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Chemical sedimentation in the semi-arid environment of the Okavango Delta, Botswana

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ABSTRACT

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The Okavango basin of northern Botswana is an area of active diagenetic carbonate and silica accumulation. The basin is formed by grabens which represent an extension of the East African Rift system. The Okavango Delta, a large, marshy, alluvial fan (22,000 km²), occupies most of the surface area of the basin. Evapotranspiration exceeds precipitation by a factor of 3 and ~96% of incoming water is lost to the atmosphere. Evaporative concentration of dissolved solids occurs and they precipitate in the capillary fringes of islands. The less soluble components $CaCO_3$ and SiO_2 precipitate in the soils, which results in a significant volume increase which has important implications for the topography of the area and the character of the sediment fill. The more soluble salts, mainly alkali carbonates, accumulate at the surface as efflorescent crusts but are leached into the soil during the rainy season. This salt accumulation destroys vegetation. Swamp abandonment leads to leaching to greater depth, and, with reflooding, to the removal of these salts, possibly to form a deep saline groundwater. Mass-balance calculations indicate that this form of chemical accumulation is the dominant aggradational process occurring in the delta at present.

Introduction

Large-scale carbonate sedimentation is normally confined to open-water bodies, frequently but not exclusively in marine environments and usually associated with biological activity. In arid environments, extensive carbonate deposits may form pedogenically, producing calcrete over extensive areas by essentially abiological processes. Such deposits are generally stratiform and are closely associated with present-day or palaeo-erosion surfaces. However, in the Okavango basin of northern Botswana, unusual depositional conditions exist in which fluvial and lacustrine sedimentation are intimately associated with active dia-

genetic carbonate and silica accumulation. A study was undertaken to investigate the processes involved in this accumulation and to examine their implications for sedimentation in this area.

2. The Okavango Delta

The Okavango Delta, situated in northern Botswana (Fig. 1), is a large alluvial fan (22,000 km²) lying within grabens of the southern extension of the East African Rift system (Scholtz, 1975; Hutchins et al., 1976). The delta currently forms a terminal depository for the Okavango River system, which drains central Angola. Topographic gradients on the fan are low (average 1:3600) and on

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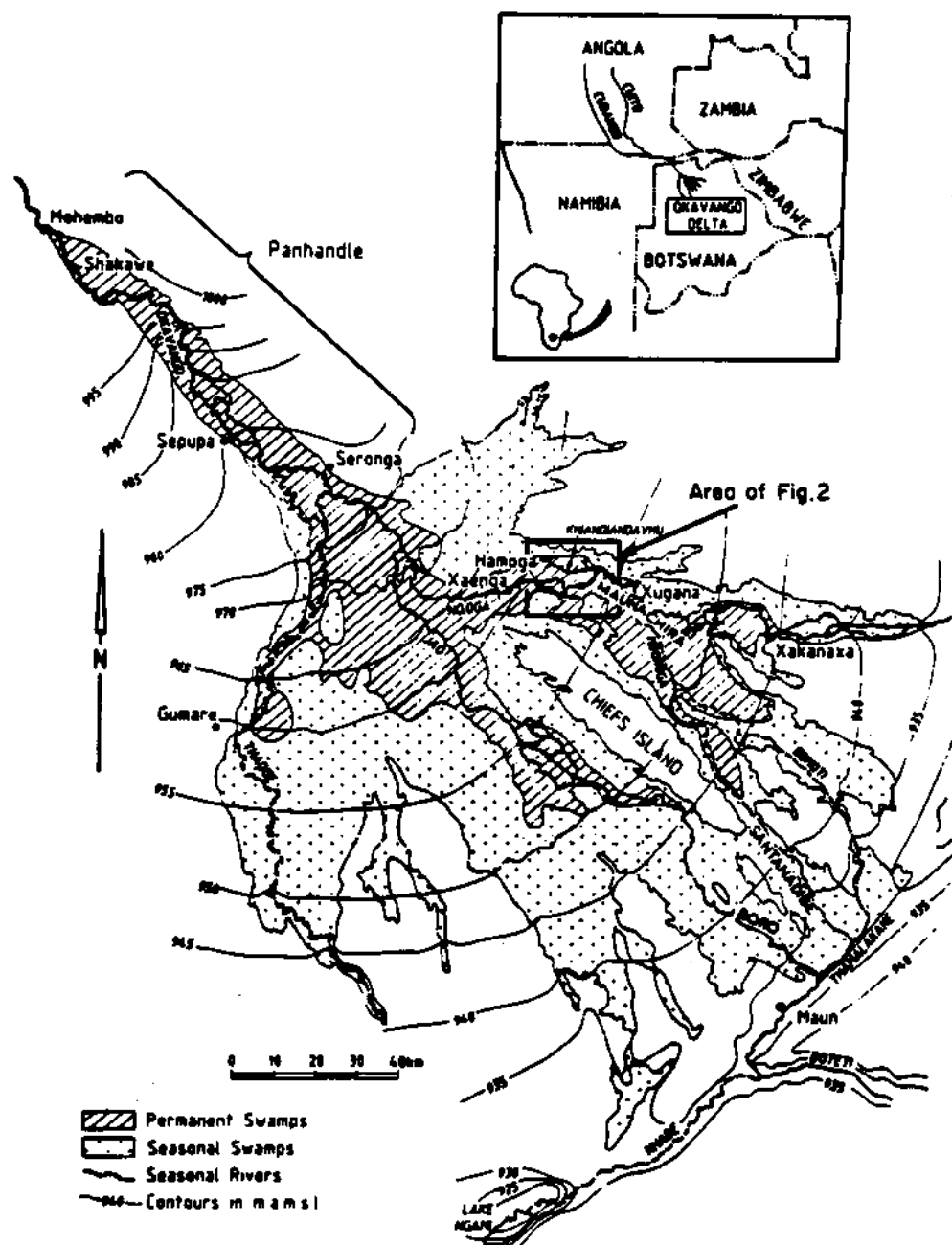*rmanent address:* IMI, P.O. Box 313, Haifa, Israel.

Fig. 1. The Okavango Delta.

reaching the fan, the Okavango River degenerates into a system of anastomosing channels flanked by perennial and seasonal swamps. Fluvial sedimentation is occurring in these channels (McCarthy et al., 1988). Changes in water distribution are a continuing feature of the delta (Shaw, 1984; McCarthy et al., 1986a). The climate is semi-arid, and local rainfall (490 mm a^{-1}) is greatly exceeded by evapotranspiration (1580 mm a^{-1}; Wilson and Dinçer, 1976). Hydrological models indicate

that ~96% of incoming water (inflow and precipitation) is lost by evapotranspiration, and only ~4% leaves as surface outflow (Dinçer et al., 1981), making the Okavango graben an essentially endorheic basin, in common with many other sections of the East African Rift system (Eugster, 1980). The high evapotranspiration rate in the delta has resulted in the local surface accumulation of Na salts, especially trona (McCarthy et al., 1986b), as in other parts of the rift (Eugster, 1980) and these

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accumulations have a devastating affect on the vegetation. In addition, calcium carbonate and silica is precipitating on the fan. However, unlike most other regions of internal drainage, the Okavango is not characterized by large, saline lakes.

3. The study area

The Okavango Delta is characterized by an upper region of perennial swamps (Fig. 1), covering an area of ~6000 km^2 and dominated by the giant sedge *Cyperus papyrus* L. and *Miscanthus junceum* (Stapf) Staph. Average water depth is ~1.5 m (UNDP, 1977). The lower reaches of the delta are dominated by seasonal swamps. Flood waters from the summer (January) rains in central Angola enter the Panhandle region (Fig. 1) in about March and gradually spread southeastward, taking ~4 months to reach the lower end of the delta at Maun. Water levels vary by ~1.5 m in the Panhandle, but in the central regions of the perennial swamps, seasonal fluctuations are <20 cm. In the seasonal swamps, seasonal fluctuations are again large, typically 2 m. The swamps are characterized by abundant islands, ranging in size from individual termitaria to Chiefs Island (Fig. 1). Some of these islands owe their origin to fluvial processes (McCarthy et al., 1988) or to drowned aeolian features, but most are of irregular form and unknown origin. Except for the occasional termitaria, topographic relief is low over the entire area, and the islands rise no more than ~1 m above water level. The soils forming the islands typically consist of well-sorted quartz sand. Details of the climate, hydrology and physiography have been presented by Wilson and Dinçer (1976), while the recent geomorphological history has been reviewed by Shaw (1988).

The area chosen for this study is situated in the remote northeastern portion of the perennial swamps on the Khiandiandavhu channel (Figs. 1–3). Water is supplied to this channel
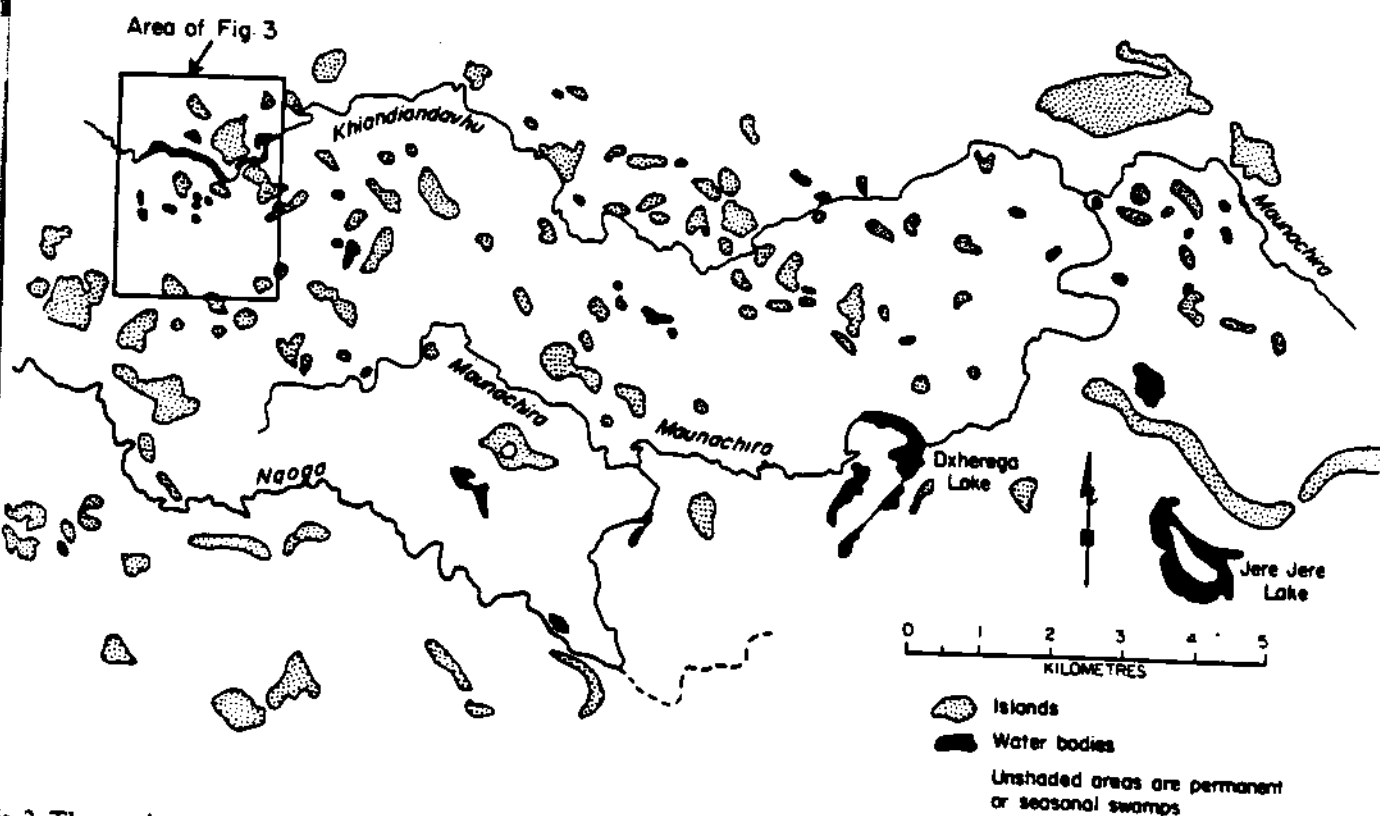

Fig. 2. The study area (see Fig. 1 for location).

Fig. 3. Aerial photograph of the study area. The *arrow* indicates the island studied. *White areas* are salt-encrusted islands; *black areas* are open water. *Grey areas* are vegetated (*Papyrus*) swamp. See Fig. 2 for location.

by leakage from the Nqoga channel through the surrounding swamps. One of a group of islands on the southern bank of the Khiandianduvhu was chosen for the study (Fig. 3). The survey was carried out during January 1989, at a time of unusually heavy summer rain. The island studied was largely devoid of vegetation (Fig. 3), except for a narrow (50 m) zone flanking the channel which was covered by large trees and undergrowth. The barren area was littered with dead trees, indicating that in former times the entire island was heavily vegetated. During the dry winter months, the barren surface is covered by an efflorescent crust of trona as described by McCarthy et al. (1986b), but because of the heavy rains at the time of the present study, this salt had been leached into the soil.

4. Study methods

As this study was concerned with processes of carbonate and silica accumulation, it involved both detailed investigation of material collected in the field as well as laboratory experiments. Soil samples were collected from a series of pits dug across the island. On a brief subsequent visit, a portable diamond drill was used to obtain samples from depth. The samples were subjected to petrographic and chemical analysis as described in Section 4.3. Much of the surface of the islands lies within or near the capillary zone, because of the low topographic relief. The nature of the capillary zone and evaporation therefrom were examined in the laboratory to obtain insight into this important zone.

4.1. Nature of the capillary fringe

Typical Okavango sand (mean grain size 0.25 mm; $X_\phi = 2.0$; s.d.$_\phi = 0.45$) was used in this experiment. Wet sand was placed in a 10-cm-diameter glass tube, one end of which was covered with fine Nylon® mesh. The mesh-covered end was immersed in water, and a 60-W tungsten lamp lowered down the tube to a height of ~ 10 cm above the wet sand. As the surface sand dried under the effect of the heat, it was removed. This process was continued until equilibrium was established between capillary rise and evaporation, and the surface sand remained cohesive.

4.2. Evaporation experiments

Apparatus was set up to measure evaporation off water-saturated Okavango sand. These consisted of 5-l, sand-filled, insulated containers fitted with constant water-level devices. The volume of water evaporated through 15- and 30-cm layers of wet sand was measured. Open-water evaporation was recorded as a control. The volumes of water evaporated

were recorded every few days over a period of several months.

4.3. Petrographic analysis

Petrographic analysis was carried out using microscopic and X-ray diffraction (XRD) techniques. The proportion of matrix surrounding sand grains in duricrusts in the soil was estimated by point counting (1000 points per section). Replicate determinations (10 times) yielded a standard deviation of 1.65 at 6.5% matrix. Quartz was determined quantitatively by XRD as described by McCarthy et al. (1989). The precision of this method was established by replicate determination (10 times) which yielded a standard deviation of 1.48 at 55.2% quartz.

4.4. Chemical analysis of soil samples

Water-soluble metals were determined using atomic absorption spectrophotometry (AAS) on leachates prepared by placing 1 g of powdered soil sample in 100 ml of deionized water. The solutions were analysed for Ca, Mg, K and Na, but only the latter two yielded significant results. Acid-extractable metals were also determined by AAS. One gram of sample was treated with 20 ml of 1 M HCl and then diluted to 100 ml. The resulting solutions were analysed for Ca, Mg, Na and K. Total analysis of the soil samples was carried out by X-ray fluorescence spectrometry using the fusion method (Norrish and Hutton (1969). This technique was modified slightly in that sample powders were preheated to 1000°C prior to fusion and sodium nitrate oxidant was omitted from the fusion mixture. Analytical precisions are as quoted by McCarthy (1976). Sulphur and chloride were determined on undiluted sample powder briquettes. Both primary and secondary mass absorption corrections were made. Calibration was established using international rock standards.

4.5. Soil pH measurement

Soil pH measurements were made by mixing 20 g of dried sample with 50 ml of deionized water, allowing the mixture to equilibrate for 1 hr. and then measuring the pH using a Zeiss® model 300 pH meter, calibrated against UNIVAR® buffers (pH 7 and 9). Replicate determination (10 times) yielded a standard deviation of 0.02 pH unit at pH 10.18.

5. Results

5.1. The nature of the capillary fringe in Okavango sand

The thickness of the equilibrium capillary fringe was 40 cm and consisted of two zones; a lower zone, 10 cm thick in which virtually all open spaces were filled with water, and an upper zone in which sand grains were surrounded by a film of water but pore spaces were open. The transition between the two was abrupt.

5.2. Evaporation of water through sand

The ratio of evaporative loss through a 15-cm layer of sand relative to water loss off open water of the same area was found to be 1.16 (s.d. 0.15) and the equivalent ratio for a 30-cm layer of sand was 0.69 (s.d. 0.13). The greater rate of evaporation through a thin sand layer relative to that off open water may be an expression of evaporative pumping (Hsü and Seigenthaler, 1969; Hsü, 1984) or evaporative suction (Sonnenfeld, 1984) or more efficient absorption of radiation. Transpirational losses from grass-covered areas appeared to exceed evaporative loss through sand (Wilson and Dinçer, 1976). Because of the very low topographic relief of the islands, much of their surfaces lie within the capillary zone and it is likely that evapotranspirational losses off these areas will be similar to that for open water.
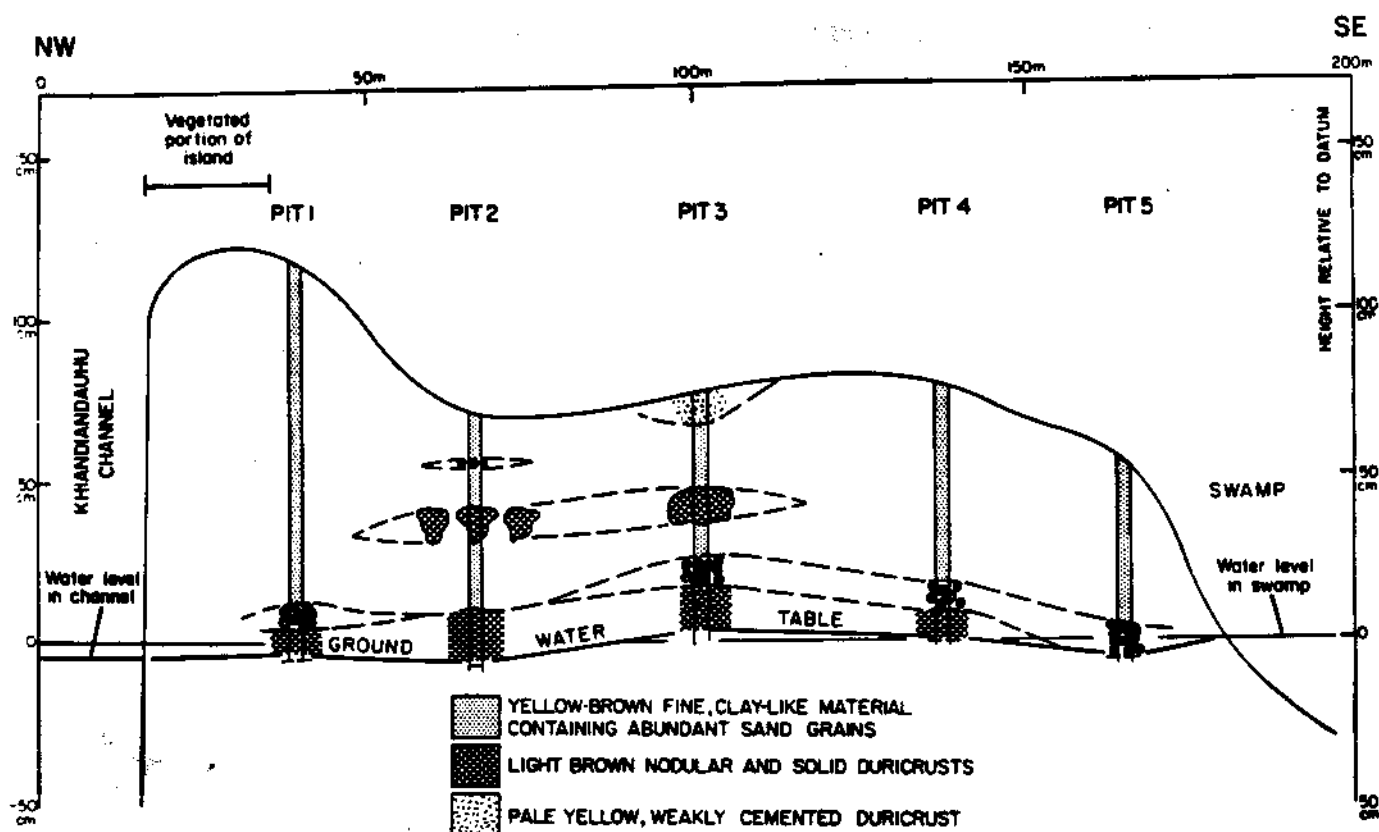
Fig. 4. Soil profiles across the study island.

5.3. Soil profiles

Measured soil profiles are shown diagrammatically in Fig. 4 in the form of a transect across the island. The soils are very sandy but the sand is dispersed in a fine matrix. Immediately above the water table, the soils were nodular and with increasing depth became totally cemented and very hard. Drilling adjacent to pit 3 indicated that this hard material
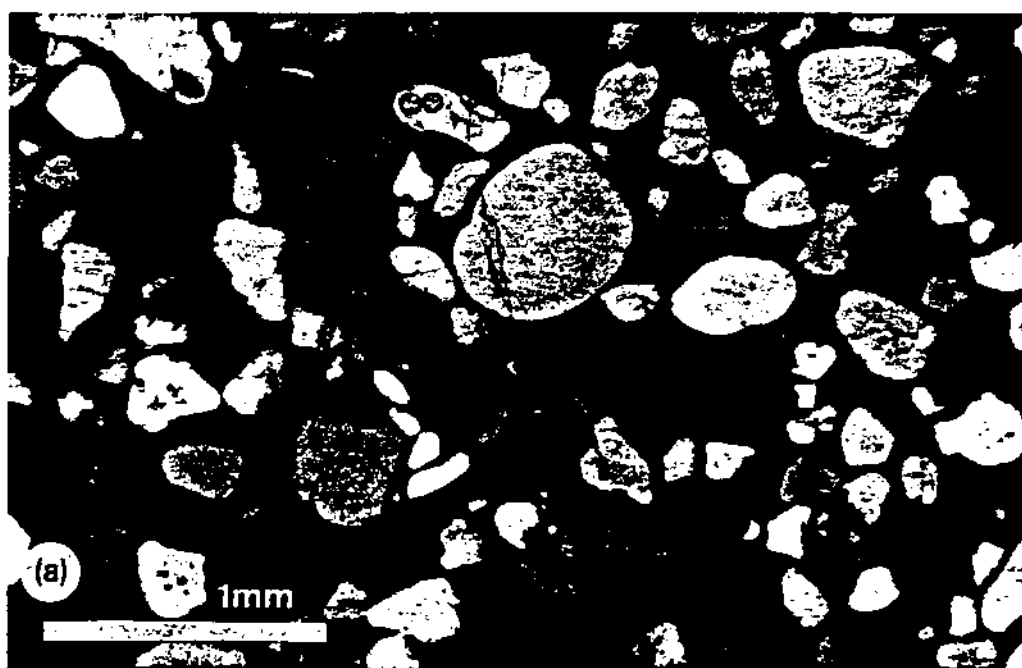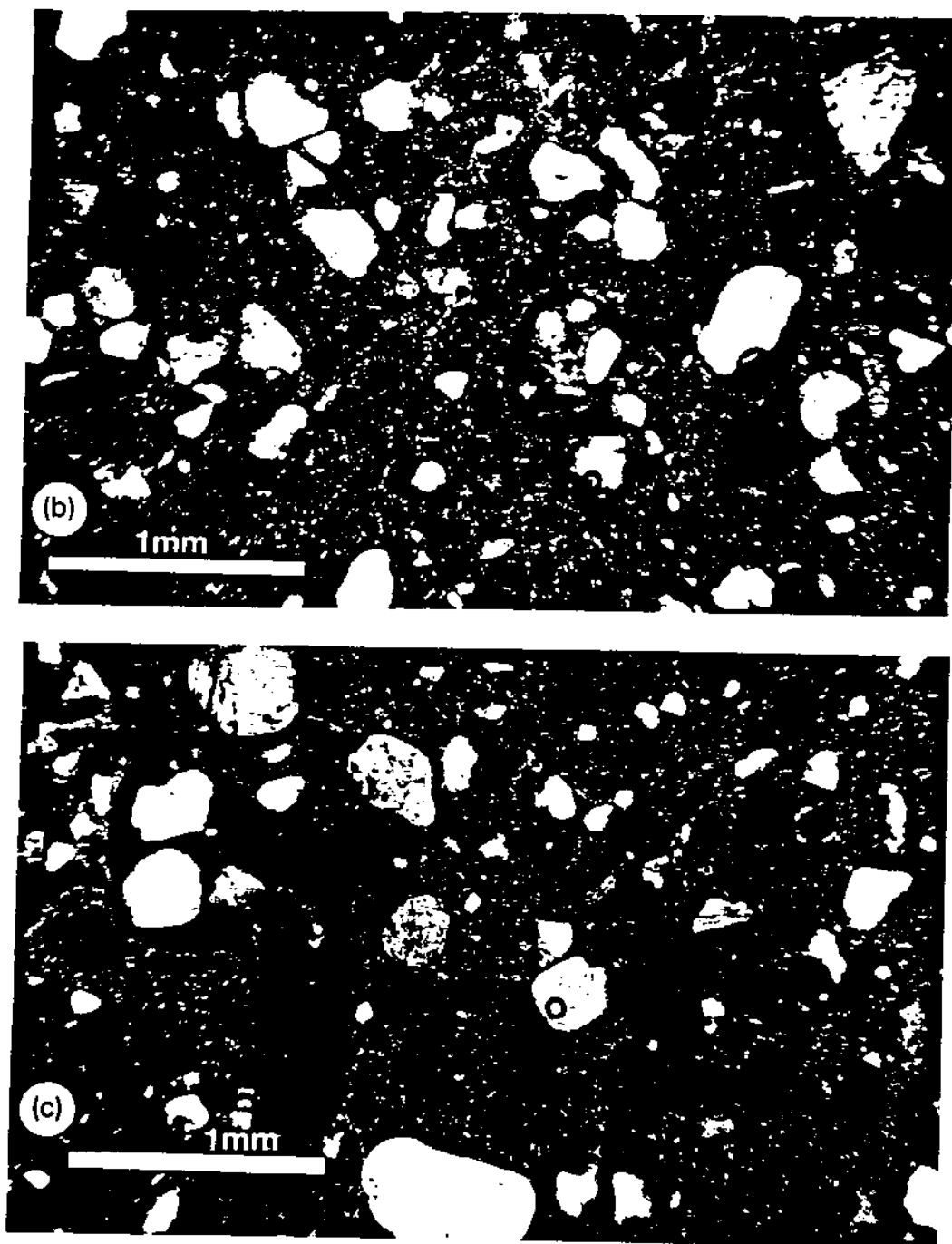
5. a. Photomicrograph of a grain mount of the acid-insoluble residue of a soil sample.
Photomicrograph of moderately cemented subsurface sample.
Photomicrograph of strongly cemented subsurface sample.

tends to a depth of at least 1.75 m below sur-ce, i.e. 1 m below datum in Fig. 4.

4. Soil mineralogy and chemistry

Petrographic examination indicated that the ils consisted of rounded to sub-rounded quartz sand grains set in a brown matrix consisting of calcite and amorphous silica. Sand-sized grains of detrital carbonate were sought but not found. Sieve analysis of acid-washed material (i.e. matrix-free) yielded an average grain size of 0.19 mm ($X_\phi = 2.42$; s.d.$_\phi = 0.7$). A grain mount of this residue is shown in Fig.

TABLE I

Chemical data

Name	1 SiO$_2$	2 TiO$_2$	3 Al$_2$O$_3$	4 Fe$_2$O$_3$	5 MnO	6 MgO	7 CaO	8 K$_2$O	9 P$_2$O$_5$	10 LOI
Pit samples:										
Pit *1/1*	79.30	0.098	1.34	0.34	0.06	1.28	7.33	0.72	0.11	9.39
Pit *1/2*	75.44	0.096	1.39	0.57	0.08	1.41	8.11	0.86	0.13	11.45
Pit *1/3*	70.24	0.096	1.45	0.64	0.07	1.73	10.52	0.81	0.14	13.57
Pit *1/4*	73.78	0.087	1.49	0.61	0.07	1.59	9.68	0.82	0.11	12.12
Pit *1/5*	73.57	0.095	1.65	0.66	0.08	1.58	10.24	0.84	0.13	12.11
Pit *1/6*	73.82	0.089	1.47	0.79	0.08	1.39	9.94	0.64	0.11	11.70
Pit *1/7*	71.14	0.091	1.52	0.63	0.06	1.65	11.58	0.54	0.12	13.31
Pit *1/8*	67.55	0.089	1.55	0.63	0.05	2.02	12.84	0.48	0.13	14.72
Pit *1/9*	71.20	0.085	1.45	0.61	0.06	1.92	11.45	0.41	0.10	13.05
Pit *1/10*	72.78	0.092	1.46	0.63	0.07	2.00	10.66	0.39	0.10	12.67
Pit *1/10*	69.94	0.081	1.35	0.58	0.06	2.19	11.97	0.39	0.11	14.49
Pit *1/11*	62.70	0.085	1.48	0.54	0.07	1.98	15.46	0.36	0.07	15.67
Pit *1/13*	55.02	0.074	1.35	0.52	0.09	1.70	21.37	0.30	0.07	17.25
Weighted mean	70.57	0.090	1.48	0.62	0.07	1.74	11.61	0.60	0.11	13.21
Pit *2/1*	82.70	0.080	1.15	0.47	0.08	1.19	6.54	0.64	0.06	7.72
Pit *2/2*	81.60	0.105	1.82	0.67	0.08	1.40	5.90	1.03	0.08	7.98
Pit *2/3*	84.32	0.086	1.43	0.58	0.07	1.01	4.40	0.94	0.06	6.64
Pit *2/4*	82.98	0.098	1.68	0.68	0.09	1.28	5.46	0.88	0.07	7.59
Pit *2/5*	72.78	0.080	1.56	0.62	0.08	1.81	9.98	0.78	0.07	12.06
Pit *2/6*	75.32	0.085	1.53	0.60	0.06	1.65	9.24	0.69	0.06	11.79
Pit *2/7*	74.31	0.091	1.54	0.063	0.06	1.77	9.81	0.60	0.06	12.33
Pit *2/8*	65.85	0.075	1.35	0.54	0.04	2.81	13.55	0.55	0.07	15.54
Pit *2/9*	66.49	0.075	1.42	0.51	0.04	2.53	13.61	0.47	0.05	14.99
Pit *2/10*	58.16	0.074	1.49	0.62	0.03	2.30	18.37	0.37	0.06	18.47
Weighted mean	73.59	0.090	1.54	0.61	0.06	1.81	10.02	0.70	0.07	11.99
Pit *3/1*	79.51	0.098	1.42	0.99	0.08	1.72	6.59	0.94	0.05	8.68
Pit *3/2*	77.69	0.112	1.90	0.76	0.06	2.04	7.00	1.20	0.06	9.58
Pit *3/3*	77.29	0.099	1.84	0.86	0.08	2.13	6.17	1.45	0.06	9.78
Pit *3/4*	77.28	0.112	2.11	0.89	0.09	2.08	6.06	1.51	0.06	9.67
Pit *3/5*	78.79	0.119	2.19	0.93	0.10	2.04	6.39	1.02	0.06	9.26
Pit *3/6*	75.92	0.111	2.17	0.86	0.09	2.29	7.89	0.74	0.06	10.54
Pit *3/8*	62.99	0.104	2.23	0.82	0.09	3.35	13.61	0.64	0.08	16.25
Weighted mean	74.53	0.110	2.10	0.87	0.09	2.36	8.10	1.04	0.06	11.06
Pit *4/1*	85.27	0.066	1.20	0.43	0.05	1.15	4.97	0.46	0.05	7.65
Pit *4/2*	78.37	0.099	1.49	0.63	0.09	2.06	7.22	0.74	0.06	9.20
Pit *4/3*	75.69	0.094	1.57	0.71	0.09	2.06	7.76	0.79	0.06	10.61
Pit *4/4*	69.94	0.091	1.68	0.74	0.10	2.79	11.17	0.51	0.07	13.52
Pit *4/5*	61.41	0.069	1.25	0.51	0.05	4.14	13.89	0.36	0.05	18.15
Pit *4/6*	64.42	0.075	1.29	0.48	0.06	2.56	14.81	0.35	0.05	16.37
Pit *4/7*	62.24	0.070	1.35	0.49	0.04	3.60	14.93	0.36	0.05	17.40
Pit *4/8*	64.64	0.075	1.29	0.049	0.05	1.94	15.16	0.31	0.04	16.35
Pit *4/9*	51.89	0.069	1.45	0.59	0.05	3.76	21.09	0.50	0.06	21.97
Weighted mean	67.17	0.080	1.42	0.58	0.07	2.92	12.45	0.50	0.06	14.98

11 Total	12 ACID CaO	14 WAT Na₂O	15 ACID Na₂O	16 WAT K₂O	17 ACID K₂O	18 Cl (ppm)	19 SO₄ (%)	20 Quartz	21 pH	22 Depth (cm)	23 Height (cm)	24 Interval
00.42	7.40	0.15	0.23	0.34	0.36	81	0.09	73	9.95	1	116	1
99.88	8.52	0.27	0.39	0.41	0.49	78	0.20	70	10.42	5	112	9
99.67	10.55	0.28	0.36	0.37	0.49	91	0.19	66	10.48	15	102	10
00.76	9.91	0.27	0.36	0.25	0.53	124	0.17	54	10.50	25	92	10
01.31	9.60	0.19	0.26	0.35	0.47	220	0.13	60	10.30	35	82	20
00.18						132	0.09	60	10.06	55	62	10
00.82	11.24	0.05	0.08	0.13	0.25	103	0.10	51	9.46	62	55	5
00.33	11.73	0.03	0.05	0.06	0.16	74	0.12	61	9.03	67	50	5
00.54	11.53	0.03	0.05	0.04	0.12	66	0.13	59	8.94	75	42	10
01.05	10.49	0.03	0.05	0.04	0.12	71	0.13	54	8.89	82	35	15
01.33	11.92	0.03	0.05	0.04	0.11	70	0.15	45	8.82	100	17	10
98.71	14.26	0.03	0.05	0.02	0.11	71	0.76	47	8.56	107	10	5
98.06		0.01	0.04	0.02	0.07	49	0.65		8.70	120	−3	10
00.83	7.26	0.11	0.20	0.19	0.34	61	0.05	59	9.72	1	77	1
00.96	6.32	0.19	0.27	0.34	0.60	64	0.04	60	10.40	5	73	9
99.90	5.07	0.27	0.32	0.27	0.59	58	0.04	65	10.51	7	71	5
01.14	5.18	0.23	0.27	0.31	0.53	88	0.05	59	10.43	22	56	5
00.22	10.61	0.27	0.32	0.30	0.46	123	0.07	57	10.43	35	43	10
01.39	9.96	0.22	0.27	0.24	0.40	124	0.06	57	10.30	45	33	10
01.44	10.65	0.09	0.15	0.17	0.29	73	0.05	56	9.74	55	23	12
00.59	12.86	0.09	0.13	0.12	0.25	42	0.05	45	9.68	67	11	8
00.41	13.46	0.07	0.12	0.08	0.22	44	0.06	48	9.48	71	7	2
00.55	15.81	0.04	0.08	0.06	0.14	46	0.06	36	9.37	80	−2	8
00.43	7.08	0.22	0.34	0.40	0.65	81	0.06	69	10.17	1	77	1
00.95	7.42	0.34	0.43	0.46	0.77	52	0.03	68	10.58	3	75	4
00.42	6.70	0.38	0.59	0.47	1.00	101	0.05	56	10.86	7	71	5
00.60	6.28	0.57	0.70	0.64	1.06	315	0.12	61	10.85	15	63	10
01.20	6.70	0.22	0.24	0.28	0.57	289	0.09	65	10.34	25	53	10
01.07	12.55	0.20	0.11	0.18	0.36	121	0.05	65	9.73	35	43	10
00.53	11.19	0.07		0.14	0.30	100	0.05	54	9.22	45	33	10
01.70	6.37	0.16	0.31	0.08	0.31	87	0.04	73	9.95	1	76	1
00.51	7.32	0.36	0.46	0.24	0.41	83	0.05	60	10.80	10	67	9
00.53	7.96	0.84	1.02	0.27	0.49	220	0.17	65	10.63	29	57	10
00.16	10.79	0.19	0.23	0.08	0.22	87	0.06	58	9.83	40	37	10
00.20	12.56	0.11	0.16	0.04	0.13	40	0.09	49	9.33	65	12	15
00.73	14.51	0.09	0.13	0.02	0.12	48	0.11	50	9.38	68	9	8
00.82	13.73	0.08	0.13	0.02	0.13	38	0.08	52	9.38	75	2	7
00.60	15.06	0.07	0.11	0.02	0.10	46	0.11	55	9.24	80	− 3	5
01.71	17.59	0.03	0.08	0.06	0.20	39	0.08	40	9.04	87	− 10	5

TABLE I (*continued*)

Name	1 SiO₂	2 TiO₂	3 Al₂O₃	4 Fe₂O₃	5 MnO	6 MgO	7 CaO	8 K₂O	9 P₂O₅	10 LOI
Pit samples (cont.):										
Pit 5/1	88.09	0.058	0.79	0.37	0.05	0.76	4.46	0.27	0.03	5.60
Pit 5/2	76.35	0.095	1.58	0.73	0.08	1.57	7.38	0.52	0.06	11.99
Pit 5/3	70.71	0.105	1.90	0.88	0.07	1.94	9.97	0.58	0.07	13.43
Pit 5/4	67.36	0.113	1.84	0.86	0.07	2.65	11.97	0.44	0.05	14.49
Pit 5/5	69.45	0.100	1.84	0.86	0.09	2.67	11.16	0.38	0.05	13.87
Weighted mean	72.02	0.100	1.76	0.82	0.08	2.04	9.59	0.50	0.06	13.09
Channel samples:										
Chan. 1k1	97.74	0.065	0.82	0.35	0.02	0.08	0.05	0.15	0.03	0.72
Chan. 2k1	99.62	0.018	0.49	0.27	0.03	0	0.03	0.05	0.01	0.07
Chan. 3k1	99.43	0.020	0.39	0.13	0.01	0	0.03	0.05	0.01	0.10
Chan. 3k2	99.67	0.023	0.47	0.35	0.02	0	0.03	0.11	0.01	0.16
Chan. 5k2	99.85	0.017	0.31	0.30	0.02	0	0.01	0.05	0.01	0.09
Chan. 5m	99.71	0.014	0.25	0.13	0.01	0	0	0.05	0.01	0.06
Chan. 6c	100.25	0.017	0.31	0.23	0.02	0.02	0.02	0.05	0.01	0.06
Mean	99.47	0.02	0.44	0.25	0.02	0.01	0.02	0.07	0.01	0.18
Std. dev.	0.80	0.02	0.19	0.09	0.01	0.03	0.02	0.04	0.01	0.24

Analyst: N.Day. LOI = loss on ignition. The prefixes ACID and WAT denote acid soluble and water soluble, respectively. Column 23 records the position of the sample relative to the water table. Column 24 is the sampling width.

5a. The sand is very mature and consists almost entirely of quartz grains with occasional grains of feldspar and tourmaline. The matrix is very fine grained and the proportion of matrix is variable (Fig. 5b and c). In certain samples, especially from the deeper sections of the profiles, the matrix forms a cement to the quartz grains and the resulting material is quite hard, although still porous. Samples of this material retained their integrity after complete dissolution of the carbonate cement in dilute acid, indicating that both carbonate and amorphous silica from the cement. XRD analysis indicated, in addition to peaks for quartz, kaolinite and calcite, a weak, broad peak attributable to a poorly crystalline illite.

Results of analyses of the soils are listed in Table I. This table also shows: the depths below surface at which samples were collected; their height above the water table; the interval in the soil profile which they represent; and the pH. The average composition of local fluvial sand is also listed.

6. Discussion

6.1. Soil chemistry

Petrographic examination indicates that the soil samples consist of quartz sand in a fine matrix of calcite and amorphous silica (Fig. 5a–c). The clay component is minor, as indicated by the low alumina content. The average composition of channel sands from the study area (equivalent to fluvially reworked island sand) is listed in Table I, and consists almost entirely of silica. The soil samples differ from this in that they contain larger quantities of Ca, Mg and alumina. All of the Ca is acid soluble and hence is present only as carbonate. The concentration of sulphate in the samples is low and hence gypsum, if present, is a very minor constituent. Between one-quarter and one-half of the Mg is acid soluble, and probably occurs in solid solution in the calcite. The remainder occurs in an acid-insoluble form which could not be identified, and is apparently amor-

11 Total	12 ACID CaO	14 WAT Na₂O	15 ACID Na₂O	16 WAT K₂O	17 ACID K₂O	18 Cl (ppm)	19 SO₄ (%)	20 Quartz	21 pH	22 Depth (cm)	23 Height (cm)	24 Interval
100.61	4.80	0.07	0.09	0.05	0.13	82	0.06	83	9.48	1	51	1
100.73	7.46	0.27	0.30	0.13	0.28	73	0.09	72	10.37	10	42	19
100.26	9.15	0.46	0.49	0.23	0.34	85	0.12	56	10.26	30	22	20
100.12	11.54	0.19	0.12	0.10	0.18	68	0.09	61	9.57	55	−3	10
100.66	11.66	0.11	0.54	0.05	0.12	55	0.10	60	9.01	65	−13	10
												60
100.18												
100.74												
100.18												
100.88												
100.66												
100.23												
100.97												
100.55												
0.34												

phous. The alumina may occur as kaolinite or as other clay minerals. Also present is amorphous silica, the proportion of which was calculated by subtracting quartz from the total silica, correction also being made for the silica present in kaolinite (estimated from the Al_2O_3 content). There is an increase in CaO and the acid-soluble MgO with depth in each of the pits (Fig. 6a and b). Amorphous silica tends to be erratic, but the sum of amorphous silica, $MgCO_3$ and $CaCO_3$ (calculated from the acid-soluble fraction) increases within the pits (Table II). In contrast to this, the distribution of Al_2O_3, which is well correlated with total Fe and TiO_2 (Fig. 7a and b), is erratic.

From the textural and chemical data acquired, it seems likely that the original soil consisted of quartz sand, probably containing very minor quantities (<4 wt.%) of aluminous clay and Fe-oxides, such as are produced by the destruction of peat (McCarthy et al., 1989). This sandy material has been extensively modified by the introduction of very fine-grained carbonate and amorphous silica. The proportion of these constituents increases with depth, reaching a maximum near the water table. These fine-grained constituents have evidently been deposited directly in the soil, although it is likely that their distribution has been modified by bioturbation (McCarthy et al., 1986b).

The acid-soluble Na abundance is slightly larger than the water-soluble form, possibly as a result of occlusion of Na salts in calcium carbonate. The abundance of Cl is low (Table I) and it is thus concluded that Na must occur almost entirely as carbonates or bicarbonates. In contrast, K occurs in two distinct forms – one which, like Na, is equally soluble in both dilute acid and water, and is probably a carbonate, and the other which is acid insoluble. In the upper portion of the profiles, ~60% of the total K is as carbonate, while in the deeper portions, the insoluble form is dominant (Table I). The insoluble K mineral has not been positively identified, but may be a poorly crystalline illite. The distribution of acid-soluble K_2O and Na_2O in the soil profiles is shown in Fig. 8a and b. Unlike Ca, the abundances of these constituents peak near the soil surface. It will
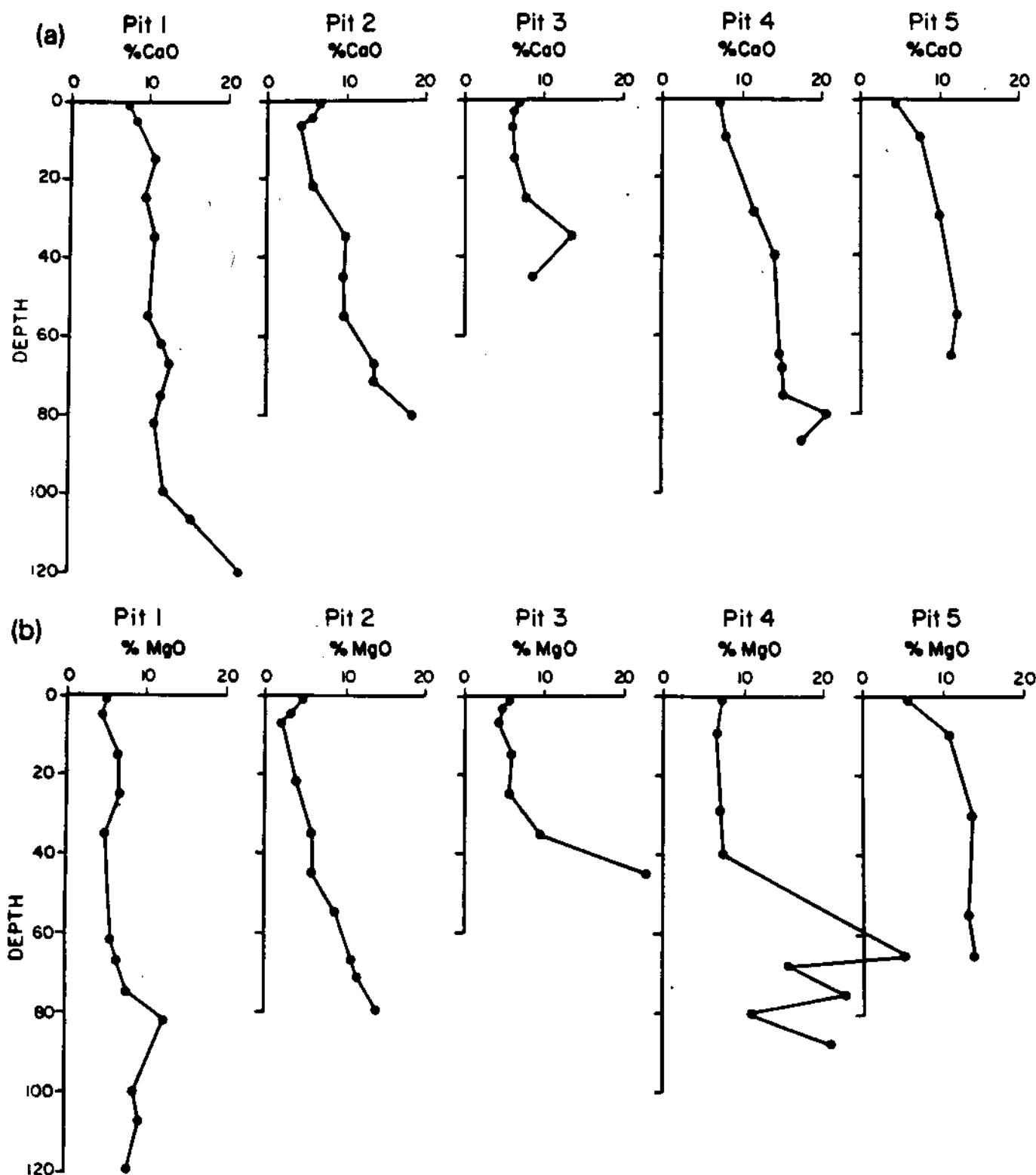
Fig. 6. a. Plots of depth vs. CaO in each of the pits.
b. Plots of depth vs. MgO in each of the pits.

be recalled that the samples were collected during the rainy season, when soluble salts are leached down into the soil profile. During the dry winter months, surface evaporation and capillary action draw the salts to the surface, where they appear as an efflorescent crust

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ABLE II

Chemical parameters

iame	1 CaCO$_3$	2 MgCO$_3$	3 CaO/MgO	4 K$_2$O/Na$_2$O	5 Amorphous SiO$_2$	6 Columns 1+2+5	7 Grains	8 Matrix	9 Expansion
it 1/1	13.08	1.04	14.88	1.58	3.62	17.74			
it 1/2	14.47	0.97	18.35	1.26	2.66	18.10			
it 1/3	18.77	1.32	16.74	1.36	1.34	21.43			
it 1/4	17.27	1.42	14.57	1.46	16.80	35.50			
it 1/5	18.27	1.04	19.29	1.83	10.27	29.58			
it 1/6	17.74				10.88	28.62			
it 1/7	20.66	1.11	21.17	3.13	17.10	38.88			
it 1/8	22.91	1.39	17.68	2.90	3.45	27.75			
it 1/9	20.43	1.60	15.11	2.23	9.30	31.33			
it 1/10	19.02	2.64	8.33	2.23	15.86	37.52			
it 1/11	21.36	1.70	14.67	2.01	22.24	45.30			
it 1/12	27.59	1.94	15.35	2.01	12.74	42.27			
it 1/13	38.13	1.60		1.79		39.73			
Weighted mean			16.01		10.36				
it 2/1	11.67	0.87	17.52	1.67	21.40	33.94			
it 2/2	10.53	0.59	22.43	2.23	17.96	29.08			
it 2/3	7.85	0.42	25.45	1.82	16.46	24.73	24	76	3.10
it 2/4	9.74	0.80	13.57	1.97	20.62	31.16			
it 2/5	17.81	1.18	18.81	1.42	12.66	31.65			
it 2/6	16.49	1.15	18.20	1.47	15.26	32.89			
it 2/7	17.51	1.84	12.12	1.95	15.23	34.58	29	71	'3
it 2/8	24.18	2.22	12.12	1.88	18.15	44.55			
it 2/9	24.29	2.33	12.11	1.79	15.65	42.26			
it 2/10	32.78	2.81	11.77	1.79	19.18	54.77			
Weighted mean			16.41		16.58		18	82	6.10
it 3/1	11.76	1.15	12.94	1.93	7.67	20.58			
it 3/2	12.49	1.04	14.91	1.79	5.89	19.42			
it 3/3	11.01	0.97	14.43	1.69	17.61	29.59			
it 3/4	10.81	1.25	10.52	1.51	12.06	24.12			
it 3/5	11.40	1.15	12.25	2.33	9.41	21.96			
it 3/6	14.08	1.98	13.28	3.35	6.58	22.64			
it 3/8	24.29	4.83	4.86	0	4.53	33.64			
Weighted mean			10.40		8.90				
it 4/1	8.87	1.46	9.14	1.01	9.87	20.20			
it 4/2	12.88	1.18	12.98	0.89	15.39	29.45			
it 4/3	13.85	1.46	11.43	0.48	7.55	22.86			
it 4/4	19.93	1.53	14.78	0.95	8.58	30.04			
it 4/5	24.79	6.42	4.10	0.82	9.91	41.12			
it 4/6	26.43	3.23	9.41	0.89	11.84	41.50			
it 4/7	26.64	4.90	5.87	0.98	7.54	39.08			
it 4/8	27.05	2.19	14.41	0.89	7.06	36.30	26	74	3.50
it 4/9	37.64	4.34	8.48	2.53	8.99	50.97			
Weighted mean			10.07		9.80		13	87	9.90
5/1	7.96	1.18	8.51	1.40	3.51	12.65			
5/2	13.17	2.15	7.25	0.93	1.19	16.51			
5/3	17.79	2.85	6.73	0.70	10.91	31.55			
5/4	21.36	2.57	9.41	1.49	2.68	26.61			
5/5	19.92	2.85	8.57	0.22	5.77	28.53			
Weighted mean			8.09		5.48				

umn 3=CaO/acid-soluble MgO; column 4=acid-soluble K$_2$O/Na$_2$O; column 6=sum of columns 1, 2 and 5; column 7, 8=area ...ction consisting of quartz grains and matrix, respectively; column 9=expansion factor calculated from column 7, assuming quartz grains occupied 60% of area of original material (see text).
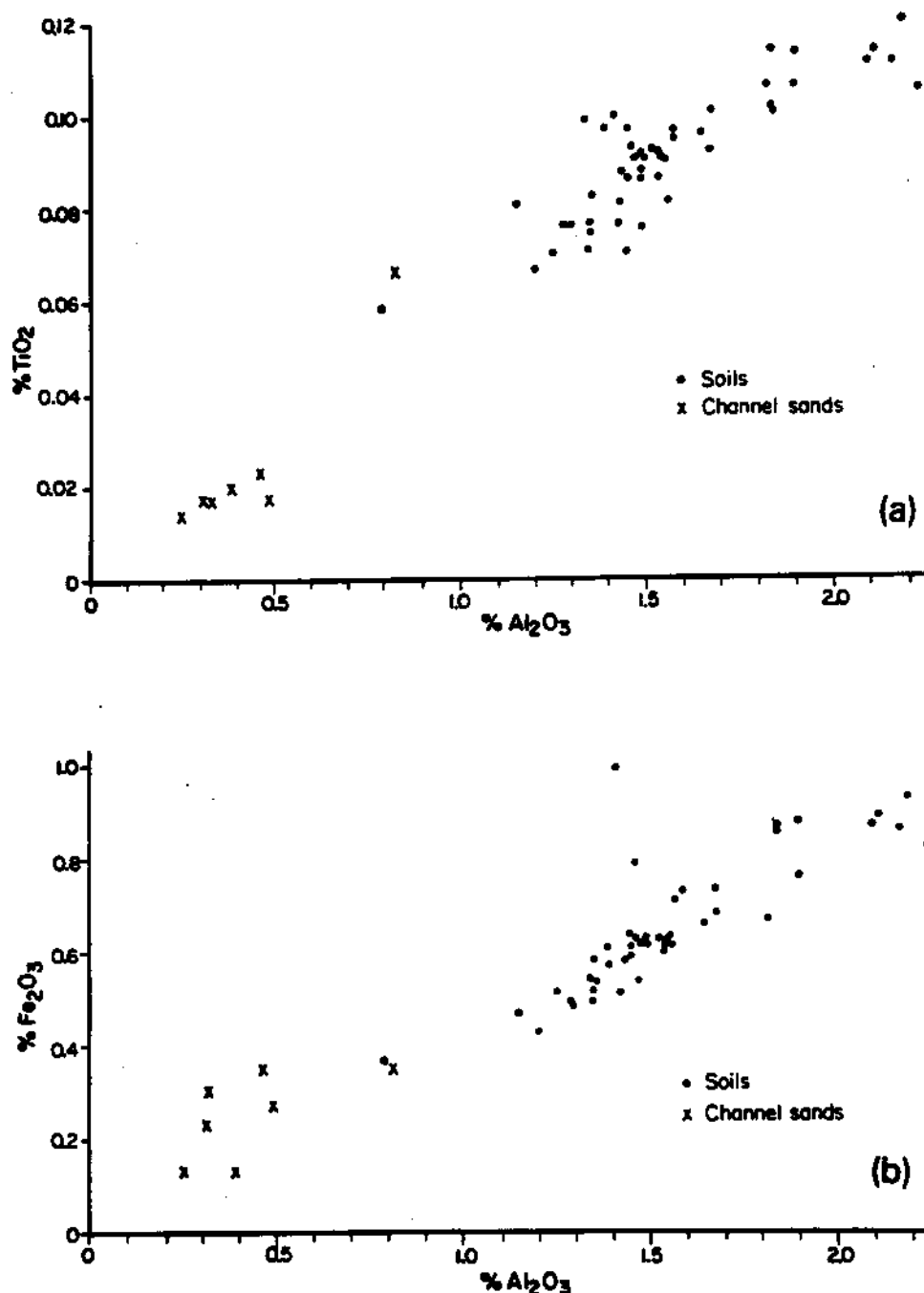
Fig. 7. a. TiO_2 vs. Al_2O_3.
b. Al_2O_3 vs. Fe_2O_3.

(McCarthy et al., 1986b).

The distribution of constituents in the soil profile is, to a certain extent, a reflection of their solubilities (Table III). The most soluble salts, sodium and potassium bicarbonates and carbonates, occur near the top of the profile (on surface in the winter), while the very much less soluble silica occurs through out the profile. Calcium carbonate, the least soluble form, occurs in the deeper regions of the profiles. The distribution of soluble Mg is not related to the solubility of magnesium carbonate or bicarbonate. The abundance of acid-soluble Mg tends to follow Ca. Within individual profiles,
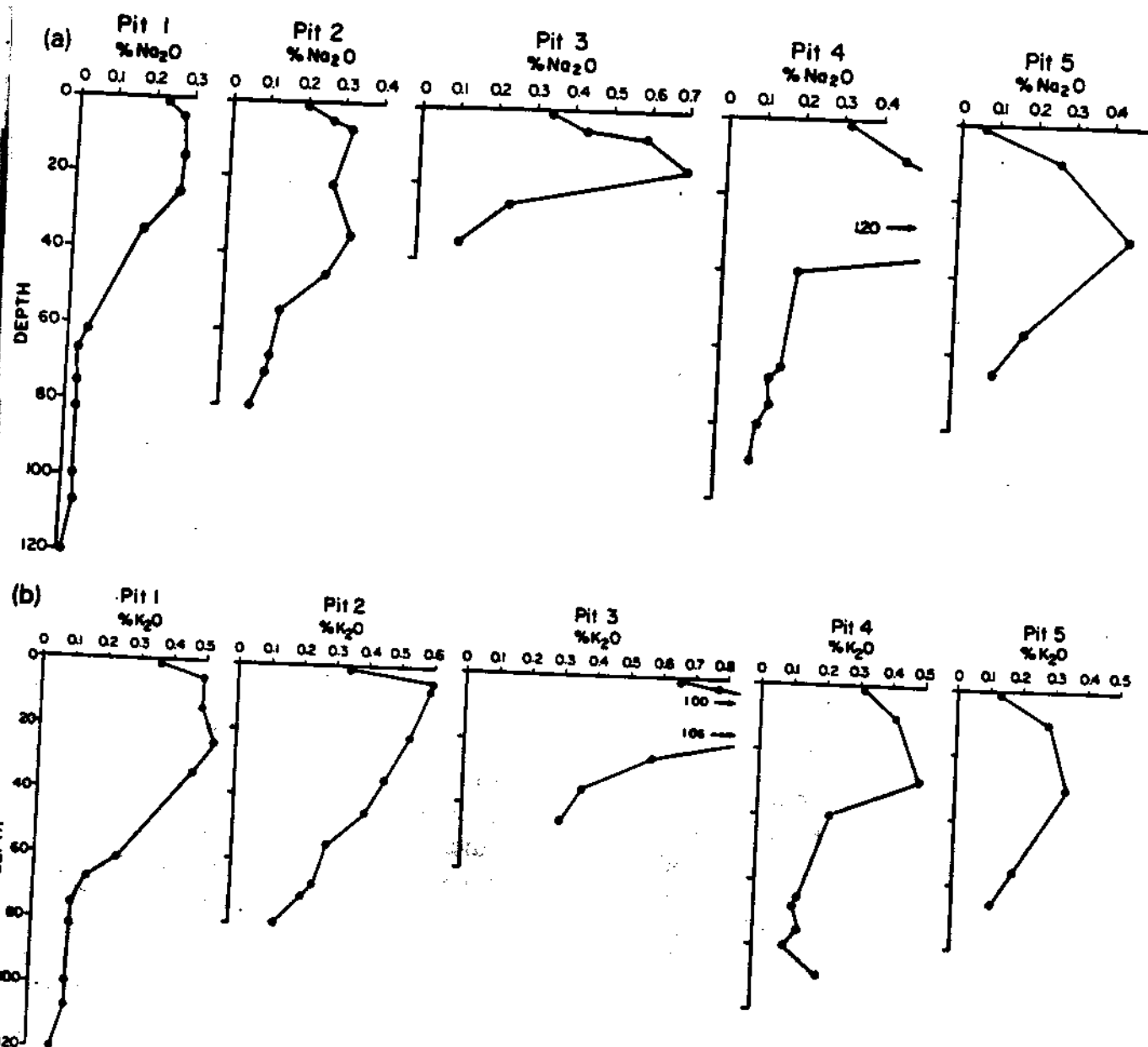
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8. a. Na₂O vs. depth.
Acid-soluble K₂O vs. depth.

Fig. 8. a. Na_2O vs. depth.
b. Acid-soluble K_2O vs. depth.

proximate solubilities of salts (g kg⁻¹)

Approximate solubilities of salts (g kg^{-1})

O_2	0.1*1
CO_3	0.014*2
CO_3	0.11*2
HCO_3	69*2
CO_3	71*2
CO_3	1,120*2
CO_3	224*2

Fournier (1985); *2CRC (1974).

the ratio of Ca to acid-soluble Mg shows no systematic pattern. However, there is a general decrease in the average ratio from a value of ~ 16.2 in pits *1* and *2* to 8.1 in pit *5* (Table II), indicating lateral fractionation across the island.

Water from the Okavango Swamps is of the carbonate-rich variety typical of continental regions (Eugster and Jones, 1979), as is shown in Table IV. The concentration of dissolved ions increases across the swamp. The data in

TABLE IV

Chemical analyses of swamp water

	1	2	3	4
Ca (ppm)	4.4	5.0	9.0	1.8
Mg (ppm)	0.8	0.6	2.0	3.3
Na (ppm)	2.9	2.0	6.5	3.3
K (ppm)	2.7	1.4	4.3	3.1
SiO$_2$ (ppm)	19.3	1.6	35	2.2
Cl (ppm)	1.2	<1	<1	
SO$_4$ (%)	0.33	<1	<1	

1=study area, January 1987 analyses, S.A. Bureau of Standards, Pretoria; *2*=Shakawe, August 1975 analyses, VBB, Stockholm, from Wilson and Dinçer (1976); *3*=Lower Boro River, August 1975 analyses, VBB, Stockholm, from Wilson and Dinçer (1976); *4*=analysis *3* divided by analysis *2* (approximately outlet water/inlet water).

Table IV, column *1*, refer to the area where the present study was undertaken.

The distribution of salts is compatible with progressive evaporation of groundwater (i.e. swamp water) in the capillary zone. Evapotranspiration exceeds rainfall by a factor of 3, on average, in the delta (Wilson and Dinçer, 1976). Experiments reported earlier indicate that evapotranspiration losses from the capillary fringe are similar to those of open water. Because of the low topographic relief, much of the surface of islands lies within the capillary fringe and hence will experience large water losses. Evaporation within the upper regions of the capillary fringe would result in subsurface saturation of the least soluble salts (Sonnenfeld, 1984), in this case calcium carbonate and silica. Coprecipitation of Mg evidently occurs, but there is a progressive decrease in the ratio of CaO to acid-soluble MgO in the soils across the island (Table II), suggesting progressive lateral evolution of capillary waters (Eugster and Jones, 1979) during lateral flow. A significant proportion of the Mg also precipitates in an acid-insoluble form which could not be identified. Gac et al. (1977) noted similar loss of Mg during an evaporation experiment of river water from tropical Africa. The most soluble salts, in this case potassium and sodium carbonates, remain in solution and are drawn

up by capillary flow and precipitate in terminal systems at the surface. Some of the K is lost in an acid-insoluble form, possibly illite. A similar loss of K was reported by Eugster and Jones (1979) in saline lakes in Central Africa. There appears to be a weak separation of Na and K, as the ratio of acid-soluble K$_2$O to Na$_2$O increases slightly but irregularly in a northerly direction across the island (from pit *5* to pit *1*, Table II) and also vertically in each profile.

During the rainy season, surface crusts are dissolved and leached down into the soil. As noted by Wilson and Dinçer (1976), the rainfall rarely contributes to the water table, and the rainfall and its dissolved salts are merely held in the profile, which was the situation during the present study. During the dry season, the salts are returned to the surface. Over time, the total quantity of these soluble salts in the soil profile increases and furthermore, an increasing area is affected by salt build-up. The high soil pH's are directly related to the abundance of Na and K salts (Fig. 9) and it is probably the combination of high pH and high salinity which destroys the vegetation.

Since calcium carbonate and silica saturate in the capillary zone, they precipitate between the sand grains, forming a fine-grained matrix. This would tend to decrease the average grain size and hence extend the zone of capillarity, therefore subjecting an increasing proportion of the island surface to capillary evaporation and evaporative pumping. Such evaporation will initially be confined to the edges of islands, but as precipitation occurs, the affected zone will move to progressively higher levels on the island until the entire island is affected. The vertical distribution of precipitates will be modified by termites and burrowing animals, which will tend to homogenize the profiles. This will apply especially to the low-solubility salts. In contrast, more soluble salts will simply redissolve and be returned to the surface if redistributed by bioturbation.

The effect of calcite and silica precipitation in the soil profile is profound. There is no pet-
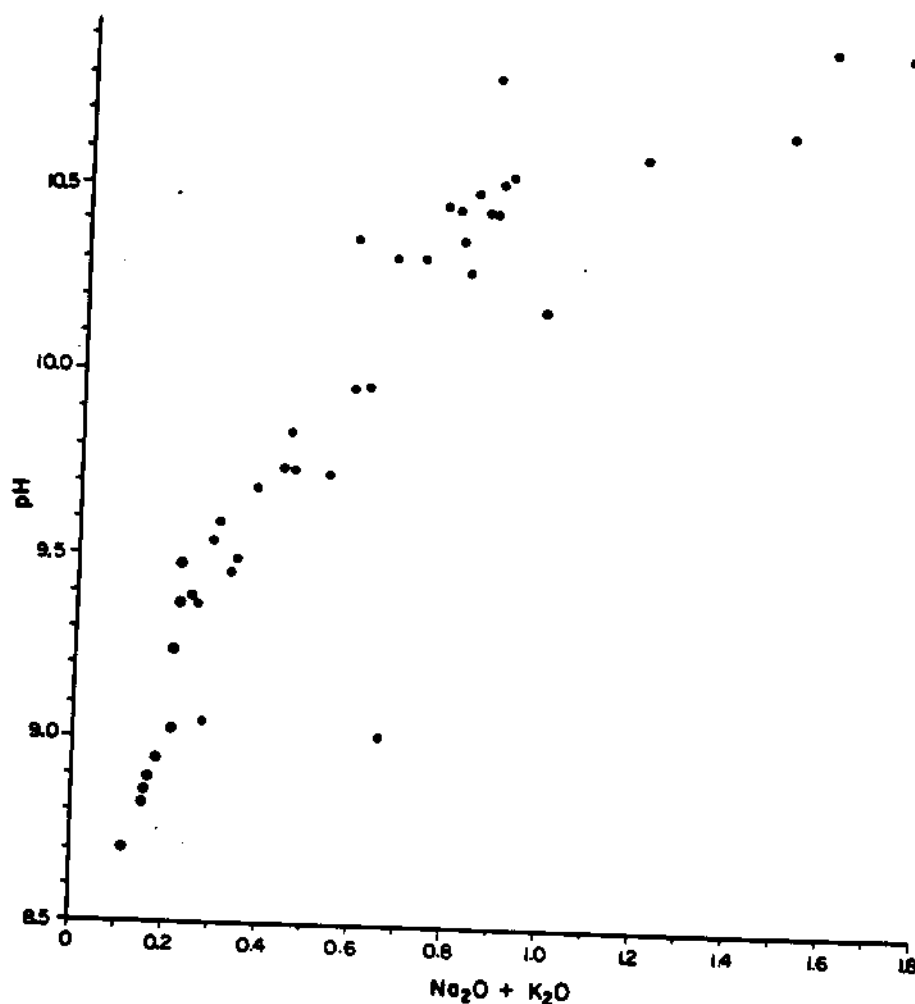
3. 9. Plot of pH against acid-soluble $Na_2O + K_2O$.

graphic evidence of replacement as the sand
ains retain their rounded shape (Fig. 5).
ecipitation occurs between the sand grains,
rcing them apart, producing F textures (Fig.
and c) (Summerfield, 1983) and therefore
using a volume increase. This volume in-
ase was estimated for several of the well-ce-
nted samples by means of point counting in
following way: A grain mount of an acid-
shed soil sample (Fig. 5a) was assumed to
present the condition of the soil prior to the
set of precipitation. Grains comprised 60%
the area of this section. The area occupied
the grains in several samples was measured.
a thin section of sample 4/9, for example,
d grains amount to 13% of the area. In or-
r to cause a decrease in the area occupied by
ins from 60% to 13%, the total area must

have increased 4.6-fold due to increase in the
proportion of matrix. This corresponds to a
linear expansion of 2.2-fold and a volume ex-
pansion of 9.9-fold. The calculated volume ex-
pansions for the samples studied are listed in
Table II and range from 2.6- to 9.9-fold. Be-
cause of lateral confinement, most of this ex-
pansion must occur vertically and must there-
fore be a significant contributor to the
topography of the swamps. In particular, local-
ized precipitation of calcite and silica may ac-
count for the hummocky topography of much
of the delta.

6.2. Salt accumulation times in the study area

It is possible to estimate the time it may have
taken to accumulate the various salts in the soil

of the study island. An average soil profile was calculated from the data in Table I. Assuming a density of 1700 kg m^{-3}, the mass of each of the introduced components in the average soil profile was calculated. Assuming an evapotranspiration rate of 1.6 m a^{-1} and a water composition as in column *1* of Table IV, the following accumulation times were calculated: Mg 22 ka; Ca 22 ka; Na 1.4 ka; and K 2.8 ka. While these are only order of magnitude estimates, they nevertheless indicate the probable great age of the deposits. A striking feature is the great difference in accumulation time between the very soluble and the very insoluble species, which suggests that a substantial proportion of the more soluble salts has been removed from the soil.

The chronological significance of the long accumulation times indicated by Ca is uncertain. It is well known that water distribution in the Okavango Delta changes on a relatively short time scale (Shaw, 1984; McCarthy et al., 1988) and it is unlikely that present conditions of inundation in the study area, which favour extreme rates of evapotranspirational loss, have persisted throughout the long interval indicated. The accumulation time indicated for Ca is therefore a minimum estimate. On the other hand, if the groundwater chemistry was substantially different in the past, specifically of higher salinity, then the calculated time may be an over-estimate. It is unlikely that the chemistry of inflowing water has changed much over the time indicated, but the possibility that local saline groundwater has been involved in carbonate accumulation at some time in the past cannot be ruled out.

The alkalis have low accumulation times relative to Ca and hence are depleted in the soil relative to the amount of Ca present. There are two possible causes: (1) dispersal of trona by wind and animals; and (2) loss to groundwater. During the dry season the efflorescent crusts may be dispersed by wind or by adhering to the feet of wild animals especially hippopotami, elephants and red lechwes which

abound in the area. During the rainy season, the crusts are dissolved and salts are leached into the soil. Normally, these would be returned to the surface during the following dry season. However, if this region of the swamp were to be temporarily abandoned due to a shift in water distribution, the salts would remain in the soil, perhaps being leached further each year. When the area is reflooded, some or all of these salts would dissolve in the rising groundwater, resulting in a solution of elevated density which would tend to sink. In this way, the more soluble salts could be transferred to deeper levels in the graben fill, producing a saline brine at depth. This latter process would be far more effective than dispersal of salt crusts by animals and wind, as it will result in flushing of the soil. This is important from an ecological point of view as it would enable islands which had become devoid of vegetation to recover. In contrast to the alkali carbonates, calcium carbonate and silica would remain in the soil because of their very low solubilities, but their presence would have no impact on the vegetation.

6.3. Salt balance

It is instructive to examine the salt balance for the Okavango Delta. The relevant information is summarized in Table V. Of the 15.5·10^9 m^3 a^{-1} of water which enters the delta, 14.9·10^9 m^3 a^{-1} is lost by evapotranspiration. The bedload and suspended sediment load are based on unpublished data (T.S.M., 1989), and refer to measurements made at Shakawe at the apex of the delta (Fig. 1). These studies have revealed that ~90% of the bedload is presently being deposited in the Panhandle region of the delta (Fig. 1), although this has not always been the case. The data in Table V show that material brought into the delta in solution and dispersed on the fan greatly exceeds the quantity of clastic material (bedload plus suspended load). It follows that the precipitation of less soluble calcium carbonate and silica

TABLE V

Annual chemical and sediment budgets for the Okavango Delta

	Inflow	Surface outflow	Sub-surface outflow
water[*1]	11·10^9 m^3	0.3·10^9 m^3	0.3·10^9 m^3 a^{-1}
Bedload[*2] (t)	170,000	nil	nil
Suspended load[*2] (t)	30,000	nil	nil
CaCO$_3$ (t)	137,500[*3]	6,750[*4]	
MgCO$_3$ (t)	22,890[*3]	2,082[*4]	
SiO$_2$ (t)	176,000[*3]	10,500[*4]	
NaHCO$_3$ (t)	81,500[*3]	7,200[*4]	
KHCO$_3$ (t)	39,500[*3]	3,300[*4]	
Total dissolved solids (t)	457,390	29,832	

[*1] Dinçer et al. (1981).
[*2] Based on T.S.M. (unpublished data, 1989): 90% of this is deposited in the Panhandle region and only 10% is deposited on the fan itself.
[*3] Calculated using data in column 2, Table IV.
[*4] Calculated using data in column 3, Table IV.

t = 1 metric tonne = 10^3 kg.

must dominate sedimentation on the fan. The water lost through subsurface outflow, if saturated in CaCO$_3$, could remove only ~18,000 from the system, indicating that an amount 113,000 t a^{-1} of CaCO$_3$ is accumulating on the fan. Similar calculations for silica indicate that ~135,000 t a^{-1} are accumulating. In contrast, the estimated subsurface outflow could remove all of the Na and K if it contained only 50 ppm alkali carbonate in solution. Thus, under present conditions, 250,000 t of chemical sediment are accumulating on the fan per year, compared to ~40,000 t of clastic sediment consisting of ~10,000 t of bedload and 30,000 t of suspended load. If the chemical sedimentation was occurring uniformly over the whole delta, accumulation rates would be negligible, but this is not the case, because precipitation is more localized as will be discussed in Section 6.4.

Dissolved salts become enriched in swamp waters due to evapotranspiration which is partly offset by uptake by peat (McCarthy et al., 1989). Provided that the water does not become saturated, the degree of enrichment for dissolved ions should be the same. The degree of enrichment between inflow and outflow is essentially the same for K, Na and Mg (Table IV, column 4), but enrichment factors for Ca and SiO$_2$ are less, even though the outflow water is not saturated in calcite or silica. It appears that the greater enrichments in alkalis and Mg relative to Ca and silica cannot be due to evapotranspiration alone. It seems that the outflow water has been enriched either by dissolving precipitates of alkali and Mg salts, or has mixed with water enriched in these components, but which has become saturated and has lost calcium carbonate and silica. It should be noted that the degree of enrichment of Mg in Table IV, column 4, is inconsistent with its accumulation with Ca on the islands. It is possible that the reported concentration of 0.6 ppm in inflow water (Table IV, column 2) is systematically too low.

6.4. A model for salt accumulation

The data discussed above suggest a model for chemical sedimentation, or, more correctly, diagenesis in the Okavango Delta (Fig. 10). Fig. 10a illustrates the situation at peak flood (July). Evaporation occurs off the water surface and off those areas of land lying within the capillary fringe. Uptake of salts by peat in the permanent swamps partly offsets the increase in dissolved salt concentration in swamp water (McCarthy et al., 1989). Within the capillary zone on the islands, water becomes saturated in calcite and silica and precipitates these constituents in the soil, while the soluble salts collect as surface crusts. The water level in the seasonal swamp falls gradually as the flood wanes, causing a migration of the zone of capillarity and hence of precipitation (Fig. 10b and c). Fig. 10c represents the situation at low water (December). The summer rains (January–February) wash the soluble salts into the
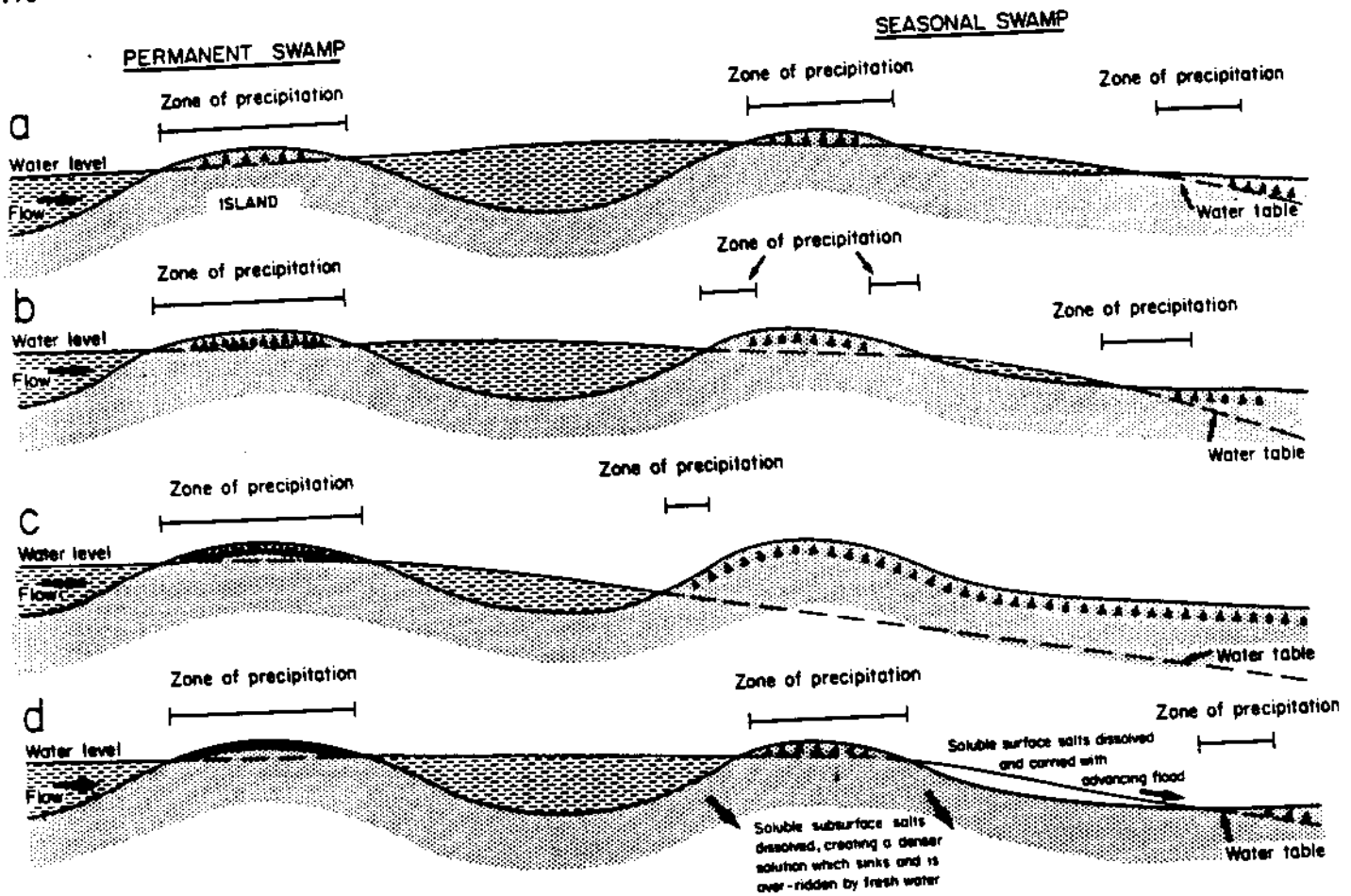
Fig. 10. Schematic diagram down the Okavango Delta illustrating the mechanism of salt accumulation and dispersal. The scales are greatly exaggerated. The vertical elevation represented is only a few metres but the total horizontal distance represented is in excess of 100 km, although this extreme horizontal scale does not apply to the islands, which are typically a few tens or hundreds of metres across.

soil, but a portion of these are returned to surface by evaporation at the end of the rainy season. With the arrival of the seasonal flood water (May or June), the more soluble salts which have accumulated at or near the surface in the seasonal swamp are dissolved, causing relative enrichments in these constituents in the outflow water. Thus soluble salts become flushed from the system, while the low-solubility salts accumulate. Saline groundwaters which may develop will be overridden by the freshwater wedge of the new flood wave and will sink into the subsurface. Their ultimate fate is unknown, but they may well leak out of the graben. In contrast to the situation in the seasonal swamps, the water level in the permanent swamps varies only slightly over the year (10–20 cm). Consequently, islands in these swamps experience salt accumulation throughout the year.

Islands in the seasonal swamps will experience gradual accumulation of salts, but in these areas soluble salts will tend to be removed by a combination of downward leaching during the summer rains and dissolution by rising groundwater during the next seasonal flood. In contrast, islands in the permanent swamps will experience continuous accumulation and hence salt build-up in this region will be greater. It is probably for this reason that trona-encrusted islands tend to be more common in the permanent swamps than in the seasonal swamps. In terms of this model, the rate of carbonate and silica accumulation is extremely variable

ver the delta, with maximum rates occurring
n islands in the permanent swamps, and min-
num rates occurring in flat areas in the sea-
onal swamps. This accumulation will result in
ifferential rise of the land surface, accentuat-
ıg topographic irregularities, and perhaps
ausing the hummocky topography of much of
ıe delta.

. Conclusions

This study has shown that chemical precipi-
ıtion is the major depositional process in the
kavango basin at present, occurring essen-
ally as a diagenetic phenomenon, but operat-
ıg in the near-surface environment. This form
sedimentation is not simply a redistribution
material within the host, but represents an
ıportant aggradational process. Mass-bal-
ıce calculations indicate that the quantity of
ıemical precipitate is at least five times that
clastic sediment. It is probable that chemi-
l sedimentation has always dominated in this
gion and the products of chemical sedimen-
tion therefore must form the major part of
e graben fill.

The main mechanism of chemical sedimen-
tion is capillary evaporation, possibly in
njunction with evaporative pumping or suc-
ın. The main areas of accumulation are the
ands. The process leads to the separation of
e less soluble salts from the more soluble
lts. The former collect in the subsurface as
ıely divided material but ultimately form a
ment consisting of calcite and silica (cal-
ete or silcrete). This precipitation is associ-
ed with a major volume increase, which ex-
esses itself in hummocky topography. The
ore soluble salts, sodium and potassium car-
nates, accumulate as efflorescent crusts.
ılorides and sulphates are absent because of
ν concentration in the source waters. The
ild-up of alkali salts ultimately destroys the
getation, but these accumulations are most
ely transient, and ultimately the very solu-
alkali salts are probably transferred to deep

brines, which are either accumulating at depth
or are leaking away into the Kalahari basin. The
removal of these salts is ecologically important
because it allows for the recovery of the af-
fected regions.

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