CONCLUSIONS

The use of percentage volumes as a sedimentary parameter offers advantages in a prospecting operation where precision is not so important as in academic programmes, but where time is very important. The sedimentary parameters such as the median, sorting coefficient and the skewness can be expressed as percentage volumes as well as percentage weights.

In an aeolian environment it is possible to prospect for shallow subsurface environments by analysing the relict sedimentary characteristics of surface samples in terms of models constructed from the different environments. This method can give viable drilling targets with the minimum of time and expense.

These sediments formed in an aeolian environment subject to subordinate water action. This environment was achieved during the northward shift of the climatic belts during the last hypothermal of 70 000 to 10 000 BP.

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ANCIENT LAKE MAKGADIKGADI, BOTSWANA: MAPPING, MEASUREMENT AND PALAEOCLIMATIC SIGNIFICANCE

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INTRODUCTION: THE KALAHARI PROJECT

From June 1975 until September 1976, the Kalahari Project, a multidisciplinary research group based at the University of New Mexico (Albuquerque, USA) conducted a program of archaeological, ethnographic and ecological studies in the Central District of Botswana (Ebert, et al 1976a). During the course of this fieldwork, a number of specific problems were addressed, including the transition from Middle to Late Stone Age technologies in southern Africa, the beginnings of food production, sedentism and the Iron Age, and mobility, sedentism and development among present-day Bushmen (Basarwa). Tying these areas of research together, however - and hopefully lending them some credence outside academic circles - was the assumption that both past and present development, especially in the moisture-stressed inner reaches of southern Africa, are joined by the common thread of climate. A major data gathering focus, then, in Kalahari Project studies is both instrumental and proxy evicence of long-term, short-term and directional climate change. Instrumental records dating to the late 1800's were collected from the governments of Botswana, Rhodesia, Zambia and South Africa and are currently being analyzed for evidence of cycles of climatic fluctuation. It has been suggested that, particularly in sub-Saharan Africa, one of the major factors in cyclic fluctuations in mean temperature is dust loading (volcanic or aeolian) in the atmosphere (Roosen et al, 1973, 1976); to investigate this possibility, a series of twice-daily measurements of the atmospheric transmission of solar radiation was made using a Volz sunphotometer and aureole photometer (Ebert et al, 1976b).

While instrumental indications are useful in determining shorter-term climatic fluctuations, however, a far greater body of information on past climate change is contained in the proxy record, which is comprised of geological and other natural indications and presently-evolved ecological distributions. Since these are often of a regional nature, remote sensing methods were employed for their detection and measurement.

REMOTE SENSING IN KALAHARI PROJECT RESEARCH

Remote sensing, the use of aerial or space photography or other imagery for the apprehension and measurement of phenomena on the surface of the earth, offers a fast and efficient means of "covering" large areas at relatively low cost, and can aid any research which requires the comprehension of geographic distributions at all stages of planning, execution and analysis. Kalahari Project uses of aerial imagery included logistics and supply planning, the location of Basarwa villages and settlements, the measurement of ecological diversity for comparison with present hunter-gatherer subsistence patterns, and the mapping of bush fires in the Kalahari. Even more useful than aerial imagery, however, in the consideration of periodic variation in the environment and large-scale geologic and ecological patterning is Landsat space imagery. Landsat imagery is derived from two satellites, the first of which was launched in 1972, devised and operated by the United States Geological Survey Earth Resources Observation Satellite (EROS) Program. These satellites, which collect data by means of 4-band electromagnetic sensora, orbit the earth in sun-synchronous orbits and provide coverage of any spot on the globe each 18 days (every 9 days when both satellites are taken into consideration). Unfortunately, a limited number of receiving stations coupled with on-board recorder failures have made this period somewhat greater, but coverage is still available for most dry-land areas of the world at periods of 1-2 months. For this reason, it was decided that Landsat-1 and -2 imagery would be employed in the inspection of short-term ecological change in Botswana, and experimentation in the measurement of vegetational diversity and its relation so subsistence activities of present-day Basarwa is currently being explored at the Remote Sensing Division, University of New Mexico, USA.

LAKE MAKGADIKGADI

An unexpected side benefit of the inspection of Landsat multispectral scanner (MSS) imagery was the location of an ancient, closed-basin lake in the Central Basin of southern Africa. At present, the lowest point in southern Africa's central plateau lies at the approximate centre of Botswana's Central District, and is occupied by the soda flats of the Sua Pan. Consisting of some 3 000 km , this pan is partially flooded during the summer wet season, being fed by the Nata River from the north, the Botletle from the west, and a number of ephemeral drainages from the east and south; the Nata Basin, the only part of the Sua Pan to be full all year, covers about 185 km and hosts one of the largest flamingo flocks in Africa. Explorers and geologists in Botswana have known of the existence of stretches of remnant lake-shore concentrically surrounding the Sua Pan for some time, suggesting that the pan lies at the centre of a once-greater closed basin lake. During the initial reconnaissance of the survey area using Landsat-1 and -2 imagery, it became apparent that certain abandoned shorelines marking stillstands of what we will call Lake Makgadikgadi.

Initial indications of ancient strandlines appeared as darker lineations against the lighter-appearing savannah and thorn forest background of the Kalahari interpreted from Landsat MMS bands 5 and 7 imagery (Fig. 1). Periodic coverage of the entire study area at a scale of 1:1 000 000 (1 mm = 1 km) was used as a preliminary interpretive medium; partial coverage at 1:250 000 scale was also employed for checking and preliminary mapping. Since the basin is not uniformly sloped on all sides, but is far more steep on the east, the discrimination of shorelines was begun on the western reaches of the ancient lake; these shorelines were not equally distinct at all points on their peripheries, intermediate strands being to a certain extent obscured by aeolian deposition and the downcutting of drainages active since the pan was dry, and interpretation is estimated in certain areas. On the southern periphery of the ancient lake, Government of Botswana and British aerial imagery at scales of 1:45 000 to 1:50 000 was employed as a secondary check on uncertain strand locations.

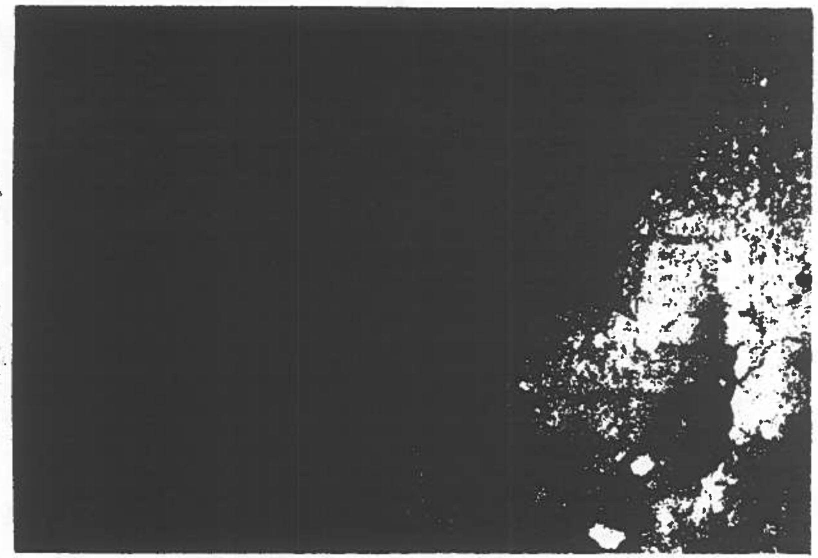

Fig. 1. Portion of Landsat MSS band 5 image, scale 1:1 000 000, showing segment of outermost parabolic western strandline of Lake Makgadikgadi as a darker line between the arrows. The Botletle River cuts the outer shoreline at A with no evidence of a delta, indicating that it was not a contributing drainage to the outer basin; an extinct delta corresponding to lake level 3 can be seen at B, where it gives evidence of a shoreline not otherwise visible in this Landsat frame. Area covered by photo is marked in Figure 2.

Ground-truth checking was also attempted in several areas with differential success; obvious rock and pebble beaches on the westernmost shores of the lake, and water-cut benches on the east, were easily verified but southern and northern shores were difficult or impossible to locate on the ground. Accuracy of mapping and measurement of the ancient shorelines is also affected by the fact that Landsat imagery is not normally fully corrected geometrically; errors, however, in final plotting and measurement are estimated to be not larger than 2%.

A schematic representation of the interpreted and reconstructed shorelines of ancient Lake Makgadikgadi is represented in Figure 2; the outermost strandline lies between approximately 24°10' and 26°25' E., and 19°45' and 21°25' S. The surface areas of each of the stillstands are listed in Table I; areas were measured from 1: 1 000 000 scale Landsat imagery using a Numonics, Inc. Model 1224 Graphics Calculator. The area of the potential drainage basin - which would obtain if all drainages (fossil, intermittent or seasonal) into the

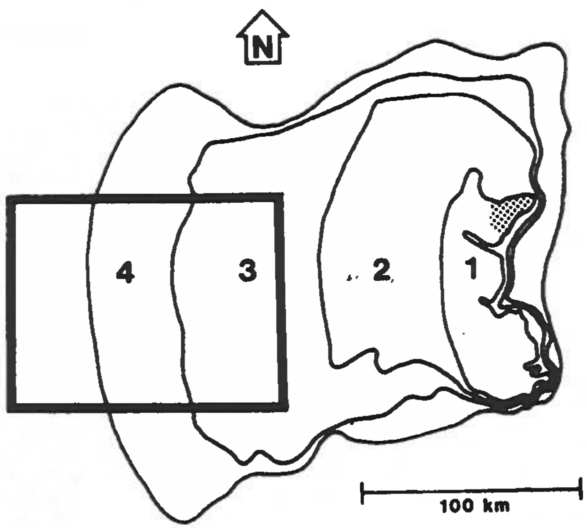

Fig. 2. Abandoned shorelines of Lake Makgadikgadi as interpreted from 1:1 000 000 scale Landsat bands 5 and 7 imagery. Basin 1 encompasses the present soda flats of Sua Pan; the Nata River basin, shaded, is the only portion of the Makgadikgadi basin flooded all year at present. Area covered by Landsat image in Figure 1 is indicated by heavy rectangle.

940 m Makgadikgadi Lake were considered - has been calculated from US Air Force map GnC16N, 1:5 000 000 scale, to be 709 090 km^2. Catchment basin area, the area of the total drainage basin minus the lake surface area for each stage, is also listed in Table I and will figure in calculations below.

Table 1.

Lake level	Lake surface (km^2)[1]	Catchment (km^2)[2]	Altitude
1	2 976.57	706 113	890 m
2	11 499.49	697 590	905 m
3	24 133.11	684 957	910 m
4	36 509.61	672 580	940 m

Notes:

[1] Area determinations made using Numonics 1224 metric graphics calculator.

[2] Derived by subtracting lake surface area from measured potential drainage basin area of 709 090 km^2.

IMPLICATIONS OF CLOSED BASIN LAKE LEVELS

Extinct shorelines and other indications of the extent of past closed-basin lakes furnish one of the palaeoecologist's most obvious indicators of hydrologic conditions in the past, and such lakes have been cited in evidence of past climatic conditions throughout Africa by a number of authors (Grove, 1969; Grove and Warren, 1968; Grove and Goudie, 1971; Butzer et al, 1972, 1973; Cooke, 1975, 1976; Street ahd Grove, 1976). Since a closed-basin lake has no outlets, a delicate balance between inflow and outflow must be maintained to produce a consistent level; inflow is a product of precipitation modified by basin loss, while outflow is primarily due to evaporation and thus temperature-regulated to a large extent. Accordingly, closed-basin lake evidence has been used by African climatologists as support of their contentions of wetter vs. drier and/or cooler vs. warmer conditions in the past.

The water-balance relationship which must be maintained to cause stillstands such as must have formed the four discrete Lake Makgadikgadi shorelines can be expressed as :

(1) $$I + P(A_1) = E(A_1)$$

where: I = Inflow (runoff from basin)
P = Precipitation
E = Evaporation
A_1 = Lake surface area

If A_c is the area of the catchment basin itself, and U the basin loss (that is, precipitation in catchment basin minus runoff into the lake), then this can be rewritten

(2) $$(P-U)(A_c) + P(A_1) = E(A_1)$$

or, dividing through by A_c,

(3) $$P_c - U = \frac{(E-P)(A_1)}{(A_c)}$$

(After: Langbein, 1961? Dury, 1973).

An important constant in this equation (for each lake level) is the ratio of the area of the catchment basin to the area of the lake surface, $\frac{A_c}{A_1}$. If R is taken to represent this ratio, then

(4) $$P_c = \frac{E - P_1}{R} + U$$

This relationship allows the reconstruction of the hydrologic balance of ancient Lake Makgadikgadi at each basin level, and provides the opportunity for the comparison of present climatic conditions and those that must have obtained in the past for the maintenance of each stillstand. The ratio R was calculated from the previously measured areas of catchment and lake basins. Annual evaporation values used here were calculated using Dury's (1973) nomogram for monthly evaporation/temperature values; average monthly temperatures within the period of meteorological record at Francistown and Maun, Botswana, were used for this purpose (Lebedev, 1968), and the mean of the two evaporation values, 3485 mm/year, taken as indicative of the present situation. A hypothetical evaporation value calculated in this same manner from present monthly temperatures minus 5°C was also figured at 2725.5 mm/year. Basin loss rates (U) are difficult to determine even through direct measurement in limited field areas, and are perhaps the least certain quantity in the present reconstruction, something which will figure in the discussion later in this report. In the area being discussed here these have been taken to be largely due to evapotranspiration, and are figured by the Lowry-Johnson method, after Dury (1973). Mean annual temperatures used in this determination were averaged from Lebedev's (1968) mean monthly temperatures. Values of U for a hypothetical annual temperature of 5°C less than present were also calculated. A simplifying assumption - which may not be entirely warranted - was made in the application of these data to equation (4); this was that, since evaporation values are higher than present precipitation values for the area by nearly a factor of 10, the subtraction of P would be omitted, making the effective equation

(5) $$P = \frac{E}{R} + U.$$

Given this equation, and having determined E and R, values of basin loss for given precipitation, which would have to have been in effect to maintain each lake level. Table II sets forth maximum and minimum precipitation values necessary to maintain each Lake Makgadikgadi level for both present-day average temperatures (Table II(A)) and a temperature assumed to be 5°C lower than at present (Table II(B), a figure which may be realistic for global temperature lowering during glacial maxima (Emiliani, 1955). Since the largest part of the total Makgadikgadi basin lies within Botswana (and almost as much within e even drier Southwest Africa) the range of recorded annual averages given by Lebedev (1968) for Botswana, 247-649 mm/year, is taken as

representative of today's average precipitation. At present E and U values, none of the basins would be expected to remain full, and of course they do not. Indeed, if maximum estimated evapotranspiration rates pertain, nearly 1000 mm additional rainfall is necessary each year in order to fill even the lowest basin, Stage 1, year-round; the possibility of such increased rainfall in the Kalahari to the west of the Makgadikgadi Lake has been supported by Cooke (1975) from cave-sinter data. The effects of lowering average annual temperatures at present rainfall levels, however, is not encouraging: even at the hypothetically reduced glacial maximum temperature, the maintenance of even the smallest basin could not be assured. In fact, given present maximum precipitation levels, a temperature lowering of nearly 10°C would be required to maintain even level 1. Cooler temperatures during a glacial maximum would be expected to allow less evaporation from ocean surfaces, fostering less convective activity than today and causing less overall rainfall in southern Africa (Büdel, 1957; Fairbridge, 1964; Hammond, 1976), casting even more doubt on temperature-lowering and lowered evaporation being the cause of the maintenance of lake stages where none exist today.

TABLE II (A): MAXIMUM AND MINIMUM PRECIPITATION REQUIRED TO MAINTAIN CLOSED-BASIN SURFACE AT EACH STAGE OF LAKE MAKGADIKGADI AT PRESENT AVERAGE TEMPERATURE. E = 3485 mm/year

			(mm/year)			
STAGE	R	$\frac{E}{R}$	U_{max}	U_{min}	P_{max}	P_{min}
1	237.2	14.69	1520	700	1535	715
2	60.6	75.51	1520	700	1578	758
3	28.4	122.71	1520	700	1643	823
4	18.4	189.40	1520	700	1709	889

TABLE II (B): MAXIMUM AND MINIMUM PRECIPITATION REQUIRED TO MAINTAIN CLOSED-BASIN SURFACE AT EACH STAGE OF LAKE MAKGADIKGADI, ASSUMED AVERAGE TEMPERATURE 5° C LOWER THAN PRESENT. E = 2725.5 mm/year

			(mm/year)			
STAGE	R	$\frac{E}{R}$	U_{max}	U_{min}	P_{max}	P_{min}
1	237.2	11.49	1295	662	1307	674
2	60.6	44.98	1295	662	1340	707
3	28.4	95.97	1295	662	1391	758
4	18.4	141.13	1295	662	1436	803

DISCUSSION

The possible influence of factors other than simple precipitation increase and lowering of temperature and thus evaporation during the glacial maximum and for some time preceding and following it (or between 12 000 and 24 000 BP, as suggested by Grove (1969), Butzer et al (1973), Bond (1963), Cooke (1975) and others) must be considered. Clearly, one of the factors contributing most heavily to the numerical reconstructions attempted above - and most in doubt - is that of basin loss, U, assumed to be due primarily to transpiration from vegetation above. The range of values given in Table II for estimated U were calculated using agricultural data, and may be unrealistic for the arid central portions of southern Africa; it has been estimated that in areas hosting a non-continuous vegetative cover, some 25% of total evaporation takes place directly from exposed soil (Milthorpe, 1960). This hints at rates of U even in excess of those estimated, compounding rather than solving our discrepancy.

Preliminary analysis of instrumental meteorological data collected by the Kalahari Project suggests another possibility. In years within the period of record, shifts to greater precipitation are accompanied by lesser seasonality of rainfall. This may be a function of rainfall in wetter years occurring as a series of less severe showers rather than random thunderstorms (Leopold, 1951).

The effects of greatly reduced seasonality during the cooler glacial maximum on vegetation and evapotranspiration might have been great. A more equitable rainfall regime, higher average water table (before rainfall sank into the Kalahari sand), and reduced erosion would favor the establishment of a continuous savannah cover in areas where extremely seasonal rainfall, fast seepage to great depths, and erosion cause only thorn scrub mosaic to be supported today. A grass savannah cover type transpires at a great rate during hotter parts of the growing period, but this is of short duration since grass quickly overruns its water requirement within the shallow root zone and aboveground foliage dies, at which point transpiration ceases. The dense root mat of continuous grass cover then enhances physical runoff and prevents immediate deep seepage and evaporation from exposed soil, and could account for the far lower basin loss rates necessary for the maintenance of higher lake stages.

In any inductive effort such as the reconstruction outlined above, of course, there are many weak links - variables estimated on the basis of erroneous assumptions, or factors not taken into consideration at all. For this reason, hypothetical models must be tested on the basis of implications arising from independent data. One such area presently being pursued is the analysis of a series of approximately 100 archaeological sites discovered during 1975-76 field operations in the Kalahari through faunal and technological techniques (Ebert, in press). These sites can for the most part be assigned to discrete lake levels, thus making correlation between material remains, the subsistence strategies they imply, and lake levels (and thus climatic conditions) possible without the absolute dating of either archaeological sites or lake

stages. The results of these analyses may in turn help define the variables important to, and the meaning of, abandoned closed basin lake levels in temperate deserts in Africa and around the world.

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NOUVELLES RECHERCHES SUR LES CUIRASSES FERRUGINEUSES EN AFRIQUE OCCIDENTALE. COMPARAISON AVEC LE SUD-OUEST AFRICAIN.

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RESUME

L'équipe de géomorphologues, composée de G. Beaudet, R. Coque, P. Michel et P. Rognon, a poursuivi ses recherches sur la limite septentrionale des cuirasses ferrugineuses en Afrique occidentale. Ce petit article indique les principaux résultats des deux missions, effectuées au Niger (en 1976) et au Mali (en 1977). Ces cuirasses sont encore très étendues dans la région de Bourem, au N.E. de la grande boucle du Niger (fig. 1). G. Beaudet et P. Michel ont fait une mission (en 1975) dans le Sud-Ouest Africain, en Namibie centrale; les anciennes surfaces et les glacis y portent partout des croûtes calcaires. Ainsi les revêtements dans ces deux ensembles géomorphologiques situés actuellement dans le domaine tropical subaride et aride, ne sont pas les mêmes malgré des positions géographiques semblables. Ces différences semblent liées surtout au déplacement de la plaque africaine et à des variations climatiques plus faibles dans le Sud-Ouest Africain pendant le Tertiaire et le Quaternaire.

SUMMARY

A team of geomorphologists, including G. Beaudet, R. Coque, P. Michel et P. Rognon, has continued fieldwork on the northern margin of the ferruginous duricrusts of West-Africa. This short paper gives the main results of two field trips in Niger (1976) and in Mali (1977). The duricrusts are extensive in the region of Bourem, N.E. of the main curve of the Niger River. G. Beaudet and P. Michel have visited central Namibia in south-west Africa (1975); here everywhere the old surfaces and the glacis are covered with calcareous crusts. In spite of similar geographical positions, the coatings are not the same in these two morphological regions which are both at present situated in the arid or semi-arid tropical zone. It seems that these differences are due to the movement of the African plate and to smaller climatic fluctuations in South-West Africa during the Tertiary and and Quaternary compared with West Africa.