Wind-blown materials and W African soils: an explanation of the 'ferrallitic soil over loose sandy sediments' profile

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SUMMARY: It is suggested that incorporation of dust from the hinterland during episodes in the Pleistocene when the Sahara encroached far S of its present limits accounts for much of the clay and Fe_2O_3 content of soils of southern Nigeria. The amount of pelagic deposition of clay reported for DSDP Site 366 on the Sierra Leone Rise in the last 1–3 million years is shown to correspond to the anomalous accumulation of clay in deep uniform subsoils of the 'red ferrallitic soils over loose sandy sediments'. Particle-size analyses of soils at seven sites (showing 10% to 50% clay in the subsoil) are given, with determinations of Fe_2O_3 in the clay fraction (5% to 9%). Silt-size quartz in the dust is thought to have been lost through solution, and feldspars and clay minerals have weathered to kaolin. Wind systems displaced 600–800 km to the S compared with the situation today would have deposited dust similar to present-day Harmattan fall-out in the N of Nigeria, in the latitude of southern Nigeria and of the Sierra Leone Rise. Creep, mass-movement, faunal activity and eluviation of clay and Fe_2O_3 have affected the incorporation of dust, in addition to mixing coarser and finer layers of sediments together.

A significant factor in the formation of lateritic ironstone on old peneplain surfaces in W and E Africa may have been deposition of clayey and ferruginous dust (Vine 1949). The addition of large amounts of such dust possibly contributed to the formation of the 'Acid Sands' soils of southern Nigeria (Vine 1956)—soils included in the more general classes of Red and Yellowish-Brown Ferrallitic Soils on Loose Sandy Sediments of the CCTA *Soil Map of Africa* (D'Hoore 1964). These ideas arose from consideration of the very sandy soils, termed the 'Northern Drift' type by Doyne *et al.* (1938), which prevail in a wide zone in the N of Nigeria and in adjoining territory. The Northern Drift soils occur partly in the form of fixed dunes, developed during arid periods in the past; present-day mean annual rainfall in this zone is approximately 150 to 800 mm. The writer regarded the sand as the residue left after the fine fractions of soils had been blown away southwards, a process that would have been most vigorous during episodes when the Sahara was advancing over areas where there had been sufficiently humid conditions for the formation of red clayey soils.

A well-known feature of the interior of W Africa at the present day is the very dry and dusty Harmattan wind which blows by day from the NE during the period October to March (Dubief 1979, pp. 29–31). The main source area of the Harmattan dust and haze was considered by Hamilton & Archbold (1945) to be the desert region around Faya Largeau 700 km NE of Lake Chad which had a particularly 'light and dusty' soil. They showed that convective uplift and gusty surface winds in this area are caused by disturbances which penetrate across the desert from the Mediterranean, and that there are severe dust storms when the convection is most intense. Kalu (1979) developed this explanation. He regarded the whole of the 'alluvial plain of Bilma and Faya Largeau' as the source of the dust carried away southwestwards by winds at altitudes of about 600 to 1200 m. The dust forms a 'plume', from which there is fall-out in progressively decreasing amounts and with a decreasing mean particle size. McTainsh & Walker (1982) accounted for the replenishment of the alluvial deposits in the region of Faya Largeau, balancing the loss of material by wind action, as the result of fluvial transportation of material from the high-rainfall regions S of Lake Chad, with intermittent overspill from the present lake area to the Bodele Depression further N. In 1976–77 they recorded 13 dust plumes with an average duration of six days passing over northern Nigeria. Most of the heavy deposition of dust tended to occur between the source area and Kano.

Clay content of Harmattan dust fall-out

Dust deposited at distances of 1000 to 1700 km downwind from Faya Largeau has been found to contain large quantities of clay and iron oxide. Doyne *et al.* (1938) collected a sample at Samaru, Zaria (not at Ibadan in southern Nigeria as McTainsh & Walker supposed), and determined the particle-size distribution by a sedimentation

method, after thorough disaggregation. The results were: 64.7% clay (<2 μm), 24.5% 'silt' (2–20 μm), 10.8% 'fine sand' (20–200 μm). The reported 'fine sand' was mostly coarse silt (20–50 μm). There was about 10% $CaCO_3$, mainly in the 'silt' size fraction. The clay fraction was analysed for SiO_2, Al_2O_3 and Fe_2O_3 (see Table 4 below).

McTainsh & Walker (1982) carried out particle-size analyses of 39 carefully collected samples of dust fall-out, thoroughly disaggregated. The results are given on a weight basis. The amount of clay fraction (<2 μm) was found to range from 2.3% to 32%; in 31 of the 39 samples it was between 10% and 30%. In four samples collected at Kano during periods of poor visibility the clay fraction ranged from 21% to 28% (average 26%), and in four collected when the visibility was better the range was 7% to 15% (average 11%). In these eight Kano samples fine sand (50–200 μm) was 4% to 32% (average 10%), coarse silt (20–50 μm) was 28% to 42% (average 35%) and fine silt (2–20 μm) was 20% to 38% (average 30%).

X-ray diffraction analysis of the clay fraction from some of McTainsh & Walker's samples collected at Kano showed about 60% kaolinite, 10% illite, and 25% smectite, with a small percentage of quartz. In the whole sediment, quartz was dominant, with varying amounts of feldspar and calcite as well as the clay minerals. The percentage of clay size material in fall-out samples collected in the same way at other places was:

Maiduguri	12%
Jos	16%
Zaria	24% (two samples)
Sokoto	28%

Wilke *et al.* (1984) analysed the minerals of the clay fractions in fall-out collected at four stations during the 1978–79 Harmattan season, with the following results:

Maiduguri	Kaolinite (60%), Illite
Jos	Kaolinite (40%), Illite
Kano	Kaolinite (40%), Mixed-layer (Illite–Smectite) (30%), Illite
Sokoto	Kaolinite (40%), Mixed-layer (Illite–Smectite) (30%), Illite.

The very fine dust-haze material

Dubief (1979) described 'dense dry haze' as a layer which persists over W Africa downwind of the stations where samples of fall-out were collected for the studies detailed above. After a particular dust storm at Bilma in early March he showed how the front of the dust haze progressed, taking $3\frac{1}{2}$ to 4 days to reach the coast between Lagos and Monrovia.

The dust present in the atmosphere at Ibadan during the 1955–56 dry season was investigated by McKeown (1958) by trapping air in a settlement counter and examining the deposit under a microscope at times corresponding to settlement of certain sizes of particle (*eg* 53 min for 1.0 μm, 5 h for 0.3 μm, 97 h for 0.06 μm). Air was sampled at 1600 local time, when the lower layers of the atmosphere were well mixed by turbulence. Size analyses were carried out on eight occasions. Six samples showed about 80% of the particles in the 0.2–0.3 μm diameter range and two showed about 75% in the 0.3–0.4 μm range.

McKeown's observations indicate that, at a great enough distance from the source, deposition can be entirely of clay-size mineral material. The deposition of such fine material is achieved by rainstorms (Dubief 1979) and may take place over the ocean.

It may also be noted that, if the rates of fall of particles 1 μm or less in diameter are as slow as indicated, then much of the clay fraction found by McTainsh & Walker (1982) in dust fall-out must have been carried as fragmented soil (silt-size aggregates) and not as single particles, because, in the three clay-fractions which they analysed in more detail, 40% to 70% of the material was less than 0.2 μm in diameter.

How much wind-blown dust has been incorporated in the 'Acid Sands' (ferrallitic soils over loose sandy sediments) and how have the deep uniform subsoils been formed?

These soils are extensive in Nigeria (see Fig. 1). In the southern part of the country all soils except some in valley bottoms show an increase in clay content with depth. The thickness of the 'eluvial horizons' is generally between 20 and 80 cm. In the Acid Sands the total amount of clay in the very thick subsoils ('illuvial' horizons) seemed to the writer to be anomalous, as in many places there was little clay in the parent material of intensely weathered Tertiary and Upper Cretaceous sandstones (Vine 1949). It was envisaged that there must have been a relative accumulation of clay over a considerable time period. This clay would be derived from the sporadic clay beds in the sandstones by leaching and eluviation whilst sandy surface soil was gradually lost by erosion. Grove (1951, p. 12) also indicated that this could be an effective process, though extremely slow under forest. The idea that deposition of clayey and ferruginous dust was a major factor (Vine 1956) offered a better explanation; but there was

sufficient amounts of dust could have been

no substantial evidence that there was a sufficient quantity of dust being deposited. Subsequently, cores drilled in the sea bed in various parts of the world have revealed the widespread presence of considerable amounts of material finer than loess that have been transported long distances and deposited as fall-out or by rain-wash.

Even more clearly than in the case of the clay content, there seems to be far more iron oxide in the profile than could be derived from the underlying sandstone and clay layers.

The clay and iron oxide may quite possibly, therefore, have been contributed both by the addition of wind-blown dust and by the break-up and dispersal of the fine layers that occur in the underlying sediments. Even so, it is remarkable that there has been thorough mixing to such great depths. Grove (1951) found that the red subsoil of the Acid Sands in the rolling landscapes which he was studying could be 12 to 18 m thick, but was less on valley slopes (*eg* 8 to 10 m in the sides of a particular gully).

There are several problems involved in explaining the origin of these soils which will be considered further in this paper:

(1) Whether the rate at which clay was deposited by dust fall-out on the Sierra Leone Rise at DSDP Site 366 during the Pleistocene can explain the amounts of clay in Acid Sands profiles at a number of sites—these sites being at different elevations and thought to be of differing age.

(2) Whether the ratio of Fe_2O_3 to clay in these soils is similar to that in Harmattan dust and could be accounted for by Pleistocene fall-out.

(3) Whether 'slope pedimentation' (Rohdenburg 1969), 'breakaway retreat' (Moss 1965), and other processes involving creep and mass movement, which might explain the landscapes where these soils occur and the depths of subsoil, can yet be fully defined.
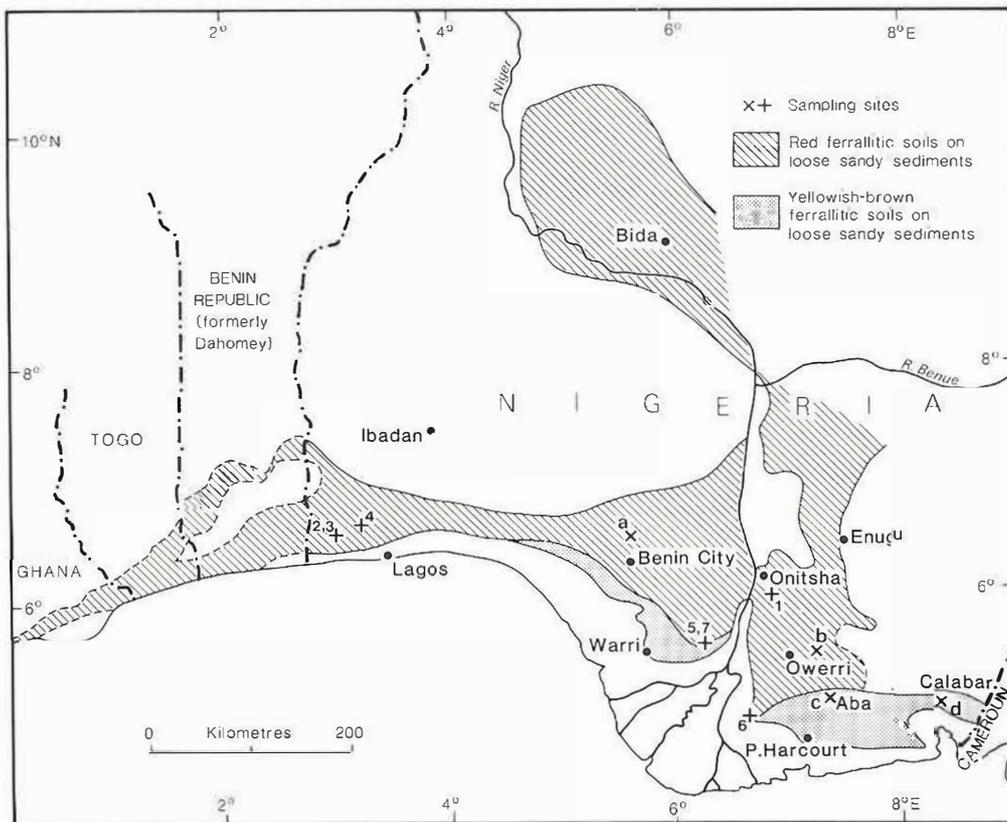

FIG. 1. Map showing occurrence of ferrallitic soils on loose sandy sediments (Tertiary and Upper Cretaceous) in the southern half of Nigeria, Benin Republic, Togo and Ghana, as on CCTA *Soil Map of Africa* 1964. The region of red soils includes three land form-related sub-types: areas almost wholly of 'Acid Sands', areas of mottled soils and 'Acid Sands', and areas of 'Acid Sands' and soils with hardened layers.

A further problem that arises is that neither silt-size quartz nor clay minerals other than kaolin, which should accumulate in aeolian dust, have been recorded. Relatively rapid weathering of these materials in humid tropical conditions appears to provide the explanation for their absence *presence in only small amounts*.

The soils in relation to geology

An easily accessible section of 'loose sandy sediments' overlain by red ferrallitic soil is provided by a large pit near Oba, 8 km from Onitsha on the modern highway to the S, on a broad rolling summit about 130 m above sea level and 110 m above the nearby Niger flood plain (Site 1, Fig. 1). An increased demand for sand for use in concrete buildings meant that by 1980 there was an excavation 20 to 25 m deep exploiting this extensive supply of unconsolidated sandstone. The sediments in this locality are believed to be Oligocene–Miocene, and have been regarded as part of the Lignite Series or Ogwashi–Asaba Formation (Grove 1951; Reyment 1965). They could now be placed in the diachronous Benin Formation as defined by Short & Stäuble (1967) and Avbovbo (1978); the cross-bedded ('false bedded') sand in the pit is typical of what Parkinson (1907) first termed Benin Sands.

Highly weathered unconsolidated sandstones similar to those in the Oba pit are exposed in gullies in several areas. The clay layers that occur

sporadically are typically about 20 cm thick. Where there are thicker clay beds they tend to prevent drainage, and lignites immediately above them are preserved. With this exception the sediments are very much altered, and in particular, originally plentiful plant remains have been oxidized and disappeared (A. M. J. de Swardt pers. comm.). It can be suggested that there would probably have been pyrites in these deltaic deposits, as a result of which acid-sulphate weathering would occur upon exposure to oxygen as the groundwater receded during uplift (in older formations and in the northern part of the Benin Formation), or during eustatic falls in sea level. Information on the Benin Formation in the unweathered state is scarce. Avbovbo (1978) notes that this formation attains a thickness of almost 2000 m at the middle of its area. He describes the deposits as having been laid down in braided streams on sandy alluvial plains and as being highly porous and freshwater-bearing. He stated: 'Mineralogically the sandstones consist dominantly of quartz and potash feldspar with minor amounts of plagioclase'.

The problematic relationship between soil and geology was very clearly seen in the pit at Oba where a random sample of subsoil at about 120 cm depth was collected as well as a piece of very weakly coherent cross-bedded sandstone from about 20 m. The section deserves a fuller study. Analyses of the two samples are given in Table 1 and X-ray difffractograms of the 0.2–0.5 mm and 0.05–0.2 mm grain size fractions are given in Fig. 2. The soil profile consists of a metre
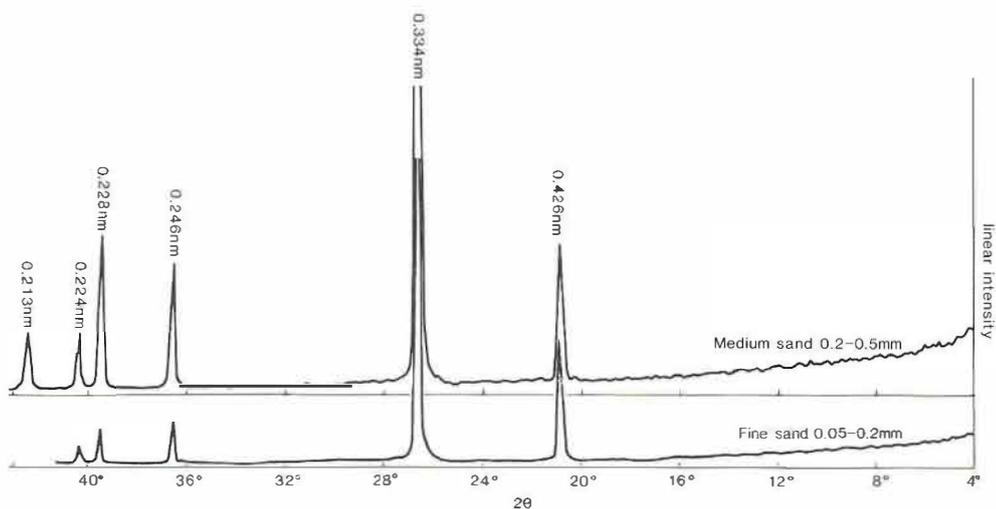

FIG. 2. X-ray diffractograms (CuKα radiation, Ni filter) of two sand fractions of weathered cross-bedded sandstone of the Benin Formation, from approximately 20 m depth at Site 1, indicating quartz alone, with no trace of feldspar or mica.

TABLE 1. *Details and analyses of soil samples from Sites 1 to 7 and deep sample of weathered cross-bedded sandstone from Site 1*

Site	Height above sea (m)	Soil series	Material sampled	Depth (cm)	Munsell colour (moist)	Particle size						Fe$_2$O$_3$*		XRD† of clay
						Gravel <2.0 mm	Coarse sand 2.0–0.2 mm	Fine sand 0.2–0.05 mm	Coarse silt 50–20 μm	Medium & fine silt 20–2 μm	Clay <2 μm	in clay fraction (%)	in whole specimen (%)	
1	130	Kulfo	Subsoil	120	10R 4/8 red	nil	74.6	9.2	1.4	1.0	13.8	6.1	—	(ii)
			False-bedded sandstone	2000	2.5Y 8/4 pale yellow	nil	90.8	4.3	0.2	1.0	3.7	—	0.083	(i)
2	40	Alagba	Soil	0–5	2.5YR 3/2 dusky red	0.1	71.1	14.1	1.3	2.6	10.9	8.1	—	—
				18–23	2.5YR 2/4 dark red	0.3	71.9	11.9	1.3	2.6	12.3	8.6	—	—
				35–50	2.5YR 3/6 dark red	0.2	56.5	8.1	0.8	1.8	32.8	8.2	—	—
			Subsoil	150–180	2.5YR 4/6 red	0.4	35.4	8.3	1.0	2.2	53.1	6.4	—	(ii)
3	40	Alagba	Soil	0–5	2.5YR 3/2 dusky red	nil	74.1	9.8	1.2	2.4	12.5	5.2	—	—
				13–20	2.5YR 2/4 dark red	nil	67.2	10.3	1.3	3.1	18.1	6.6	—	—
				35–48	2.5YR 4/6 red	nil	55.2	7.8	0.8	2.1	34.1	7.3	—	(ii)
			Subsoil	150–175	2.5YR 4/8 red	nil	34.6	7.9	1.2	2.7	53.6	7.6	—	—
4	120	Alagba–Owode	Soil	0–5	2.5YR 3/2 dusky red	nil	38.6	34.0	4.8	8.0	14.6	8.2	—	—
				18–28	2.5YR 3/4 dark reddish-brown	nil	52.6	11.7	2.1	3.3	30.3	7.3	—	—
				28–50	2.5YR 3/6 dark red	nil	39.9	8.9	1.7	2.9	46.6	7.3	—	(ii)
			Subsoil	140–175	2.5YR 3/6 dark red	nil	33.0	10.0	2.1	3.1	51.8	6.3	—	(ii)
5	30?	Kulfo	Soil	45	5YR 4/8 yellowish-red	nil	42.5	34.8	2.7	2.0	18.0	6.6	—	—
			Subsoil	90	2.5YR 4/8 red	nil	46.3	27.5	2.3	1.7	22.2	6.0	—	(iii)
6	20?	Ahiara	Soil	0–20	7.5YR 3/4 dark brown	nil	86.7	4.7	0.2	1.1	7.3	6.3	—	—
				45	10YR 5/3 brown	nil	93.1	2.8	0.7	0.8	2.7	6.6	—	—
			Subsoil	200	5YR 5/8 yellowish-red	nil	81.6	4.2	1.9	1.4	10.9	6.0	—	(iii)
7	20?	Ahiara	Soil	0–2	5YR 2/3 v. dark reddish-brown	nil	73.4	17.5	1.2	1.4	6.5	4.8	—	—
				2–22	5YR 3/3 dark reddish-brown	nil	82.9	11.4	0.5	0.6	4.6	5.2	—	—
			Subsoil	82–135	5YR 5/8 yellowish-red	nil	64.1	18.1	1.7	1.7	14.4	5.7	—	(iii)

cross-bedded

* Expressed on oven-dry basis. Extraction with dithionite–citrate–bicarbonate (Mehra & Jackson 1960).
† (i) Very well ordered kaolinite with sharp intense peaks.
 (ii) Kaolin with fairly narrow 12.3° and 24.95° peaks (CuKα radiation) and low 19.9–20.4 –21.4° and 37.8–38.3–38.5° peaks.
 (iii) Kaolin with broader 12.3° and 24.95° peaks and still lower bands at 19.9–21.4° and 37.8–38.5° than in (ii).

of loose sandy brownish layers merging downwards into red coherent but friable subsoil to 5 m. Pale yellow cross-bedded sandstone could be seen in much of the pit face from 5 m downwards. Some of it was obscured by rain-wash, but a remarkably sharp uneven line could be seen around the pit separating the red subsoil from the sandstone. The sandstone is clearly the source of the sand fractions in the soil profile. On the other hand, the analyses show that it contains very little clay, almost no Fe_2O_3, and no feldspar which might decompose to form clay.

The type of soil at the Oba pit is commonly known as the *Kulfo Series*. Similar soils with higher percentages of clay material form the *Alagba Series* (including soils that were termed *Orlu Series*). Soils with the same type of profile but lower clay percentages have been termed the *Ahiara Series*.

Areas almost wholly composed of Acid Sands

There are large rolling to gently undulating areas where only the non-mottled, non-gravelly Acid Sands soils occur, with sandy hydromorphic soils confined to incised valleys. The two main areas of the Benin Formation fall into this category and they form the immediate hinterland of the Niger Delta. They include the sampling sites 1, 5, 6 and 7 and a, b, c and d shown in Fig. 1, E and W of the Niger. Observations in these areas suggest that the amount of clay in the subsoil is related to elevation and to the age of the surface, but that the proportion of clay beds intercalated in the sands is also a factor.

At the Institute for Oil Palm Research near Benin City a rolling upland surface is occupied by soils of the Alagba and Kulfo Series, whilst the northern part of the Institute land is on the irregular slopes of an incised valley about 130 m deep, where the soil changes to the very loose sandy material of the Ahiara Series. Geomorphologically the valley slopes steeply down to an uneven terrace or bench about 1 km wide, then drops steeply again to a perennial stream. Similarly, at Ahiara, where Site b (Fig. 1) is on a rolling upland clothed with the Alagba Series soil, there is a steep drop to an uneven area where a Government Farm Centre was established on the Ahiara Series and then a further drop to a stream.

Two surfaces are clearly seen on a broader scale over the Benin Formation on the western side of the Niger. The main road E of Benin City is on an undulating surface at 150 to 250 m above sea level deeply incised by wide-spaced streams. Approximately 12 km from the Niger it drops to a lower surface which slopes down gradually to the river. A continuous scarp (of smoothed form in the unconsolidated soil and sandstone) runs many kilometres southwestwards. The upper surface rises gradually to 450 m above sea level. The soil is of the Alagba Series, in some parts having more than the average amount of clay, which is possibly due to thick beds of clay associated with the lignite. The lower surface is an undulating plain falling from about 90 m above sea level to about 20 m, and soils identified as Kulfo Series were found at several sites examined in this area. Samples used in the present study were collected in 1980 at the Oleh junction on the Ughelli–Kwale highway (Site 5) and Emakporo's palm plot (Site 7), near the lowest part of the undulating plain. The profiles were identified as the Kulfo and Ahiara Series respectively.

East of the Niger, Site 6 (Ahiara Series) is on a low undulating surface interrupted by swampy areas. The broad summit where Site 1 (Kulfo Series) is located may be a continuation of an intermediate surface which widens around and beyond Owerri (Fig. 1). E and NE from the locality of Site 1, Acid Sands soils occur over two extensive uplands, with summit levels rising to 350 m (the Awka–Orlu Uplands, formed of Eocene strata) and 450 m (the Udi Plateau, formed of Upper Cretaceous strata). Of these, the former appears to have somewhat more clayey soils and subsoils (Grove 1951), but a few figures given by Obihara *et al.* (1964) for the main Acid Sands soil of the Udi Plateau, termed the Nkpologu Series, indicate even there, there is considerably more clay in the soil than in the examples from the Kulfo Series at Sites 1 and 5.

Areas of mottled soils and Acid Sands

These are large areas immediately NE and NW of Lagos, correlated stratigraphically with the Benin Formation of the Niger Delta region, but with a larger proportion of clay or sandy clay. Profiles either show red or orange-brown non-mottled soil (in the Owode and Agege Series) over red-mottled sandy clay at approximately 1 to 2.5 m depth or are of the Acid Sands type (mainly the Alagba Series) as at Sites 2 and 3. It will be seen in Table 1 that the subsoils at these two sites contained 53% clay-sized material. A large proportion of this could have been derived from the varied sedimentary provenance but it is suggested that deposition of dust, as elsewhere, is a major source—in particular, it accounts for the iron oxide. A borehole sunk 8 km WSW of here recorded 10 m of 'earthy red sandy clay', underlain by alternating 'variegated sand and clay' and 'brown fine-grained sand', in equal amounts, down to 30 m (Jones & Hockey 1964). The altitude of about 40 m does not imply correlation

in age with the low undulating plain described above (*ie* with Site 5 at about 30 m). The Niger Delta region is obviously one of relatively rapid subsidence, with a gentle folding of surfaces.

Areas of Acid Sands and soils with hardened layers

These are areas of broken topography where short steep slopes are associated with resistant layers in the subsoil. Moss (1965) depicted the formation of soil profiles containing great amounts of ferruginous gravel (Asaba Series) in the talus below a lateritic ironstone, which merged laterally into deep non-gravelly Acid Sands soil (typically, the Alagba Series). He envisaged that, whilst the scarp retreated slowly, the ferruginous gravel of the Asaba Series dissolved away and the fine (< 2 mm) residue became Alagba Series. In course of time this soil would become more extensive and the hardened upper land surface would eventually disappear. He suggested that such a process might account generally for the formation of Acid Sands soils involving the

mixing together of materials from finer and coarser layers. It can be objected that the ferruginous rubble and gravel would not dissolve away and that the clayey material would containing dispersed iron oxide. The problem of the formation of the Alagba Series in this situation is probably the same as it is in simpler landscapes— the sand fractions are derived directly from more or less unconsolidated sediments, together with some of the clay and a smaller proportion of the Fe_2O_3. The suggestion that deposition of Pleistocene wind-blown dust accounts for the rest of the clay and Fe_2O_3 also applies.

The problem of the great depth of the soils

An intensive pedological study of soils of this group was made by Fauck (1972) (for localities see Fig. 4). He considered the red subsoil to be a very thick illuvial horizon (B horizon). He mentioned that clay skins were reported in these soils in Benin Republic (Dahomey). Ogunwale *et al.* (1975) also reported thin clay coatings in root channels from 80 cm downwards in a 3 m deep
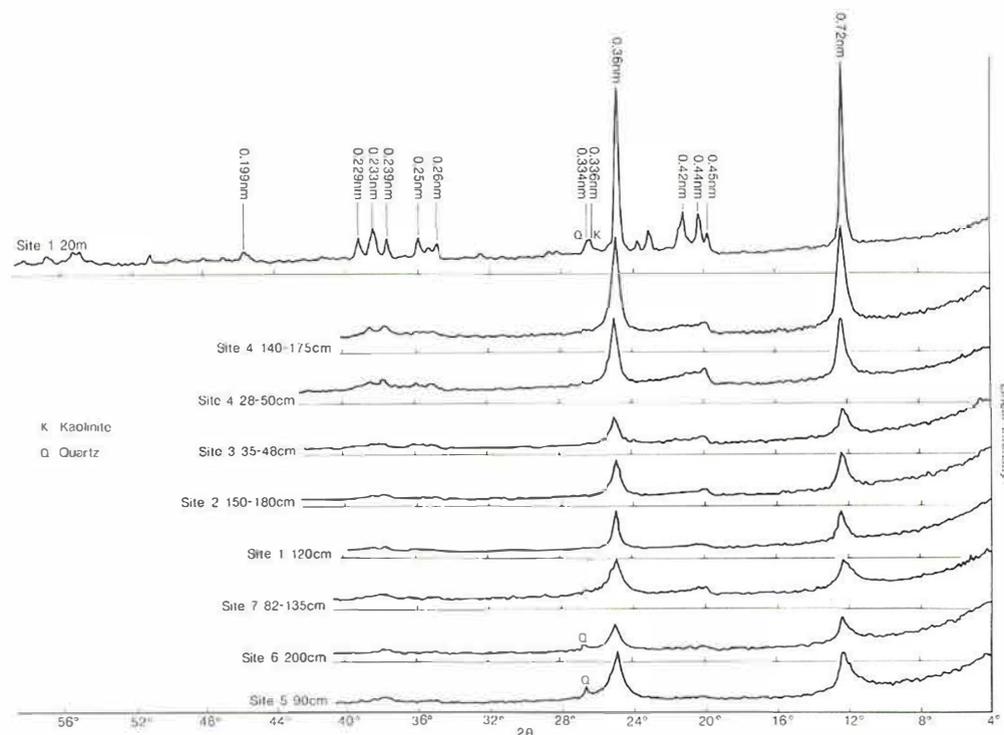

FIG. 3. X-ray diffractograms (CuKα radiation, Ni filter) of clay fractions. Sample No. 121 is (top) clay <2 μm, with Al-exchangeable cation, from weathered false-bedded sandstone at approximately 20 m depth at Site 1. The others are clay <1.6 μm, with Mg-exchangeable cation, after cleaning with dithionite, from soil profiles at Sites 1 to 7. No trace of any clay mineral other than kaolin can be seen.

They

pit in Alagba Series dug close to Site a (at the ●il Palm Research Institute, Fig. 1). He cited this as evidence of the process of illuviation from the upper layers.

Fauck remarked that this red illuvial layer could be over 6 m thick. He elaborated a very interesting theory in which the whole profile was developed *in situ* from the parent rocks. He did not envisage incorporation of wind-blown material, but suggested accumulation of clay and Fe_2O_3 by dissolution of quartz and removal of dissolved silica in drainage waters. He stressed the importance of organic compounds ('fulvic acids') as complexing agents, effecting the downward movement of clay and Fe_2O_3, and reported analyses showing some organic matter at the base of the profile. Soil microbes are particularly important in the formation of such complexing agents in the topsoil.

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It seems that the processes described by Fauck could lead to as much as 12 to 18 m of soil in southern Nigeria if the addition of wind-blown material was sufficiently prolonged. It is doubtful, however, if the thorough incorporation of material of the varying parent rock strata is brought about without considerable mass-movement. The 'slope pedimentation' process which Rohdenburg (1969) considered in relation to the sedimentary rock region of southern Nigeria, involving alternating stability and instability due to climatic change, is mainly concerned with surface movement and the accumulation of a gravelly layer. Grove (1951) showed that collapse of the sides of deep gullies tended to be brought about by sliding

on fine-grained layers where water collects after very heavy rains.

Soil analyses

Samples representing profiles of red ferrallitic soils over loose sandy sediments at Sites 1 to 7 (see Fig. 1) were selected for the examination of particles from different size fractions. Separation had to be complete, but with a minimum of mechanical attrition of sand. Because of the low percentages of fine sand and silt, the procedure was first to remove the coarse sand, and then as much as possible of the clay-sized fraction including finely disseminated iron oxide. The amount of clay-sized material obtained was increased by heating with hydrogen peroxide to decompose organic components. Clay in suspension in dilute alkali was repeatedly decanted, after allowing a settling time of 24 hours. This gave a separated clay fraction with a nominal maximum diameter of 1.6 μm.

The remaining sediment was treated with citrate, bicarbonate and dithionite (Mehra & Jackson 1960) to dissolve Fe_2O_3. The cleaned fine sand (50–200 μm) was removed by sieving and the coarse silt (20–50 μm) and fine and medium silt (2–20 μm) were separated by sedimentation. *and 2 ky (<2 μm)*

Examination of clay fraction

In approximately 0.1 g subsamples of the < 1.6 μm clay fraction, Na was replaced by Mg as the exchangeable cation. The specimen was
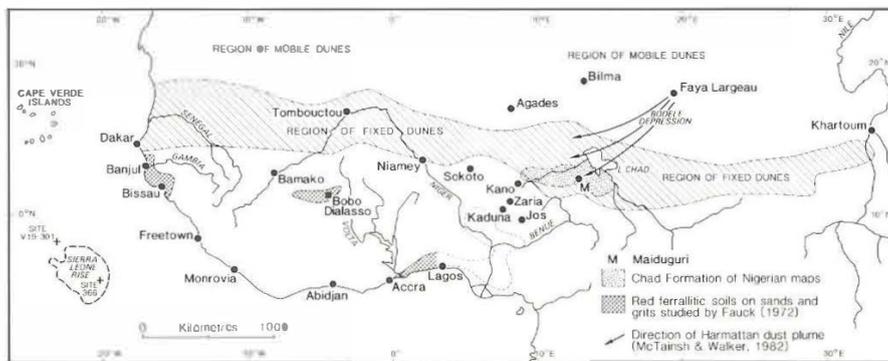

FIG. 4. Map based on Grove (1958), showing limits of occurrence of late Quaternary fixed dunes in parts of present-day Sahel and Sudan and of active dune formation in regions of the present-day Sahara, and of the area of the Plio–Pleistocene Chad Formation recognized in Nigeria but not mapped separately elsewhere. Also shown are: Site V19–301 studied by Parkin (1974) and Parkin & Padgham (1975) and DSDP Site 366: the areas of red ferrallitic soils and loose sandy sediments in which are marked the sites studied by Fauck (1972), from the CCTA *Soil Map of Africa*, 1964; is the main origin of the present-day Harmattan, are taken from McTainsh & Walker (1982).

then mixed to a paste with water on a glass slide, smeared with a spatula and air-dried. Diffractograms were obtained with CuKα radiation and Ni filter.

Iron was determined colorimetrically by the thiocyanate method.

All the clay specimens are dominated by 'kaolin' (Fig. 3). No other clay mineral is indicated by any discernible peak or band. There is notably no sign of illite. A trace of quartz is present in three specimens. The clays from the red subsoils at the Oba pit (Site 1) and the other six sites all appear to consist of disordered kaolin giving poorly-defined peaks. The sharpest peaks are given by those from 28–50 and 140–175 cm at Site 4, where the profile is intermediate between the Alagba Series and the Owode Series. In contrast, the diffractogram for the clay present in small amounts in the weathered sandstone at Site 1 is remarkable. It is almost identical in the positions, sharpness and relative heights of peaks to that reproduced in Brindley & Brown (1980) for 'the very well-ordered geode kaolinite from Keokuk, Iowa', which is regarded as well crystallized.

Previously (Vine 1949), SiO_2/Al_2O_3 ratios very close to the value 2.00 for pure kaolinite were obtained in analyses of clay fractions of samples from a depth of about 120 cm in Acid Sands profiles at Sites a, b, c and d (Fig. 1). The clay content was about 30% in all of these samples. The results are shown in Table 2.

Jungerius & Levelt (1964) reported X-ray diffraction studies of soils of southeastern Nigeria, including five profiles which seem fairly typical of Acid Sands soils. Kaolin was dominant, but traces of mixed-layer clays were found in three of the five profiles, and one also contained more than a trace of gibbsite. Ogunwale *et al.* (1975) also found a trace of a mixed-layer clay (mica–smectite) in their Alagba Series profile, close to Site a.

Comparison between soils and deep-sea sediments

The southeastern part of the Sierra Leone Rise, where DSDP Site 366 was located, is a 15 000 km^2 plateau under 2700–2900 m of water. It was chosen to provide a complete record of pelagic Tertiary and Upper Cretaceous deposits in the eastern North Atlantic, away from turbidity currents and above the Carbonate Compensation Depth (Lancelot *et al.* 1977). Over 800 m of sediment have accumulated since the Palaeocene. The top 120 m were assigned to the Pliocene and Pleistocene, a period of 6 million years. Sediments of this part of the column have between 64% and 70% porosity. The whole of 'Unit 1' (the top 136 m) is mottled, the top 63 m are yellowish-brown in colour (10YR 5/4–5/8), and the next 73 m are very light grey to light olive-grey (N8 to 5Y 6/1). The $CaCO_3$ content increases from around 60% in the top 63 m (marls and oozes), to 75% in the next 73 m (nanno-fossil oozes). Clay interbeds 5 to 15 cm thick occur at places in the top 136 m. These could represent very fine dust material.

Mélières (1977) carried out X-ray diffraction studies on samples from Site 366. He stated that quantitative estimates were made using an internal standard so that absolute percentages could be given, the crystalline components summed, and a rough estimate made of amorphous material. The amount of amorphous material was found to be correlated with terrigenous quartz, feldspar and clays, and was therefore thought to be terrigenous also. Its chemical nature is unknown, but presumably some part of it was formed from siliceous microfossils. According to fig. 2 in Mélière's paper, the top 25 m of deposits are Pleistocene, with Pliocene reaching down to 100 m. No date is indicated for the division between these two. Three specimens taken within

TABLE 2. *Clay-fraction analyses (Vine 1949) and derived molar ratios*

Site	Rainfall (mm)	Colour	% in ignited clay			Total Fe_2O_3 % calculated on oven-dry basis	SiO_2/Al_2O_3	Fe_2O_3/Al_2O_3
			SiO_2	Al_2O_3	Total Fe_2O_3			
a	1800	Red	46.4	40.7	12.6	11.0	1.94	0.198
b	2200	Red	47.9	41.6	12.2	10.6	1.96	0.187
c	2500	Orange-yellow	48.5	41.6	10.0	8.7	1.98	0.152
d	3300	Yellow	48.4	41.8	10.1	8.8	1.97	0.154

Samples from depth of 150 cm, clay content of each approximately 30%.

H. Vine

[handwritten marginal note at top right: consisted, on average, of 5% 20–63 µm particles, 20% 6–20 µm, and 75% 2–6 µm (by weight).]

the top 25 m contain 15.7% of clay on average (Table 3). The 25 m would become 17 m if compressed from about 65% porosity to 45%, which is the average porosity measured in subsoils of Alagba Series. Thus there is a Pleistocene accumulation of the equivalent of 3 m of 100% clay at 45% porosity—1 m each of kaolin, smectite, and illite plus mixed-layer minerals.

In the Kulfo Series profile at the Oba pit (Site 1) it is estimated that there is the equivalent of 4.5 m of soil with 22% clay, or 1.0 m of 100% clay. For a typical Alagba Series soil there *may be* is an average clay content of 33% over a thickness of 15 m. In this case the total clay accumulation would be the equivalent of 5.0 m of 100% clay, at 45% porosity. Ogunwale *et al.* (1975) recorded 33% clay between depths of 1.5 and 3.0 m in their pit near Site a. The full thickness of the red subsoil around that site has not been recorded but only a few hundred metres away a pit was dug to 9.5 m without change in the material for which figures of about 31% of clay and 2–20 µm silt combined were recorded (Oil Palm Research Station 1948).

There is therefore fair agreement between the amount of clay (including kaolin, smectite, illite and interstratified minerals) deposited during the Pleistocene at Site 366 and that in soils of the Alagba Series. Clay accumulation probably occurred during only about the last quarter of that time around Site 1. The low surfaces, of Ahiara Series soils, might be about one-tenth the age of the older soils.

The simplifying assumption has been made that clay minerals other than kaolin have been *altered* to kaolin by weathering in hot moist and seasonally moist conditions. This would be consistent with the very high degree of disorder indicated in the diffractograms.

There is a major discrepancy in silt-size quartz between the Pleistocene deep-sea sediment and the soils. The average figures in Table 3 show almost as much quartz as kaolinite in the sediment samples. Fütterer (1977) examined the silt-size material in detail. Qualitatively there was no doubt, from the fossil content and the size-range of mineral particles, that the non-calcareous

mineral part of the silt was wind-blown terrigenous material. Angular quartz grains appear in SEM photographs of 2–20 µm fractions, together with various microfossils. Some flaky particles were considered to be mica. Few quartz grains exceeded 20 µm. If an attempt is made to put some of the data from chemical analysis and grain counts together, it appears that the quartz makes up on average 75% (by weight) in seven samples from Pleistocene layers.

Greenwood (1933) first reported analyses of Acid Sands soils, and remarked that the figures showed that the coarse sand and the clay fraction were predominant, and the comparative absence of fine sand and silt gave the wet soil a peculiar gritty feel. For the Ogba Experimental Farm near Benin City he found 1.5% 2–20 µm silt at 0–22 cm, 1.8% at 85 cm, and 2.2% at 120–210 cm. For Site a (Fig. 1) an average of 1.3% of 2–20 µm silt was found from 5 to 180 cm, with 3.0% in the 0–5 cm layer (Vine 1949). Ogunwale *et al.* (1975) gave very similar values for their pit close to Site a. It must be noted that Ogunwale *et al.* reported a small amount of feldspar (1% to 3%) in the silt from this profile, which appears to contradict what has been said earlier about the complete decomposition of feldspar. However, the writer has found titanium minerals in the 2–20 µm fraction of Acid Sands soils, with peaks in diffractograms at 0.325 nm (rutile) and 0.352 nm (anatase). Small peaks indistinguishable from these can be seen in the diffractogram given by Ogunwale *et al.*, and it is virtually certain that their identification of feldspar from the peak labelled 0.323 nm was mistaken.

Larger amounts of silt have been found in numerous analyses of soils from adjoining areas in Nigeria over Basement Complex rocks, particularly gneisses. A number of soils of the Basement Complex areas have also been fractionated by the methods described in this paper and the silts examined by X-ray diffraction. Surprisingly, the greater amounts of silt proved not to be due to much more quartz, but to silt-size particles of kaolin and sometimes mica. This result has removed an apparent obstacle to explaining the very low silt percentages, compared with those in

TABLE 3. *X-ray mineralogy of Pleistocene samples from Site 366 (Mélières 1977)*

Sample	Depth (m)	Quartz (%)	Feldspar (%)	Calcite (%)	Halite (%)	Illite (%)	Mixed layer (%)	Smectite (%)	Kaolinite (%)	Amorphous (%)
366 1–2, 6–7	1.9	3.0	—	53	2.0	1.8	1.0	2.2	4.2	32
366 2–2, 19–20	11.5	7.1	—	29	1.8	4.8	2.0	6.3	7.3	40
366A 2–3, 63–64	13.5	5.2	0.8	51	1.6	2.0	2.5	6.6	6.5	23
Mean of three		5.1	0.3	44	2.0	2.9	1.8	5.0	6.0	32

the sea-floor sediments, as due to the dissolution of fine quartz in percolating rainwater.

Silt-size particles, identified by X-ray diffraction as almost entirely of quartz, generally make up about 1% to 3% in the Acid Sands soils. Table 1 shows one surface soil with 4.8% coarse silt and 8.0% 2–20 μm silt; there is also three times as much fine sand as in the 18–28 cm depth sample, and the explanation lies in the sifting of particles by worms, ants, *etc.* Some unpublished SEM studies of fine sand, coarse silt and 2–20 μm silt of some of the Acid Sands soils show clearly that, in the hot humid conditions of southern Nigeria, solution weathering is producing silt by disintegration and flaking of pitted and fissured sand grains whilst smaller particles disappear. This is in accordance with Fauck's indications of the dissolution of quartz taking place at a much greater rate than hitherto recognized.

It is interesting to note that approximately equal amounts of quartz and clay minerals were found by Parkin (1974) and Parkin & Padgham (1975) in samples from a core of the top 12 m of sea-bed deposits at Site V19-301. This site is under 4724 m of water, close to the slope down from the Sierra Leone Rise (see Fig. 4). There appears to be a possibility of the deposits being partly derived by downslope movement. The average rate of accumulation at this site in the last 700 000 years is clearly identified from the magnetic reversal at 11.25 m depth in the core. The average $CaCO_3$ content was about 20%. On a carbonate-free basis the accumulation rate was 9 m in 0.7 million years. This is twice the average rate at Site 366 during the 6 million years of the Plio–Pleistocene record; the apparent difference in the rates of deposition could be real, and not the result of downslope movement. Samples taken at close intervals in the core were studied by X-ray diffraction. Ignoring the possible presence of amorphous matter, the averages of carbonate-free material are: 52% quartz, 33% kaolin plus chlorite, 13% illite, 3% smectite. From all the evidence it seems likely that these deposits consist mainly of Harmattan dust washed out by rain in the Doldrums.

The source of dust at the present time and during the Pleistocene

McTainsh & Walker (1982) presented the chemical analyses of a 'lake deposit' near Faya Largeau and of two samples of Harmattan dust, pointing to their similarity and supporting the idea of the Faya Largeau area as a main source of the dust material. One of the dust samples was collected by McTainsh & Walker at Kano; this was one of the three samples in which it was possible to determine particle size fractions below 2 μm, showing 40–70% of the <2 μm clay to be less than 0.2 μm. The other dust sample was collected by the Geological Survey, presumably at their headquarters at Kaduna, and was examined microscopically and analysed at the Imperial Institute in London (Jones 1938). Table 4 shows the percentages of SiO_2, Al_2O_3 and Fe_2O_3 in these samples, together with those found by Doyne *et al.* (1938) in the clay fraction of dust fall-out at Samaru, Zaria. For comparison, the percentages are on the basis of the ignited weight (*ie* weight after heating to redness, driving off H_2O).

The iron content is best considered in terms of the ratio of Fe_2O_3 to Al_2O_3 (Tables 2 and 4) because this would not change in a material at first containing feldspars, *etc.* which had become weathered to clays after transportation or deposition. Comparing the soils with Harmattan dust it is remarkable that there is more than enough iron in modern Harmattan dust to account for the iron in the Red and Yellowish-brown Soils over Loose Sandy Sediments. The total amounts of Fe_2O_3 in the clay fractions of soils from Sites 1–7 were not determined. The dithionite-extractable Fe_2O_3 in the clay fractions of Alagba and Alagba–Owode soils at Sites 2, 3 and 4 (Table 1) was somewhat lower than the total Fe_2O_3 for Sites a, b, c and d. This is probably because some Fe_2O_3 may not have dissolved in the buffered dithionite extraction process.

McTainsh & Walker (1982) suggested that the system of deposition of material into low ground

TABLE 4. *Analytical data for three dust samples and a specimen of a suggested source deposit*

Specimen	% in specimen (ignited weight basis)			Molar ratios	
	SiO_2	Al_2O_3	Fe_2O_3	SiO_2/Al_2O_3	Fe_2O_3/Al_2O_3
Harmattan dust—Kano (McTainsh & Walker)	75.7	12.7	5.1	10.1	0.256
Harmattan dust—Geological Survey	66.5	13.9	5.6	7.9	0.256
Clay fraction of Harmattan dust—Zaria (Doyne *et al.*)	67.5	22.9	10.8	5.0	0.302
Lake deposit—Borkou, near Faya Largeau	52.5	8.4	5.0	10.6	0.381

H. Vine

and removal from there in dust storms of the Harmattan could be taken as a contemporary model 'against which to test hypotheses about aeolian systems of the Quaternary'. It seems that the same system may have functioned during most of the Quaternary, when lake deposits were being laid down in various parts of the Chad Basin. Exposed to arid conditions, they would supply the finer part of the dust mobilized by the moving sand which also supplied the quartz in the dust cloud.

The source area of the dust storms would certainly have shifted many times through several degrees of latitude. The time scale of climatic changes is indicated by the recognition in the vicinity of Lake Chad of three periods of dune activity during southward advances of the Sahara in the last 60 000 years, and a considerable number before then, possibly as far back in time as 2 or 3 Ma (Durand & Mathieu 1980; Servant & Servant-Vildary 1980). It is realistic to visualize

that there were 'Harmattan' dust plumes across the middle and southern parts of Nigeria when there were source areas much further S than they are now.

A wider question is how much dust may have been produced in regions to the E and W of the Chad Basin during the Pleistocene and been deposited in soils, as well as in marine sediments. For example, Prospero (1981) shows that even nowadays the course taken by dust outbreaks from the central Sahara can be as far S as the 10° N line.

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