nodules, petrified roots
1.2 shallow water conditions	— spherulites, ooliths
1.3 artesian water conditions	— travertine
2. Cementation, by	
2.1 pedogenic processes	— coatings
2.2 evapo-(transpi-)ration of	— filaments
surface water	— petrified roots
groundwater	— calcified sand and gravel
capillary rise	— horizons with calcite formation in
artesian water	the form of lime-pendants under
2.3 redeposition of altered	pebbles, etc.
calcium-carbonate rich bedrock	
3. hardpan development/induration to non-solid layers, by	
3.1 pedogenic processes	— plugged horizons
3.2 evapo-(transpi-)ration of	— calcrete sandstone
running surface water	— calcrete conglomerate
stagnant water	— non-solid, laminar layers
artesian water	
3.3 redeposition of altered calcium-carbonate rich bedrock	
4. crust development/solid layer formation, by	
4.1 pedogenic processes	— stratified or non-stratified
4.2 evapo-(transpi-)ration of	laminated crusts
running surface water	
stagnated water	
artesian water	
II. Poly-genetic	
A. Gradual, single and/or complex calcrete profile development:	
5. cementation by combined processes (see 2)	— coatings — filaments — calcified sand and gravel
6. induration by combined processes (see 3) in a:	— plugged horizons — calcrete conglomerates — non-solid, laminar layers
6.1 "normal" evolution, change in internal circumstances, e.g. due to increasing calcium-carbonate content and decreasing permeability	
6.2 change in external circumstances, e.g. change in climate, geomorphic processes, and topographic situation	
7. crust development by combined processes (see 4) in a:	— stratified or non-stratified laminar crusts
7.1 "normal" evolution, change in internal circumstances, e.g. due to increasing calcium-carbonate content and decreasing permeability	
7.2 change in external circumstances, e.g. change in climate, geomorphic processes, and topographic situation	
B. Abrupt, complex calcrete profile development:	
8. Formation of various horizons by different, agents, *with* a systematic sequence, e.g. pedogenic horizons followed by shallow lake deposits, etc.	— complex calcrete profile with a single sequence in various horizons of different or combined origin — complex calcrete profile with a systematic repetition of various horizons of different or combined origin
9. formation of various horizons by different agents *without* a systematic sequence	— complex profile with various horizons of different or combined origin without a discernible sequence
10. formation of a calcrete profile by calcrete and non-calcrete forming processes, e.g. transport by slope-processes and/or crumbled by freeze-thaw activities of older calcrete and cemented by secondary limestone	— calcrete rubble — calcrete gibbers — boulder calcrete

of these materials undertaken up to 1963 (Butzer, 1963).

Recent summary classifications of calcretes on a genetic basis include those of Van Zuidam (1976, Table 19) (Table II) and Carlisle (1978, 1980, Fig. 3.1) (see Section XII).

Gile's (1961) classification is one of the best scientific and research classifications available and with minor modification should be adequate for South African ca horizons. His induration grades and infiltration rates could be useful in engineering, but several other features essential in an engineering geological classification are lacking (Section III). All other classifications seem to be either too simple or too complicated, the latter being of scientific rather than engineering value. The one with the most potential is that of Ruellan (1971), part of which was adopted for road use by Horta (1979, 1980).

Engineering systems for soil and rock classification can be divided into two types:

1. Those based on particle-size distribution and Atterberg limits and intended largely for use on disturbed samples, such as that of Casagrande (1947), the variants of it, i.e. those contained in the British Standard Code of Practice (BS CP) Number 2001 (British Standards Institution (BSI), 1957), the American Society for Testing Materials (ASTM) D 2487 (ASTM, 1968a) and the Unified (Bureau of Reclamation, 1974); and that of the American Association of State Highway and Transportation Officials (AASHTO) M 145 (AASHTO, 1974).
2. Those based on visual description and intended also for use on undisturbed samples, cores and *in situ* soil and/or rock masses, such as the systems of the ASTM D 2488 (ASTM, 1968b), BS CP 2001 (BSI, 1957), BS CP 2004 (BSI, 1972), Geological Society Engineering Group Working Party (1970, 1977), Core Logging Committee of the Association of Engineering Geologists (AEG) (1978), Jennings *et al.* (1973), Bieniawski (1973) and the Commission of Engineering Geological Mapping of the International Association of Engineering Geologists (IAEG) (1979).

All of these systems have their particular applications and their limitations. Purely geological or pedological classifications usually mean little to the engineer and are seldom adequately quantitative or defined in terms of meaningful engineering parameters, while purely engineering classifications based upon temperate zone experience mostly fail to take the geology into account, thus frequently omitting important information especially necessary when dealing with the non-traditional materials of the tropics and arid zones. The descriptive engineering methods are better in this respect than those relying solely on particle size and Atterberg limits. The best results for engineering geological purposes are probably yielded by a combination of all three approaches, in its simplest form consisting of a genetic term such as "calcrete", "calcified", "ferricrete", "ferruginised", etc., plus a traditional engineering soil or rock term such as "sand", "gravel", "rock", etc., e.g. calcrete gravel, calcrete rock (Netterberg, 1976a). This approach was recommended by the Speciality Session on Pedogenic Materials (1976) and is not dissimilar to that adopted for the classification of near-shore carbonate sediments for engineering purposes by Fookes and Higginbottom (1975). A similar approach has also been advocated by Horta (1980) who suggested adding, among others, the groups "calcrete gravels" ("graves d'encroûtement") (GE), "calcrete sands" ("sables d'encroûtement") (SE) and gypsum sands (SY) to the Unified classification.

III. REQUIREMENTS OF AN ENGINEERING GEOLOGICAL CLASSIFICATION

While such complete information is not required in every case, any classification of calcretes for roadmaking and general engineering geological use either must possess the following attributes or be capable of extension to include them:

1. The divisions must be of engineering significance, i.e. the engineering properties of each class must be significantly different from each other.
2. If possible, the divisions should also be of geological significance.
3. The divisions should be readily distinguishable *in the field* both by a geologist and an engineer, technician, or construction worker with limited geological background.
4. The terminology must be simple and as short and explicit as possible, to allow its use by persons without formal geological training. At the same time it should be geologically accurate.
5. In the case of calcified soils, nodular and powder calcretes, it should convey an idea of the grading, plasticity, and aggregate crushing strength.
6. In the case of hardpan calcretes it should provide an indication of the strength of the intact material, the degree of weathering, and the spacing, orientation, separation, roughness, waviness, continuity, and filling of any fractures.
7. In the case of calcrete boulders and cobbles it should provide an indication of the size of the fragments, the strength of the intact material, the degree of weathering, and the nature and relative proportion of interstitial soil.
8. In the case of all materials, it must convey some idea of the strength, compressibility, permeability, ease of excavation and thickness, dip and strike of the layer.
9. The classification should when necessary be capable of further expansion by means of common laboratory test results and further field observations.
10. It should be complementary to the existing engineering classifications.
11. It should employ existing terminology as far as possible.

It is suggested that the simplified classification by secondary structure described in this paper meets most of these requirements.

IV. APPLICATION OF STANDARD SOIL AND ROCK DESCRIPTORS

It is intended that the classification be used, when necessary, with a systematic method of engineering soil and rock description such as that of Jennings *et al.* (1973), as modified by the AEG (1978), which in turn may be supplemented by one or more purely engineering classifications, such as the AASHTO or Unified. As calcretes vary in quality from loose soils to very hard rocks, and in thickness from a few millimetres to 100 metres (Du Toit, 1954), methods suitable for both soils and rocks in pits, shafts, outcrops and borehole cores are required. In general, the material is first described as an engineering material and this is followed, when necessary, by a geological or pedological description (Netterberg, 1966, 1969a, 1976; Jennings *et al.*, 1973).

A. Moisture Condition

Calcretes are generally encountered in a dry to slightly moist condition, but much depends on the season and the depth of the water table.

B. Colour

Colour is a useful guide to the overall quality and other properties of a calcrete. Reddish and brownish calcretes generally possess lower plasticity indices and harder aggregate than white or grey calcretes, while greenish materials are likely to be saline. The colour of the aggregate fraction of a nodular calcrete is not always the same as that of the fines, and it is suggested that the latter appear first in the description, e.g. in "light brown, silty, sandy gravel; white, nodular calcrete", or "light brown, silty, sandy, white, nodular calcrete gravel", "light brown" refers to the overall colour of the horizon caused by the silty sand fines, while "white" refers to the predominant colour of the freshly broken gravel-sized nodules. Another method of description would be "white gravel in a matrix of light brown, silty sand; nodular calcrete". However, apart from being longer (12 words in place of eight), this method does not state unambiguously whether the material as a whole is a sand or a gravel.

The colours predominant in calcrete and its fines (if any) are usually various shades of white, grey, red, brown, and green. Most calcretes are creamy white, light brown or light grey in colour.

C. Consistency and Hardness

A method for estimating the consistency and hardness of calcretes should provide an estimate of the uniaxial and/or aggregate crushing strength as appropriate of glaebules, boulders, cobbles, hardpans, etc., and the excavation characteristics, compressibility, bearing capacity, etc., of the whole mass. The methods of Gile (1961), Jennings and Brink (1961), Jennings *et al.* (1973), Bieniawski (1973), the Geological Society (1970, 1977a, 1977b), the AEG (1978) and the IAEG (1979) contribute towards the estimation of all but aggregate strength in terms useful to the highway engineer. The latter requires an estimate in terms of one of the recognised aggregate strength tests, i.e. the aggregate crushing value (ACV) or ten per cent fines aggregate crushing test (ten per cent FACT) in South Africa. Unfortunately, it is not easy to convert from uniaxial compressive strength (UCS) to aggregate crushing strength, the only known correlation (Markwick and Shergold, 1946), showing a large scatter. Moreover, the correlation appears to be in error at low strengths and the UCS testing was also almost certainly carried out on 25 mm × 25 mm cylinders. A further complicating factor is that cohesive soil consistencies were devised in terms of saturated clays, not dry, cemented materials. Cohesion in calcretes may be supplied by clay, carbonate, or opaline silica. Further work is required to provide a universal consistency and hardness classification and, for pedocretes, grades of cementation (Gile, 1961; National Institute for Road Research (NIRR), 1965; Williams, 1973) may be more appropriate. In the interim, the consistency terms given in Jennings and Brink (1961) have been used, based largely on ease of excavation, with the addition of the terms shown in Table III to cover unpickable calcretes, the idea of using Mohs hardness being obtained from NIRR (1965).

In addition to Mohs hardness, other tests found useful for estimating aggregate crushing strength of calcretes include water absorption and a simple aggregate pliers test (Netterberg, 1967, 1969a, 1978a). With certain types of calcretes, such as powder, nodular and honeycomb, it is important to describe both the overall consistency of the layer and the consistency of the aggregate. Thus in "loose, sandy gravel; very hard, nodular calcrete", or "loose, sandy, very hard, nodular calcrete gravel", "loose" applies to the overall consistency of the layer and "very hard" to the aggregate. The consistencies of calcretes range from the soft or loose soil of Jennings and Brink (1961) to the very hard rocks as defined in Table III. Calcretes with Mohs hardnesses over six or ACVs less than 18 have not been encountered.

D. Weathering

Calcrete hardpans undergo both mechanical and chemical weathering (solution) to form discrete boulders and cobbles. Calcrete nodules, most hardpans, and boulders and cobbles formed by solution would generally classify as "unweathered" according to the AEG (1978) classification. Outcropping fossil hardpans and boulders may be up to "medium weathered".

E. Structure

The engineering geological structural and fabric terminology of Jennings *et al.* (1973) and the AEG (1978) is suitable for use on calcretes, although the correct use of the calcrete classification alone will convey a very good idea of the structure. Powder, nodular and honeycomb calcretes are usually intact, possessing no mechanical structures, while all other calcretes and calcareous and calcified soils may possess mechanical structures, such as bedding inherited from the host material, as well as other mechanical structures such as joints. Inherited features tend to diminish with development of the calcrete; thus, bedding is rare in hardpans and even rarer in boulders. Jointing is only common in outcropping fossil hardpans, boulders and cobbles undergoing mechanical weathering. Joint spacing is seldom closer than 100 mm and the joints may be open or filled with soil. Their orientation is generally more or less vertical, but they have not been well studied. Brecciation is common in the older hardpans. Slickensiding and microshattering have not so far been observed in southern African calcretes.

Structures will be described in more detail with the particular variety of calcrete with which they are associated. According to Reeves (1976) the following macrostructures have been recorded from calcretes: pseudobedding, birdseye, breccia, conglomerate, buckle cracks, concretions, fractured cobbles, glaebules, honeycomb, irregular masses, laminae, nodules, papules, pedodes, pipes, pisolites, plates, septaria, slickensides, pseudoanticlines, root shields, and pedotubules.

F. Soil and Rock Type

The 6–2–0,6 mm method of particle size classification is recommended, but field descriptions like "silty, sandy gravel" must be employed. This implies that there is more gravel than sand and more sand than silt. The description "gravelly silty sand" would imply scattered gravel *floating* in a matrix of silty sand, in which case the material would behave as a silty sand and not as a gravel. Triangular charts which make provision for particles coarser than 2 mm have been given in Central African Standard A43 (Standards Association of Central Africa,

TABLE III
Calcrete Hardness Terminology

Hardness		Approximate ACV	Approximate 10% Fact	Usual most arduous use	Approximate AEG (1978) Equivalent	
Term	Mohs Number	%	kN		Term	UCS MPa
Hard	3–5	33–22	80–170	Base, concrete, asphalt	Very hard	70–200
Very hard	5–6	22–18	170–210	Surface treatment(1)	Very hard	70–200
Extremely hard	>6	<18	>210	Rolled-in chips(1)	Extremely hard	>200

(1) Calcretes have not so far been used for these purposes in Southern Africa.

1971) and in a new draft edition of BS CP 2001 (Construction News, 1973).

Some comment on the actual grading, such as "well graded" or "uniformly graded" is also desirable. From the pedological viewpoint all pedogenic calcretes, however hard, are soils or, more correctly, soil *horizons*. However, for engineering purposes anything which can be "cored with a normal diamond bit and single tube corebarrel using water as a drilling fluid" (Jennings and Brink, 1961), which has a (preferably soaked) uniaxial compressive strength of more than 700 kPa (Jennings *et al.*, 1973) to 1 000 kPa (AEG, 1978) or which requires blasting for excavation (South African Institution of Civil Engineers and others, 1973) is best considered as rock.

G. Origin and Inclusions

Calcretes qualify under the headings of both origin and inclusions. Scattered nodules should be recorded simply as inclusions in the stratum while well-developed calcretes should be considered as soil strata in their own right (Netterberg, 1969a; Jennings *et al.*, 1973). The origin referred to in the system of Jennings *et al.* (1973) is the geological and not the pedological origin. Pedogenesis does of course also give rise to the development of distinct horizons, the onset of which is used as a pedological definition of soil.

H. Detailed Description

It is suggested that the methods of Jennings *et al.* (1973) and the AEG (1978), slightly modified as outlined, be applied in the normal way, but that this then be followed by the calcrete description. Thus, for example, a dry, Type 1, nodular calcrete, of which more than half the particles are visible to the naked eye and of which

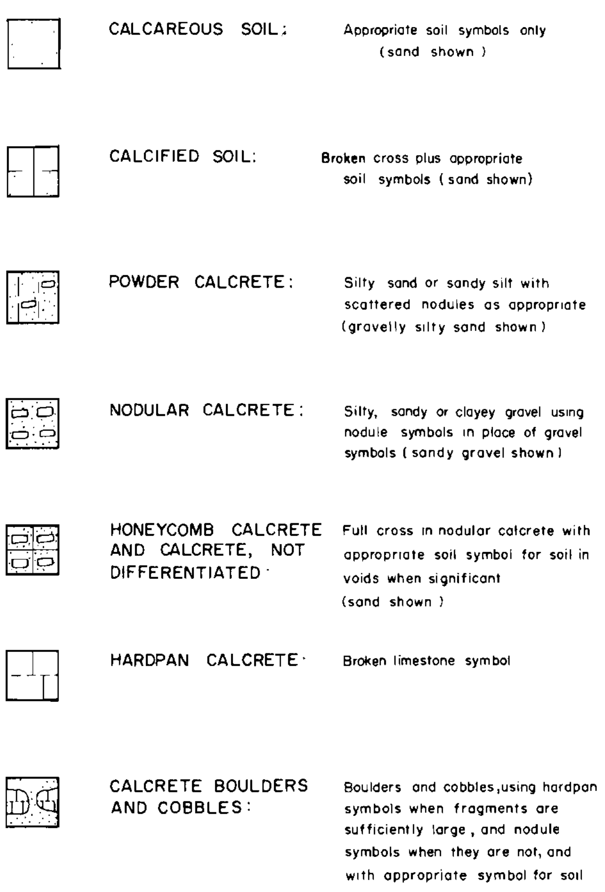


Figure 1
Suggested calcrete profile symbols.

fraction more than half again is pale brown, hard, intact aggregate of a botryoidal shape between about 6 and 60 mm in diameter, with an appreciable amount of nonplastic, silty, sandy, calcareous fines of alluvial origin, the overall mass of which can be excavated readily with a hand shovel, might be described as a dry, white (10 YR 8/1), loose, poorly graded, silty, sandy GRAVEL; GM; pale brown (10 YR 6/3) hard, intact, botryoidal, Type 1, nodular calcrete (pedogenic, host material alluvial). *Inferences* are given in parentheses and the Unified or extended Casagrande classification may be added if desired (GM in this case). Such a full description is not always required, but the bare minimum would be "calcrete gravel" or "nodular calcrete".

I. Profile and Borehole Log Symbols

The symbols recommended by Jennings *et al.* (1973) and the AEG (1978) are employed except when it becomes necessary to distinguish the different varieties of calcrete. For such purposes the profile symbols shown in Fig. 1 are suggested.

The symbol used for hardpan calcrete is also often used for calcretes in general, but the symbol suggested for the latter purpose has the advantage of being easily modified for silcretes and ferricretes. Several ideas for profile symbols and methods of description were gleaned from NIRR (1965). An alternative to the use of the cross in Fig. 1 to indicate cementation is the thickened outline employed by Jennings *et al.* (1973).

V. CLASSIFICATION BY SECONDARY STRUCTURE

The classification suggested is a descriptive one based largely on secondary (chemical) structure and sequence of development. It is considered that the materials actually form more or less in the order described, a nodular calcrete eventually growing, via a honeycomb calcrete, into a hardpan calcrete, for example (Table IV). On genetic grounds this classification therefore should include all the possible basic varieties. The only materials which usually present difficulty in classification are those which have been subjected to more than one phase of calcification and the occasional occurrence of very thick hardpan calcrete.

While the term "calcrete" has on genetic grounds been usefully and validly applied to any authigenic soil carbonate accumulation — and it was precisely to avoid such "long and awkward circumlocutions" that Lamplugh (1902) invented the term — in this classification it is only applied to materials containing more than about 50 per cent $CaCO_3$ equivalent by mass or more than about 50 per cent K-fabric by volume. No minimum strength or degree of cementation is required. These views are in conflict with those of Aristarain (1971) and Goudie (1972), but are in accordance with the recommendation of the Speciality Session on Pedogenic Materials (1976), which largely represented engineering and engineering geological opinion only. The figure of 50 per cent carbonate by mass also coincides with the lower limit usually set for a limestone. The term "calcrete" is therefore equated with "surface limestone".

The following classification is useful for general geological and engineering geological use, or whenever a reasonably detailed classification is required. It is unnecessarily detailed in some places for general engineering use, and a simplified version is suggested for this purpose in Section IV. It is inadequate on its own for pedological purposes, although it can serve as an adjunct to such methods.

A. Calcareous Soil

The term "calcareous" is used to imply little or no cementation, and such soils are usually soft or loose and

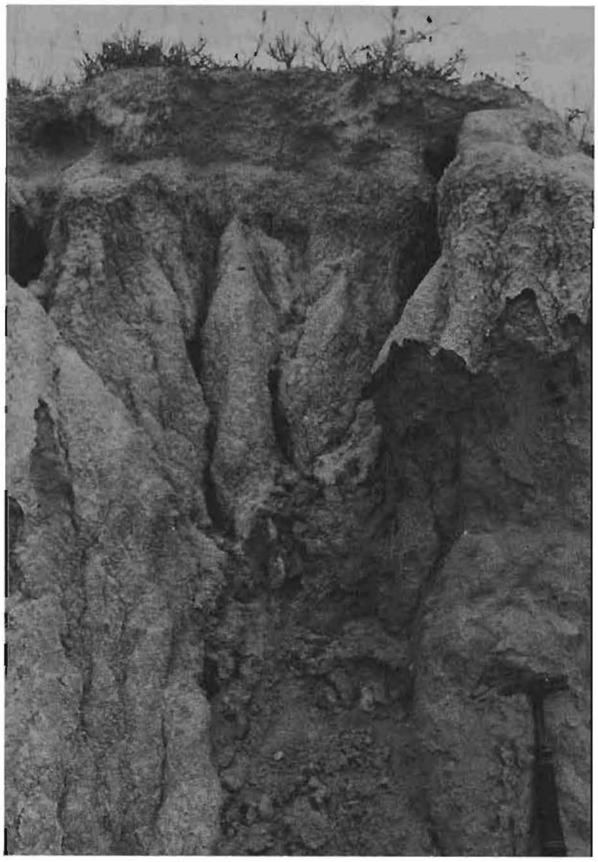
TABLE IV
Stages in the Development of Calcretes (Modified from Netterberg, 1969b)

Stage	Host material			
0	Weathered rock	Shattered clay	Mixed texture	Clean sand or gravel
1	CALCRETE SOLUANS IN CRACKS	CALCRETE POWDER SOLUANS IN CRACKS	SCATTERED CALCRETE GLAEBULES IN HOST SOIL	CALCRETE-COATED GRAINS
2	CALCIFIED WEATHERED ROCK	POWDER CALCRETE (sandy silt or silty sand)	GLAEBULAR CALCRETE (clayey, silty or sandy gravel)	CALCIFIED SAND OR GRAVEL (massive)
3			HONEYCOMB CALCRETE (partially coalesced nodules or soluans)	
4			HARDPAN CALCRETE (rock-like sheet)	
5			CALCRETE BOULDERS, COBBLES OR GRAVEL (discrete fragments formed by weathering)	

very weakly or completely uncemented by the small carbonate content (Fig. 2), which occurs mostly as grain coatings, patches of powdery carbonate and pseudomycelia (Ruellan, 1968) (exudations, coatings or veinlets (Lebedeva and Ovechkin, 1975)). While *scattered* nodules or other carbonate concentrations may also be present, apart from ion exchange effects, the small carbonate content has not significantly altered the engineering properties of the original host soil. The total carbonate content expressed as $CaCO_3$ (the "$CaCO_3$ equivalent" of pedology) generally lies between one and ten per cent. Materials transitional between calcareous soils and nodular calcretes (10–50 per cent carbonate) are probably best described as, for example, gravelly, calcareous, clayey SAND; scattered white stiff, calcrete nodules; or gravel-sized calcrete nodules floating in a matrix of calcareous, clayey sand; or simply as nodular, calcareous, clayey sand. The material in Fig. 3 falls into this general category. However, the *individual* carbonate concentrations considered in isolation would classify as calcretes. According to Brewer's (1964) fabric classification of soil features, such calcrete fissure-fillings represent the variety of cutans called "soluans" and, if of calcite, "calcitans". Some of Durand's (1963) "nodules farineaux" ("floury nodules") and "nodules conrètionnes" (concretionary nodules) may also be soluans. These calcrete soluans may be observed almost anywhere in outcropping weathered rocks of the Karoo Supergroup in the drier half of the Cape Province. (The calcrete dykes recorded by Winterbach and Weinert (1961) near Riet River near Kimberley may represent large soluans.) Some calcareous soils slake when placed in water and would be weak or moderate ca horizons according to Gile (1961) and simply ca horizons according to the K horizon concept of Gile *et al.* (1965). The material in Fig. 3 would classify as a moderate ca horizon according to Gile (1961). Calcareous soils include both Stages I and II of Gile *et al.* (1966), but the term is more restrictive than that of pedology (e.g. Soil Survey Staff, 1975; Dregne, 1976; Macvicar *et al.*, 1977), where it is used for any "soil containing sufficient free calcium carbonate or calcium-magnesium carbonate to effervesce visibly when treated with cold 0.1N hydrochloric acid" (Soil Science Society of America, 1978) apparently as a replacement for the obsolete term "pedocal".

B. Calcified Soil

A calcified soil is a soil cemented by carbonate to a usually firm or stiff consistency. While often just friable, it does not slake. It possesses little or no nodular development. The carbonate may be evenly distributed throughout the particular horizon in the profile as in calcified sands (Fig. 4), and gravels (Fig. 5), or it may be confined to fissures as, for example, in a weathered rock (Fig. 6) — the "melikaria" of Burt (1928 *in* Pettijohn, 1957). Such features may be regular (Fig. 6) or irregular in pattern (Fig. 7), presumably depending on the rock fracture pattern, and may develop into honeycomb calcretes. The term "calcified" is used rather than "calcareous" in order to imply cementation of the whole *hor-*



0–0,30 m: Dry, grey, soft, intact silty SAND; roots; (disturbed aeolian and alluvial topsoil).

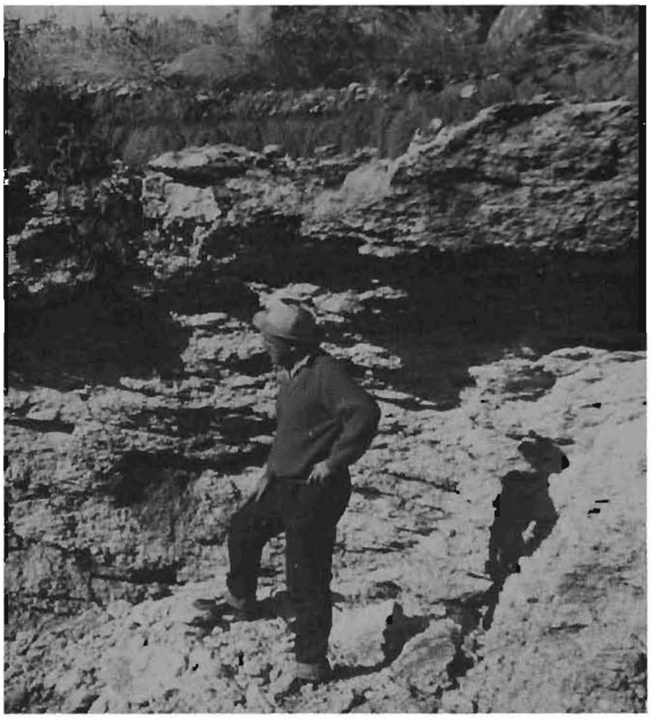
0,30–2,0 m +: Slightly moist, pale olive (white on dry exposed face), soft-firm, intact, slightly calcareous, slightly clayey SAND; (alluvially redistributed sand of Kalahari type).

Figure 2
Calcareous sand exposed in side of road borrow pit 26,7 km from Ondangwa on old Namutoni road, Owambo, South West Africa.

0–0,15 m (not shown): Slightly moist, black, soft, intact, sandy CLAY; roots; (residual from dolerite).

0,15–2,4 m +: Slightly moist, olive, soft, fissured, gravelly sandy SILT; fissures filled with hard calcrete cutans; (residual from dolerite).

Figure 3
Calcareous, gravelly, sandy silt residual from dolerite containing calcrete fissure fillings (cutans) exposed in side of road borrow pit near Sipofani, Swaziland.



0–0,1 to 0,3 m: Dry, reddish brown, medium dense, intact, slightly silty SAND; roots; (aeolian).

0,45–3,0 m: Dry, white, stiff, becoming firm by 0,6 m, shattered in places, bedded and thinly bedded, CALCIFIED SAND; roots; (sand alluvial); in places capped by up to 150 mm of hard calcrete hardpan, boulders or cobbles.

3,0–8 m +: (not shown): Dry?, whitish, very stiff, CALCIFIED, sandy densely packed, gravelly BOULDERS; (allogenic material alluvial and mostly well-rounded Ventersdorp andesite, indurated mudrock and chalcedony).

Figure 4
Thinly bedded and very thinly bedded calcified sand exposed in diamond digging in "Current Gravels" (Younger Gravels IIA), of Vaal River ar Riverview Estates, Windsorton, Cape Province.

Figure 5
Calcified gravels capping side of Sesriem canyon, between Maltahöhe and Solitaire, South West Africa.

Figure 6
Regular calcrete boxwork structure forming calcified weathered Dwyka shale transitional to honeycomb calcrete, near Lichtenburg, Transvaal. Pen is about 150 mm in length. Photo: Courtesy A. Albertyn, Blue Circle Cement, Johannesburg.

izon. The amount of carbonate present, usually about 10–50 per cent, is sufficient to have altered the engineering properties of the original soil. It is probably reasonable to apply the term "calcified" in place of "calcareous" when the horizon as a whole is cemented to a consistency of at least one class above that of the presumed host material. The horizon as a whole in Fig. 3 is not cemented, therefore it does not classify as a calcified soil. Calcified soils can generally be dug with a pick and shovel. However, well-cemented calcified gravels may require pneumatic tools or even blasting for economic excavation. Calcified sands are seldom more than a few metres in thickness, while calcified gravels in excess of 10 metres are known on the Vaal, Ugab and other river terraces, along the Weissrand, and forming the walls of the Sesriem Canyon in South West Africa.

The author (Netterberg, 1967) previously used the term "calcified soil" to include all materials apparently transitional between calcareous soils and nodular calcretes, but now prefers to reserve it for materials as described above, i.e. cemented *horizons*.

A calcified sand or gravel, such as the materials in Figs.

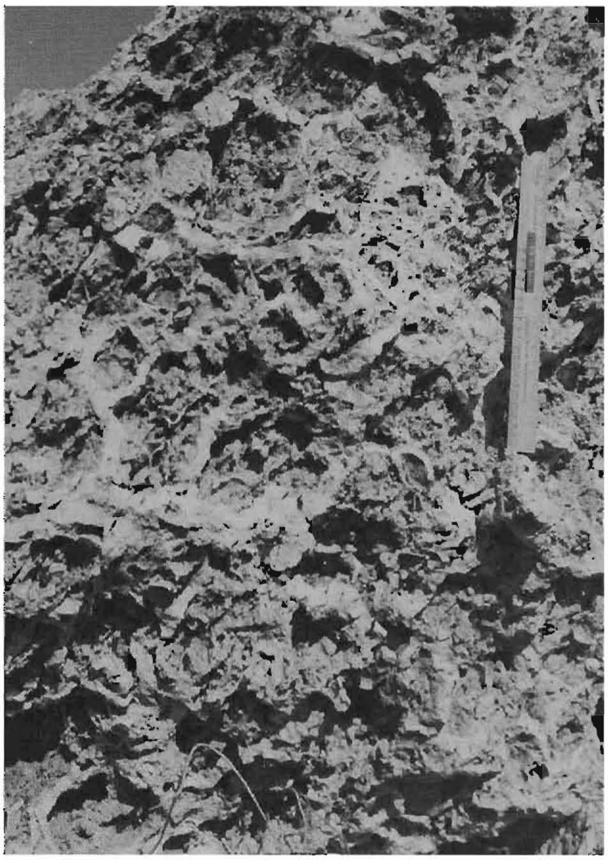


Figure 7
Irregular calcrete boxwork structure in weathered Dwyka mudstone near Lichtenburg, Transvaal. Scale is about 300 mm in length. Photo: Courtesy A. Albertyn, Blue Circle Cement, Johannesburg.

4 and 5, would qualify as a K horizon since they possess more than 50 per cent of K-fabric, but the calcified weathered rocks (Figs. 6 and 7) would not. The calcified soils in Figs. 4 and 5 would classify as strong ca horizons according to Gile (1961) and the calcified gravels into Stage III of Gile *et al.* (1966) sequence. Calcified sands and gravels would probably fall into Wilbert's (1962) category of "encroûtement diffuse" (diffused encrustation) and Ruellan's (1967) category of "accumulation diffuse" (diffuse accumulation). Most aeolianites could be described as calcified sand. Knox (1977) has described such material at Saldanha Bay as semi-indurated.

C. Powder Calcrete

Powder calcrete is a fine, usually loose, but sometimes up to stiff *in situ*, intact powder, high in silt-sized calcium carbonate with few visible host particles and little or no nodular development (Fig. 8).

Powder calcretes form initially as small irregular patches and lenses, often preferentially along joints and bedding planes, in clays and weathered mudrocks, and may eventually reach thicknesses of several metres of almost pure silt-sized calcite crystals grading downwards into the host material (Fig. 9).

After grading analyses had been carried out on ten powder and 30 nodular calcretes initially classified visually into these two varieties, it was found that nine out of the ten (90 per cent) powder calcretes possessed grading moduli of less than 1,5 and 29 out of the 30 nodular calcretes (97 per cent) grading moduli greater than or equal to 1,5, representing an overall reliability of 95 per cent. (The grading modulus (Kleyn, 1955) in its metricated form is defined as the sum of the cumulative mass percentages retained on each of the 2,00 mm, 0,425 mm and 0,075 mm sieves divided by 100.) It was also found that 90 per cent of the powder calcretes possessed at least 75 per cent by mass passing the 2,00 mm sieve and that all of the nodular calcretes possessed less than 75 per cent finer than 2,00 mm, representing on overall reliability of 98 per cent. In 85 per cent of the samples the powder calcretes

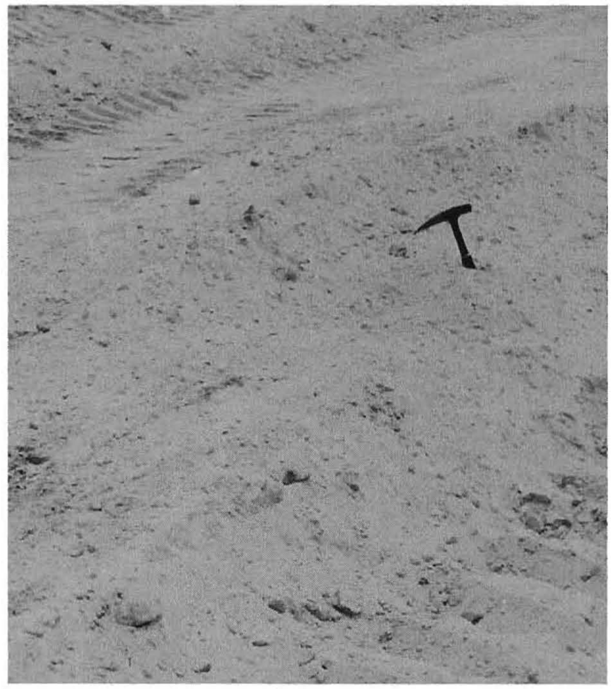


Figure 8
Powder calcrete exposed in floor of road borrow pit near Oshivello, Owambo, South West Africa.

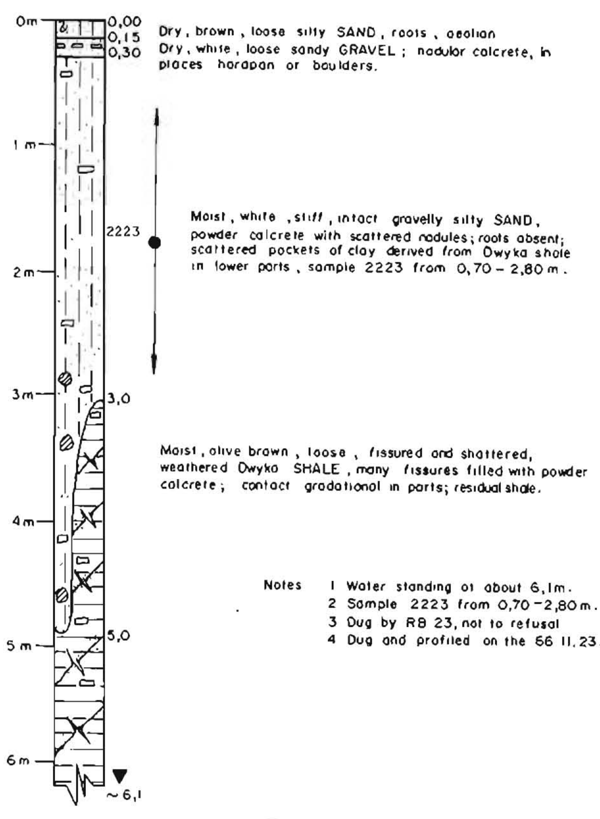


Figure 9
Profile description of powder calcrete exposed in foundation excavation near Lichtenburg, Transvaal. Similar in appearance to right-hand synclinal abutment in Fig. 37.

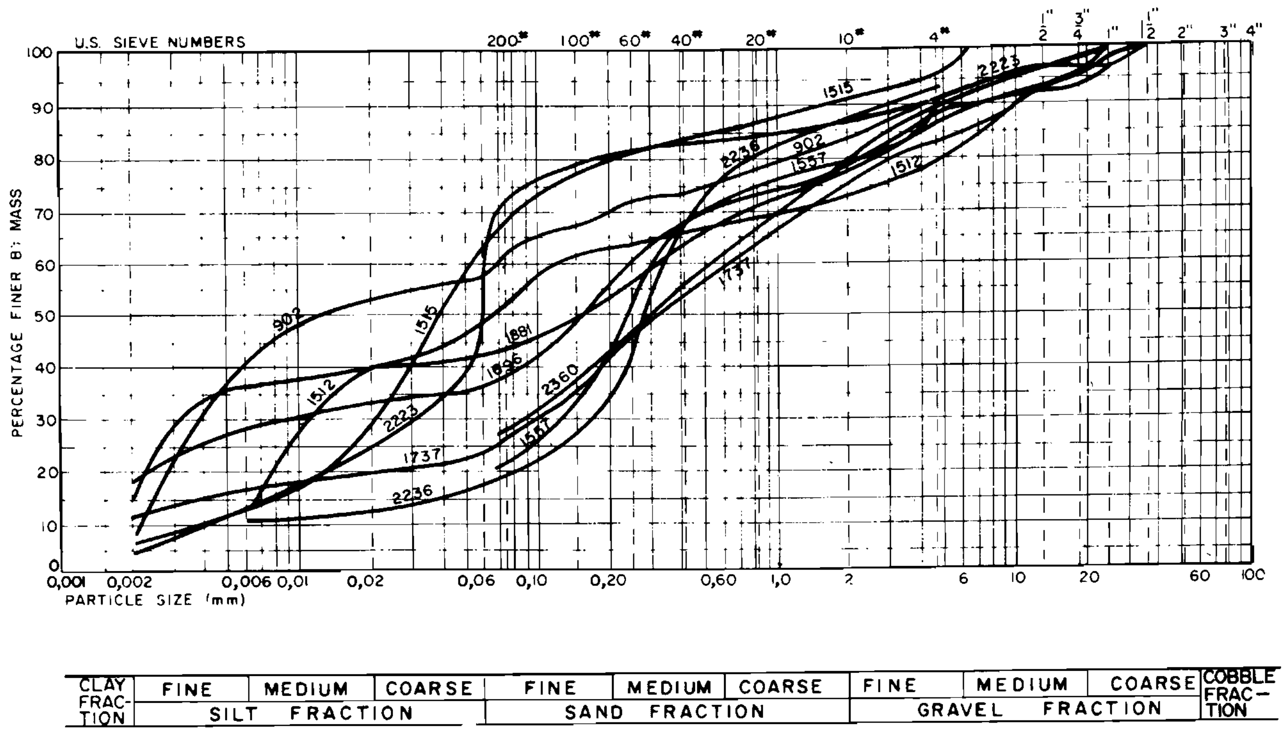


Figure 10
Particle-size distributions of some powder calcretes from South and South West Africa.

possessed more and the nodular calcretes less than 55 per cent finer than 0,425 mm and in 90 per cent, 30 per cent finer than 0,060 mm. A grading modulus of 1,5 was chosen since this represents the lower limit often specified for rural road subbases in the Transvaal and South West Africa and, at least in the case of calcretes, can be readily estimated in the field. Grading analyses of some typical powder calcretes are shown in Fig. 10. These materials range from the type specimens 1515 and 2223 which were made up largely of silt- and fine sand-sized calcite with grading moduli of 0,6 to coarser materials with some nodular development. Powder calcretes possessing grading moduli between 1,0 and 1,5 could be termed "nodular powder calcretes". Nodules in powder calcretes are often weak and friable. Powder calcretes vary from loose to stiff *in situ*, but the latter usually degrade to a powder when worked or during grading analyses.

Powder calcretes are equivalent to Gillette's (1934) "flourlike caliches", Wilbert's (1962) "encroûtement crayeux" (chalky encrustation), Durand's (1963) "calcaires pulverulents" (pulverulent limestones), and could be K1, K2 or K3 horizons according to the K horizon concept of Gile *et al.* (1965). They mostly belong to Price's (1933) and Reeve's (1970, 1976) "young caliches". The origin of Durand's "calcaires pulverulents" may not in all cases be the same as that of powder calcretes. It is difficult to decide how to classify powder calcretes according to Gile's (1961) method, but they would probably be called "nonindurated massive" ca horizons. They do not appear to fit exactly into any of his weak, moderate, strong or very strong ca horizons. The nearest would probably be "moderate". The up to stiff *in situ* varieties may be equivalent to Bretz and Horberg's (1949) "chalky caliche". Powder calcretes appear to be equivalent to the "accumulations diffuses" of Ruellan (1967, 1968, 1971), the "very fine calcareous tuffs" of Hamrouni (1975) and the uniform "impregnations" of Lebedeva and Ovechkin (1975). Some powder calcretes may possibly be equivalent to the "alm" of Vidal *et al.* (1966).

Loxton (1968) has suggested the use of the term "indurated pedogenic materials" to cover the materials calcrete, ferricrete and silcrete, and that therefore by definition a powder calcrete should not be called a calcrete at all. While there is merit in the pedological practice (Dregne, 1976; Macvicar *et al.*, 1977) of restricting the term "calcrete" to indurated materials and the use of the terms "hard" (1902) and "indurated" (1907) suggests that this was Lamplugh's intention, the author does not believe that it is compelling. In addition, the up to stiff *in situ* powder calcretes could be termed indurated, since they do not slake in water. Similarly, it is considered that the terms "pedogenic materials" or "pedocretes" alone should be adequate.

D. Glaebular Calcrete

Glaebular calcretes are discrete, usually intact, soft to very hard, concentrations of carbonate-cemented and/or replaced soil in a usually loose, usually strongly calcareous soil matrix (Fig. 11). The shape of the carbonate concentrations (calcrete glaebules) varies from spherical through botryoidal to highly irregular (Fig. 12) while platy, elongated and cylindroidal forms are also occasionally seen. The diameter of individual glaebules, or discrete botryoidal aggregations of glaebules, ranges from a few μm to about 60 mm. At least a quarter, and usually about half of the material is gravel (i.e. 2–60 mm in size). The grading modulus varies from 1,5 to 2,5 (see previous section). Grading analyses of some typical samples are shown in Fig. 13. In addition to the grading, descriptions of glaebular calcretes for roadmaking purposes should pay particular attention to the nature of the fines, whether they adhere to the aggregate, and to the hardness or strength of the aggregate.

Glaebular calcretes can usually be bulldozed without ripping to produce a fair to excellent natural gravel road base.

For all such concentrations, whether the cement (Brewer's (1964) "plasma") is carbonate, silica, sesquioxides, manganese oxide, sulphate, or clay, Brewer and Sleeman (1964) and Brewer (1964) have proposed the general term "glaebule", derived from the Latin for clod or lump of earth. The term "accretion" (Todd, 1903, *in*

0–0,45 m: Dry, dark brown, medium dense, slightly fissured, silty SAND; roots, non-calcareous, aeolian?

0,45–3 m +: Dry, brown, loose, silty, sandy, fine and medium GRAVEL; light grey, very hard, Type 3, botryoidal nodular calcrete, roots.

Figure 11
Nodular calcrete exposed in pit near Pienaar's River, Transvaal.

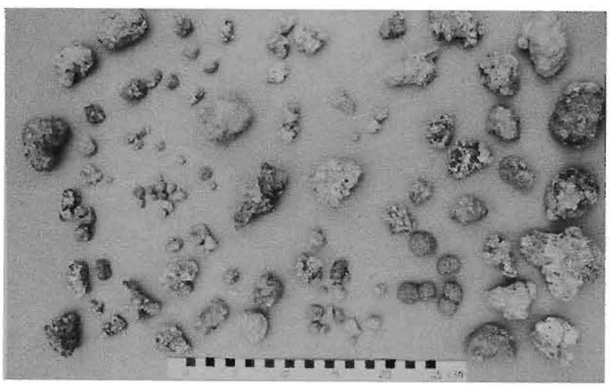


Figure 12
Some calcrete nodules from South and South West Africa.

Pettijohn, 1957) has been used for an even wider range of features (Pettijohn, 1957, 1975). Brewer and Sleeman (1964) have criticised the term "accretion" because of its genetic implications, and "glaebule" is to be preferred as a general term for this type of calcrete. The structureless nodular type is, however, by far the most abundant and little error will accrue by the retention of this term for engineering purposes. The term "concretion" has been used for "so many features obviously of diverse origins" that it has no exact meaning (Pettijohn, 1957). In this and subsequent papers the term will be restricted to glaebules with a concentric fabric.

The best classification of glaebules appears to be that of Brewer and Sleeman (1964), which in turn is based on that of Pettijohn (1957). They have established the following criteria upon which glaebules may be classified:

1. internal fabric (undifferentiated, concentric, lamellar, etc.);
2. mineralogy (sesquioxidic, manganiferous, calcareous, etc.);
3. distinctness (sharpness of boundary and ease of removal of the glaebule from the soil mass);
4. shape (spherical, botryoidal, tuberose, etc.).

Using these criteria in the above order of importance, these workers classified glaebules into six types:

1. nodules (undifferentiated, i.e. structureless fabric);
2. concretions (concentric fabric);
3. septaria (glaebules traversed by sets of radially and concentrically running cracks);
4. pedodes (pedological equivalents of geodes);
5. glaebular haloes (weakly cemented halo surrounding another glaebule);
6. papules (glaebules composed mostly of clay with continuous and/or lamellar fabric, such as Pettijohn's (1957) clay galls).

Nodules are by far the most common form of calcrete glaebules. Concretions, septaria and pedodes are rare, and glaebular haloes have only been noticed around calcrete nodules at the very earliest stages of development. Papules have not yet been recorded from southern African calcretes, although Reeves (1976) describes them as "common in young to mature caliche profiles" and they may have been missed. Calcrete nodules appear to form only in soils of mixed texture and grow larger and more numerous until what is here described as a nodular calcrete is formed. Thicknesses seldom exceed about 3–5 metres, although nodular calcretes up to 13 metres thick are known on the Springbok Flats north of Pretoria (Wagner, 1927). Nodules greater than about 60 mm in diameter are rare because adjoining nodules tend to touch and to become cemented into a honeycomb calcrete before they reach this size.

Glaebular calcretes correspond to Bretz and Horberg's (1949) nodular caliches, Wilbert's (1962) "encroûtement granulaire ou nodulaire" (granular or nodular encrustation) and Durand's (1963) "nodules pulverulents" (pulverulent nodules).

They could be K1, K2 or K3 horizons according to Gile *et al.* (1965) K horizon concept, but are all Stage III

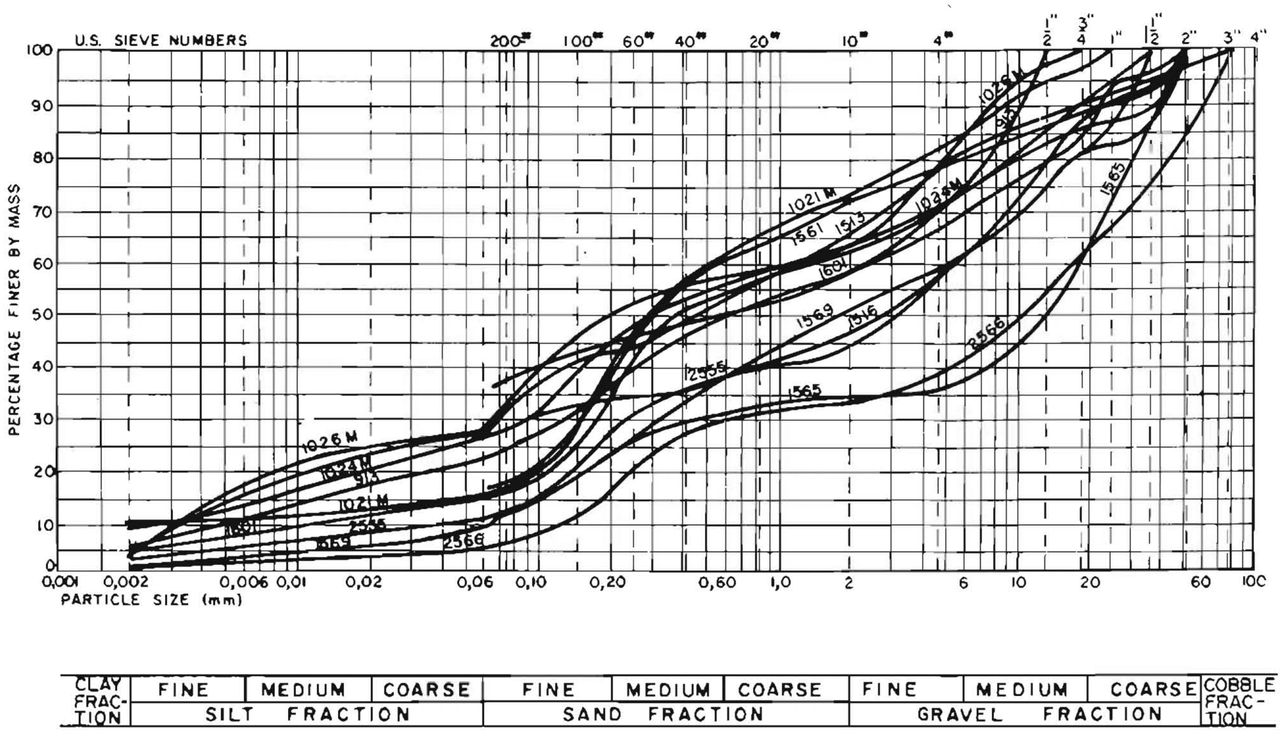


Figure 13
Particle-size distributions of some nodular calcretes from South and South West Africa

materials according to their (1966) sequence of development. Gillette's (1934) classification does not include an adequate niche for this type of calcrete, undoubtedly the most important variety from the roadmaking point of view. They would probably be called nonindurated nodular (or cylindroidal, concretionary, etc.) strong ca horizons according to Gile's (1961) classification. Glaebular calcretes fall into Price's (1933) category of "young caliches", Reeves's (1970, 1976) "mature", and Chapman's (1974 *in* Reeves, 1976) "immature". Botryoidal calcrete nodules would correspond with Durand's (1963) "nodules concrétionnes" (solidified nodules). The "kankar" of Uppal and Singh (1958) is equivalent to calcrete nodules, but the same and similar terms are used by other authors for all varieties of calcrete. Ruellan's (1967) "amas friables" (friable lumps), "granules", "nodules" and "rognons" (kidneys) are different kinds of glaebules classified according to size, consistency, and shape, though "rognons" are larger than the largest nodules and are probably calcrete boulders or cobbles. It is not clear whether his "encroûtement nodulaire" (nodular encrustation) is equivalent to a nodular or honeycomb calcrete, or both. Nodular calcretes may be roughly equivalent to Hamrouni's (1975) "granular calcareous tuffs", soft-shelled calcrete glaebules to Kasatkin and Krasyuk's (1917, *in* Lebedeva and Ovechkin, 1975) "white eyes", and hard glaebules to Lebedeva and Ovechkin's (1975) "dolls".

E. Calcrete Pedotubules, Cutans and Other Structures

Two secondary structures which are not glaebules according to Brewer's (1964) classification, but which can probably be included under that heading for engineering purposes, are pedotubules (Figs. 14 and 15) and soluans, i.e. soluble cutans (Fig. 3). Pedotubules, which vary from a few mm to several cm in diameter, appear to be calcified stems and branches of vegetation or casts thereof, often possessing a hole, sometimes filled with organic matter, or even a root, running down the centre, but origins other than this have been suggested (e.g. Coetzee, 1975). They correspond to Dobrovol'skiy's (1961) "tubular concretions", Durand's (1963) "racines pétrifiées" (petrified

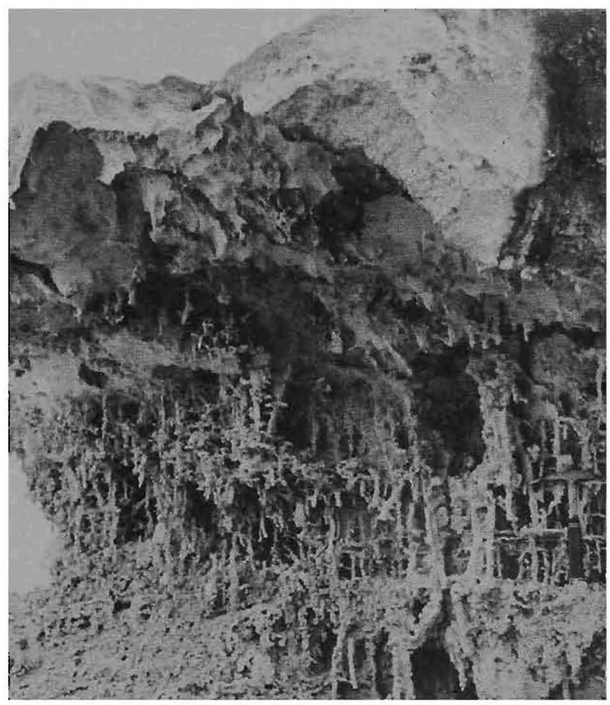


Figure 14
Pedotubules in aeolianite under hardpan calcrete at Swartklip, False Bay Coast, Cape Province.

roots) and the "rhizoconcretions" of Kent and Rogers (1947) and Reeves (1976). Such features were possibly first recorded in 1836 by Darwin (1906, p. 433) from Western Australia.

Being usually calcitic, the soluans in calcretes are usually "calcitans" according to Brewer's (1964) classification.

Crotovinas (calcified dune mole and other burrows) occur in aeolianite along the False Bay coast and Reeves (1976) has noted the occurrence of other irregularly

Figure 15
Some pedotubules from South and South West Africa.

shaped masses of calcrete in the United States. Scholz (1969) has described "Zapfenkalke" (cone calcretes) up to 500 mm long and 50 mm in diameter from South West Africa. While "calcareous cone-in-cone structures are minor features of some shales" (Pettijohn, 1957) they do not appear to have been recorded previously from calcretes. Various other forms of "carbonate secretions confined to soil animal casts and frequently having strange shapes", notably those associated with coprolites, have been described by Lebedeva and Ovechkin (1975).

F. Honecomb Calcrete

The nodules in a nodular calcrete grow larger and more numerous until they partly coalesce and/or some of the fines become cemented to form a honeycomb calcrete. Honecomb calcrete is stiff to very hard, open honeycomb-textured calcrete with the interstitial voids filled with what often appears to be the original host soil. The voids are seldom greater than about 30 mm in diameter and are interconnected in the less well-developed varieties. An example at a fairly advanced stage of development is shown in Fig. 16 and a section sawn through a sample from this horizon is shown in Fig. 17. While honeycomb and boulder calcretes can be considered as varieties of hardpan, their geotechnical properties are sufficiently different to warrant separate categories for these two materials. Although honeycomb calcretes seldom exceed about 500 mm in thickness, they are valuable materials as they can usually be ripped and grid-rolled to yield an excellent gravel road base.

Honeycomb calcretes can also form a calcified weathered rock such as is shown in Figs. 6 and 7. The honeycomb of Reeves (1976) appears to be of this type only.

Honeycomb calcretes correspond with the "honeycombed nodular calcretes" and "concretionary limestone with honeycombed texture" of Caiger (1964), working in South West Africa, and the term was first suggested to the author by him (pers. comm., 1965). They appear to correspond with the "massive honeycomb structures" of North Africa mentioned by Butzer (1963), and the "encroûtement nodulaires" (nodular incrustations) described by Ruellan (1967) from Morocco, and the "massive calcrete with honeycomb structure" of Horta (1980, Fig. 5) from Algeria, although the latter author classified his honeycomb calcrete as only sand (SE).

G. Hardpan Calcrete

A hardpan calcrete is formed when most of the larger voids in honeycomb calcretes become filled by carbonate and the host grains in calcified soils begin to float in the carbonate cement. It is a firm to very hard, often outcropping, relatively impervious, sheetlike layer of calcrete normally overlying softer or looser material (Fig. 18). The lower contact may be sharp or gradational, but the upper contact is usually relatively sharp. While individual layers of hardpan are seldom more than about 500 mm thick, caprocks several metres thick are known along the Weissrand east of Mariental and elsewhere. Occasional hard, massive, calcrete-like limestones several metres thick apparently not overlying softer or less developed material are also found. The terms "hardpan" and

0–0,40 m: Dry, brown, very stiff-hard, intact, HONEYCOMB CALCRETE.

0,40–3 m +: Dry, brown, stiff, intact, CALCIFIED sandy GRAVEL; (very hard Kuibis quartzite talus).

Figure 16
Honeycomb calcrete at an advanced stage of development exposed in a road cut at Holoog, South West Africa. In this example the soil normally filling the voids appears to have been washed out by rain.

Figure 17
Sawn section of Holoog advanced honeycomb calcrete showing previous nodular structure. Scale in cm.

"caprock" are inappropriate in such cases and such materials are possibly best described simply as massive calcretes or calcrete rock.

The weaker hardpans can be dug with a pick, and ripped and grid-rolled to yield a good gravel road base, but the harder ones must be blasted and crushed for such use.

Depending on whether they are rippable, all varieties of hardpan would fall into Gillette's (1934) "semihard" or "hard" caliche categories, while Price (1933) would probably have called all hard hardpans "old caliches" and the softer ones "mature caliches". Durand's (1963) "encroûtements" (encrustations) and Ruellan's (1967) "carapaces calcaires" appear to be equivalent to hardpan calcrete in general and Ruellan's (1967) "croûte" (crust) to a generally massive, intact, nodular, or pseudo-bedded hardpan. Hardpan calcretes in general would probably have been described by Gile (1961) as "very strong ca horizons", by Gile *et al.* (1965) as K2m horizons", by Gile *et al.* (1966) as "indurated plugged horizons", by Chapman (1974, *in* Reeves, 1976) as "mature duricrusts", by the Soil Survey Staff (1975) as "petrocalcic horizons", and by Knox (1977) as "indurated caliche" or simply as "calcrete". A hardpan calcrete overlying limestone is known as "nari" in Israel (Yaalon and Singer, 1974).

Hardpans may be intact (unbroken) and massive (structureless) or they may possess a number of mechan-

TABLE V
Classification of Hardpan Calcrete Macrostructural and Macrotextural Features According to Probable Origin

Mechanical		Chemical
Pseudo-bedding		Tufa
Inclusions		Plates
Joints		Laminae
Buckle cracks		Stalactites
Slickensides		Veins
Birdseye		Potholes
	Fractured cobbles	Channels and pipes
	Pseudo-anticlines	Miscellaneous voids
	Breccia	
Inherited	**Growth**	**Weathering**
Pseudo-bedding	Voids	Joints
Inclusions	Plates	Potholes
Buckle cracks	Laminae	Channels and pipes
Birdseye	Pseudo-anticlines	Voids
Voids	Joints	
Pipes	Slickensides	
Fractured cobbles		Veins
Pedodes		Stalactites
Tufa		Breccia

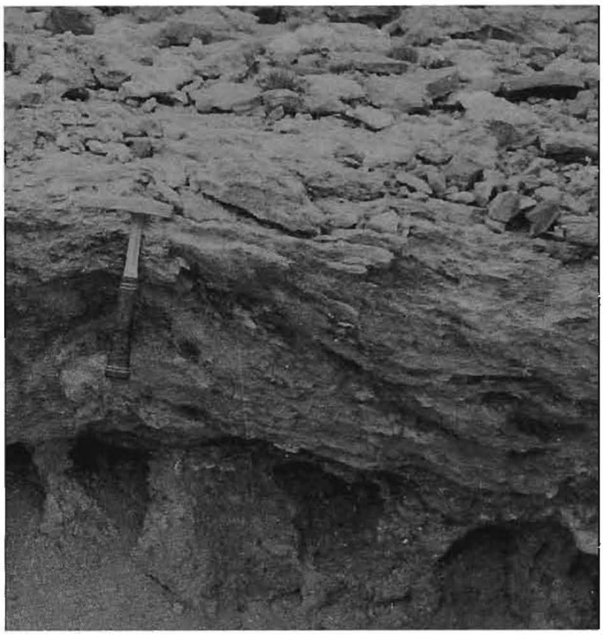
0–0,4 m: Dry, cream veined with brown, hard, intact, HARDPAN CALCRETE.

0,4–1,2 m: Dry, white, dense, faintly thinly bedded, gravelly SAND; (firm, nodular, powder calcrete).

0,4–2,0 m (not shown): Dry, reddish brown, medium dense, bedded silty SAND; (alluvial).

2,0 m + (not shown): Dry, white, hard, HARDPAN CALCRETE.

Figure 18
Intact hardpan calcrete overlying nodular powder calcrete exposed in road borrow pit at Barberspan, Transvaal.



0–0,6 m: Dry, white (weathered, reddish brown), very stiff, laminated, HARDPAN CALCRETE; hornfels fragments.

0,6–1,0 m +: Dry, white, loose, gravelly silty SAND; firm — very stiff powder calcrete with hornfels fragments.

Figure 19
Laminated hardpan calcrete overlying powder calcrete exposed in road borrow pit near Guibes on old Keetmanshoop–Aus road, South West Africa.

ical and chemical structures and textural features, either singly or in combination (Table V). Most of these have been discussed by Reeves (1976) and only those commonly found in southern Africa will be described here.

1. Pseudo-bedding

Bedding or laminae apparently inherited from the host material is occasionally found in some calcretes (Fig. 19) and is probably best described as "pseudobedding" (Reeves, 1976) or relic bedding.

The layers are usually 10–50 mm thick and are probably best described in modified sedimentological terms as follows (modified from Pettijohn, 1957, 1975):

Thinly pseudo-laminated	: <2 mm thick
Pseudo-laminated	: 2–10 mm thick
Very thinly pseudo-bedded	: 10–50 mm thick
Thinly pseudo-bedded	: 50–600 mm thick

2. Inclusions

Macroscopic inclusions in calcretes usually take the form of host gravel and sand-sized particles of quartz, rock, and relic inclusions of older, pre-existing calcretes. The original nodules can occasionally be seen in hardpans formed from nodular calcretes (cf. Fig. 17). Relic calcrete inclusions can often be distinguished from these nodules by their greater size and hardness, fewer host grains, and their concretionary appearance caused by a partial or complete laminated rind or skin (Fig. 20). As the ratio of authigenic carbonate to host material increases with growth of the calcrete, it both affords a measure of the degree of maturity and also affects the mechanical properties of the calcrete. A suitable classification of calcrete hardpans, boulders, cobbles, glaebules, honeycomb and stiff *in situ* powder calcretes is as follows:

Non-sandy (or non-gravelly)	: No grains visible to naked eye
Slightly sandy (or gravelly)	: <10 per cent grains by volume
Sandy (or gravelly)	: 10–20 per cent grains by volume
Moderately sandy (or gravelly)	: 20–40 per cent grains by volume
Very sandy (or gravelly)	: 40–60 per cent grains by volume

Figure 20
Thinly laminated calcrete rind partially enclosing a relic calcrete cobble and completely enveloping the enclosed relic fragments of older calcretes, one of which is a 30 mm thick fragment of laminated hardpan rind. Such features should not be confused with algal stromatolites, which may also be found around pans in the Kalahari (Lancaster, 1977), nor with calcrete nodules. Scale in mm.

Classification by human judgement is probably best assisted by such a three- or five-fold grouping. Alternative methods are to record the percentage of grains, the grain/cement ratio, or the cement/grain ratio. Calcified soils, powder calcretes and nodular calcretes should be described as soils. Calcretes containing many host inclusions are distinguished from the less well-developed calcified soils by their higher cement/grain ratios, greater induration, and the presence of floating grains. They usually occur as cappings to these other deposits (Fig. 21).

Inclusions of practically all sizes, apparently split apart by the growing carbonate cement, have been noted in the United States by Rothrock (1925) and Young (1964), in South Africa by Du Toit (1926, *in* Macgregor, 1930; 1954) and the author, and in South West Africa by the author.

Other inclusions in calcretes include a variety of fossils and stone artefacts (Netterberg, 1969a, c, 1974b, 1977).

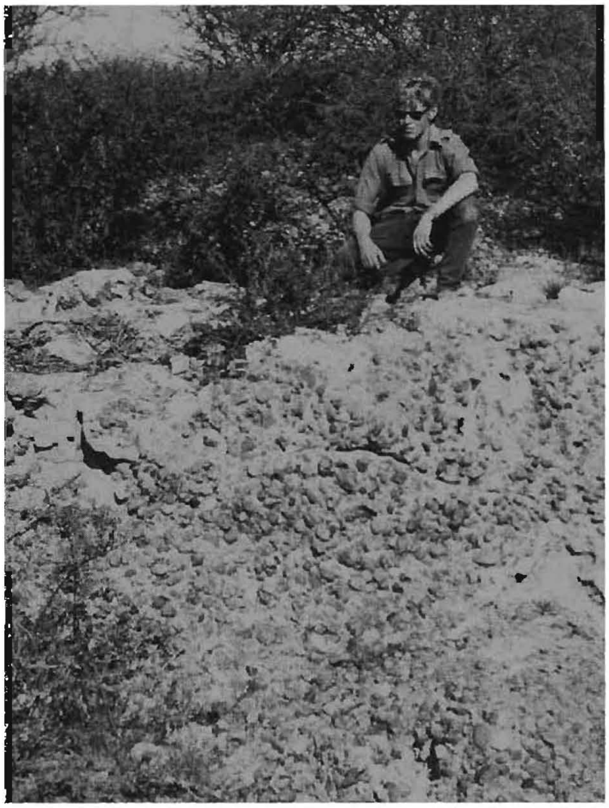


Figure 21
Very gravelly hardpan calcrete capping the calcified 60 m gravels at Suurkree, Windsorton, Cape Province.

3. Voids, Pedodes, Pipes and Birdseye

Voids of one kind or another are common in all calcretes and may even be the major component by volume of some tufaceous hardpans. Porosities of up to 75 per cent have been recorded in tufaceous hardpans, although values of 30–50 per cent are more typical. Porosities of other hardpans typically range from one to 20 per cent, the harder ones usually being below 10 per cent.

Voids possibly inherited from the parent material and which are particularly common in tufaceous hardpans include termitary-like channelling (Fig. 22) occasionally actually inhabited by termites, possible gas bubble cavities, voids possibly resulting from decayed organic matter (Fig. 22), root and reed stem-like pipes (Figs. 23 and 24), and diatom and gasteropod shells. Pedodes lined with drusy calcite or opaline silica may be present in the harder hardpans, but the quartz linings mentioned by Newbold (1844) in India and Reeves (1976) in the United States have not been recorded in southern Africa. Birdseye (Reeves, 1976) has also not yet been found here.

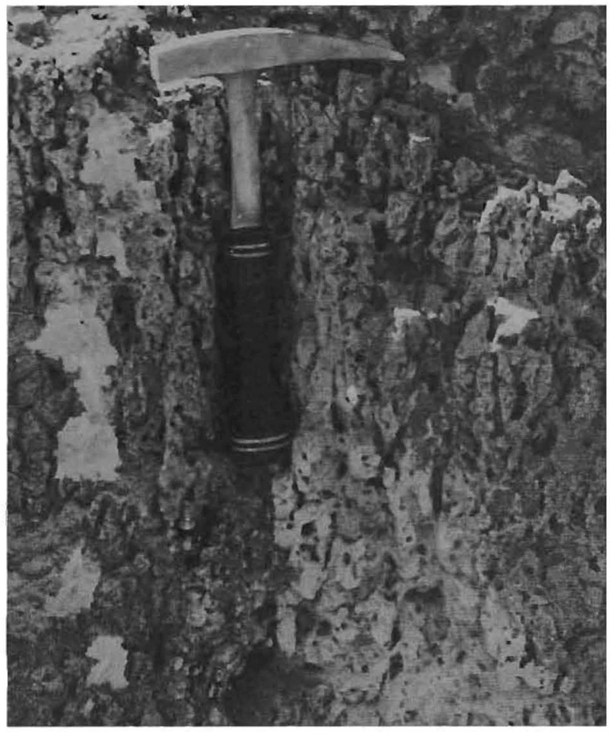


Figure 22
Tufaceous hardpan calcrete showing termitary-like channelling. The white patches to the left of the hammer indicate the colour of the fresh material. Exposure on side of road borrow pit in bank of Kansukwa Omuramba, near Runtu, Kavango, South West Africa.

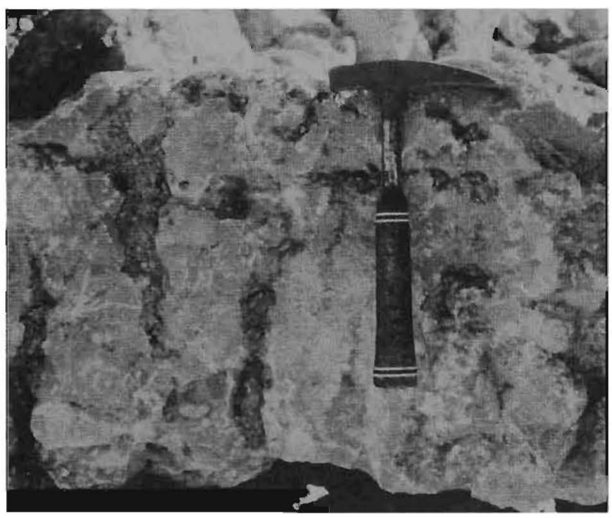


Figure 23
Side view of vertical, soil-filled, pipe-like channels penetrating hardpan calcrete ripped from road cutting at Haalenberg, between Lüderitz and Aus, South West Africa.

Small caves and burrows partly excavated and often inhabited by animals are common along calcrete scarps (Figs. 16 and 19), especially below hardpan calcretes. Those along the Auob River may be over 10 metres deep but seldom more than one metre high (Goudie, 1973).

4. Tufa

Greyish, tufaceous hardpan calcretes (Fig. 22) of low bulk density (1 000–2 000 kg/m^3), low strength and high porosity (30–75 per cent) are commonly associated with present-day and former pans, vleis, and water courses, especially in and around the area covered by the Kalahari

Figure 24
Top view of channels in Haalenberg calcrete.

Beds. Many contain "roughly vertical tubular passages largely the casts of vegetation" (Du Toit, 1954). The upper portions of tufaceous hardpans are generally denser than the lower and the surface may be coated with a very hard, impervious rind of opaline silica or laminated calcrete. The rest of the layer is seldom more than stiff in consistency. Tufaceous hardpans invariably contain fossil diatoms and gasteropods, and Rogers (1936) noted that they could be classified apart from other calcretes by the presence of fossil water snails. However, not all snail shells in such calcretes are water snails. Tufaceous hardpans should not be confused with honeycomb calcretes, nor with calcareous tufas of spring or cliff (Young, 1925; Peabody, 1954; Butzer *et al.*, 1978) origin.

Tufaceous hardpans are equivalent to the "Pfannenkalktuff" of Passarge (1904), the "vlei limestone" of Wybergh (1918, 1920), the "surface limestone tufa" of Wybergh (1919), the "diatomaceous limestones" of Kent and Rogers (1947) and probably to the "encroûtement crayeaux ou tuffeaux" (chalky or tufaceous encrustation) of Ruellan (1967) in Morocco, and to some of the "calcareous clayey tuffs" of Hamrouni (1975) in Tunisia. Thus far they do not appear to have been recorded from other than southern and northern Africa, although some of the deposits in India described by Newbold (1844) may fall into this category.

5. Plates

Platy hardpan occurs as very thin to very thick plates (Fig. 25) capping spring tufas or other calcrete hardpans. Such plates typically exhibit bifurcations, sudden terminations and highly variable attitudes, as illustrated by Knox (1977, Fig. 3.III), and Mohs hardnesses of 6 are common. This platy feature appears to be a genuine secondary structure and the plates probably merely represent thin hardpan horizons. Pedological nomenclature is therefore appropriate. That in common use in the United States and South Africa is as follows (Soil Survey Staff, 1951):

Very thin platy	: <1 mm thick
Thin platy	: 1–2 mm thick
Medium platy	: 2–5 mm thick
Thick platy	: 6–10 mm thick
Very thick platy	: >10 mm thick

The caliche plates described by Reeves (1976) and illustrated in his Figs. 3–12 represent weathered platy hardpan.

6. Laminae

A very thinly to thinly laminated, wavy rind of very hard, silicified calcrete (Fig. 26) is often found coating and sealing the surface of mature calcrete hardpans. These rinds also occur as stalactitic rinds below calcrete boulders and weathering hardpans, as veins (crack

Figure 25
Thick and very thick platy hardpan calcretes with intervening sand lenses exposed in road cutting at Saldanha Bay, Cape Province.

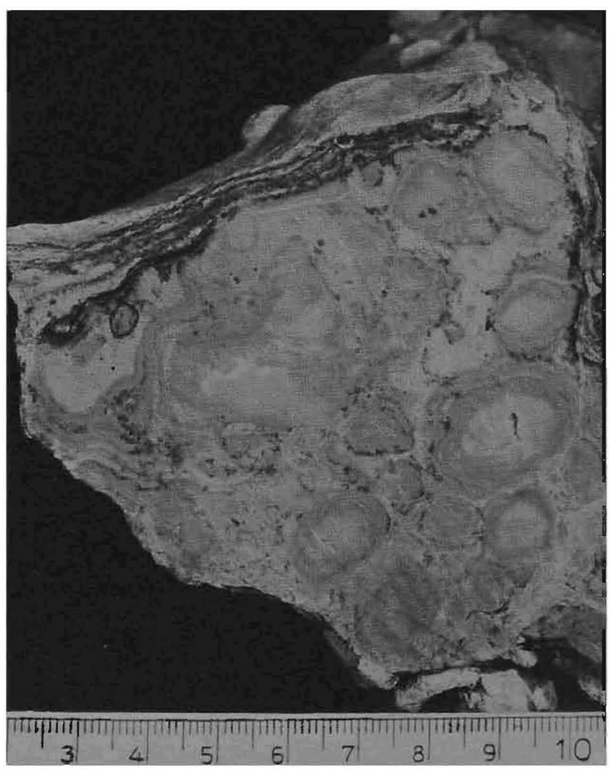


Figure 26
Laminated rind capping fragment of hardpan calcrete showing former nodular structure. Scale in cm.

fillings) and as pothole linings. Thicknesses seldom exceed 25 mm and alternating laminae of brown, reddish brown and black are common. These features are genuine secondary structures. Those coating the surface of a hardpan form "when the profile is effectively plugged to infiltrating water, thus forcing the soil water to lateral distribution" (Reeves, 1976). Some controversy exists as to whether such coatings can form under a thin soil cover or whether surface exposure is necessary. Both origins appear probable.

Such laminated rinds have been noted by, among others, Passarge (1904), Wybergh (1919), Rogers (1936), Mountain (1937) (coating basins in aeolianite), Van der Merwe (1940, 1962), Scholz (1971) and Knox (1977) in Southern Africa, Breazeale and Smith (1930), Bretz and Horberg (1949), Gile *et al.* (1966) and Reeves (1976) in the United States, Brewer and Sleeman (1964) in Australia, Charles (1949) (his "carapace zonaire" or zoned or stratified hardpan) and Durand (1963 and earlier) in Algeria (his "croûte zonaire" or stratified crust), Wilbert (1962) (his "croûte lamellaire" (or "zonaire") or lamellar crust) and Ruellan (1967) in Morocco (his "pellicle rubanèe" or thin ribboned film), Goldberg (1958, *in* Yaalon and Singer, 1974), in Israel (their "laminar nari crust"), and by Dobrovol'skiy (1961) in Kazakhstan (his "collomorphic crust-groove"). Laminated rinds are in fact extremely common in and on most hardpan calcrete horizons, and may also coat rock surfaces and fragments.

These rinds were previously thought by some authors to be algal in origin, for example Passarge's (1904) "Algenrinde", although most later authors have favoured a non-algal and completely or partly inorganic origin. The last few years have seen a revival of interest in a bacterial or algal origin (see discussion by Vaudor and Clauzon, 1976). No algal structures appear to have been confirmed from southern African calcretes, although such structures are known in what appear to be silicified calcretes at Sambio on the Okavango River (Netterberg 1974a). The Oncolites-like structures (Fig. 27) at Elandsfontein near Hopefield (Netterberg, 1969a; 1974b) may represent eroded remnants of successive rind infillings to solution hollows more or less as suggested by Butzer (1973).

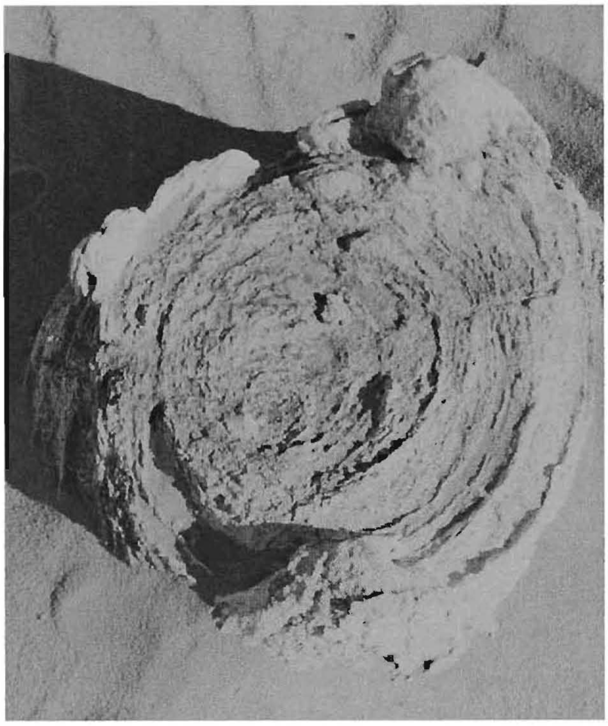
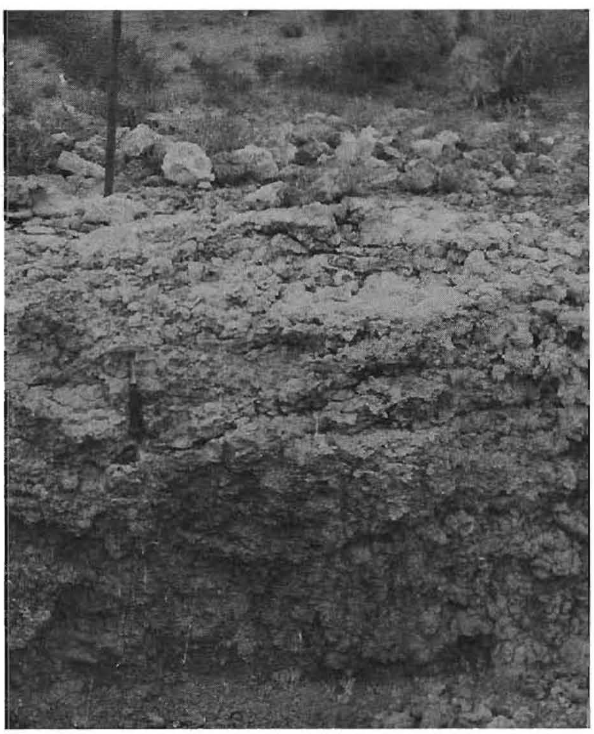


Figure 27
Pseudo-algal (?) structure in calcrete (?) exposed by deflation on the "calcrete ridge" at the Elandsfontein fossil site near Hopefield, Cape Province. Diameter approximately 350 mm.

7. Joints and Faults

Fissuring and shattering in calcretes undergoing mechanical weathering are common (Fig. 28), but it is likely that tension cracks due to deformation on crystallisation



0–1,0 to 1,3 m: Dry, white, very stiff, shattered HARDPAN CALCRETE.

1,0 to 1,3–2,0 m +: Dry, light reddish brown, medium dense, sandy fine and medium GRAVEL; light brown, firm — very stiff nodular calcrete.

Figure 28
Shattered hardpan calcrete overlying nodular calcrete exposed in road borrow pit 60 km from Rietfontein on Vanzylsrus road, Cape Province. Shattered hardpans usually possess more vertical jointing than shown here.

also occur. Roughly vertical and horizontal jointing spaced at 200–300 mm is not uncommon, but no information is available on precise spacings and orientations. Closely shattered or fissured hardpans should not be confused with calcrete nodules, cobbles or boulders, or with honeycomb calcretes, although for engineering purposes they may have to be described simply as gravel, cobbles or boulders. Buckle cracks and slickensided joints (Reeves, 1976) have not been recorded from southern Africa, but probably do exist.

Calcretes in southern Africa cut by faults have not been observed by the author. However, Schwarz (1926) stated that "the angular course of the Botletle has been caused by lines of weakness produced by faulting in the Kalahari limestone", and faults truncating calcretes in the Kwihabe Hills of Botswana have been recorded by Cook (1975). Calcretes in and on joints and faults are more common.

8. Solution Hollows and Pinnacles

Hollows varying from a few centimetres (Fig. 29) to one or two metres (Fig. 30) in diameter, separated in the more advanced stages of weathering by pinnacles (e.g. Du Toit's, 1907, Fig. 7) are common in soil-covered calcrete hardpans, especially under relatively high rainfall conditions. The sides of the hollows are generally relatively smooth and they may or may not be lined with a laminated rind. Most authors, other than Du Toit (1907, Figs. 6C and 7) and Van der Merwe (1940, 1962), agree that these features, variously termed "basins" (Mountain, 1937), "potholes" (Van der Merwe, 1940, 1962) "solution cavities" (Bretz and Horberg, 1949), "solution hollows (Van Riet Lowe, 1953), and "makondos" (Partridge and Brink, 1967) appear to owe their origin to solution rather than growth. They simply represent a stage of weathering between hardpan and boulder calcrete.

Figure 29
Small solution basins in hardpan calcrete capping aeolianite at Swartklip, False Bay coast, Cape Province.

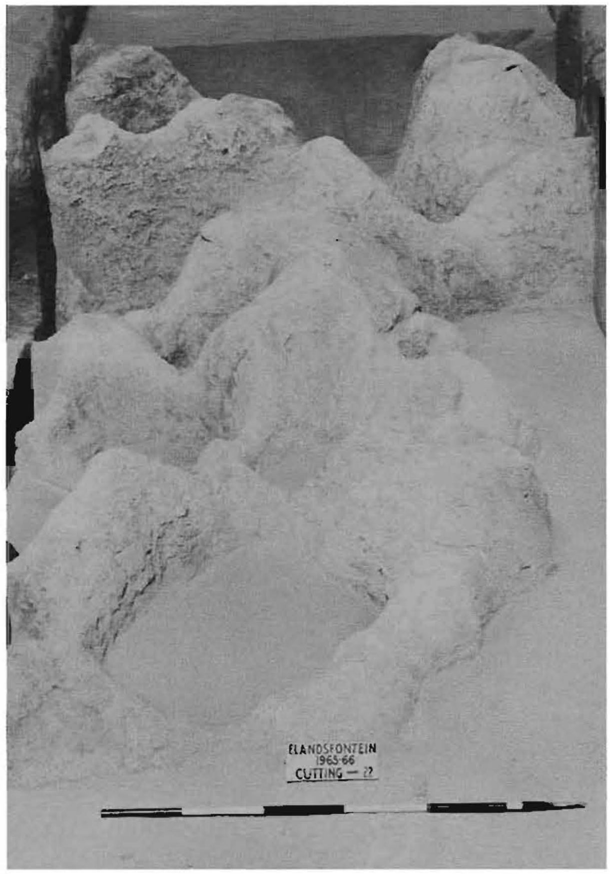


Figure 30
Large solution hollows and holes in hardpan calcrete weathering to calcrete boulders exposed in excavation on the calcrete ridge at Elandsfontein, near Hopefield, Cape Province. Scale in feet. Photo: Courtesy J. Wymer and R. Singer, University of Chicago.

Small-scale karst features of most types have been observed in calcretes.

9. Solution Channels and Pipes

Calcrete hardpans undergoing chemical weathering by solution always exhibit roughly vertical, smooth-faced channels and pipe-like features varying from a few millimetres to perhaps 500 mm in diameter which appear to represent solutionally enlarged joints and root or stem holes (Fig. 31) and solutionally deepened potholes analogous to those described in aeolianite by Coetzee (1975). These features normally completely penetrate the hardpan layer concerned. They correspond to the "soil-filled pipes" of Gile *et al.* (1966).

10. Veins, Recalcified Voids and Stalactites

Open or soil-filled voids of any type may become recalcified; thus joints may become veins (Fig. 32), solution hollows may become recalcified (Gile *et al.*, 1966; Partridge and Brink, 1967; Knox, 1977), as in Fig. 33, and carbonate may be leached from the upper parts of hardpan and boulder calcretes and deposited on their lower surfaces as stalactitic rinds (Bretz and Horberg, 1949) or pendants (Soil Survey Staff, 1975). Such features are common in hardpans which either have undergone or are undergoing solutional weathering by infiltrating meteoric waters and may lead to anomalous ^{14}C dates (Netterberg, 1978b; Netterberg and Vogel, in press).

Figure 31
Soil-filled solution channels in 350 mm thick hardpan calcrete weathering to boulders at Sambio, Kavango, South West Africa. Groove cut along Later and Middle Stone Age artefact horizon shows interface between overlying red sand of Kalahari type and intervening nodular ferricrete horizon.

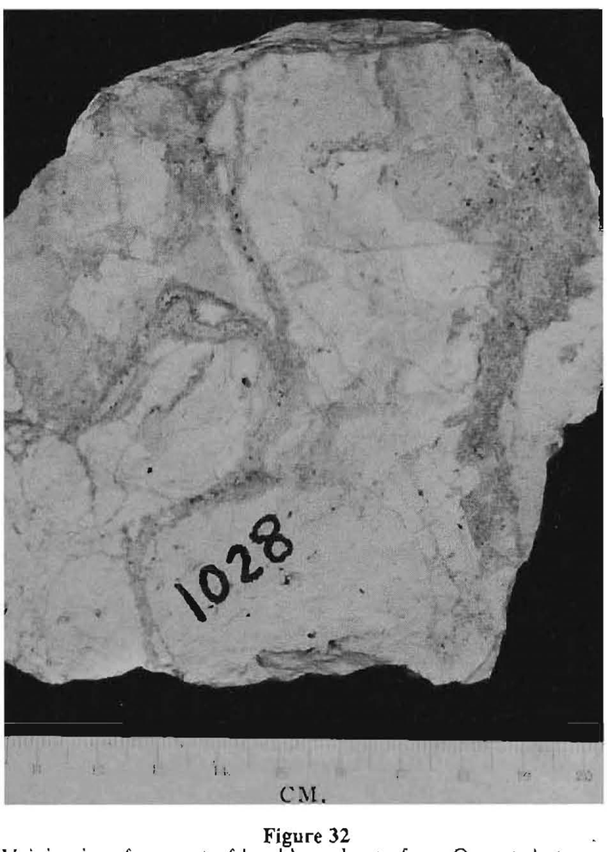


Figure 32
Veining in a fragment of boulder calcrete from Operet, between Oshivello and Tsumeb, South West Africa.

11. Breccia

Several cycles of fracturing and recementation may produce a calcrete breccia (Fig. 34), termed "Rock House structure" by Bretz and Horberg (1949). This feature is relatively rare and is usually confined to the older calcretes, although it has been noted in calcrete presumably younger than Middle to Late Pleistocene at Saldanha Bay by Knox (1977). It certainly only occurs in calcrete hardpans, boulders and cobbles. Its mode of origin was clearly recognised by Du Toit (1939, 1954).

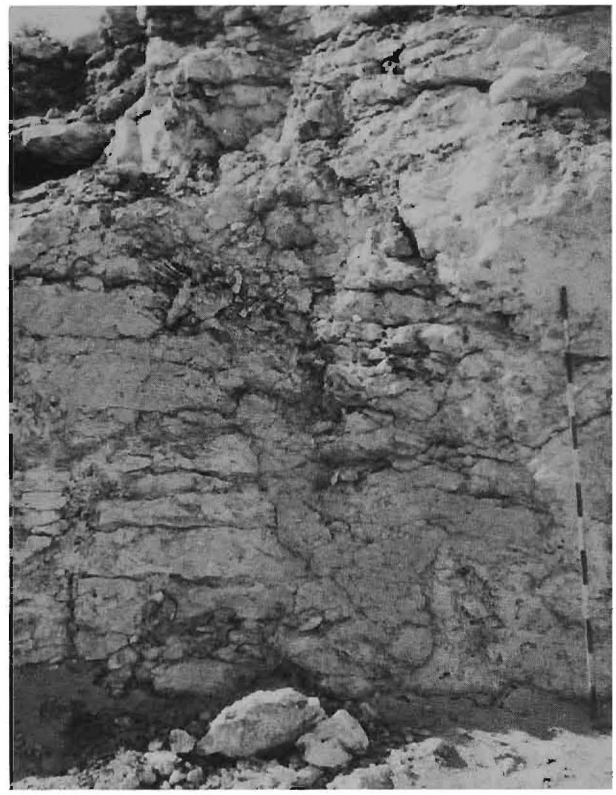


Figure 33
Recalcified burrow or solution cavity in hardpan calcrete at Lichtenburg, Transvaal. Scale in feet. Photo: Courtesy A. Albertyn, Blue Circle Cement, Johannesburg.

H. Calcrete Boulders and Cobbles

On weathering, calcrete hardpans undergo disintegration and dissolution to form discrete boulders (i.e. fragments of diameter greater than 200 mm) (Fig. 35) and then cobbles (60–200 mm) and smaller fragments as in Fig. 36. These generally hard to very hard calcretes frequently occur in an often red, sandy, non-calcareous soil matrix. When covered by soil their upper surfaces are usually smooth and rounded as in Fig. 35 and Du Toit's (1907) Fig. 6A, due to solution by infiltrating rainwater, but when cropping out they weather in the usual limestone-like fashion and fragments may be subangular, sometimes with rounded lower surfaces. Gaps between discrete boulders, or voids between incompletely separated boulders, are filled with soil and often accommodate roots or even whole trees. Such boulders have been incorrectly used (Du Toit, 1907, Figs. 6A and B) as evidence for upward calcification. Calcrete boulders and cobbles may or may not overlie another calcrete; they may occur as the only calcrete in the whole profile, especially in the higher rainfall areas.

Sizes smaller than cobbles, i.e. of a size similar to that of nodules, are also found. All these sizes, including boulders and cobbles, are frequently confused with nodules, from which they can be distinguished by their usually greater size and hardness, lower grain/matrix ratio, sharper and smoother boundaries, and a frequent partial or complete coating of laminated rind, giving them a pisolitic or concretion-like appearance, as in Fig. 20. They have seldom been distinguished from nodules in the literature and their importance as a weathering feature has generally gone unrecognised. They may become included in younger calcretes of any type, e.g. as in Rogers' (1907) Fig. 11.

Calcrete boulders and cobbles are equivalent to the boulder calcrete of Netterberg (1967, 1969a, b) and may be equivalent to Wilbert's (1962) "encroûtement à taches

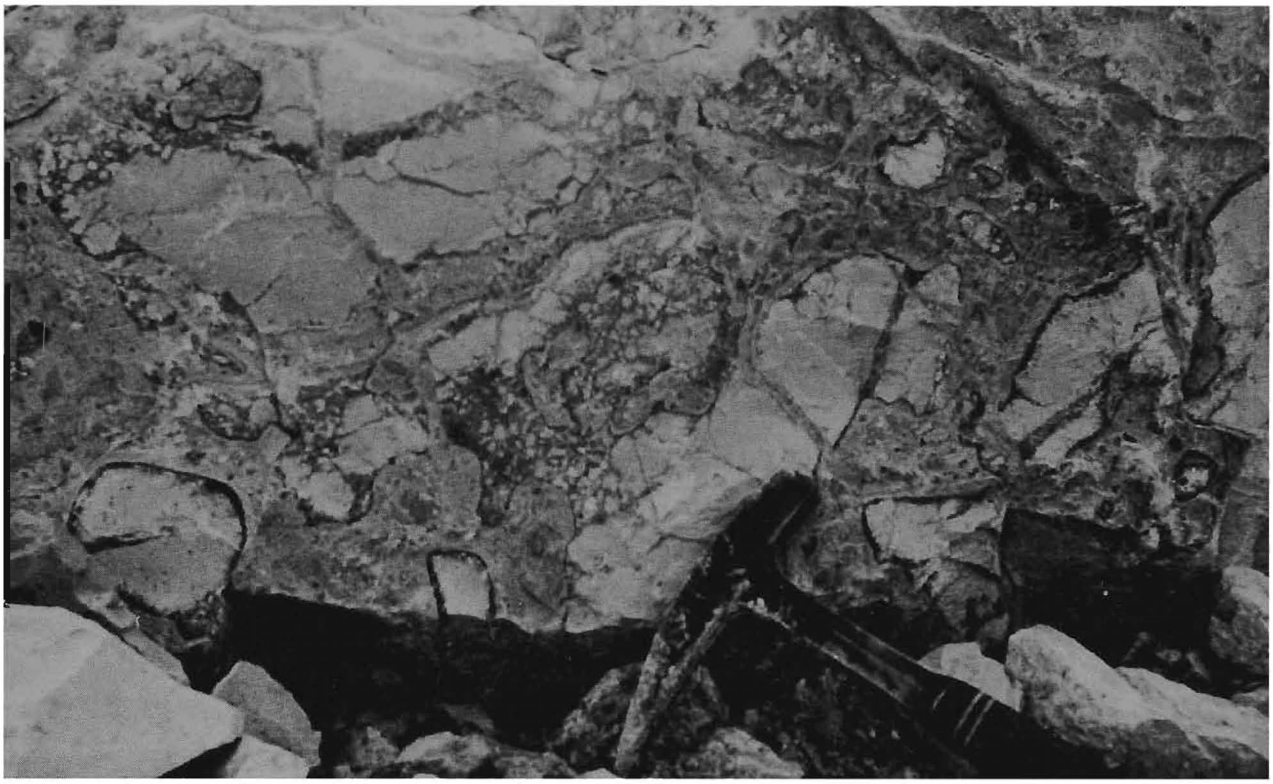


Figure 34
Brecciated, very hard hardpan calcrete exposed by blasting for road quarry near Tsumeb, South West Africa.

Figure 35
Calcrete hardpans weathering to boulders exposed in quarry near Pienaars River, Transvaal. Note rounded tops of boulders in upper boulder horizon.

Figure 36
Calcrete boulders weathering to cobbles and gravel exposed in road cutting at Saldanha Bay, Cape Province.

calcaires" (encrustation in calcareous patches), Ruellan's (1967) "rognons" (kidneys) and some of Gillette's (1934) "semi-hard" types. The upper "nodular development", "plates" and "near surface to surficial, laminated and pisolitic" young caliche shown in Reeves's (1976) Figs. 3–10A, 3–12 and 5–6 respectively, probably all represent platy cobbles, i.e. weathered hardpan, while the "pisolites" in his Fig. 3–11 probably represent cobble and smaller-sized fragments of weathered hardpan which have become more or less completely coated with a laminated rind during rotation. A horizon of weathered hardpan fragments would probably classify as a K1 horizon according to Gile *et al.* (1965). Although Horta (1980) has stated that "Boulder calcrete as defined by Netterberg (1971) does not seem to be found in North Africa", at least some of the materials shown in the upper part of his Figs. 7–10 would probably classify as calcrete boulders and cobbles, while Ruellan's (1967, 1968, 1971) "dalle compacte" (compact slab) appears to represent very hardpan calcrete weathering to slab-shaped boulders.

VI. GEOTECHNICAL PROPERTIES

The properties of calcretes will be discussed in detail in later papers, but a summary of some properties is shown in Table VI in order to illustrate the classification.

TABLE VI
Some Geotechnical Properties of Calcretes and Calcified and Calcareous Soils

Material	Total carbonate as $CaCO_3$ %	Grading modulus	AASHTO classi-fication	Extended Casagrande classifi-cation	ACV[1] %	MOHS hardness[2]	Usual overall consistency of mass	Excavation character-istics
Calcareous soil	1–10[3]?	Variable	Variable	Variable	Variable	Variable	Variable	Variable
Calcified sand	10?–50	1,5?–1,8?[5]	A-1-b to A-2-7	GP-GF? to SF-GF?	35?–55?	2–3	Medium dense — dense or firm — stiff	Bulldoze-rip
Calcified gravel	10?–50	>1,5?[5]	A-1-a to A-1-b	GW to GF?	25?–35?	2–3+?	Medium dense or very dense — firm — very stiff	Rip-blast
Powder calcrete	70–99	0,4–1,5	A-2-4 to A-7-5	ML to GF	33?–55	2–3	Loose — stiff	Bulldoze-face shovel
Glaebular calcrete	50–75	1,5–2,3	A-1-a to A-6	SF-GF to GP	20–57	2–5	Loose — medium dense	Bulldoze-face shovel
Honeycomb calcrete	70–90[4]	>2,0[5]	Rock?	Rock?	16–35	3–6	Stiff — very stiff	Rip
Hardpan calcrete	50–99	>2,0[5]	Rock?	Rock?	19–53	2–6	Stiff — very hard	Rip-blast
Calcrete boulders and cobbles	50–99[4]	3,0	Boulders	Boulders and cobbles	20–33	3,5–5	Very stiff — very hard	Rip

[1] Of the naturally occurring or crushed 9–13 mm fraction
[2] Essentially that of the carbonate cement (of glaebules in the case of powder and nodular calcretes)
[3] Up to 50 per cent when many glaebules present
[4] Without the loose soil in the large voids of honeycombs and between the fragments of boulder and cobble calcrete
[5] Not applicable unless excavated

VII. ATTITUDES, PSEUDO-ANTICLINES AND DYKES

Calcrete horizons are generally horizontal to sub-horizontal in attitude. Steep dips are rare and, soluans apart, are most frequently seen in the case of hardpans developed in aeolianite. Some appear to represent former dune configurations, while others may represent slump structures or partially eroded pseudo-anticlines. Occasional such "pseudo-anticlinal" (Price, 1925) or "expansion distortion" (Evans, 1956, *in* Reeves, 1976) structures ranging in amplitude from centimetres to metres have been recorded in Dwyka shale near Kimberley (Du Toit, 1907) and Lichtenburg (Fig. 37), and elsewhere in southern Africa (Watts, 1977; and the author), from the United States (Price, 1925; Bretz and Horberg, 1949; several authors in Reeves, 1976) and Australia (Jennings and Sweeting, 1961). Watts (1977) recognised four types according to their mode of formation. The low hummocky and ridged topography in the calcrete country between Tsumeb and Namutoni may possibly have a similar origin. The calcrete dykes and wedges (analogous to giant soluans but probably due to upward rather than downward movement of carbonate) recorded by Du Toit (1907), Winterbach and Weinert (1961) and Goudie (1973) appear to have caused the contortion of the intervening Dwyka shale by precipitation of carbonate along joints and probably classify as the Type 1 folds of Watts (1977). Such polygonal development (in plan) was evident on airphotos of the Taung area (Goudie, 1973). Contrary to a statement by Reeves (1976), pseudo-anticlines are not confined to "massive caliche profiles", but may occur in all well-developed calcrete profiles, even those containing only powder calcrete, as in Fig. 37.

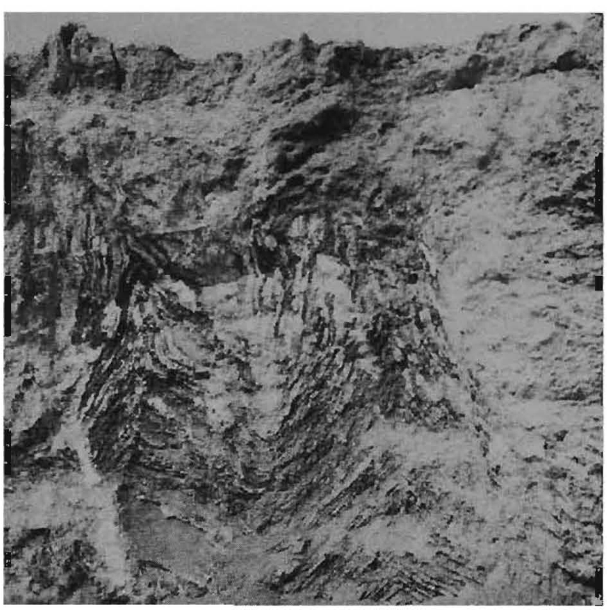


Figure 37
Powder calcrete forming pseudo-anticlines in Dwyka shale at Lichtenburg, Transvaal. Note the relatively pure powder calcrete in the synclinal troughs (Fig. 9). Cut face is approximately 4 m high. Photo: Courtesy A. Albertyn, Blue Circle Cement, Johannesburg.

On a more regional scale the lower surfaces of calcrete horizons may be less horizontal and regular than the upper. For example, the Kalahari Limestone is known to be thickest in old drainage lines, whereas the upper surface is remarkably even (Gerrard, 1965, *in* Goudie, 1973).

VIII. FURTHER CLASSIFICATION

A. By Colour, Texture, Hardness, Fracture, Crystallinity and Mineralogy

Calcrete nodules, honeycombs, hardpans, boulders and cobbles can be subdivided on the basis of their colour, texture, hardness, fracture, crystallinity and mineralogy. These are designated simply as Types 1 to 6 (Table VII).

TABLE VII
Classification of Calcretes According to Colour, Texture, Hardness, Fracture, Crystallinity, and Mineralogy

Type	Description[1]	Dominant Mineralogy
1	Usually pBr (10 YR 6/3) to Br (10 YR 5/3) dry, rarely dkGrBr (10 YR 4/2), ltR (2,5 YR 6/6) to RBr (2,5 YR 4/4) or Wh (10 YR 8/1), with a conchoidal or subconchoidal fracture and a Mohs hardness of 4 to 5. The content of sand-sized quartz grains seldom exceeds 10 % by volume. Sometimes occurs as laminated rinds, plates or veins with colours as above coating or veining other types.	Calcite and quartz, rarely dolomite
2	Wh (10 YR 8/1) or ltGr (10 YR 7/1) dry, with a usually conchoidal or subconchoidal and less often an earthy fracture, and a Mohs hardness of 2,5. No sand-sized quartz grains are visible in the hand specimen.	Dolomite, calcite, sepiolite
3	Essentially ltGR (10 YR 7/1) to Br (10 YR 5/3) when dry Type 1, speckled and banded with black manganese oxide, but almost invariably occurs encrusted by Type 4. It has a dominantly subconchoidal fracture and a Mohs hardness of 4 to 5, while the content of sand-sized quartz grains seldom exceeds 20 %.	Calcite and quartz
4	Usually ltGr (10 YR 7/1) to pBr (10 YR 6/3) dry, with an earthy to uneven fracture and a Mohs hardness of 1,5 to 3 (rarely up to 4). The content of sand-sized quartz grains varies widely.	Usually calcite and quartz, rarely dolomite and quartz. Clay content variable
5	pOl (5 Y 6/3) to ltOlBr (2,5 Y 5/4) dry, with a dominantly conchoidal fracture and a Mohs hardness of 5 to 6 (rarely up to 7). The content of sand-sized quartz grains varies widely, but is usually high (>30 %).	Dolomite, quartz and calcite
6	Mostly BrY (10 YR 6/6) to pBr (10 YR 6/3), but may be mottled with ltGr, ltBr, ltR and Wh, with or without brecciation. Subconchoidal to uneven fracture, dull to resinous lustre, and a Mohs hardness varying from 2,5 to 4. Calcite crystals up to 1 mm in size, but no clearly discernible rhombs. Sand-sized quartz grains absent.	Calcite

(1) Munsell colour notations

Types 1, 3, 4 and 5 were found to exist in nodular, honeycomb, hardpan, boulder and cobble varieties, while Type 2, which may be equivalent to Brewer and Sleemans' (1964) "papules" was only found to exist in a form which could best be described as a calcified clay. Type 6 has been observed by this author only in the form of hardpan at Lichtenburg. Type 5, some Type 2, and rare Type 4 and 1 materials are really dolocretes in that the cementing medium is mainly dolomite.

Types 1 and 5 are readily distinguished by their colour, while the manganiferous, black, speckled and/or dendritic nature of Type 3 (Fig. 38) is the main diagnostic feature of this type.

Figure 38
Type 3 advanced honeycomb calcrete. Scale in cm.

Non-sandy varieties of Type 4 can usually be distinguished from Type 2 by their fracture and colour. Type 6 is the only type which is crystalline to the naked eye, or even under a hand lens. Its granular appearance and colour closely resembling that of lumps of "government" (slightly sticky, light brown, incompletely refined) sugar is also characteristic.

Types 1 and 4 are by far the most common, followed by Type 3. Types 2, 5 and 6 are rare.

B. By Dolomite Content

Bissell and Chilingar's (1967) recommended compositional classification of carbonate rocks based on that of Cayeaux can be readily adapted for use on calcretes (Table VIII). On this basis most calcretes would probably classify as magnesian or dolomitic calcretes. While other compositional classifications of limestones such as those of Leighton and Pendexter (1962, *in* Burnett, 1979),

TABLE VIII
Classification of Calcretes by Dolomite Content

Suggested term	% Dolomite by mass of total carbonates	Aprox. equivalent % $MgCO_3$[1]
Calcrete	<5	<2
Magnesian calcrete	5–10	2–5
Dolomitic calcrete	10–50	5–25
Calcitic dolocrete	50–90	25–40
Dolocrete	>90	>40

(1) $\% \, MgCO_3 = \dfrac{MgCO_3}{MgCO_3 + CaCO_3} \times 100$

Fookes and Higginbottom (1975) and Burnett (1979) can similarly and usefully be applied to calcretes, most textural limestone classifications are not so suitable for calcretes as they are intended for marine rocks.

Terms like "calcrete" and "calcified" will be used somewhat loosely in subsequent papers and include all compositional types unless specifically stated otherwise.

C. By Origin

The origin of calcretes will be discussed in detail in a later paper, but it would appear that calcretes can be clas-

sified by their origin into two main types, groundwater and pedogenic, which may be defined briefly as follows:
1. groundwater or non-pedogenic calcretes are formed by the precipitation of carbonate in a host soil above a perched or permanent groundwater table.
2. pedogenic calcretes are formed by the downward leaching of carbonate from the upper soil horizons by infiltrating meteoric waters, which transport it in solution to lower horizons where it is precipitated.

Fluvial and lacustrine origins have been proposed for some calcretes, but the author favours the application of the term "calcrete" only to authigenic soil carbonates, i.e. deposits formed within a soil, and the exclusion of other than minor contributions by other processes.

D. By Occurrence

Scholz (1971) has classified the calcretes of South West Africa according to their mode of occurrence as follows:
1. "surface calcretes;
2. calcretes within the soil;
3. calcretes as sintric deposits;
4. calcretes on banks of rivers and depressions;
5. calcretes on geological faults;
6. calcretes on lacustrine sediments;
7. calcretes on dune sands".

The mode of occurrence and distribution of calcretes within southern Africa will be discussed in a later paper.

E. By Age

As a calcrete is not the result of a discrete event, carbonate of many different ages may be present, and included fossils and stone artefacts provide only maximum ages. Moreover, as the application of radiometric methods to calcretes is in its infancy, the absolute ages of these deposits remain uncertain. However, the maximum probable ages of southern African calcretes can be divided into five categories (Netterberg, 1969c):
1. pre-Pliocene;
2. Pliocene;
3. calcretes containing Later Acheulian stone artefacts (Middle Pleistocene?);
4. calcretes containing Later Middle Stone Age artefacts (Upper Pleistocene);
5. Recent.

Apart from the probably Pliocene Kalahari Limestone, calcretes containing Later Middle Stone Age artefacts, i.e. those classified as (4) above, are particularly common. The correlation and dating of calcretes has been discussed by Netterberg (1978b).

F. By Maturity and Stage of Development

Starting with Price (1933), a number of workers have attempted to classify calcretes according to their degree of maturity or stage of development. Considerable disagreement is evident over what, for example, constitutes a "young" and a "mature" calcrete, and it is probably more useful to classify according to clearly recognisable stages of development as has been done here. In terms of maturity, the author regards Stages 1 to 3 in Table IV as representing immature forms, hardpan (Stage 4) as representing mature calcrete, and boulders and cobbles (Stage 5) as representing senile forms.

The varieties of calcrete listed in Table IV represent single-phase calcretes, i.e. they were formed by one phase of calcification. Multiphase calcrete profiles owing their origin to a number of phases of calcification, possibly interspersed with phases of weathering, are not rare and may present considerably more complicated profiles than are illustrated and described in this paper. However, the distinct stages listed in Table IV can usually still be recognised.

IX. CLASSIFICATION FOR GEOTECHNICAL USE

Much of the foregoing is of scientific interest only, and for most engineering purposes classification into calcareous soils, calcified soils, powder calcrete (plus perhaps nodular powder), nodular calcrete, honeycomb calcrete, hardpan calcrete, and calcrete boulders and cobbles is probably sufficient. Description as an engineering material by, for example, the method of Jennings *et al.* (1973), and classification by the AASHTO and/or Unified methods is of course also necessary.

Further classification may also be attempted when necessary. For example, Type 6 calcretes and dolocretes are usually saline, a factor of considerable importance in roadbuilding, while groundwater calcretes are likely to be thicker and more consistent in quality than pedogenic calcretes.

X. CLASSIFICATION FOR STRATIGRAPHIC STUDIES

Calcretes possess some, albeit limited (Netterberg, 1969c; 1978b), stratigraphic value and the classification outlined should prove useful in such studies. A classification strongly influenced by the work of Firman (summarised in Firman, 1979), and based chiefly upon the superficial deposit in which the carbonate occurs, chronology, soil stratigraphic unit (pedoderm), form and amount of carbonate, texture, and the type of boundary with the overlying layer was used for this purpose by Wetherby and Oades (1975) to divide the carbonate horizons of the northern Murray Mallee area of South Australia into six classes.

XI. CLASSIFICATION FOR LAND USE

The form and composition of the calcrete present have a decisive influence on the types of natural vegetation as well as the types of crops which can be grown and the soil preparation necessary (various authors in Goudie, 1973; Reeves, 1976; Wetherby and Oades, 1975). In addition, the material may have uses as a source of construction material in the road, railway and building industry (Netterberg, 1969a; Goudie, 1973; Reeves, 1976), a source of limestone in the cement, lime, sugar (Reeves, 1976), iron and possibly other (Reeves, 1976) industries, a source of groundwater (Netterberg, 1969a; Goudie, 1973; Reeves, 1976; Firman, 1979) and as a source of uranium (Reeves, 1976; Carlisle, 1978, 1980), while the variable and/or karstic nature of some calcrete profiles and the presence of loose material below some thin hardpans must be taken into account when designing foundations for structures (Netterberg, 1969a). All this requires that the presence, variety and composition of any calcrete horizons present be considered in land use planning. No single classification is likely to be completely adequate for this purpose. However, the one presented will serve as an excellent basis for additions according to the requirements of each potential use. A similar type of classification has been applied to agricultural land use planning in South Australia by Wetherby and Oades (1975) and Firman (1979).

XII. CLASSIFICATION FOR URANIUM PROSPECTING

Not all calcretes are likely to possess appreciable uranium contents. Those non-pedogenic calcretes formed by lateral and capillary transport have the greatest potential (Carlisle, 1978, 1980) (Fig. 39).

XIII. CONCLUSIONS

Previous classifications of calcretes have generally been inadequate for most engineering geological purposes. However, such carbonate segregations within the soil profile exhibit sufficiently regular and consistent morpholo-

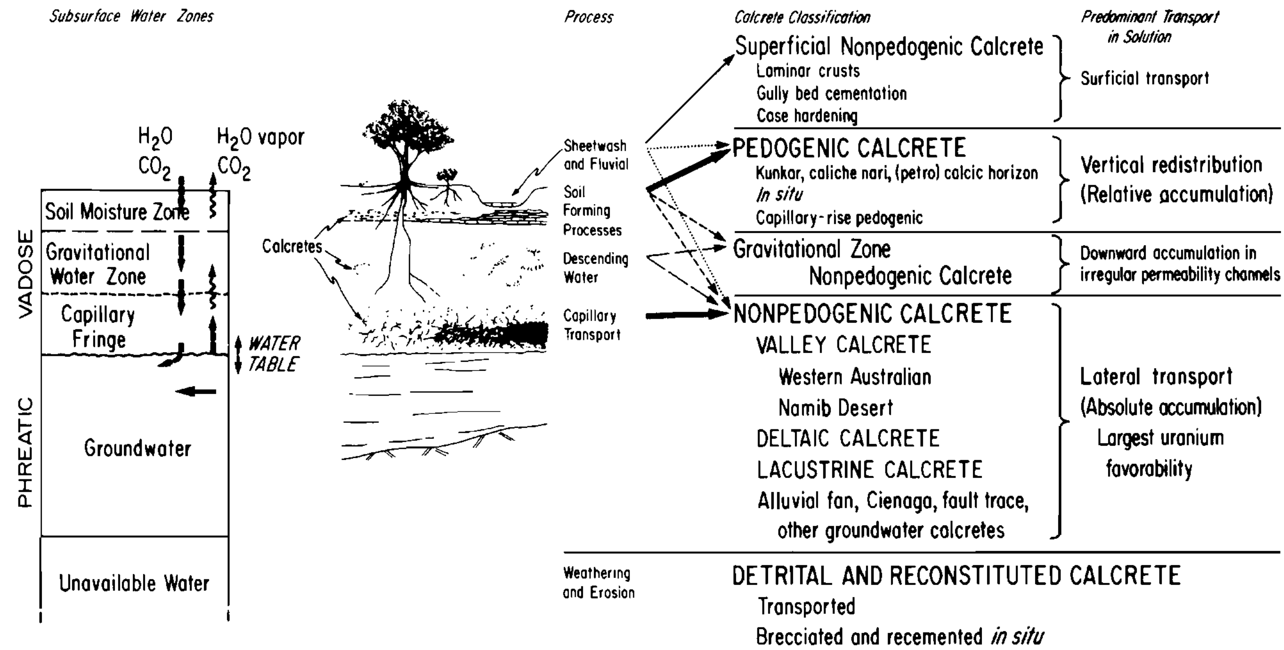


Figure 39
A genetic classification of calcretes and their uranium favourability after Carlisle (1980). Figure: Courtesy D. Carlisle, University of California, Los Angeles.

gies to render them amenable to classification according to their secondary (chemical) structures and other features. On this basis such materials can be simply classified for most geological purposes into calcareous soils, calcified soils, glaebular calcretes, calcrete cutans, calcrete pedotubules, honeycomb calcretes, hardpan calcretes, and calcrete boulders and cobbles. Each such major variety possesses a significantly different range of geotechnical properties, is easily recognised in the field, and also represents a particular stage of calcrete development. The typical mature calcrete profile consists of a hardpan horizon capping a less mature variety, while boulders and cobbles represent weathered hardpan fragments. A number of morphological and macrostructural and textural features can be recognised within each variety which are largely of geological interest, while for geotechnical and other purposes standard soil and rock classification systems can be applied with but minor modifications to a slightly simplified system.

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