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THE LOCATION, SELECTION AND USE OF CALCRETE FOR BITUMINOUS ROAD CONSTRUCTION IN BOTSWANA

by

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ABSTRACT

A long term project has been undertaken to specify the use of calcrete for road construction in Botswana, under different conditions of environment, road design and traffic. Calcrete is a rubbly or powdery calcareous material that occurs within the Kalahari sand, in association with a number of distinct landforms. Research has focused upon the distribution of calcretes and the possible use of soft types for highway engineering. This report describes the aims of the project, concentrating on the survey and mapping aspects.

The mapping study compared different remote sensing techniques to identify calcrete landforms in a corridor between Jwaneng and Ghanzi (17,000 sq km), considered to be typical of southern Botswana. Test strips of colour and multi-spectral small format aerial photography were specially flown, but it was found that the full range of calcrete landforms can be identified using standard black and white aerial photographs, which provide good detail and a stereoscopic view, and Landsat imagery, which gives good colour differentiation, especially when digital images are enhanced by computer.

The engineering properties of calcrete were studied in the laboratory and on site. It is recommended that grading, hardness and plasticity are measured in the field as an initial assessment of quality. A full scale road experiment, constructed using a range of calcretes, including soft types, has successfully carried more than 100,000 equivalent standard axles of traffic, and has been used to establish a new specification for sealed calcrete bases in lightly trafficked roads.

Recommendations are given for planning calcrete surveys, and a map showing potential sources of calcrete in the project area is included.

1. INTRODUCTION

1.1 *Background*

Botswana is a country more than 700,000 km^2 in area, three quarters of which is covered by the sands of the Kalahari desert on the western side. The Kalahari region is dry, sparsely populated, and has undergone little development. In recent years attention has been given to the need to improve road communications between the more developed eastern part of the country where the main towns occur, and the west which is an important cattle farming area, as well as the possibility of constructing road links with Namibia and the Atlantic coast. The existing road across Botswana runs from Kanye to Ghanzi (Fig. 1), a distance of 550 km, consisting mainly of a sand track which is very loose and difficult to drive on. The Botswana government decided to upgrade this route as a first step towards improving the road network within the Kalahari region as a whole. However, a problem was encountered in the design of the road pavement, because no conventional road construction materials exist in the area, and calcretes, which occur regularly along the line of the road, are apparently of too poor quality to be used in construction.

Calcrete is a gravelly or powdery calcareous material that occurs within the Kalahari sand. Apart from a few isolated and scattered outcrops of rock protruding through the sand, calcrete is the only source of road construction material in the Kalahari region of Botswana. Problems in its use arise from the fact that soft calcretes can make satisfactory road bases under appropriate conditions of design, construction, climate and traffic, even though few of them meet existing specifications. Powder calcrete can be compacted into a strong road base that retains its density and strength provided it is sealed. Hard forms of calcrete are well known as good materials for road construction, but they are relatively scarce in the central Kalahari. Soft calcretes are far more abundant, but prior to this project the circumstances under which soft calcretes can be used had not been defined. There were indications that a lower specification could be acceptable for roads carrying relatively little traffic, thereby allowing many more powder calcretes to be used in their construction. However the degree to which the existing specification could be relaxed was not known.

Tests by the Ministry of Works and Communications on samples of material taken along the line of the Kanye–Ghanzi road showed that most of the calcretes are too poorly graded and/or too plastic to meet the Botswana specification for natural materials used as road bases under a bituminous seal (Ministry of Works and Communications 1976), or as gravel surfacings for unpaved roads. The specification is intended for design traffic levels of up to 0.8 million equivalent standard axles over a ten year design life, the normal life expectancy of a road in Botswana before upgrading is required. The specification is derived from South African practice, where strict control of plasticity, grading, CBR and aggregate hardness is applied (National Institute for Transport and Road Research 1980a; 1980b), and is suitable for roads in the populous east of Botswana but not for the Kalahari region where traffic volumes as low as 0.1 million standard axles are expected over the design life.

A lower specification for smaller traffic volumes, also originating in South Africa (Netterberg 1971), has recently been adopted by the MOWC (Ministry of Works and Communications 1982), but this is intended for design traffic levels of up to 0.2 million standard axles, which was still felt to be too stringent for Kalahari routes.

It was considered that by introducing a specification for sealed calcrete roads taking up to 0.1 million standard axles over a ten year design life, many more of the calcretes occurring near the line of the new Kanye–Ghanzi road would be admitted into the specification, and the cost of this and other roads in the Kalahari region would be substantially reduced. In addition, the reduced costs of maintenance and vehicle operation on a sealed road would significantly reduce the total cost of the road over its design life.

1.2 *TRRL programme of research into calcretes*

The Botswana Ministry of Works and Communications invited TRRL to compile an inventory of calcrete deposits over the route corridor between Jwaneng and Ghanzi, and to assess their properties as road making materials. Recommendations were also sought for an alignment and pavement design for the new road. In response to the Ministry's requests, TRRL carried out a research project that was concerned with the field occurrence of calcretes as well as their engineering properties, under the following headings.

1) Mapping calcrete resources.

To test the use of remote sensing techniques in mapping calcretes, as a means of assessing calcrete resources within large areas.

Remote sensing is the science of acquiring information about an object by the analysis of data collected from a distance, using a sensing instrument carried in an aircraft or satellite. Remote sensing is considered to be important in locating calcrete deposits because the flatness of the Kalahari landscape and the presence of vegetation make the finding of calcrete by field methods alone extremely difficult. Also vehicular access for site investigation is made difficult by the limited road network, and the loose sand surface and dense vegetation in open ground.

The principal aim of the remote sensing study was to determine which of several remote sensing techniques is most effective in detecting calcrete-bearing landforms. The intention was also to find out whether remote sensing could be used to identify different types of calcrete, from which better-quality calcretes could be selected.

2) Engineering evaluation of calcretes.
To determine which engineering properties of calcretes, as measured in the field or laboratory, can be used to predict their behaviour in a road.

3) Specification and use of calcretes.
To study the performance of different types of calcrete under known traffic conditions, from which a minimum specification for calcrete could be derived.

a) The study concentrated on the performance of calcretes in sealed road bases, and involved the construction of a 1.2 km section of experimental road incorporating four different types of calcrete, representative of the route corridor as a whole. A summary of the experiment is given in Appendix 1.

b) A further aspect of the research project has been to establish guidelines for the selection and testing of calcretes that are to be used as gravel surfacings, using data collected from fifteen 1 kilometre test sections established on gravel roads around Botswana.

As a result of the performance of the full scale experiment so far, TRRL has recommended a new specification for calcrete bases carrying up to 100,000 equivalent standard axles, that has been incorporated into the most recent edition of the Botswana Road Design Manual (Ministry of Works and Communications 1982). The findings of the research have also been used as the basis of two reports submitted to the MOWC (Newill and Toole 1982, Toole 1982), giving recommendations for the road alignment and pavement design between Sekoma and Ghanzi. The chosen alignment takes account of the availability and quality of materials, forecast traffic levels, and estimated construction costs.

This report summarises TRRL work to date under research headings (1) and (2) above, ie the location and engineering evaluation of calcretes. Recommendations to engineers for carrying out surveys of calcrete deposits, for selecting materials, and for estimating reserves within a region are given at the end of the report.

2. STUDY AREA

The study area was selected to take in the existing road from Jwaneng in the south east to the Okwa River in the north (Fig. 1). It includes large areas to the north and west of the present road, where obvious possibilities for alternative alignments exist. The total area covered in the study is approximately 17,000 km^2.

2.1 *Terrain and environment*

The area lies entirely within the region of Kalahari sand, whose thickness varies between more than 50 m around Kang to zero at the Okwa Valley (Geological Survey Department 1979). The sand is underlain by Precambrian rocks, granitic in nature in the north and sedimentary in the south. The prominent outcrops of quartzite and conglomerate that occur in the vicinity of Jwaneng reappear sporadically at least as far west as Kokong, but no outcrops are known further north between Kokong and the Okwa Valley (Mallick, Habgood and Skinner 1979).

The rainfall ranges from 400 to 450 mm p.a. from north to south, falling in a seasonal but highly variable and unreliable manner. For this reason the vegetation is more sparse than might be expected (Plate 1). Grasslands predominate in the south, where the plains are relieved by isolated patches of Acacia shrubs and low trees. Further north, around Kang and Lone Tree, the shrub and tree cover increases to a maximum ground cover of 65 per cent. Around Takatshwanne patches of grassland and shrub savanna are intermingled in an irregular pattern. Trees and large Acacia shrubs are largely absent from pans and depressions, which are colonized instead by grasses and low shrubs, or may even be devoid of vegetation in the centre. These plant communities contrast with the grasslands and shrublands of the surrounding plains, enabling pans and depressions to be picked out easily in aerial photographs and satellite images.

The Kalahari sands of the study area fall into two natural terrain regions that appear very different in small scale aerial and space images (Fig. 1; Plates 1, 2 and 3). The region between Jwaneng and Kang is occupied by an undulating sand plain lacking any regular dune features, but rippled and pockmarked over most of its surface. It is thought that the swells and hollows are the remnants of a low dune system, oriented in a south or south-westerly direction. The former dune pattern is now only discernible on Landsat images as sub-parallel "swarms" of grey sand areas. The linear arrangement is not detectable on the ground. The well-known Kalahari pans which are a major source of calcrete occur randomly throughout the region, in groups or singly. Parts of the plain, such as the area between Jwaneng and Sekoma, are practically featureless, almost devoid of pans or hollows.

In contrast, the sand plain to the north of Kang has been worked into a regular series of longitudinal sand dunes, now subdued by erosion and stabilized by vegetation. The interdune hollows, spaced at 2–3 km intervals, contain elongated pans and calcareous grey sands. The shape of the pans is in strong contrast to the typically circular pans of the plains to the south.

In the northern part of the region the dune sands are very thin, allowing the underlying ancient river system to show through in the vicinity of the Okwa and Hanahai rivers. Within these valleys layers of hard calcrete may be found on the valley sides and also as terrace deposits just above the valley floor. The tributaries of the Okwa are traceable to the south west until eventually they are submerged by the sand cover. The river systems can be traced by lines of pans in the interdune hollows at the point of intersection of the river course with the hollow (Plate 3).

Traces of ancient valley forms also exist in a few places between Jwaneng and Sekoma. They are filled with deep sand and are broader and much less distinct than those to the north. The most obvious is the Naledi Valley, running north west through Jwaneng, from which calcrete used in the construction of the TRRL full scale experiment was extracted. Some 30 km to the west a much less obvious valley runs towards Sedikane, which yielded gravel for the Jwaneng-Sekoma road. These valleys are difficult to distinguish on the ground but are evident in Landsat imagery.

3. DESCRIPTION AND CLASSIFICATION OF CALCRETE-BEARING LANDFORMS

A number of authors (Goudie 1973, in Reeves 1975) have classified calcretes on morphological or genetic characteristics. The classifications reflect the range of types within the locality studied, and the purpose of the classification.

Although there are obvious similarities between the types of calcrete described, no definitive classification has emerged, because calcrete is an inherently variable material, and between all well-defined types there exist innumerable intergrades, making classification difficult. For example, different types of calcrete are frequently found within a profile in distinct horizons, although not always in the same order. The composition and plasticity of the fines (material smaller than 0.425 mm) can vary considerably, as can the degree of calcification. The calcification process may reach such a stage that a strongly-cemented nodular horizon assumes the characteristics of hardpan calcrete. Another form of variation is in the thickness of the material itself. Calcrete profiles can vary in thickness from a few centimetres to more than two metres, and the material can occur at the surface or may lie buried beneath an overburden of sand at a depth of many metres.

A simple morphological classification was adopted for the TRRL study, that expresses the range of calcretes found within the study area. Four types were recognised that relate to South African groupings (Netterberg 1971, 1980), and which are distinct both physically and in their engineering properties. They are calcified (or calcareous) sand, powder calcrete, hardpan calcrete (including "boulder" calcrete) and nodular calcrete, and are described in Appendix 2. Most of the calcretes are soft enough en masse to be fairly easily excavated with a geological hammer, although many contain indurated layers of dense powder or hardpan calcrete up to 30 cm thick. Some of the boulder calcretes are hard enough to be usable as a crushed stone base or surface dressing aggregate, and in parts of northern Botswana they can occur in sufficient quantities to be economically workable for this purpose. In the project area very hard calcretes are almost absent, although thin outcrops occur along the valley of the dry Okwa River.

3.1 *Classification of calcrete-bearing landforms*

Calcrete is associated with a number of distinct landform features such as inter-dune hollows, old river channels, topographic depressions and the very distinctive low-lying pans of the Kalahari landscape. Only in a very few cases has calcrete not been found in association with these features. This important circumstance has enabled remote sensing images to be used effectively in mapping calcretes.

Before carrying out the mapping it was first necessary to produce a classification of calcrete-bearing land surface features that a) reflected as well as possible the type and quantity of calcrete that lies beneath, and b) were visible in aerial photographs and satellite images. The classification is based primarily upon the landforms that are known to be the chief sources of the material, but attempts were made to refine the classification by incorporating more detailed surface features, as follows. Their relevance was tested during the field survey.

- size of topographic feature
- shape as seen from the air
- cross sectional profile
- presence of a dune. (A crescent-shaped sand dune is very commonly present around the southern margin of larger pans)
- presence of a "platform". (The term "platform" has been applied to the low terrace that occurs round the rim of many pans, raised one or two metres above the level of the floor (Plate 4). The platform is often relatively small in extent, existing as a narrow crescent at one point on the edge of a pan. It rarely encircles the whole pan.)
- type and extent of vegetative cover
- sand colour
- association between small features and large ones, eg the occurrence of a small pan within a valley.

Intensive field work showed that a large degree of inconsistency exists between topographic features and the amount and type of any calcrete that may lie beneath. Of the features listed above, those that consistently indicate the presence of good quality calcrete are the size of a pan and the presence of a platform. The platform is the most reliable indicator of an abundant supply of fairly hard calcrete.

Vegetation and sand colour were considered for inclusion in the classification, because they indicate the presence of calcrete at depth and can be detected in aerial and space images. The neutral grey tone of the grey sands is easily distinguishable in colour images from the red or brownish hues of surrounding non-calcareous sands. Vegetation was considered because of the attraction that calcareous soils have for certain species of plants (Netterberg 1978a). But vegetation eventually had to be excluded because it was found that plants are an insufficiently reliable indicator of calcrete to justify the flying of large scale aerial photography that would be necessary for the identification of the plant communities. Moreover, species that are indicative of calcrete change from region to region, making generalisation difficult. Also, in this study it was not possible to evaluate the influence that the season of the year may have on the contribution that plants could make in picking out calcrete-rich areas. The assistance that calcrete-loving plants can give to calcrete surveys is at present restricted to indicating better sampling sites to teams in the field.

The following simple classification system was finally adopted for practical mapping purposes, based on landform type, size, and the presence or absence of a platform.

1) Pans, 500 m or more across, with a platform (Plates 4, 7 and 8). The coincidence of a large, well-developed pan and a platform gives a virtual certainty of finding large quantities of calcrete of reasonable quality. Calcrete taken from elsewhere in the pan is likely to be too soft or too plastic to be of use for road construction.

2) Pans, 500 m across or more, without a platform. Large pans without a platform occur at about one-third the frequency of those with a platform. The calcrete from them is much less likely to be of good quality.

3) Pans, less than 500 m across, with a platform. As in group 1, the platform can be expected to yield a good quantity of hard calcrete, although both quantity and quality are less predictable in the small pans. Small pans can be distinguished from depressions in group 5 by the flatter and sparsely-vegetated pan floor. The lack of vegetation is brought about by a combination of alkaline or saline conditions, and trampling by grazing animals at times when the pan contains water or a flush of new grass.

4) Pans, less than 500 m across, without a platform (Plates 5, 7, 9, 10, 11). These features contain calcrete whose quality is not predictable, but which is generally better than the small features in groups 5 and 6.

5) Depressions (Plates 6, 8 and 11). Topographic depressions are distinguished from the many wind-blown hollows and ripples in the surface of the sand plain by a distinctive but not always obvious vegetative zoning. Grasses grow in the almost flat or concave floor of the depression, to the exclusion of shrubs which are common on the surrounding plains. Depressions can usually be detected easily in aerial photographs by their round or oval shape and pale tone. They contain calcrete, generally of poor quality, and the overburden is likely to be 1.5 m or more.

6) Grey sands (Plate 12). The grey sands have little or no relief expression, but are distinguished solely by their neutral grey colour which contrasts with the usual reddish-brown of the Kalahari sand. In the Sekoma-Kang area they form a fairly dense network. They offer a potential source of calcrete in areas where no pans or depressions exist, although the quality tends to be poor and the overburden usually exceeds 1.5m.

7) Valleys (Plates 3 and 11). Before the deposition of the Kalahari sand central Botswana had a well defined river drainage system. The valleys are now filled with sand but many of them can still be traced. Around Takatshwanne where the sand is thin the old drainage lines are obvious, but where the sand is deep they peter out into vague linear features.

Valleys are considered to be relevant to this classification because they contain pans, depressions and grey sands scattered along their length which are obvious sources of calcrete. They form narrow zones along which to concentrate a search for calcrete. There is evidence that large concentrations of calcrete can occur within a valley, but so far a reliable method of predicting the sites of accumulations has not been found. It has not been possible to study valleys adequately, for three reasons.

a) There are very few of them in the study area (–four, plus traces of one or two others).

b) They are more than 100 km long. It has not been possible to examine calcrete development along their length.

c) They occur in different land regions, two in the Jwaneng-Sekoma sand plain and traces of others in the longitudinal dunes near Takatshwanne. The morphological characteristics of the valleys differ considerably in these two areas, and similarities between them could not be assumed without field confirmation.

8) Inter-dune hollows (Plates 2 and 3). Like the valleys, the hollows between linear dunes in the area north of Kang contain the majority of pans and grey sands where calcretes may be found.

4. REMOTE SENSING

Black and white aerial photography and Landsat satellite imagery formed the basis of the remote sensing study, being types of imagery that are readily available in Botswana. These were supplemented by test strips of colour aerial photography that were specially flown for comparison. The effectiveness of each type of imagery in mapping calcrete landforms was judged on three criteria:

1) Ability to resolve terrain details that help in the identification of calcrete-rich areas.
2) Ability to detect minor changes in relief.
3) Ability to show tonal (colour) differences of the ground surface.

Table 1 shows the degree of importance of these criteria in the recognition of the various calcrete-bearing landforms. Although both colour and a stereoscopic image are essential for recognising the landforms, the resolution of fine detail is not important for recognising any except platforms.

4.1 *Black and white aerial photographs*

Black and white aerial photographs at 1:50,000 and 1:70,000 scale formed the basis for the field work and the mapping of calcrete-bearing landforms. Features having distinctive vegetation contrasts and some relief were easily identified, although the time taken to examine all the photos (about 350), record the features and transfer them to a base map was about 10 man/days. They were effective in mapping all the calcrete-bearing features within the project area, with the exception of the grey sands, which they are unable to distinguish from the surrounding red sands. In areas lacking pans and depressions they would be ineffective for mapping grey sands alone as potential sources of calcrete.

TABLE 1

Table to show the relative importance of different image characteristics in mapping calcrete-bearing landforms

Image characteristics \ Calcrete-bearing landform	Bare Pans		Platform	Grassed pans (vegetative zoning)	Valley and inter-dune hollow		Depression (no vegetative) zoning)	Grey sand areas
	500 m across or more	Less than 500 m across			Well-defined	Diffuse		
Resolution of fine detail (eg small shrubs)	D	C	A	C	D	D	B	D
Resolution of moderate detail (eg sand tracks)	C	B	A	A	D	D	A	D
Stereoscopic image	D	C	A	B	D	D	A	D
Tonal discrimination (or colour)	A	A	D	A	A	A	C	A

A – essential B – useful C – minor importance D – not necessary

The photography was taken with a super wide angle lens (120°, of 87 mm focal length), which gives a greater degree of relief exaggeration under a stereoscope than lenses of longer focal length. This characteristic is extremely useful in the Kalahari where the land is very flat. The observer is able to detect very small variations in the ground level that can be important in finding calcrete, especially for the identification of a calcrete platform, whose slight elevation above the floor of a pan is an essential distinguishing characteristic. For a given scale of photography the amount of relief displacement in a stereo pair is proportional to the frame size of the camera and the focal length of the lens. The black and white photography has a theoretical relief exaggeration five times greater than that of the 70 mm TRRL photography, although in practice this is reduced to about 2.5 times by the increase in flying height.

4.2 *Small format multi-spectral aerial photography*

Aerial photography was specially flown over test strips between Jwaneng and Sekoma, and in the areas of Fox Pan and Motsobonye Pan, using the TRRL small format camera system (Heath 1980). This system consists of a single 5-inch camera or four 70 mm cameras, mounted in a small housing that is attached to the side of a Cessna single-engined aircraft, via the luggage door. The advantages of such a system are that the equipment is inexpensive and portable: light aircraft can be hired locally at moderate cost, and sorties can be flown over small areas or at short notice, depending on the requirements of the survey. The films used were:

Colour negative film	in 5-inch format at 1:15,000 scale (125 mm lens)
Colour reversal film Panchromatic film with blue, green and red filters False colour infra-red reversal film Black and white infra-red film	in 70 mm format at 1:25,000 scale (100 mm lens)

The infra-red films were intended for distinguishing different types of vegetation, but owing to the time of year (dry season) very little infra-red light was being reflected from the plant leaves, and distinctive reflectance values were not apparent. The subtle colour difference between the grey and red sands was largely masked by the strong cyan hues of sparsely-vegetated ground reproduced by this film. The narrow-band films were used to generate colour images in an additive viewer, but the images thus produced did not yield any information that could not be obtained from the natural colour photographs.

The natural colour photographs showed most of the calcrete bearing features very well, but suffered a disadvantage in the subdued relief effect caused by the relatively long focal length of the lenses used. They are very effective in detecting minor colour variations that occur in the sands. The colour reversal film was better than the 5-inch colour prints in this respect. Normally the greater resolution of the 5-inch film over the 70 mm would have been an advantage for interpretation, but this advantage is not apparent in the Kalahari, for two reasons. Firstly, the long grass and fine-leaved trees soften the appearance of the ground surface and give an impression that the photographs are slightly out of focus, and secondly high image resolution is not essential for the identification of most calcrete features (see Table 1).

Since the critical aspect in identifying grey sands, as well as most of the other calcrete-bearing landforms, is ground colour, 35 mm colour reversal film would probably be adequate, taken obliquely through the open hatch of an aircraft. A wide angle lens would be advantageous, and the camera should be held as near vertical as possible, to look down through the vegetation, and to minimise haze effects which would tend to mask colour differences in the sands. Because of the featureless nature of the landscape it would be important to begin and end photographic runs at easily-identifiable points, and to maintain continuity in the run by overlapping the frames. Aerial photography taken in this way would enable an interpreter to identify the main concentrations of grey sand areas, sufficient to direct the explorations of field parties. The technique has not been tried by TRRL, but could provide a simple and cheap method of obtaining imagery if a light aircraft is obtainable.

4.3 *Landsat satellite imagery and air photo mosaics*

Aerial photographs are useful for covering small or even moderately large areas of terrain, but studies carried out over very large areas often benefit from the regional view afforded by Landsat images. Landsat satellites generate images 185 x 178 km in size, covering an area of some 33,000 km^2 (Plate 3). The whole of Botswana is covered by about 21 Landsat scenes: the area from Kanye to the Okwa River spans three scenes. Landsat images are available to the interpreter in two forms, photographic products and digital images displayed on a television monitor via a computer. Both types were used in the field for this study, the digital images having been reproduced as photographic prints. Landsat photographic products have recently become available at very moderate cost from the Satellite Remote Sensing Centre, Johannesburg. A range of standard photographic products of images is offered from stock, and specialised processing and printing are available upon request.

The ability of non-stereoscopic forms of remote sensing imagery (for example, Landsat and air photo mosaics) to discriminate calcrete-bearing landforms depends upon the contrast that the landforms have with their surroundings. High contrast objects are easy to see, even though they may be very small; low contrast objects are difficult to see. Landsat imagery can be used for mapping small pans whose surface is bare of vegetation, giving a high contrast in the image, but grassed pans merge in with the surrounding sand plains and are very difficult to discern. It was noted that depressions, which are small and have little vegetative zoning, are invisible on Landsat images.

A test was carried out to compare the ability of an experienced and an inexperienced interpreter in mapping pans from Landsat imagery and air photo mosaics. The results are shown in Table 2. The air photo mosaic gave a more reliable interpretation, principally because of the large amount of detail that is visible in the image. Inaccuracies in mapping are due to features that are not pans being counted, and some pans being missed. The success rate for large pans is markedly better than that for small pans because of their larger size and high tonal contrast.

TABLE 2

Percentage of pans correctly identified by two observers using two kinds of imagery

LANDSAT SATELLITE IMAGE (1)

	Large pans	Small pans	Total pans (2)
Experienced interpreter	97%	45%	55%
Inexperienced interpreter	87%	32%	26%

AIR PHOTO MOSAIC

	Large pans	Small pans	Total pans
Experienced interpreter	90%	56%	61%
Inexperienced interpreter	Not differentiated		46%

Notes (1) 1:1 million Landsat false colour composite transparency, enlarged to 1:100,000

(2) Total number of pans = 156, as determined by mapping from stereoscopic aerial photographs. Total number of large pans = 31; total number of small pans = 125.

The main advantage of Landsat imagery to the interpreter is that it records subtle colour changes in the terrain surface. This facility enables the interpreter to see most of the calcrete-bearing landforms, although the resolution of the image, (a maximum of approximately 80 m on the ground), is rather coarse for the smallest features. The Landsat images are able to show:

1) All pans down to a size of about 100 m across, provided there is a colour contrast between the pan and its surroundings. However, it was not possible, even by digital image enhancement techniques, to identify the platform associated with many pans, that is so important an indicator of good quality calcrete. This is due to the wide range of colours that a platform can have because of variations in surface cover, and lack of a stereoscopic effect.

2) Ancient drainage lines and valley forms. These are shown up far better by Landsat than even 1:70,000 aerial photographs, because of the very large area covered by the image. Some valleys such as the Naledi Valley at Jwaneng, are very distinct, while others,such as the Okwa tributary that extends southwards from Takatshwanne to beyond Maito-a-Puduhudu, are extremely diffuse and only traceable at scales of about 1:500,000 and smaller. A calcrete deposit near km 25 on the Jwaneng-Sekoma road occurs on the margin of a diffuse ancient valley that runs to the north west from this point (see Fig. 2). The presence of calcrete here was first suspected by the appearance and colour of the valley in Landsat imagery, although the valley itself is undetectable in black and white aerial photographs, and very difficult to discern on the ground.

3) Grey sand areas. These were first detected as reticulate surface patterns on Landsat images, but were not positively identified as grey sands until a comparison could be made with colour aerial photography. The image is capable of depicting virtually all grey sand areas down to about 150 m in size.

Photographic Landsat products can be used to demonstrate at least where grey sands occur frequently, and where they are sparse or non-existent. There is no evidence to suggest that calcretes are of better quality in areas where grey sands are frequent, but survey parties now have a means of locating areas where grey sands occur most often, and hence where the chances of finding calcrete are high.

Digital Landsat images are able to show grey sand areas far more clearly than photographic products because of the mathematical transformations and versatile colour enhancement techniques that can be applied. A principal component analysis of the data proved to be very effective in bringing out the grey sand areas for this study, and has been used as the base for the map of calcrete potential (Fig. 2) (Lawrance, 1984). An image of the second principal component, which shows the pans and grey sand areas clearly, is reproduced in black and white in Plate 12. This image was enhanced to exclude the background and leave only the grey sand areas, shown in black in Fig. 2. The processing has resulted in some losses of information in a few areas, but these imperfections do not affect the overall usefulness of the map. The grey sands could only be mapped by this method as far west as Kang. Further west and north, in the region of longitudinal sand dunes, grey sands occur less frequently, and the vegetative cover is more dense. For these reasons Landsat imagery was not able to map grey sands as reliably as further east.

4.4 *Remote sensing summary and the compilation of maps of calcrete potential*

Table 3 summarises the ability of three remote sensing systems to show each of the calcrete-bearing landforms. None of the systems alone shows all the features, but they can be used in combination to cover the range. Black and white photographs are most useful overall by virtue of their high resolution and stereoscopic relief (which to some extent makes up for their inability to distinguish coloured features), and availability within Botswana. Colour aerial photography gives the most reliable interpretation, but little if any exists in Botswana. An effective compromise can be found by using black and white aerial photographs in conjunction with Landsat false colour composite images, whose advantages are complementary.

In making a map of potential calcrete deposits (Figs 2 and 3) the first priority should be to map the location of large pans 500 m or more across in relation to a proposed road line. 76 per cent of those in the study area were found to contain a calcrete platform. Such a map can be produced from topographic maps, Landsat imagery, air photo mosaics or individual aerial photographs. Each pan should be individually examined in stereoscopic aerial photographs to determine whether or not a platform is present.

If the frequency or spacing of large pans is shown to be insufficient to meet the needs of the survey, a more detailed map of calcrete-bearing landforms should be made. Features smaller than the very obvious large pans are more difficult to identify and more effort is required to map them. Although far inferior to large pans in their calcrete potential, small pans less than 500 m across (17 per cent of which have been found to possess a platform) are the next best source of calcrete, and are relatively easy to locate in the field. Individual aerial photographs are the most appropriate means of mapping small pans and finding those which possess a calcrete platform. Landsat imagery is useful for mapping small pans if they contrast well with their surroundings, but reliability is low for features less than about 200 m across. Landsat imagery is also good for mapping concentrations of grey sands, especially if digital enhancement techniques are used to emphasise them.

4.5 *Extension of calcrete mapping outside the project area*

It is important to estimate how far conditions within the project area continue beyond its boundaries, and to what extent the principles of mapping described in this report can be applied to other areas of Botswana. A classification has been made of the principal terrains of the Kalahari region of Botswana, shown in Fig. 4, based

TABLE 3

Ability of three remote sensing techniques to identify calcrete-bearing landforms

Calcrete-bearing landform / Remote sensing technique	Bare pans		Platform	Grassed pans (vegetative zoning)	Valley and inter-dune hollow		Depression (no vegetative zoning)	Grey sand areas
	500 m across or more	Less than 500 m across			Well-defined	Diffuse		
Black and white air photographs (stereo) Scale 1:50 000 and 1:70 000	Very Good	Very Good	Good	Good	Moderate	Poor to not able	Good	Poor to not able
Natural colour air photographs (stereo) Scale 1:15 000 – 1:25 000	Very Good	Very Good	Good to Moderate	Very Good	Poor	Poor to not able	Good	Very Good
Landsat satellite imagery (photographic product) Scale 1:500 000	Very Good	Moderate	Not able	Not able	Good to Moderate	Good	Not able	Moderate
Landsat satellite imagery (digitally processed) Scale 1:50 000 – 1:250 000	Very Good	Good	Not able	Poor	Very Good	Very Good	Not able	Good

on patterns of sand dunes interpreted from Landsat imagery. It is probable that those parts of Botswana that are covered by a continuous sand sheet have a range of calcrete-bearing landforms and materials broadly similar to those found within the project area. The frequency and arrangement of dunes influences the distribution of calcretes, and it has been assumed that regularity of dune pattern indicates similarity in the occurrence of calcrete, although it has not been possible to check the validity of this assumption except in the project area. The boundaries on the map therefore indicate areas where a given range of calcretes can be expected to occur, even though the mode of occurrence may differ considerably from calcretes in the study area.

The two terrain regions containing the project area appear to extend over most of the southern half of Botswana. The range of conditions described in this report can therefore reasonably be expected to apply over this area. Dune patterns in the north of the country are not the same as those in the south, and possible analogies that may exist between north and south have not been considered. The non-dune regions of the Okavango Delta, Ghanzi rock ridges and the Makgadikgadi pans would be expected to have little or no correlation with the Kalahari sand regions.

5. ENGINEERING PROPERTIES OF CALCRETES

5.1 *Laboratory tests*

Although it is necessary to employ a wide range of tests to fully assess the quality of a calcrete for road construction, it is possible to reduce tests to a minimum when making a preliminary appraisal of a large number of samples. TRRL have investigated the extent to which the "essential" tests reflect the potential of a calcrete, to assist reconnaissance surveys for calcrete resources in Botswana. Essential tests for use in the field are described in Section 6 (para 5). The full list of laboratory tests is shown in Table 4 and Fig. 5, which compare NITRR and Botswana MOWC recommendations of acceptability with TRRL figures for each of the tests.

The principal properties of calcrete that influence its behaviour in a road are the grading of the material, the strength and proportion of hard particles, and the plasticity of the fines. These properties can be summed up in four easily-measured values, the grading modulus, percentage passing the 0.425 mm sieve, the aggregate pliers value and the linear shrinkage. They are defined in the notes to Table 4. The product of the linear shrinkage and percentage passing the 0.425 mm sieve gives a good estimate of the California Bearing Ratio of the sample, as shown in Fig. 6, and thus eliminates the need to carry out the less convenient CBR test. The value also gives a measure of the effective plasticity of the material: for example, a higher plasticity can be tolerated if the plastic fraction occupies only a small percentage of the whole. The product of the aggregate pliers value and grading modulus gives an indication of the proportion of hard particles and their durability.

The four tests, combined into two composite expressions, can be plotted as a cluster diagram (Fig. 7). The diagram shows a considerable amount of variation in the properties of calcretes, even when grouped into the calcrete-bearing landforms from which they came. However, it illustrates the generally poorer nature of material taken from minor features, which tend to lie along the y axis, indicating low strength, poor grading, and in several cases, high plasticity.

Superimposed on this diagram are limits of acceptability for specifications laid down in NITRR RR 286 (Netterberg 1971), the original Botswana MOWC specification (Ministry of Works and Communications 1976), TRRL Road Note 31 (Transport and Road Research Laboratory 1977) and the TRRL Interim specification (now in Ministry of Works and Communications 1982) for calcrete in low-volume roads. Several of the best materials

TABLE 4

Comparison of guideline specifications for lightly-trafficked calcrete bases (see also grading envelopes in Fig. 5)

Test	Botswana MOWC Specification (1) <100,000 esa (2)	NITRR RR 286 (3) <200,000 esa	TRRL Road Note 31 (4) <500,000 esa	Botswana MOWC Specification (5) <800,000 esa (Category 1)
Minimum grading modulus (6)	1.15	1.5	1.95 (7)	2.0
Maximum size of material (mm)	75	38	37.5 (8)	53
Maximum % passing 425 μm sieve	80	55	12–25	10–30
Maximum % passing 63 μm sieve	20	Not specified	5–15	5–15 (9)
Maximum liquid limit	Not specified	40	25	25
Maximum plasticity index	30	15	6 (10)	6
Maximum linear shrinkage	14	6	4	3
Maximum LS x % passing 425 μm (11)	600	320	120	90 (7)
Minimum CBR after 4 days soaking	50 (12)	80 (12)	80 (13)	80 (12)
Minimum relative field compaction	98% mod AASHTO	98% mod AASHTO	100% BS (13)	98% mod AASHTO
Minimum Aggregate Pliers Value	Not specified	50 (14)	Test not used (15)	Test not used (16)
Total soluble salts (17)	0.2%	0.2%	Test not used	0.2%

NOTES

1. Originally the TRRL Interim Specification, based on the performance of the Jwaneng full-scale road experiment after a total of 310,000 vehicle passes for both directions, representing 100,500 equivalent standard axles (esa) in the Jwaneng-bound lane, up to May 1983.
2. Equivalent standard axles.
3. Netterberg (1971).
4. Transport and Road Research Laboratory (1977)
5. The existing Botswana MOWC Specification (Botswana Roads Department 1976) corresponds to Road Category C: designs for granular bases, given in South African specifications (National Institute for Transport and Road Research 1980a and 1980b).
6. Grading Modulus (GM) = $\frac{300 - \text{sum of \% material passing 2.0 mm + 0.425 mm + 0.075 mm sieves}}{100}$
   GM lies between 0 and 3.
7. Test not used. Figure given for comparative purposes only, calculated from values of related properties given elsewhere in Table.
8. Particle size limits given for RN 31 are based on Imperial-equivalent metric sieve sizes.
9. Figure quoted is for the 75 μm sieve, the smallest specified in South Africa.
10. Owing to the low rainfall (about 400 mm p.a.) and sand subgrades the maximum PI could probably be raised to 12.
11. The Atterberg limits of a soil (LL, PL, PI) are related and it is considered that a calcrete's properties can be defined using two parameters, linear shrinkage and % material passing 425 μm. Linear shrinkage is preferred to plasticity index.
12. At specified field compaction, normally 97% British Standard compaction, 4.5 kg rammer method (or 98% Modified AASHTO compaction).
13. At 100% British Standard compaction, 2.5 kg rammer method. (In practice, normally carried out at a specified field compaction of 97% British Standard compaction, 4.5 kg rammer method, or 98% modified AASHTO compaction).
14. Alternatively a minimum value of 70 kN should be applied in a 10% Fines Aggregate Crushing Test. The results of this test correspond linearly to Aggregate Pliers Values (Netterberg 1971).
15. A minimum 10% Fines Aggregate Crushing Test value of 50 kN or alternatively a maximum Modified Aggregate Impact value of 40% is recommended by TRRL (Hosking and Tubey 1969).
16. Aggregate tests are not specified, but an Aggregate Crushing Value of 30% and a 10% Fines Aggregate Crushing Test value of 110 kN are commonly applied in the Republic of South Africa.
17. Netterberg and Maton (1975).

would be acceptable under RR 286, but none pass RN 31 or the original Botswana MOWC criteria. The TRRL specification permits much wider limits in both strength and plasticity, and only the poorest materials lie outside the line. Table 5 demonstrates the higher pass rates achievable under the TRRL specification compared with the NITRR specification. The TRRL full scale experiment (see Appendix 1), has demonstrated that even poor calcretes can perform adequately in sealed bases carrying up to 100,000 standard axles of traffic, in support of the case to reduce the existing specification to admit a wider range of materials.

TABLE 5

Percentage pass rate of material from classified landforms related to guidelines for road bases

Calcrete-bearing landforms	Guidelines for road bases		No. in sample
	TRRL (MOWC 1982)	NITRR RR 286	
Platform of pans 500m or more across	83%	33%	7
Platform of pans less than 500 m across	78%	33%	9
Pans and valleys, without a platform	88%	6%	11
Depressions and grey sand areas	50%	11%	26

5.2 *Qualitative characteristics of calcretes related to engineering properties*

During the course of the main field survey, many more sites were described than could possibly have been sampled, resulting in a considerable amount of qualitative data that form a background to the measured properties of calcrete. Recalling that calcrete is variable by nature, this body of qualitative information indicates trends and "norms" in the field occurrence of calcrete that are not apparent from the limited amount of test data available. The qualitative characteristics described below augment the laboratory test results by indicating circumstances in which better quality calcretes are most likely to be found.

1) *Proportion and strength of hard particles.* An estimate of the proportion and strength of hard particles was made as part of the calcrete profile description. The strength of the hard particles was based on a scale 1–6 (see Fig. 8). Unfortunately the field estimate of hardness could not be correlated easily with Aggregate Pliers Values of samples tested in the laboratory, because the field assessment expresses a range of hardness rather than a value equivalent to an APV. However, Fig. 8 clearly shows that calcrete profiles combining the advantages of a high proportion of strong particles are concentrated in the platforms of large pans.

2) *Variations in calcrete properties within calcrete-bearing landforms.* Tests on samples taken from different parts of a calcrete-bearing landform show that considerable variations in quality can occur. A sampling programme to demonstrate this was carried out in three types of landforms, a large pan with a platform, a large pan without a platform, and two ancient valley forms containing minor calcrete features. The data reproduced in Fig. 9 illustrates these variations, and emphasises the need to prospect at several points within a feature to find the best material.

   Good quality calcrete can usually be found on a platform, and any other area within a pan produces poorer material. The quality of calcrete obtained in valley forms is less predictable, and a wide variation in quality can be expected. However, the linear nature of a valley form helps to confine the search for calcrete, with improved chances of success.

3) *Relationship between calcrete type and landform.* The frequency with which different types of calcrete occur, in relation to landform type, is shown in Fig. 10. The figure shows that only one-quarter of the sampled landforms contain nodular or hardpan calcrete, but that these calcretes occur in 63 per cent of platforms within pans. Calcified sand and powder calcrete predominate in the remaining calcrete features.

4) *Relation between sand overburden, calcrete thickness and landform.* Fig. 11 shows calcrete thickness plotted against overburden depth, for a range of calcrete-bearing landforms. As would be expected, overburden is independent of calcrete thickness, but the landform types are strongly grouped, emphasising the importance of pans with a platform. The depressions and grey sands show a wide variability in the thickness of calcrete found, but have a consistently deep overburden. The probability of finding calcrete within a range of depths is given in Table 6, again demonstrating the advantage of pans with platforms.

TABLE 6

Percentage probability of finding calcrete within a given depth

	At or near surface	Within 0.5 m	Within 1.0 m	Within 1.5 m	Within 2.0 m	No. in Sample
Platforms	81%	81%	86%	100%	100%	21
Pans without platform	13%	13%	29%	66%	100%	38
Depressions	0%	0%	8%	59%	93%	49
Grey sands	0%	0%	5%	61%	94%	18

5.3 *Estimation of calcrete quantities*

During reconnaissance materials surveys, difficulties are experienced in assessing reserves of calcrete, owing to inherent difficulties in measuring a variable substance that lies buried beneath the ground. The chief problems in obtaining accurate measurements are as follows.

1) Calcrete is unpredictable in thickness and extent, although it is more likely to be consistent in situations where its associated surface landform is strongly developed.

2) The presence of a deep overburden and hard layers in the profile has often deterred field parties from digging pits to the full depth of material.

3) A powder calcrete layer often fades out at the base into a calcareous sand, leaving the thickness of useable material in doubt.

4) The amount of material available depends upon the use to which it is to be put. For high volume roads only good quality calcrete can be used, but for low volume roads poorer quality calcrete will often suffice, and would normally occur in much larger quantities.

5) When interpreting calcrete-bearing landforms in remote sensing images it is not always possible to positively identify the extent of a platform in a pan in aerial photographs, or the extent of a grey sand area in Landsat images. Also, there are examples of pans whose platform extends beyond the boundary of the pan itself, beneath a layer of sand. These factors lead to uncertainty in the area of the feature bearing measured.

It should be possible to improve estimates of reserves if comprehensive pitting is carried out at the survey stage, and if records are kept of the volume and quality of material removed from borrow pits. The volume of material extracted does not necessarily indicate the total amount of material available, as pits are often only partially worked, to leave a reserve of material available for maintenance of the road at a later date. In the case of platforms in pans it should be possible to make a reasonable estimate of total volume. Fig. 11 suggests an average thickness of about 0.9 m for calcrete on platforms. The volume of material in the platforms of nineteen pans in the Sekoma area was calculated using this assumed thickness. The approximate amount of material in the nine pans that are 500 m or more across was calculated to vary between 30,000 m^3 and 445,000 m^3 (average 217,000 m^3). The amount in nine smaller pans ranged from 30,000 m^3 to 72,000 m^3 (average 46,000 m^3): (this excludes one small pan containing 388,000 m^3, which is felt to be an unusually large amount.) These figures demonstrate the very large amounts of material that are potentially available from platforms, assuming that the whole of the platform is productive.

It is doubtful whether any accurate method will be found of estimating the volume of calcrete lying beneath grey sand, owing to variations in the material and the difficulty of mapping grey sands accurately. The latter problem should be alleviated when satellite images with improved resolution become available, as they will within a few years.

Estimates of material available from small pans and depressions are almost as difficult to make as with grey sands. A small amount of data from the Jwaneng-Sekoma road project indicates that about 7100 m^3 of material have been extracted from each of ten pits in the vicinity of the alignment, but how representative this figure is of depressions and small pans generally is not known.

6. RECOMMENDATIONS FOR THE PLANNING AND EXECUTION OF CALCRETE SURVEYS

The Kalahari desert covers a vast area and accurate navigation to any part of the terrain lying more than a few hundred metres from an access track is extremely difficult. Considerable problems exist in carrying out materials surveys efficiently in areas where new road construction is to take place. The use of a systematic procedure for field investigations will alleviate the problems of planning and executing surveys: recommended stages to follow are given below.

1) Compilation of a map of calcrete resources

   During the planning stages of a road project consideration is given to materials resources within a route corridor. The compilation of a map of calcrete resources assists the survey for initial construction, as well as the planning of any future upgrading programme. Before commencing a materials survey it would be advisable to assess the relative frequency and importance of the various calcrete-bearing landforms in the area by making a breakdown of the major terrain types into natural terrain regions, and mapping the calcrete landforms in each.

   In areas where large pans are abundant it may be considered necessary to map these features only, but over most of Botswana large pans are widely separated and construction materials will have to be sought in smaller and less conspicuous calcrete-bearing landforms. Aerial photographs are most efficient for this. Use of a stereoscope is essential for mapping calcrete platforms within pans, and depressions.

   In the absence of pans in an area, it will be necessary to search for calcretes within grey sand patches and ancient valley systems. Landsat imagery is most appropriate for mapping these features by virtue of its good colour resolution and coverage of large areas. If access to computerised image processing facilities is available, then digitally-processed images, being more detailed and easier to interpret, should prove a worthwhile investment. Landsat imagery can be used to compile information from air photo mapping if no convenient base map exists.

2) Selection of specification
The new Botswana Road Design Manual (Ministry of Works and Communications 1982) contains three specifications for natural gravel bases under a bituminous surfacing, appropriate to design traffic levels of up to 0.1 million, up to 0.2 million and up to 0.8 million equivalent standard axles. An estimate should be made of expected traffic over the life of the road, after which the appropriate specification can be adopted.

A knowledge of calcrete resources and quality, as indicated by a calcrete resource map, could modify the initial standard of construction and long-term strategy for upgrading the road. For instance, if resources of good material are scarce it may be economic to use low grade materials for initial construction, and conserve better quality calcrete for upgrading at a later date. If a high standard is required at the outset but good quality materials are not available, stabilization with cement should be considered as an alternative. Specifications for stabilized bases exist in South Africa (National Institute for Transport and Road Research 1980).

3) Location of sampling sites
Aerial photographs should be used in the field to pinpoint sites where pits are to be dug. The final selection can be made by observation of plant communities and field experience. It is important to examine several localities within a calcrete-bearing feature to ensure that the best site is selected.

The spacing of sampling pits should cover an area at least as large as the proposed quarry site, and the number of pits should be sufficient to confirm that the material is reasonably consistent over the whole area of quarry operations. Pits should be deep enough to allow a realistic estimate of potential quantities to be made.

4) Methods of excavation
The present method of excavation by hand is very time-consuming, and often results in pits stopping short of full depth, because of excessive overburden or hard layers within the profile. It is important to overcome these problems and excavate the calcrete profile to full depth. The use of a self-propelled mechanical digger would be a great asset in saving time, both in removing the overburden and in penetrating hard layers. Failing this, a portable jack hammer and generator would be useful to break through tough calcretes. In the absence of mechanical aids, more time and labour should be allowed, with additional tools such as a sledgehammer and crowbar, to open up pits to full depth.

The calcrete probe, a steel rod driven into the sand, can be used to supplement a pit survey as a means of determining the depth of overburden. It cannot be used to predict the predominant type of calcrete in a profile, although with experience it is possible to judge the nature of the top layer.

5) Field sampling, testing and reporting
A good estimate of the suitability of a calcrete for road construction can be obtained by making a few simple measurements of its grading, plasticity and hardness in the field. The practice of rapidly testing samples in the field can be recommended for making an inventory of calcrete resources within an area, from which a programme of utilisation can be drawn up. It is considered important that the selection of calcrete borrow areas should be made in the field with the support of preliminary engineering test data, rather than waiting until samples have been tested in a laboratory before the siting of quarries is finalized. In this way the engineer who carries out the survey is directly responsible for selecting quarry sites, using his experience of local field

conditions. He is also in a position to carry out extra field work if some materials are found to be unsuitable in the light of preliminary testing. Although the time and expense of field work may be increased in this way, a more effective survey will result. In the past it has sometimes been found necessary to reappraise materials resources at the construction stage, after laboratory tests have shown that material from proposed borrow areas does not meet the specification. Field testing would help to avoid this, especially in areas where all the materials are poor and where an objective method of assessment is necessary.

During the period of field work the engineer will acquire an appreciation of the field characteristics of the materials in relation to their engineering properties. Field testing will enable the engineer to relate the properties of material to their field occurrence, and to feel confident that sites nominated as borrow areas contain material that will pass the specification. Samples taken to a central laboratory for testing can be limited to those that are likely to pass the specification, resulting in savings in transport costs, in time in testing the samples, and in redundant testing of samples that prove to be unsuitable.

A recommendation for field testing does not imply that full testing in a central laboratory is unnecessary. Full testing is the only means by which a material can be properly evaluated, and must be carried out even though a material may have already been tested in the field. Conversely, the fact that materials could "pass" the field tests and yet subsequently be found to fail a specification does not suggest that field testing is inaccurate. Field tests are intended to group materials into suitable, marginal and unsuitable types, but inevitably, some compromises in testing have to be made. For example, wet sieving is unlikely to be practicable, so a dry sieve analysis is recommended, to give an indication of the grading of a material in the middle and coarse size range. On the other hand, some properties, such as the size, proportion and hardness of oversized material can only be accurately assessed in the field: much of the oversized fraction is bound to be omitted from samples taken for testing at a central laboratory.

It is recommended that field testing facilities are set up at the base camp of a field party, and a technician provided to carry out tests on samples brought in. The testing programme should keep pace with field work, so that further explorations can be made if the test results show that materials examined so far are unacceptable. It is suggested that two samples are taken at each site, one for testing in the field and the other for testing in the laboratory. If field tests show that a material is unsuitable or no longer required for any reason, the second sample can be discarded.

A field reporting and testing procedure should be carried out on the following lines.

a) Give a brief description of the layers in the calcrete profile. Record the profile thickness and the depth of overburden. Note the characteristics of hard layers in the profile (hardness, thickness, degree of fracturing). Describe the type of landform feature in which the profile is situated.

b) Make a note of the type of mechanical plant that would be considered appropriate for opening up a quarry on the site and excavating the calcrete.

c) Sampling. From the test pit take a sample that is representative of the whole profile, to the full depth of intended quarry operations, eg. cut back the face of the pit for 15–25 cm over its full depth. Pile the sample onto a sheet of canvas or equivalent and mix thoroughly. Describe the material in the stockpile in terms of the shape and nature of the hard particles, and the composition of the matrix. Oversized lumps may be ignored unless they predominate in the profile and are considered to be too hard to be broken down during the processes of excavation, laying and compaction.

d) Quarter and riffle the sample down to an amount suitable for performing a sieve analysis, linear shrinkage and aggregate pliers test. This amount will vary between 2 and 20 kg, depending on the coarseness of the material (National Institute for Transport and Road Research 1979, British Standards Institution 1975). Take the sample back to base camp for testing.

e) Testing

(i) Sieve analysis. Under normal circumstances it will not be practicable to carry out a wet sieve analysis. Dry sieving will give an indication of the grading and quality of the material, although the Grading Modulus (see Table 4) cannot be assessed accurately. Use sieves 75 mm, 37.5 mm, 20 mm, 14 mm, 2 mm and 0.425 mm in size. Compare the grading curve with the grading envelopes given in Fig. 5. If a high proportion of a material is greater than 75 mm in size, and if the large particles are too hard to be broken down during the process of excavating and laying, then the material must be considered unsuitable for road construction unless it is first crushed or screened.

(ii) Linear shrinkage. The linear shrinkage test can be used as a simple method of measuring the plasticity of the matrix. Samples should be prepared according to the methods described in TMH1 (National Institute for Transport and Road Research 1979) or BS 1377 (British Standards Institution 1975) for the one-point liquid limit test. After air drying for a few hours, the drying process can be completed by placing the linear shrinkage troughs on a metal plate and warming them on a fire until dry. Although tests have shown that even plastic calcrete (PI 24.5) is not liable to buckle under accelerated drying, excessive heat from the fire should be avoided.

(iii) Aggregate pliers value (Netterberg 1971). Perform an aggregate pliers test on 100 particles of material between 14 and 20 mm in size.

6) Full laboratory testing

Information collected during the pit survey and preliminary field testing provides a means of selecting a number of sites for possible quarry location. A sample of calcrete should be taken, large enough to allow the full range of tests, set out in Table 4, to be carried out in the laboratory. The overall quality of all pits can be seen at a glance if the test data are summarised in a chart, including a 'pass' or 'fail' mark for each against the three operating specifications. Where a sample fails to meet a specification a brief note should be given indicating the reason.

7) Storage of engineering data

The TRRL research programme has opened up new prospects for the use of calcretes in low volume road construction, yet the distribution of calcretes in Botswana and the range of uses that they may have are still largely unknown. Much work remains to be done in collating information on their engineering performance in relation to field occurrence and laboratory properties, under various conditions of traffic loading and maintenance strategy. It is recommended that data records are kept of these factors, from which rational policies for road planning can be formulated. The system for collecting the information need only consist of a set of standardised data forms, but it should be designed as an integrated whole, to allow cross-referencing between different sets of data. Collection must also be carried out on a regular and methodical basis.

7. CONCLUSIONS

1) The existing specification used in Botswana for the selection of natural base materials for bituminous roads places unrealistically high limits on materials that are to be used in the construction of trans-Kalahari routes, where traffic volumes are not expected to exceed 100,000 equivalent standard axles over a ten year design life. Few calcretes in the central Kalahari region between Sekoma and Ghanzi meet the existing specification, which has led to problems in the design of the proposed Sekoma-Ghanzi road. Results to date from a TRRL/MOWC full scale road experiment at Jwaneng show that a reduced specification, appropriate for low volume surfaced roads, would admit many more calcretes into the limits of acceptability without any reduction in the design life of the road. A new specification, the TRRL Interim, was derived from the results of the full scale experiment, and has been incorporated into the recently-published Botswana Road Design Manual (Ministry of Works and Communications, 1982). The introduction of this new specification will minimise overall road costs and make the best use of available construction materials throughout the life of a road.

2) There is a relation between calcrete type and certain types of landform, although wide variations in both quality and quantity can be expected at all except the most favourable sites. The "platform" (raised rim around the floor) of large pans provides the best chance of finding good quality calcrete in large quantities, where the material usually exists at or near the surface. Pans without a platform, depressions and grey sand areas respectively contain poorer quality calcrete, usually at a depth of more than one metre.

3) Remote sensing methods are invaluable in locating calcrete-bearing landforms in the flat and trackless expanses of the Kalahari. Black and white aerial photographs remain the most practicable method of making detailed maps of these landforms. When viewed as stereoscopic pairs they show most of the calcrete-bearing landforms, and are the only reliable means by which platforms in pans can be identified from the air. Air photo mosaics are useful for mapping pans and some depressions, but they cannot supplant aerial photographs in the search for platforms because no stereoscopic view is obtainable.

Landsat satellite imagery is useful in support of air photo surveys as a means of compiling information from perhaps hundreds of thousands of square kilometres onto a reasonably accurate and detailed topographic base. In areas where pans and depressions are scarce, Landsat imagery could be vital to a calcrete survey in showing where grey sands, which cannot be mapped in black and white aerial photographs, exist. It may be necessary to analyse digital satellite data in a computer to see the grey sands clearly (displayed on a television monitor or output to a film writer).

For small areas it may be sufficient to use 35 mm colour photography taken by hand from a light aircraft, to map the main concentrations of grey sand, although this technique has not been tested.

4) The four commonly-recognised groups of calcretes, nodular, hardpan, powder and calcareous sand, do not fully indicate the value of a material for engineering purposes. Grading, the strength of the hard particles, and the plasticity of the matrix are required as a guide to quality. The proportion of these types varies greatly from profile to profile. Hard forms are more likely to occur in large, well-developed calcrete landforms, but the type expected at any location is very uncertain and remote sensing techniques cannot be used to make this prediction.

Apart from thin, hard horizons, most of the calcretes in the study area can be excavated with a geological hammer. Certain calcretes ("boulder" types) are hard enough to be used as a crushed stone base or surface dressing aggregate, but in the project area boulder calcrete only occurs in the Okwa Valley. In northern Botswana boulder calcrete can be sufficiently abundant to be economically workable as a hard stone material.

5) It has not been found possible to measure the quantity of material available without carrying out a full pitting survey, although an estimate can be made by measuring the area of a calcrete-bearing feature and assuming an average thickness of one metre. This method is likely to be reasonably accurate in the case of platforms on large pans, but for features other than platforms a wide variation must be expected.

6) The practice of making use of vegetation types to find calcrete beneath the surface is widely used in southern Africa, but has not been pursued in this study. Expertise is required in knowing the species involved and the manner in which plant communities vary from region to region. These skills exist in Botswana.

7) It is believed that the results of the present survey would be applicable to Kalahari sand areas in the southern half of Botswana, where the terrain appears to be the same as in the project area. Similar conditions may also exist in parts of the dune areas of the north, but the dune patterns are different from those of the south and these areas have not been studied. The materials of the Okavango swamps, the Ghanzi ridges, the Makgadikgadi pans and the eastern margin of Botswana have few or no parallels with conditions in the Kalahari sand areas.

8) The results of the TRRL research programme could be consolidated and made more generally applicable by the introduction of a system for recording profile data, test results, engineering performance and maintenance activities carried out on calcrete roads. An understanding of the range of calcretes occurring in Botswana and of limitations in their use would be of great benefit to the long term planning and design of Botswana's expanding road network.

8. ACKNOWLEDGEMENTS

The work described in this report is part of a long-term research project of the Overseas Unit, TRRL. Much of the field work, materials testing, and construction and monitoring of the full scale experiment were carried out by Mr M Stewart, under the guidance of Mr D Newill, of the Materials Section of the Overseas Unit.

The authors wish to thank Mr E Irgens, former Chief Roads Engineer to the Botswana Ministry of Works and Communications, for his co-operation during the course of the research project. Thanks are also due to the staff of the Central Materials Laboratory for the MOWC, in particular to Mr E Lemmenyane, whose experience in prospecting for calcretes was of great assistance in the field, and to Mr R Nduna and Mrs E Moletsane, who performed the tests on the materials.

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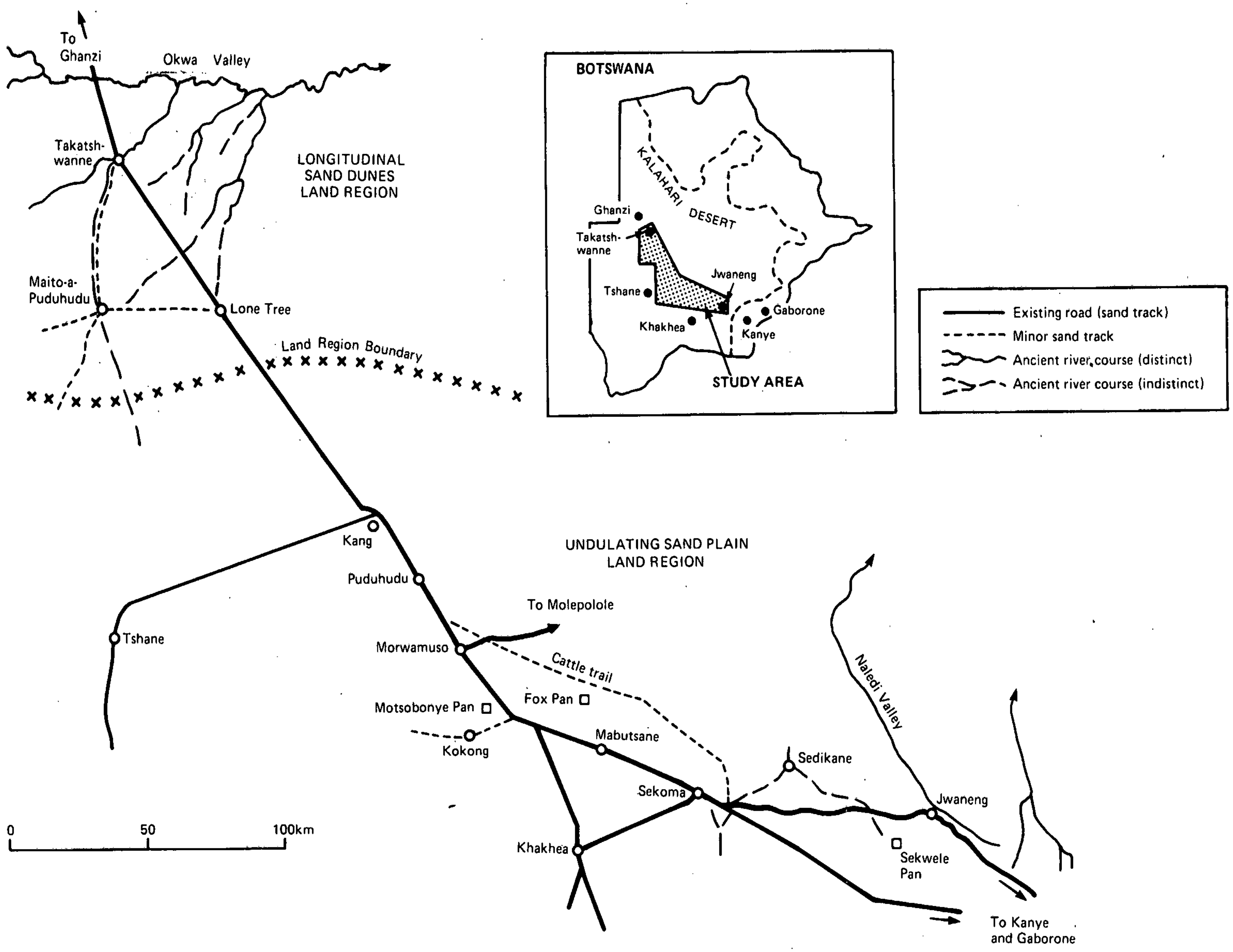

Fig. 1 Location map of study area

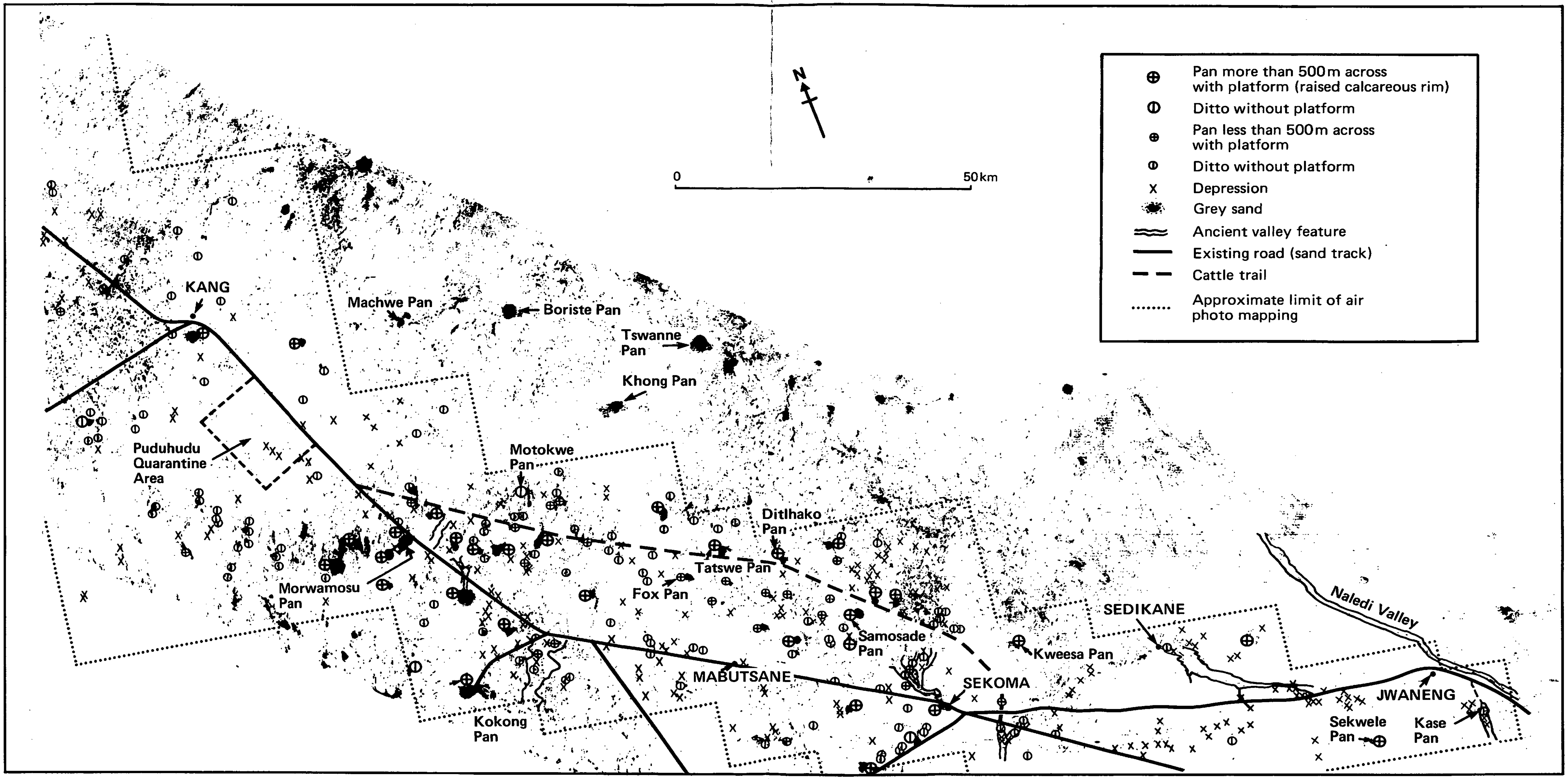

Fig. 2 Map of calcrete potential — eastern half, Jwaneng to Kang

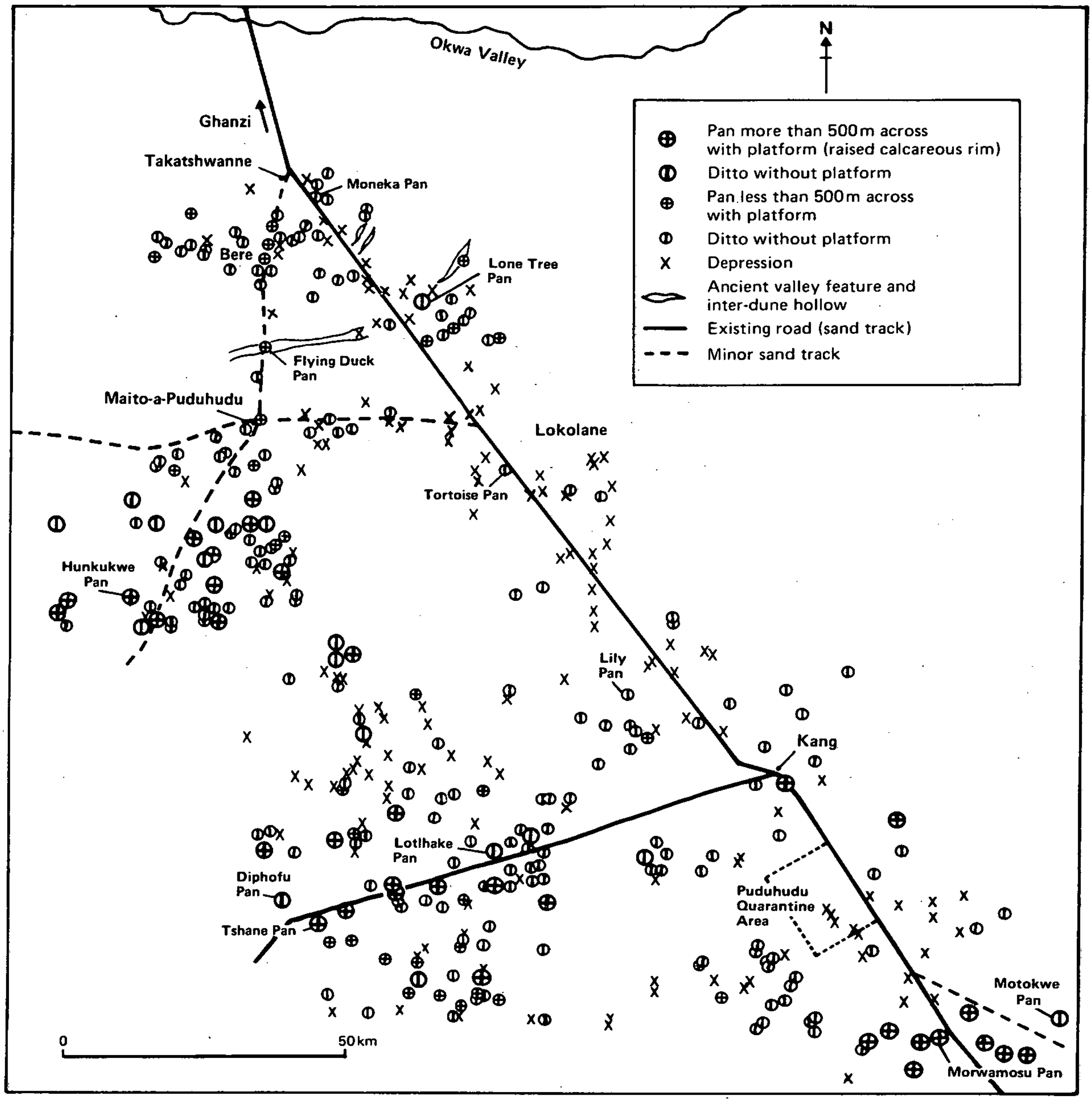

Fig. 3 Map of calcrete-bearing features between Morwamosu and Takatshwanne

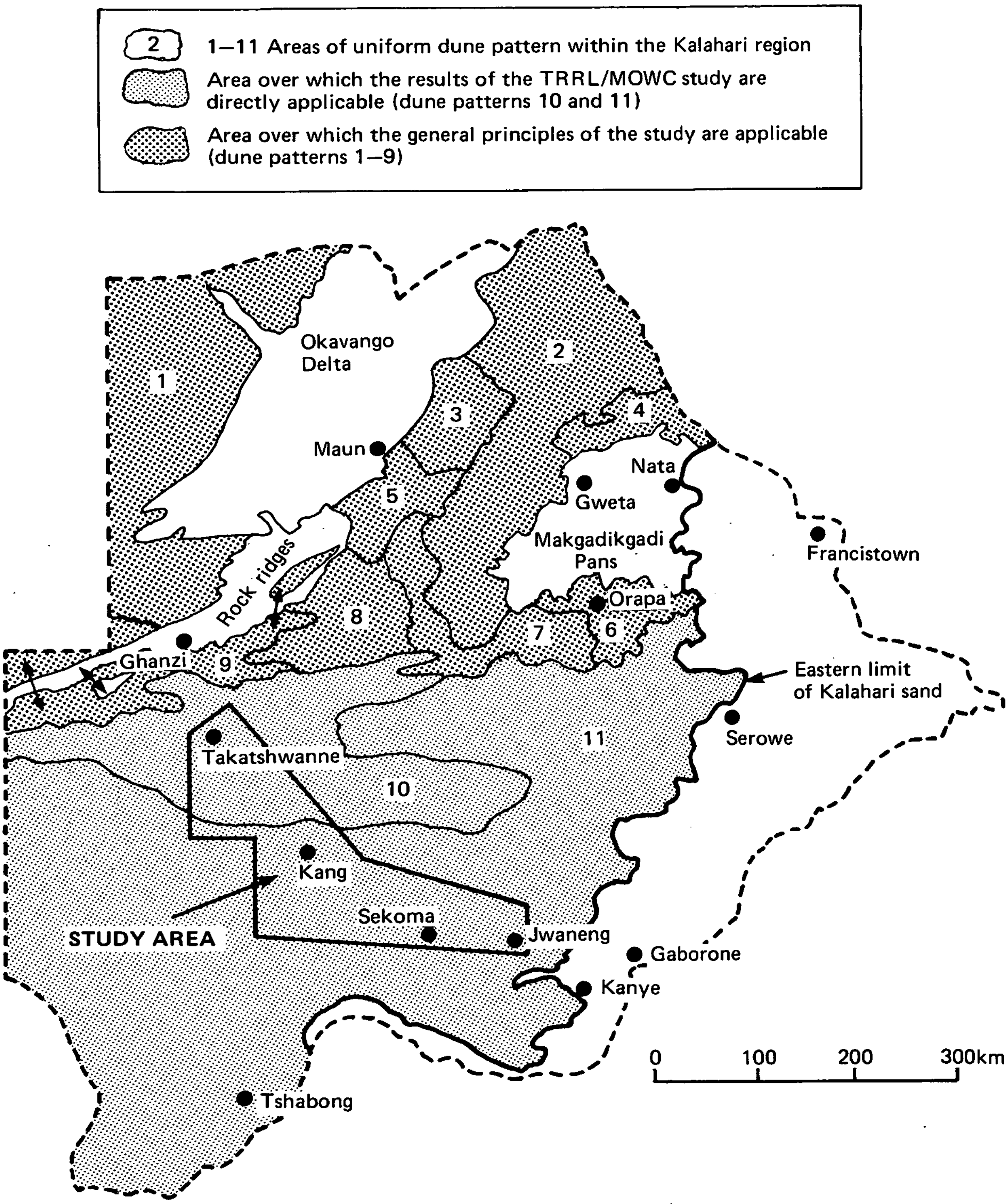

Fig. 4 Classification of sand dune patterns in Botswana

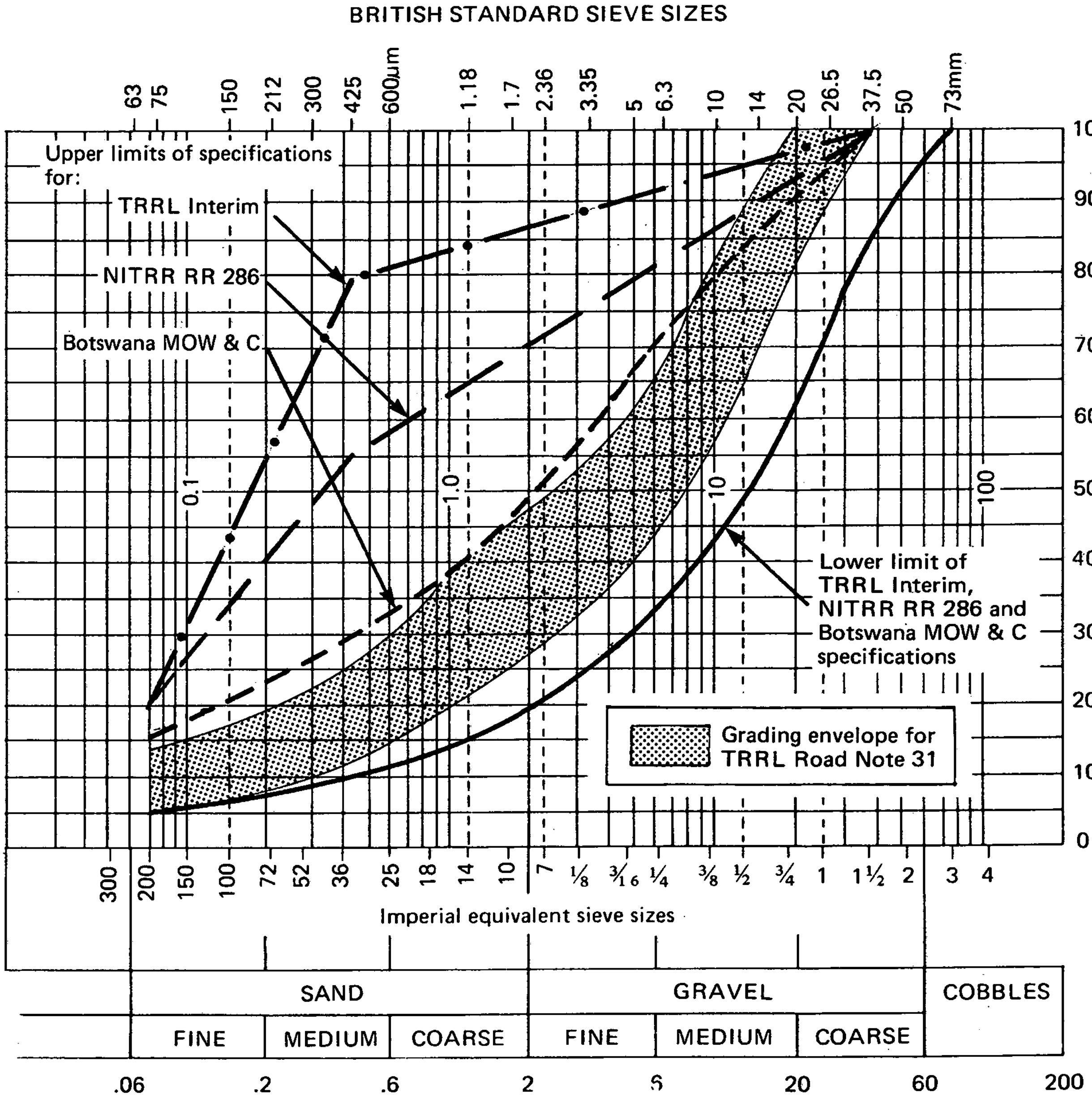

Fig. 5 Comparitive grading envelopes for four specifications of natural gravel road bases

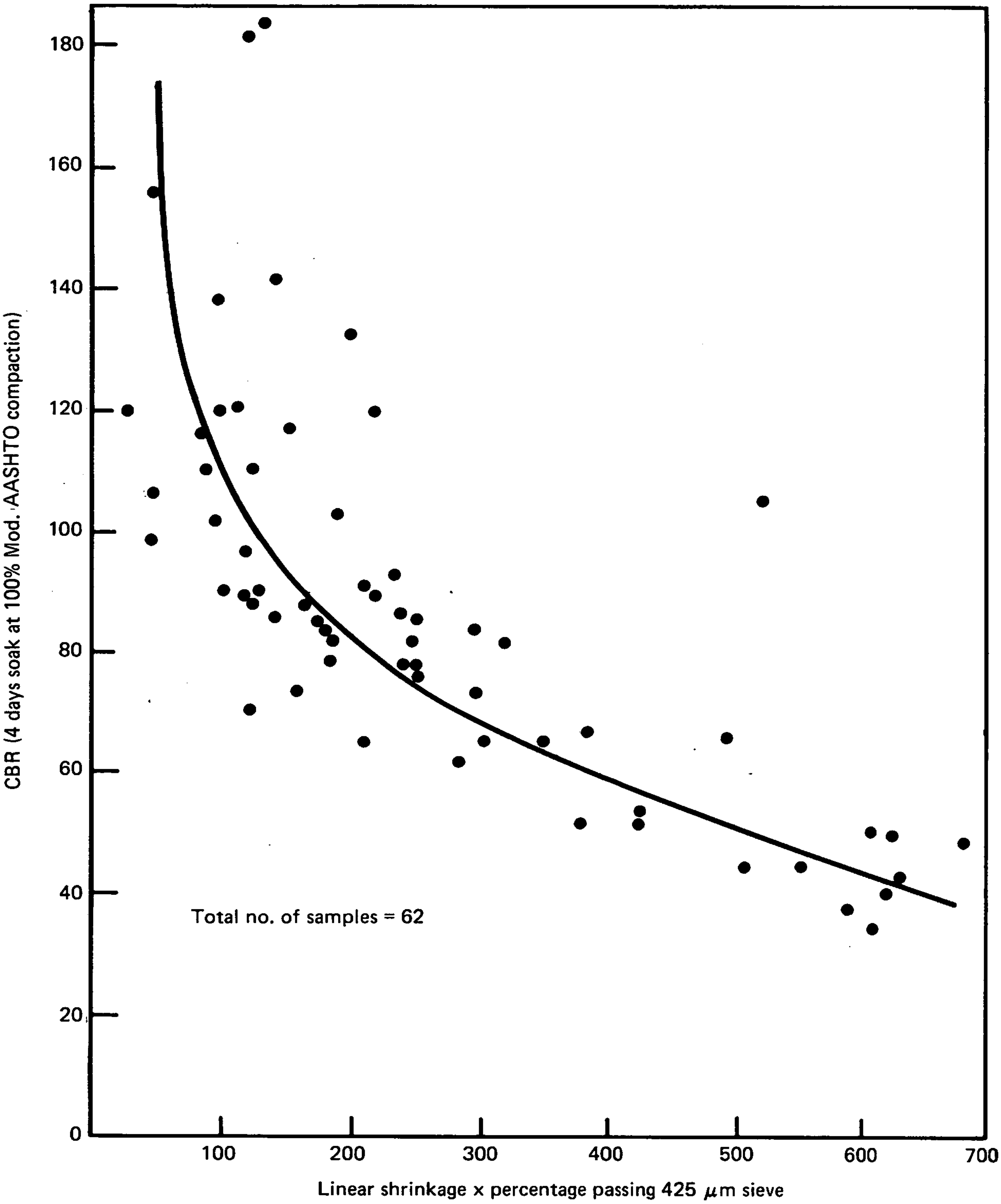

Fig. 6 Relationship between California Bearing Ratio and product of linear shrinkage and percentage passing 425 μm sieve (curve fitted by eye)

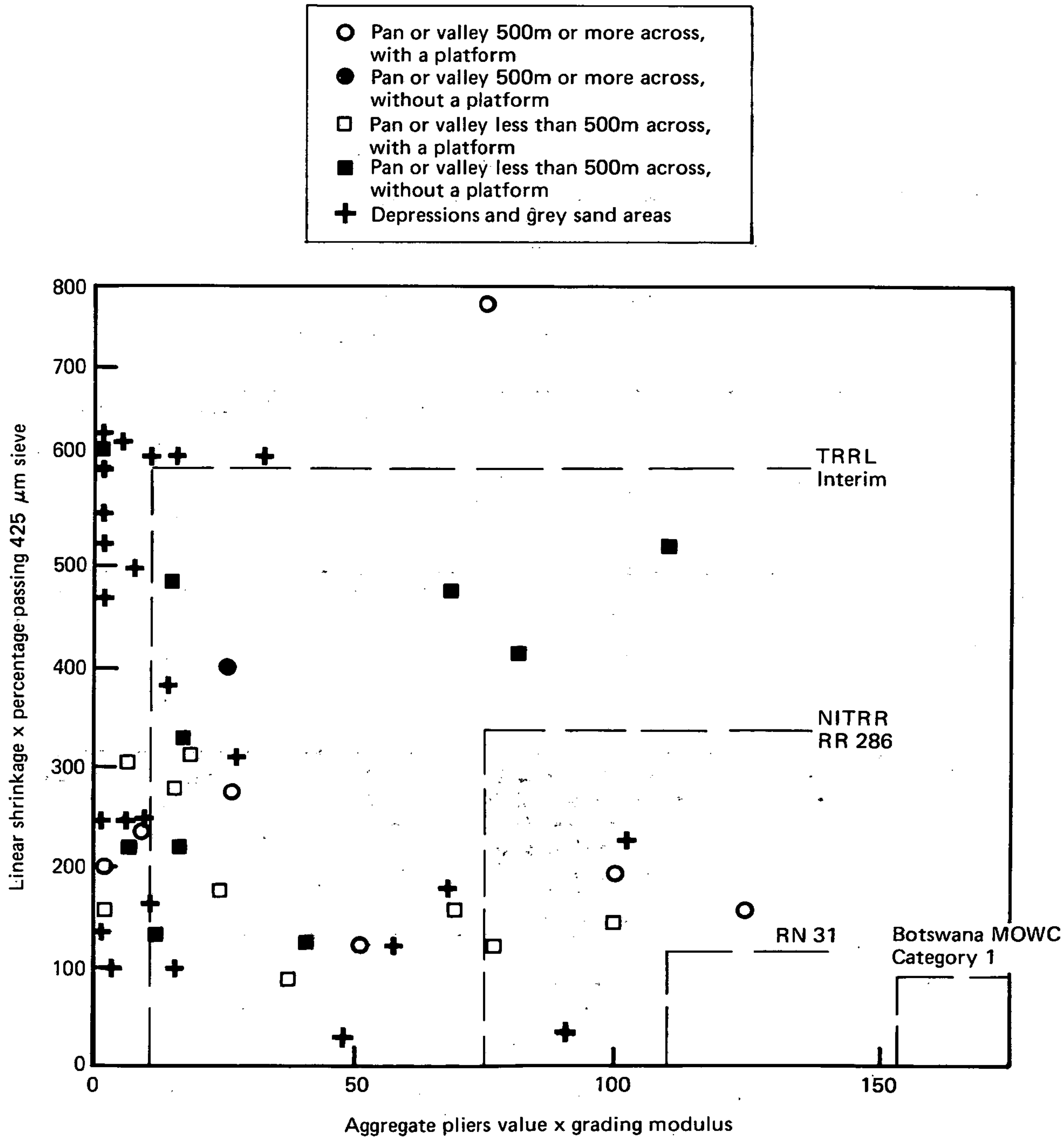

Fig. 7 Relationship between laboratory test properties of calcretes, and landform

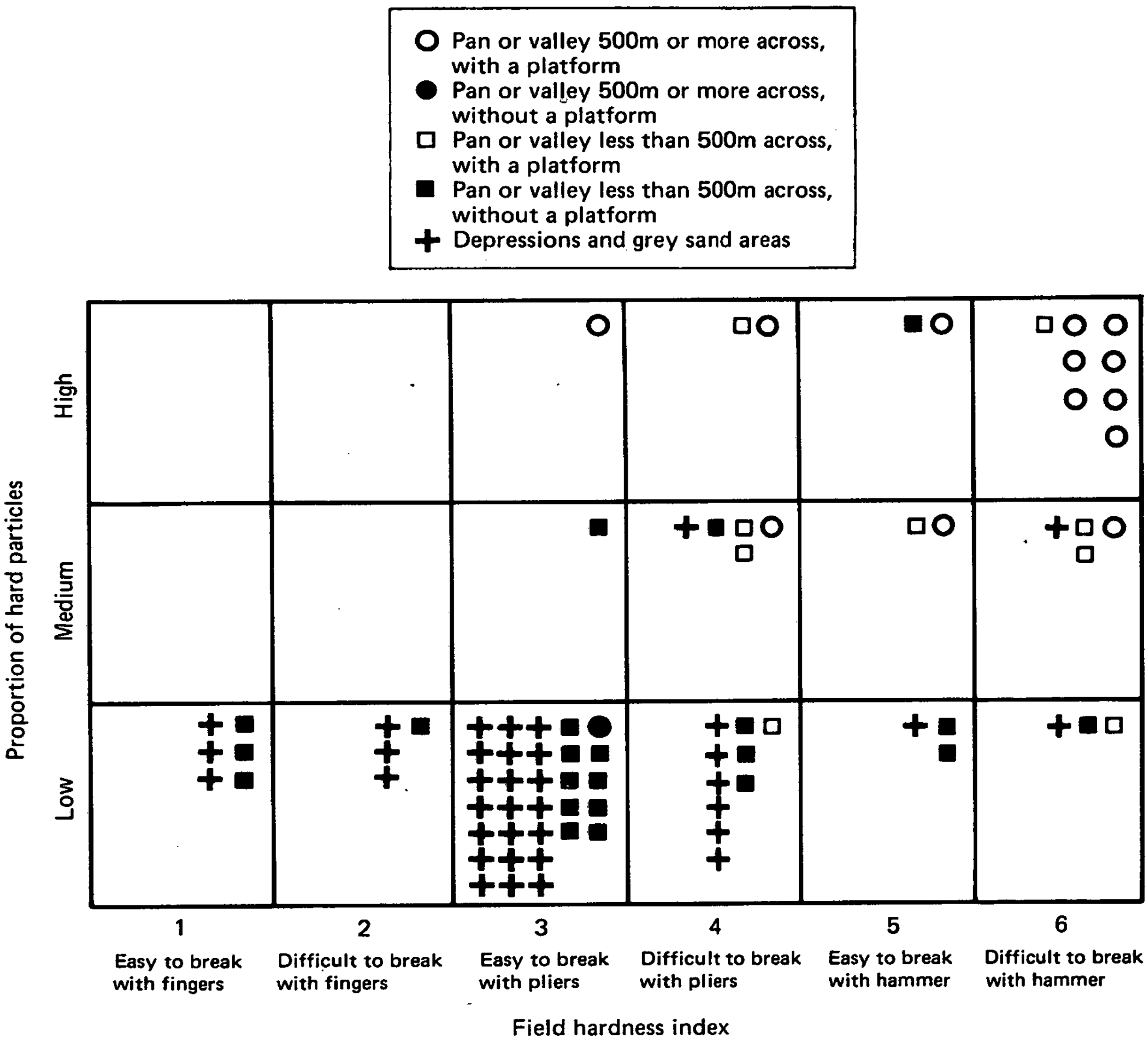

Fig. 8 Qualitative assessment of hardness of calcrete particles

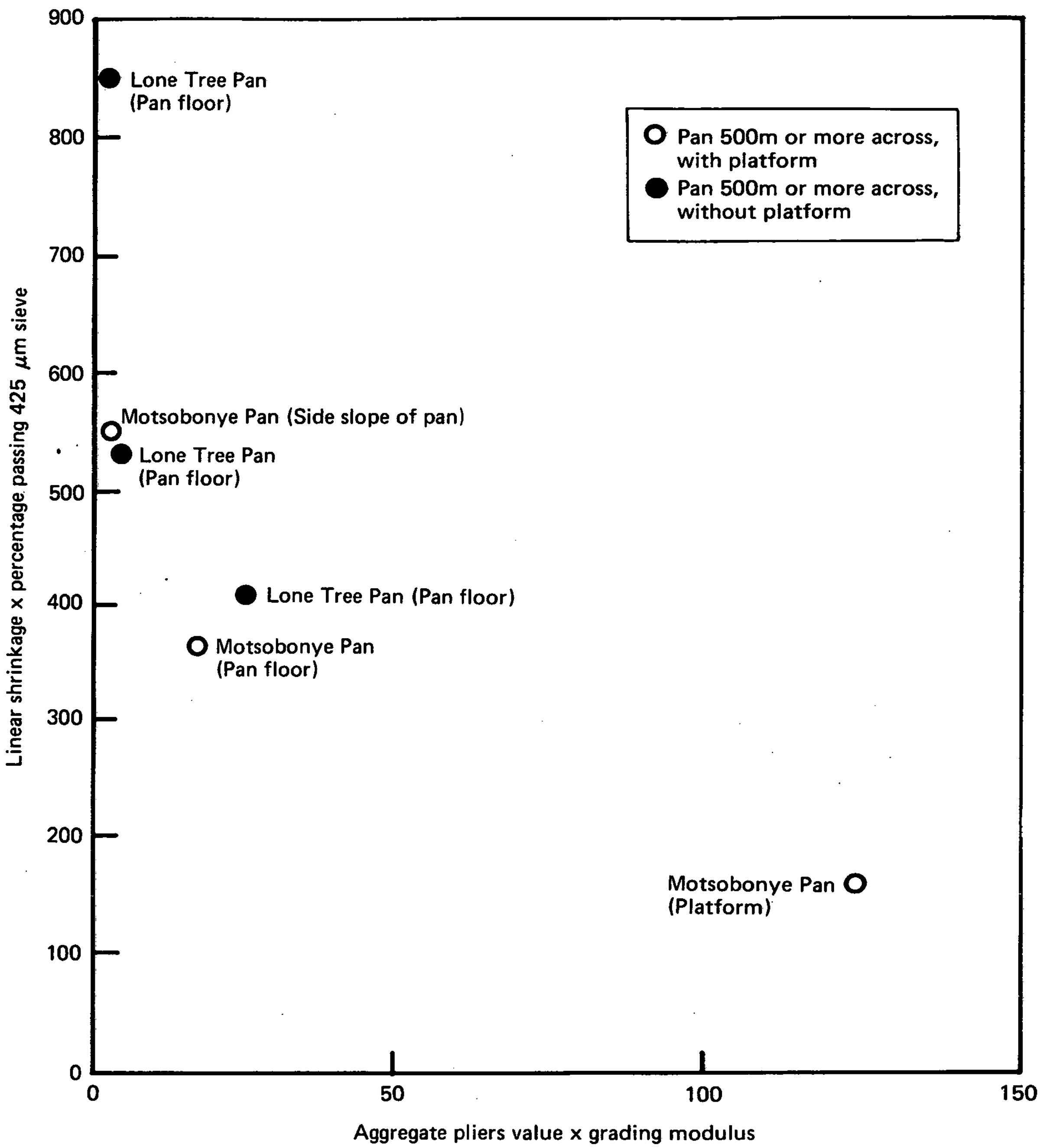

Fig. 9 Variability of calcrete test properties within a landform feature

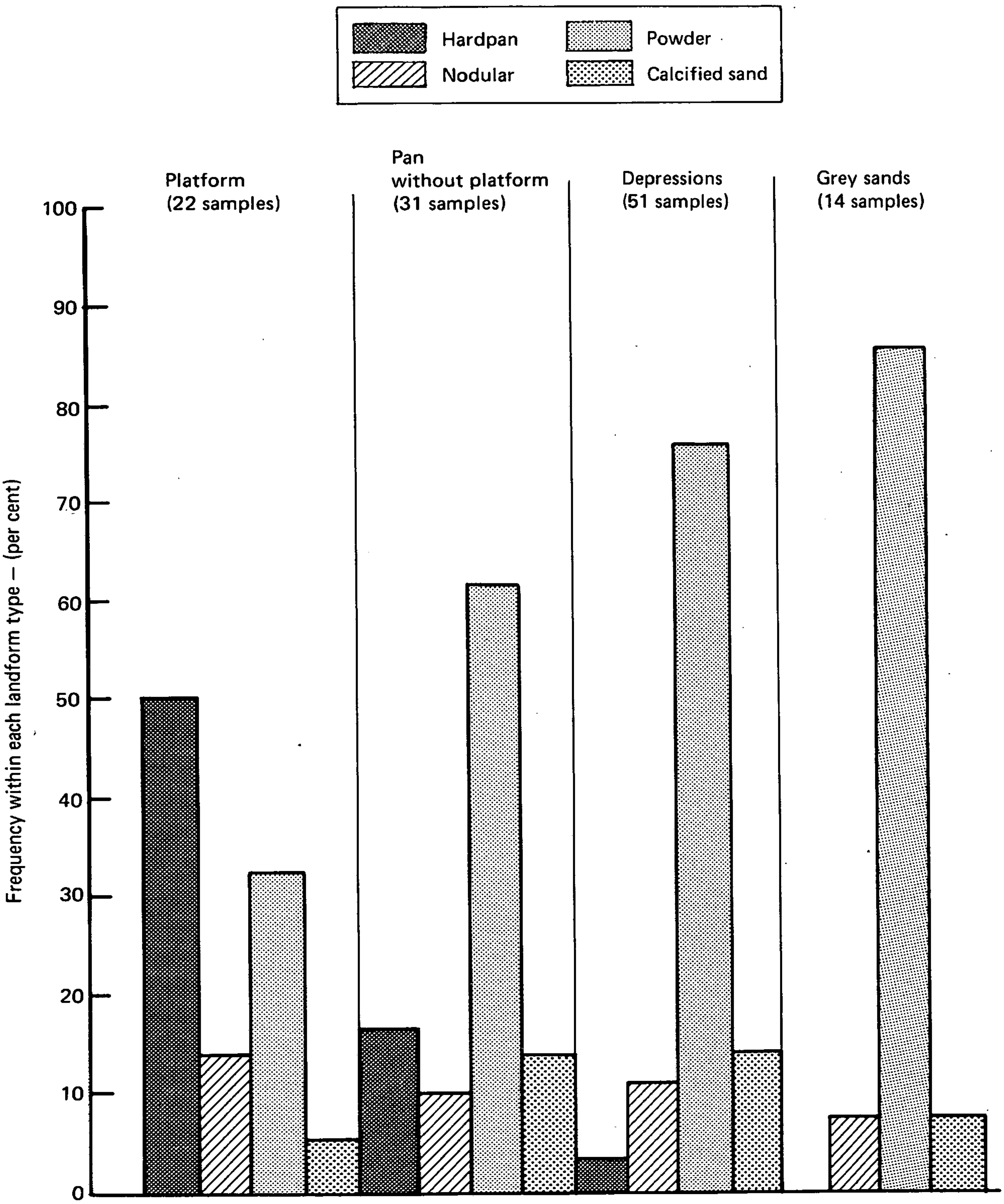

Fig. 10 Relative frequency of calcrete types occurring within calcrete-bearing landforms

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Plate 1 Kalahari sand landscape near Jwaneng. Vegetation cover of knee-high tufted grasses with exposed sand between, and patches of Acacia trees and shrubs

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Plate 2 View across ancient linear sand dunes near Takatshwanne. Viewpoint is from the top of a dune looking across an inter-dune hollow to the next dune. Note change of vegetation between crest and hollow, and denser vegetation than the grasslands further south, shown in Plate 1

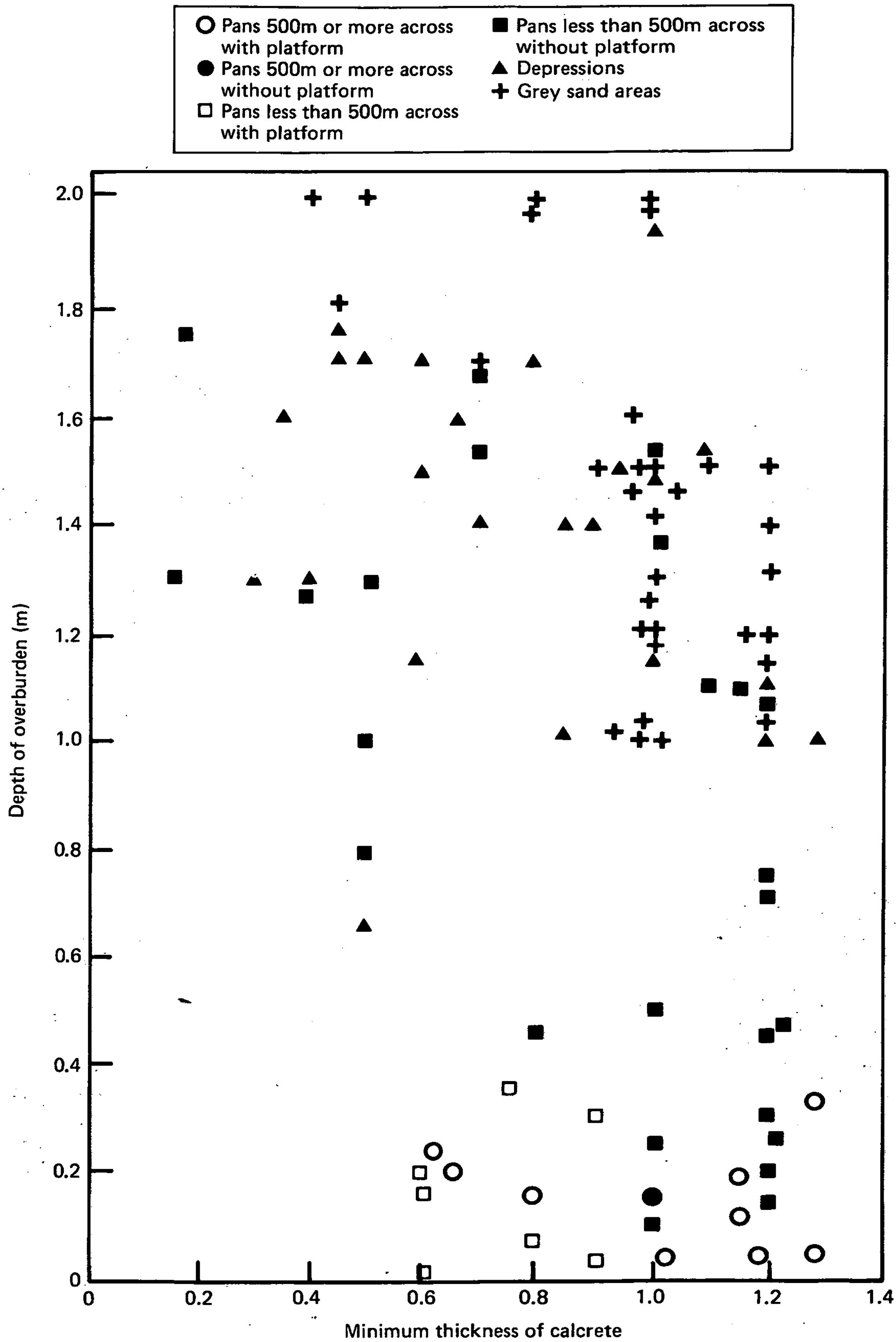

Fig. 11 Overburden and thickness of calcrete related to landform

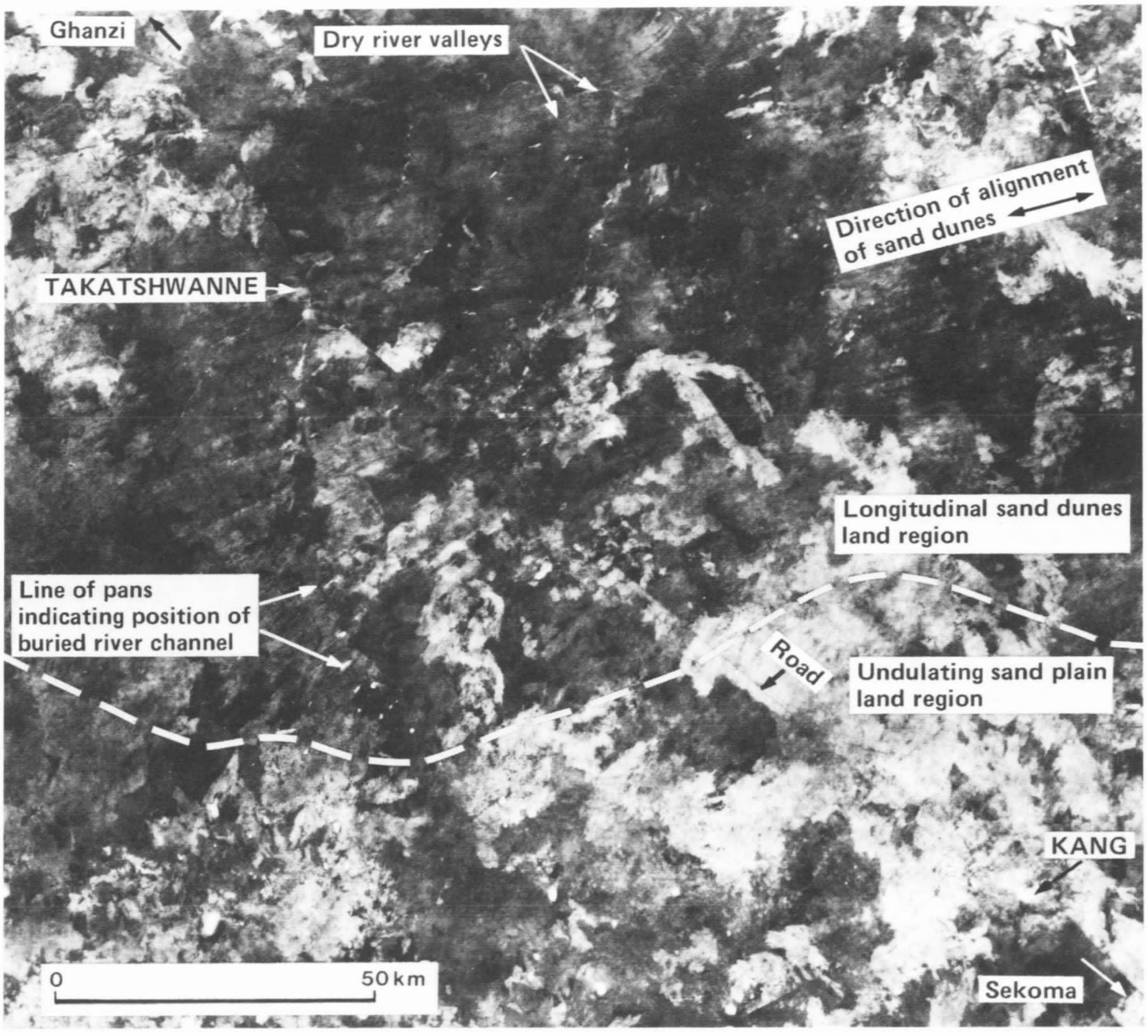

Plate 3 Landsat satellite image of Kang-Takatshwanne area. Date 19 May, 1979
Multi-spectral scanner band 5 (red)

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Plate 4 The platform is the area upon which the person and car are standing, raised about 1.5m above the pan floor

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Plate 5 Small grassy pan, 250 m across. Acacia mellifera, a calcrete-indicating shrub, is growing in the foreground. Note the absence of large shrubs in the pan itself

Plate 6 Depression. The depression is occupied by a group of trees behind the person in the middle distance

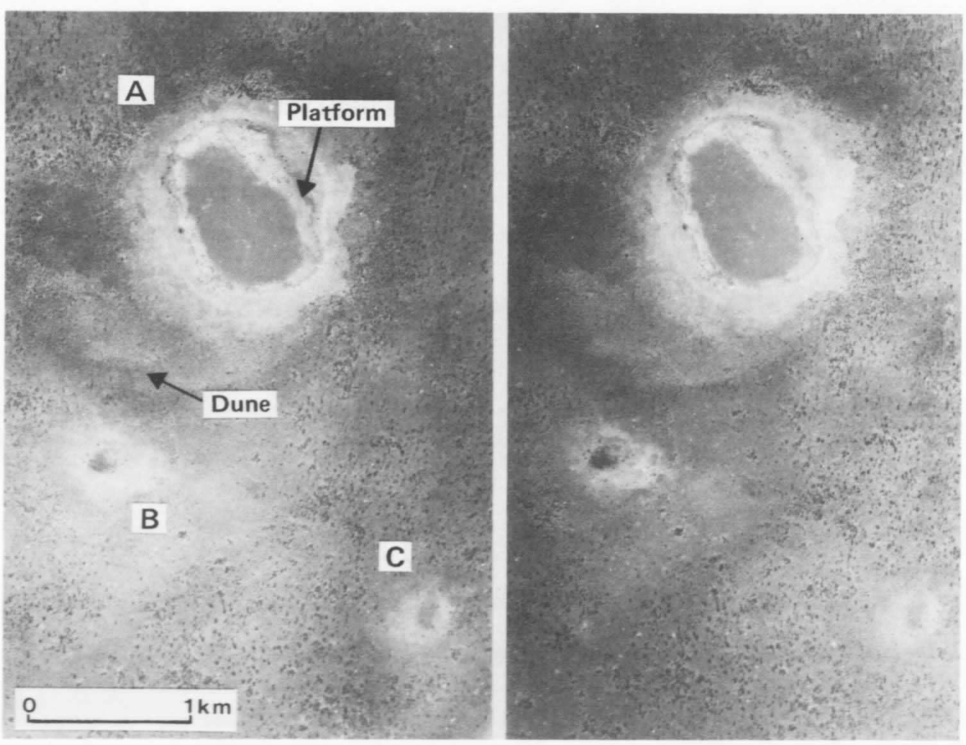


Plate 7 Stereoscopic pair of aerial photographs showing a large pan with platform (Diridiri Pan, A), and two small pans (B andC). Original in colour at 1:15 000 scale (TRRL photograph)

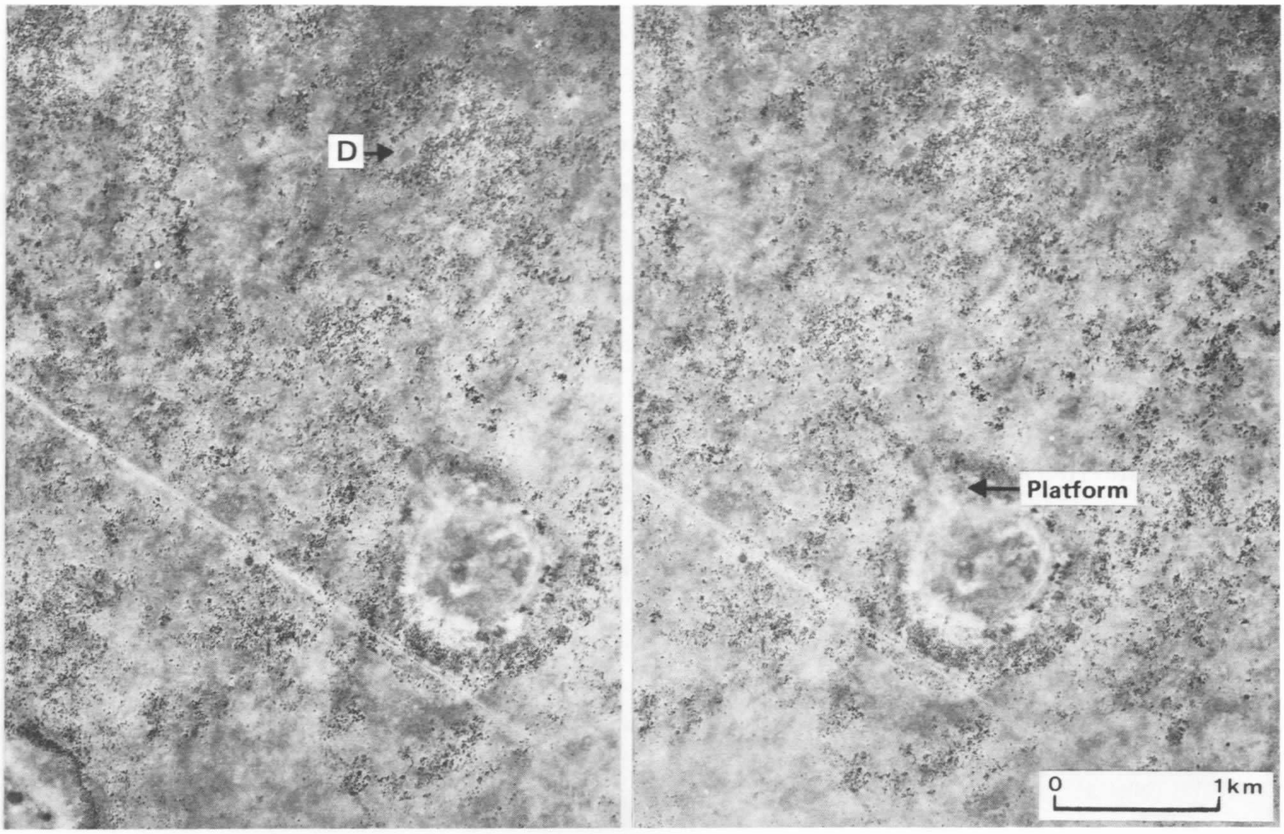


Plate 8 Stereoscopic pair of aerial photographs showing a large pan with a platform at the northern end. A depression (D) is also shown. Original in black and white at 1:50 000 scale

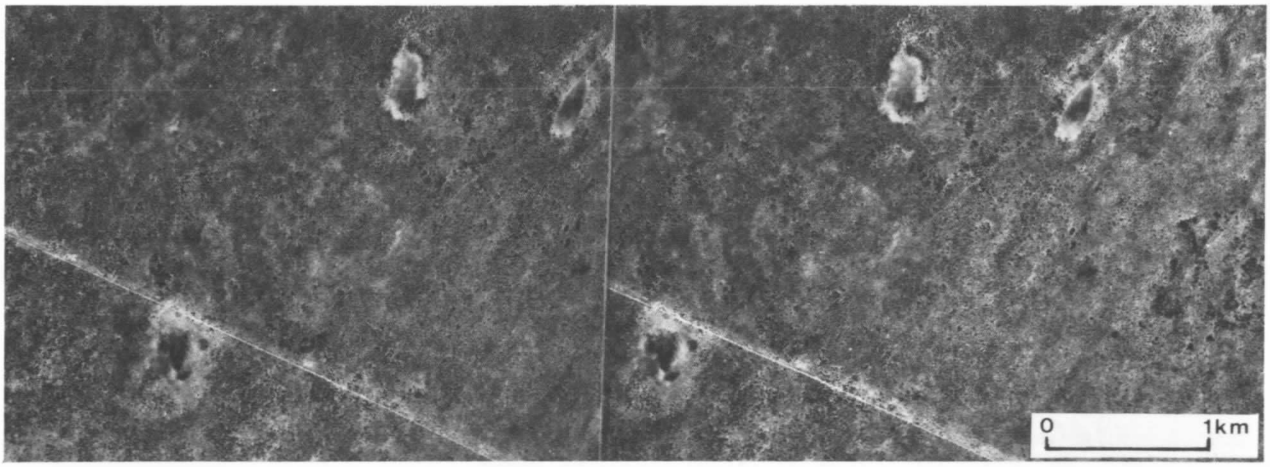


Plate 9 Stereoscopic pair of aerial photographs showing three small bare pans. The largest has a small platform at its southern end

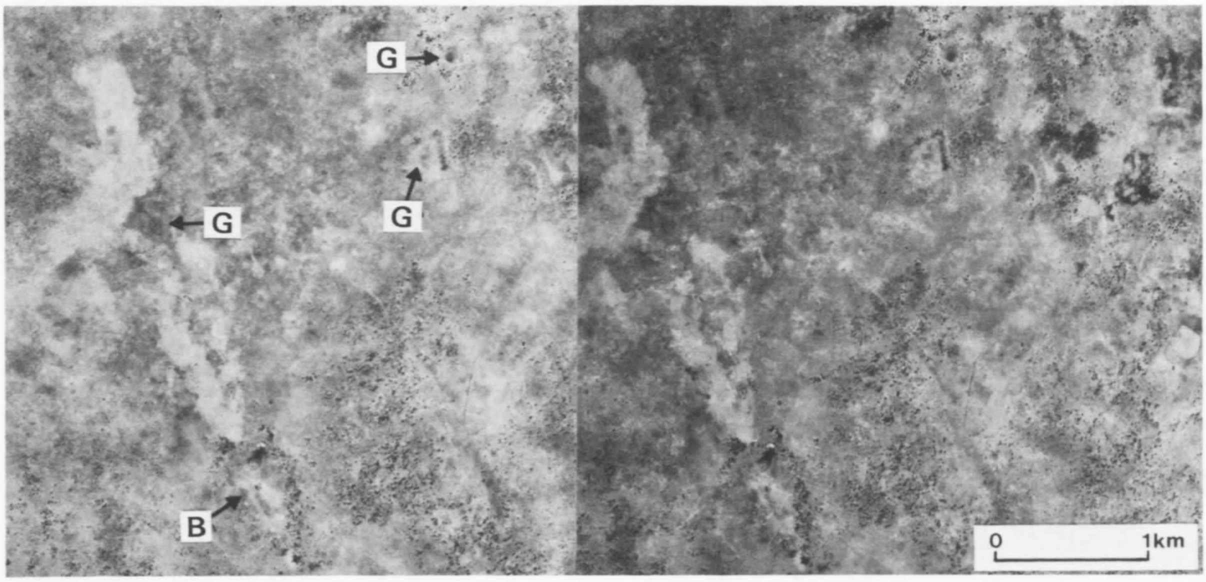


Plate 10 Stereoscopic pair of aerial photographs showing four small pans (B and G). The largest, a bare pan (B), contains a small development of platform. Three grassed pans (G), almost invisible unless viewed under a stereoscope, illustrate the difficulty of picking out calcrete-bearing features in this low-contrast terrain

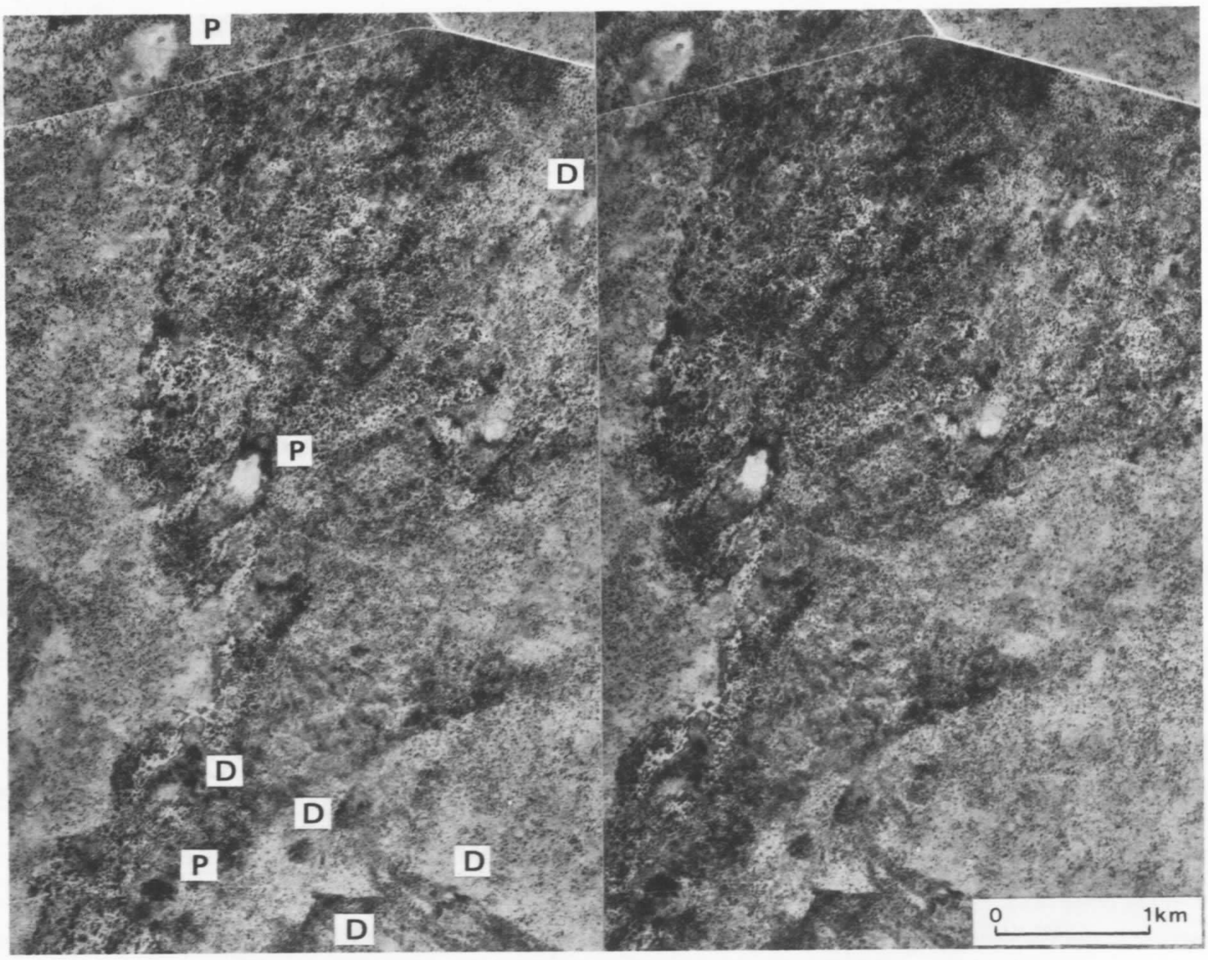


Plate 11 Stereoscopic pair of aerial photographs showing pans (P) and depressions(D) lying in what is thought to be the course of an ancient watercourse, now buried. The dark areas of burnt grassland are thought to indicate the approximate zone of water influence

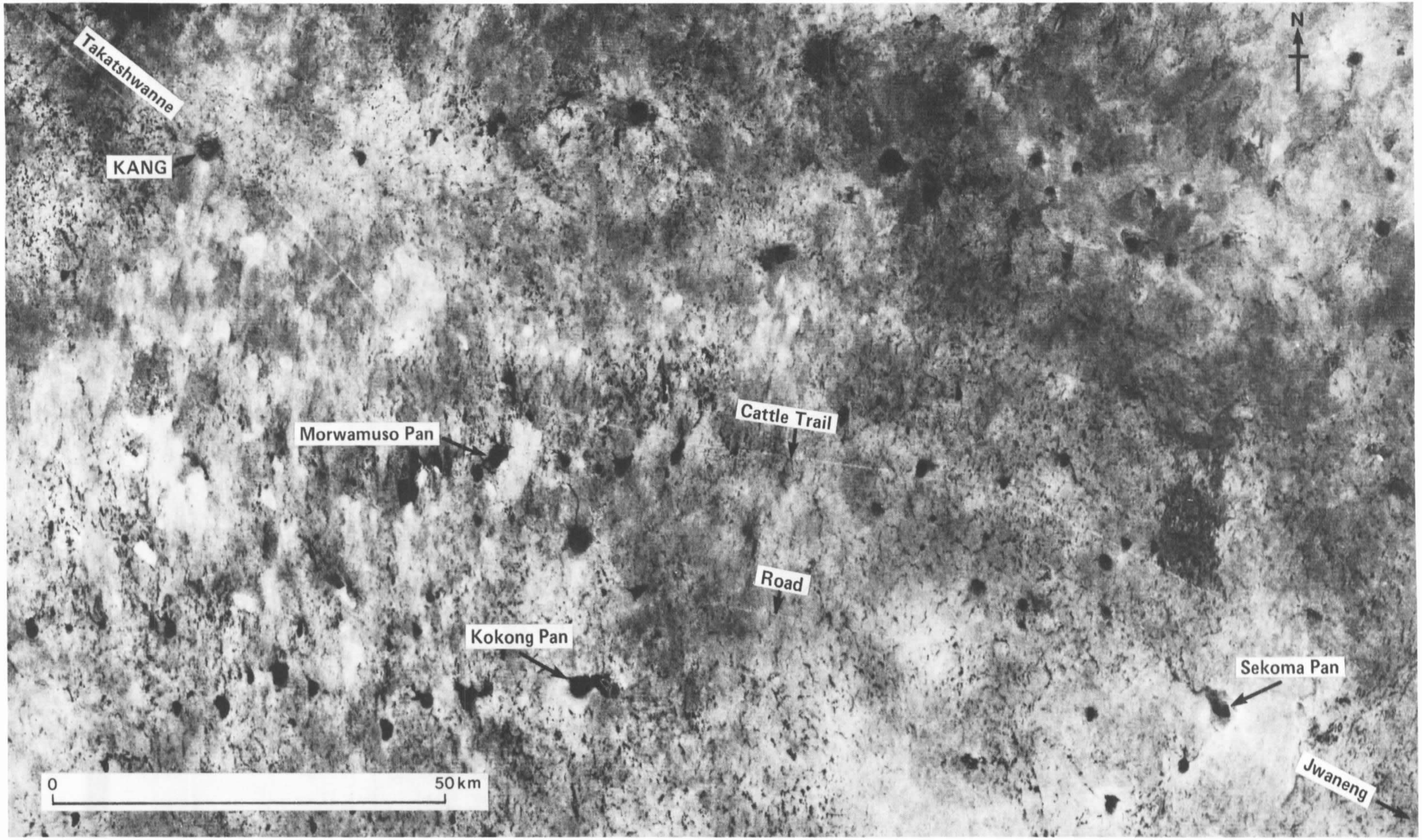


Plate 12 Landsat satellite image of Sekoma – Kang area. Image of the second principal component, generated by computer from original data. Pans and grey sands shown in black

APPENDIX 1

THE TRRL FULL SCALE EXPERIMENT

Following detailed field surveys of materials along the alignment of the existing Kanye-Ghanzi road, four different types of calcrete representing a range of those found within the route corridor were selected for use in a TRRL full-scale experiment at Jwaneng. The main aim of the experiment was to assess calcretes for use as road bases for lightly-trafficked bituminous sealed roads in Botswana. The seal is used to protect the base from abrasion, and can be economic even on roads carrying very little traffic in areas where only soft calcretes are available, or where maintenance teams cannot cope effectively with the maintenance of very long lengths of road.

Jwaneng was a convenient location for the experiment because there exists a deep sand cover overlying bed-rock that is typical of conditions in the Kalahari region. Jwaneng is situated on the route from Kanye to Sekoma and Ghanzi, and is the site of a new town that has been built to service a recently-opened diamond mine. The level of traffic moving in and out of Jwaneng during the development of the mining area subjected the road to a heavy axle loading in the early life of the experiment.

For the experiment eleven sections of road, each 100 m long, were constructed using the four selected calcretes. The engineering properties of the calcretes are summarised in Table 1. The compacted layer thickness of the base in each section was 150 mm and this was laid directly onto the compacted Kalahari sand. A separate sub-base layer was not considered necessary as the CBR strength of the Kalahari sand was in excess of 25, at both the field density and when compacted in the laboratory at the BS maximum dry density and optimum moisture content (2.5 kg rammer method). The sand was not tested in the soaked condition because the overlying base and surface dressing were considered to be effectively impermeable under the prevailing climatic conditions.

TABLE 1

Summary of laboratory test results for the four types of calcrete used as road base in the TRRL full scale experiment

Material description	LL	PI	LS	Grading Modulus (Note 1)	Maximum nominal size (mm)	% passing 425 μm	% passing 75 μm	Aggregate pliers value (%)	BS Heavy compaction		
									MDD (Kg/m³)	OMC (%)	4 Day soak CBR (%)
Hardpan calcrete	28	8	3.7	2.2	75	34	6	23	1972	9.5	110
Nodular calcrete	57	31	13.8	2.07	75	38	11	53	1964	10.5	105
Powder calcrete	36	7	2.9	1.88	75	44	15	6	1490	25.0	90
Plastic powder calcrete	41	17	7.6	1.15	37.5	80	20	28	1836	12.2	50

Note 1 Grading modulus $= \frac{300 - \text{sum of \% material passing } 2.0 \text{ mm} + 0.425 \text{ mm} + 0.075 \text{ mm sieves}}{100}$

As well as the overall aim of assessing calcretes for road bases the full scale experiment was designed to examine:-

(i) the effect of cement stabilisation and lime stabilisation on a poor quality calcrete. In areas where good quality calcrete is scarce the stabilisation of poor calcretes may prove to be economical.

(ii) the effect of mechanical stabilisation on good quality calcrete when mixed with an equal proportion of Kalahari sand. The reduction in the amount of calcrete hauled could reduce construction costs.

(iii) the effect of compacting calcrete at a moisture content considerably drier than the optimum moisture content for compaction (BS 4.5 kg rammer method) to determine whether, in an arid environment, the amount of water normally required for compaction can be reduced.

From the time of construction in November 1979 until May 1984 the number of equivalent standard axles passing over the road amounted to 113,400 during which time all the experimental sections performed satisfactorily. A full account of the experiment, monitoring programme and test results is being prepared.

From the results of the experiment so far it has been possible to introduce a new specification for calcretes into the Botswana Road Design Manual (Ministry of Works and Communications 1982) for traffic levels up to 100,000 standard axles. The experiment will continue to be monitored in order to determine the highest traffic loadings that each type of calcrete can accept, from which a final specification for various traffic categories will be derived. It is already clear that the standard of construction used in the full scale experiment can confidently be applied to the design of the Sekoma-Ghanzi road.

In the full-scale experiment the performance of different bituminous seals on the different types of calcrete base has also been examined. The work has shown that single or double surface treatments have performed satisfactorily on all the calcretes. Sand seals using the local Kalahari sand have only performed satisfactorily on the better quality calcretes, that is those containing an appreciable quantity of coarse hard particles. These provide a surface finish that permits good penetration of the binder film. Extensive potholing occurred to a powder calcrete with a sand seal, due to poor penetration of the prime coat into the base. Trampling by cattle hooves caused the surface dressing to separate from the base, leaving a damaged road surface that turned to potholes. (Any road in the central Kalahari is likely to be subjected to high point loading from cattle hooves). For the design of the Sekoma-Ghanzi road, sand seals can only be considered when good quality calcrete is available for construction of the road base.

APPENDIX 2

TYPES OF CALCRETE OCCURRING WITHIN THE STUDY AREA

Calcrete is a member of the pedogenic soils group, in which a host soil is modified by the addition of soluble minerals brought in by groundwater. In Botswana the host soil is the medium to fine-grained Kalahari sand, to which carbonates of calcium or magnesium are added to form rubbly or nodular horizons within the sand. Calcretes are widely distributed throughout the Kalahari region of southern Africa, both laterally and vertically in the sand. But it is thought that they are all fossil forms and that none is forming today in central Botswana.

The amount and type of carbonate present, and its degree of crystallinity, give rise to a variety of calcareous deposits, all called calcrete, varying from loose calcified sand to massive, hard "rock". The proportion of sand to carbonate, and the degree of induration, determine its hardness and to some extent its grading, two of its most important properties from an engineering point of view. A certain amount of mineral fine material is also introduced into many calcretes during their formation, by the action of groundwater.

The four main groups of calcrete recognised in the course of a field survey of the Jwaneng-Takatshwanne route corridor may be defined as follows. The range of grading in calcrete is illustrated by particle-size distribution curves of four calcretes taken from the study area, shown in Fig. 1.

1) *Calcified (or calcareous) sand* (Plates 1 and 2) consists mostly of host soil grains and may exhibit the characteristic uniform particle-size distribution of an unaltered Kalahari sand. Weak cementation between sand grains may have occurred although the in-situ deposit is generally loose and of a whitish-yellow colour. The amount of calcium carbonate is normally low (often less than ten per cent by weight) and any gravel-sized particles are easily broken.

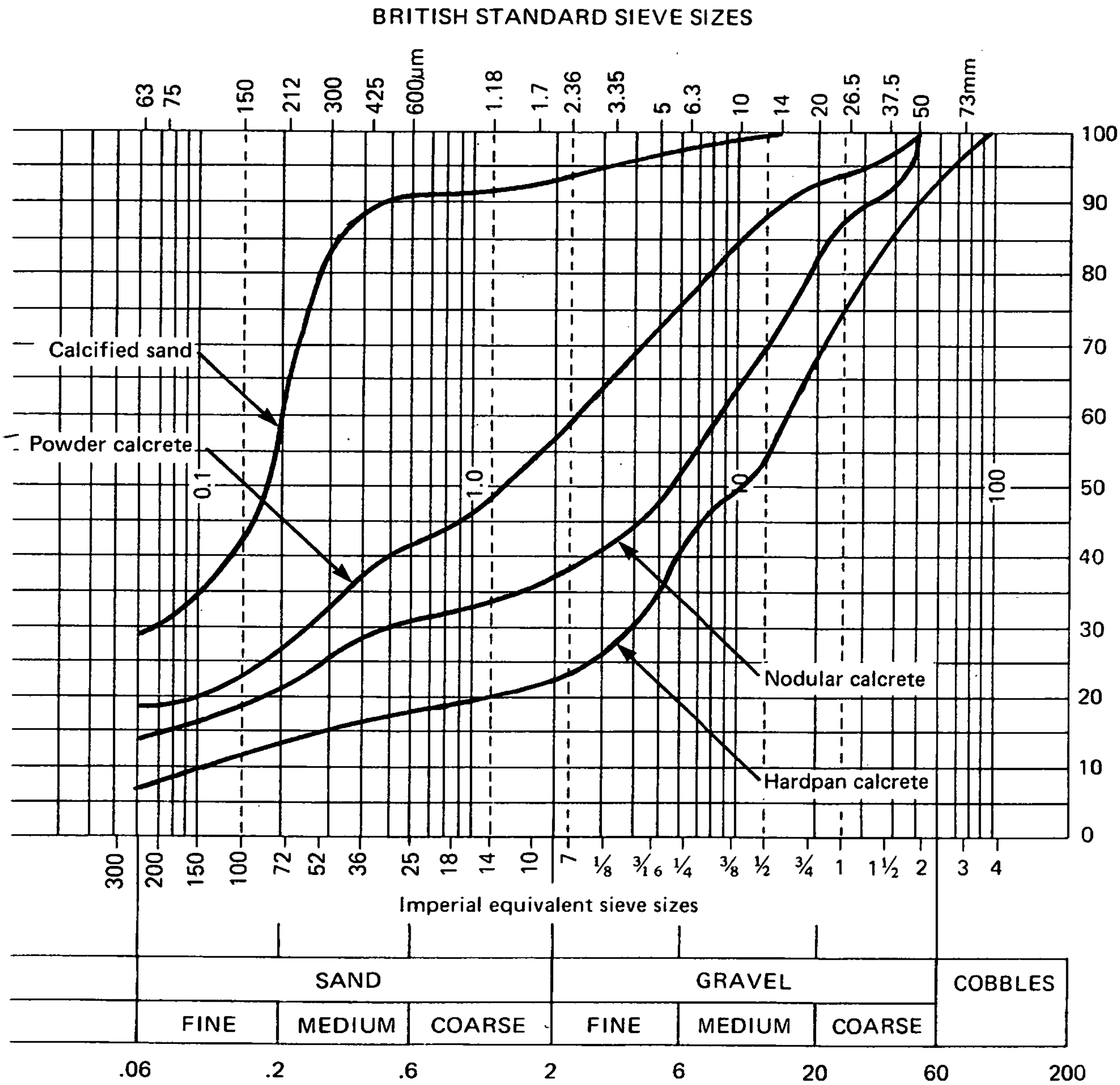
2) *Powder calcrete* (Plates 1 and 3) contains a higher proportion of calcium carbonate (greater than thirty per cent) with the host soil grains proportionately less visible. The in-situ material may have acquired a laminar, blocky or massive structure, and can normally be excavated with a pickaxe, although it can be very tough and difficult to remove. With restricted handling the material may retain its original proportions of the various fractions but due to its essentially soft nature, being composed largely of a fragmented mass, it is easily broken down in handling.

3) *Hardpan calcrete* (Plates 1 and 4) may be considered as a development of a powder calcrete into a calcrete rock. The calcrete is generally much harder, and excavation requires the use of a mechanical ripper. Subsequent breakdown of particles during handling and compaction is considerably less than powder calcrete, and frequently crushing, screening or grid rolling is necessary to remove oversized pieces or reduce them to a specified maximum size.

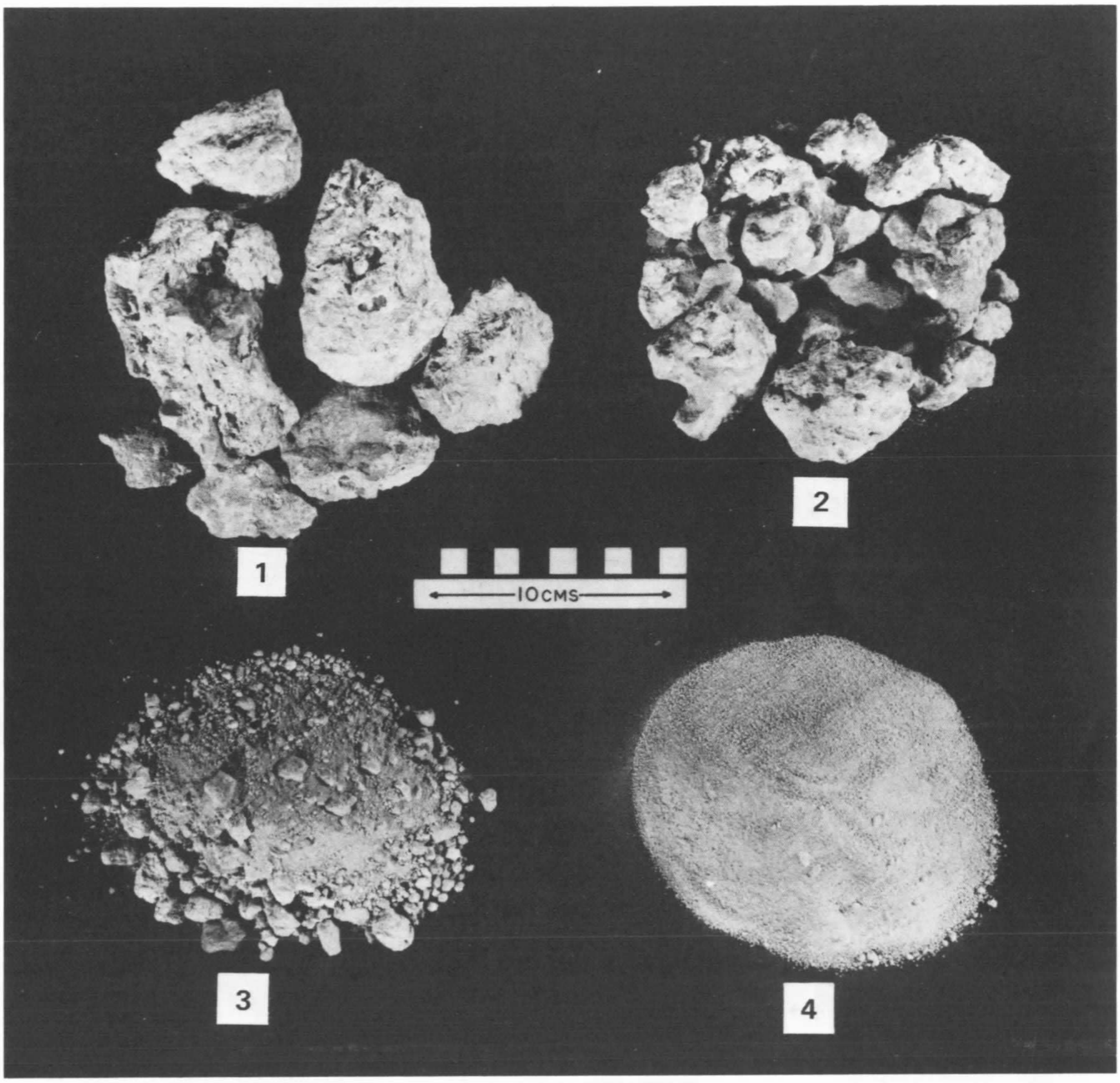
   Completely indurated hardpan separates into discrete boulders upon weathering, to form "boulder" calcrete. Unweathered, massive hardpan and large boulders can be very difficult to remove and blasting may be necessary. However, the material may be useful in areas where no rock exists, for it can be hard enough to be used as a high quality road base or surfacing aggregate.

4) *Nodular calcrete* (Plates 1 and 5) is a natural calcrete gravel, composed of a high proportion (greater than fifty per cent by weight) of rounded gravel-sized nodules of calcium or magnesium carbonate and quartz, in a matrix of powder calcrete or calcified sand. The material is typified by a generally 'well-graded' particle-size distribution and a hard aggregate fraction, although the hardness of the nodules varies greatly.

Nodular calcretes are often considered the most useful calcrete for pavement layer construction, by virtue of their relatively good grading, lack of oversize particles and mechanical interlock.



App. 2 Fig. 1 Four particle-size distribution curves to illustrate the range of grading found in calcretes



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App.2 Plate 1 Examples of the four main types of calcrete found within the project area. 1 — Hardpan; 2 — Nodular; 3 — Powder; 4 — Calcified sand

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App. 2 Plate 2 Sampling calcified sand. Note the extreme looseness of the material. The upper part of the profile is more coherent, approaching soft powder calcrete

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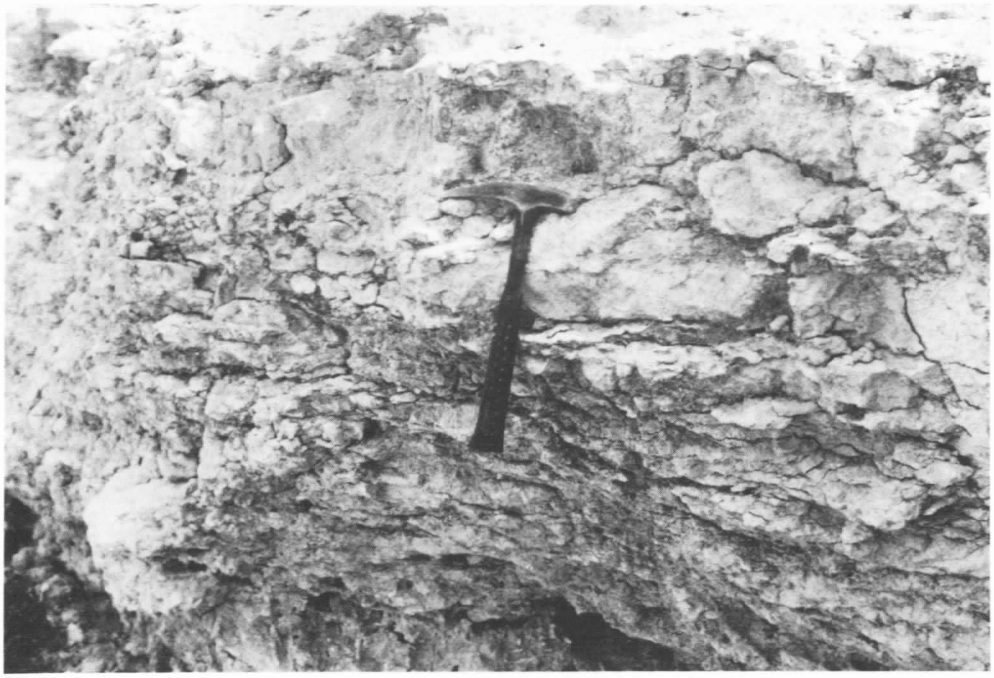
App. 2 Plate 3 Powder calcrete in pit. About 1 m of grey sand and calcrete rubble overlies a massive blocky horizon of powder calcrete. A geological hammer towards the right rests on a junction between the powder calcrete and underlying calcified sand



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App. 2 Plate 4 Hardpan calcrete. The horizontal laminar structure is typical. The material grades downwards into tough powder calcrete at the bottom of the photograph

App. 2 Plate 5 Nodular calcrete. The hammer rests on the junction between a horizon of densely packed nodules and loose nodules in a matrix of powder calcrete

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ABSTRACT

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The mapping study compared different remote sensing techniques to identify calcrete landforms in a corridor between Jwaneng and Ghanzi (17,000 sq km), considered to be typical of southern Botswana. Test strips of colour and multispectral small format aerial photography were specially flown, but it was found that the full range of calcrete landforms can be identified using standard black and white aerial photographs, which provide good detail and a stereoscopic view, and Landsat imagery, which provide colour differentiation, especially when digital images are enhanced by computer.

The engineering properties of calcrete were studied in the laboratory and on site. It is recommended that grading, hardness and plasticity are measured in the field as an initial assessment of quality. A full scale road experiment, constructed using a range of calcretes, including soft types, has successfully carried more than 100,000 equivalent standard axles of traffic, and has been used to establish a new specification for sealed calcrete bases in lightly trafficked roads.

Recommendations are given for planning calcrete surveys, and a map showing potential sources of calcrete in the project area is included.

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