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Volcanically influenced calcareous palaeosols from the Miocene Kiahera Formation, Rusinga Island, Kenya

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Abstract: The Miocene Kiahera Formation at its type locality on Rusinga Island in the Kenyan part of Lake Victoria consists of a sequence of alluvial sedimentary and pyroclastic strata and calcareous palaeosols. The 80 m thick formation was formed by braidplain aggradation and pyroclastic airfall in response to volcanism from the nearby Kisingiri volcano.

Numerous fining-upward sequences approximately 5 m to 15 m thick make up the bulk of the Kiahera Formation. A complete sequence contains sandy and conglomeratic beds at the base which fine upward to sandy siltstones, calcareous palaeosols and airfall tuffs. The fining-upward sequences may have been produced by aggradation during phases of volcanic eruption. During major eruptive episodes, scoriaceous nephelinite detritus flooded the alluvial system to create the lower, coarse-grained beds. As eruptive activity waned, airfall ash and overbank flood deposits accumulated on the landscape forming the upper, fine-grained beds of the sequence. Calcareous soils formed on these highly alkaline ashes between large ash fall events.

The calcareous palaeosols are grouped broadly into two main types: tuffaceous clayey Inceptisols with distinct Ck horizons (Chido palaeosols) and sandy Inceptisols consisting of nephelinitic rock fragments and subordinate amounts of tuff (Okoto palaeosols). Both types show only weak to moderate soil development interpreted to be a result of episodic rejuvenation by fresh airfall ash and flood deposits. Comparison of depth of the calcareous subsurface horizon from these palaeosols with those in calcareous modern soils from the Serengeti Plain that also developed on alkaline volcanic ash allow for rainfall estimates of between 550 mm a^{-1} to 750 mm a^{-1} for the Kiahera palaeosols. This together with root traces, soil structure, and major element chemistry of the two palaeosol types are evidence of a landscape with sandy, stream-side woodland soils (Okoto palaeosols) and clayey, floodplain grassy woodland soils (Chido palaeosols).

Miocene palaeosols that formed on an alluvial apron of the large, highly alkaline volcano of Kisingiri in southwestern Kenya provide excellent examples of alluvial responses to episodic volcanism and formation of sequences of palaeosols in volcanic successions. Although the study of palaeosols generally has received much recent work, the analysis of palaeosols within volcanic sequences has largely been untouched. Palaeosols within the Kiahera Formation reported here not only are sufficiently well exposed to be related to volcano-sedimentary units, but also record a critical transitional time between early Miocene forests and middle Miocene grasslands in East Africa (Retallack *et al.* 1990). They are explored here both as guides to the role of soil formation in volcano-sedimentary systems and as clues to the Neogene environmental history of East Africa.

Our study of these palaeosols involved stratigraphical mapping, sedimentary facies recognition and field classification of palaeosols, as well as bulk chemical analysis using X-ray fluorescence and atomic absorption. A novel approach has been the use of atomic rather than molecular weathering ratios, as potentially closer to the actual cation abundance during hydrolytic weathering. Scatter diagrams of chemical composition determined by electron probe microanalysis were also used to reveal weathering trends in the palaeosols. These new approaches are appropriate to the complexity of volcanic soils of mixed epiclastic and primary volcanic parent material, and may be applicable to palaeosols elsewhere.

General setting and stratigraphy

The Rusinga Group including the Kiahera Formation formed around the 50 km diameter stratovolcano of Kisingiri. At present, the main mass of Kisingiri volcano lies in a graben bounded on the northwest by the Mfangano fault and on the southeast by the Kaniamwia fault (Fig. 1). The graben is an extension of the Nyanza Rift (formerly Kavirondo Rift, Pickford 1982), which is an E–W structure to the west of the main N–S Gregory Rift, a Miocene to Recent continental rift system and alkaline volcanic province (Baker 1986, 1987). The East African Rift area during the early Miocene was a broad plateau uplift with scattered nephelinite-carbonatite volcanic centres (Baker *et al.* 1971, 1972; Le Bas 1987). By mid-Miocene time, rift faulting and lava eruption began in the Ethiopian Highlands (Baker 1987). The Kisingiri volcano is one of a group of early to mid-Miocene nephelinite–carbonatite central vent volcanoes that formed during the initial stages of East African Rift volcanism (Bishop 1968; Le Bas 1977, 1987).

The Miocene Kisingiri volcano is now mostly dissected but retains volcanogenic features indicative of large, central vent nephelinite–carbonatite volcanoes (Fig. 1B). These features include a circular arrangement of outward-dipping strata consisting of tuff breccia, intrusions, and lava and a central, domed area consisting of vent breccia and fenitized Precambrian basement rocks (Shackleton 1951; McCall 1958; Le Bas 1977).

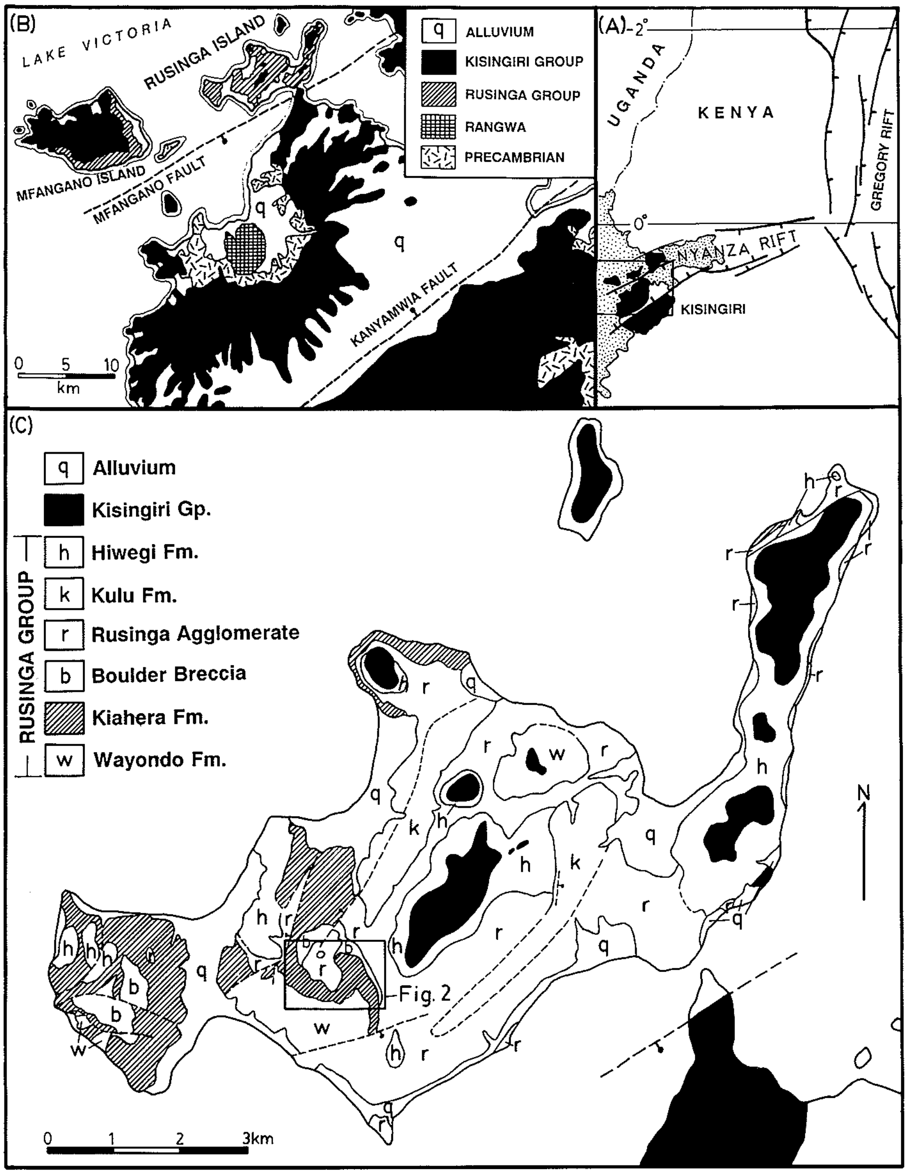

Fig. 1. (**A**) Location map of the Kisingiri area. (**B**) Generalized geological map of the remnants of the Miocene Kisingiri volcano showing the distribution of the Rusinga and Kisingiri groups, the Tertiary intrusive centre of Rangwa, and the Precambrian rocks.
(**C**) Generalized geologic map of Rusinga Island. Maps compiled and modified from McCall (1958), Van Couvering (1972), Pickford (1984), Drake *et al.* (1988), and Bestland (1991).

The Rusinga Group is the lower of two groups that resulted from the growth of the Kisingiri volcano (Shackleton 1951; Whitworth 1953; J.A. Van Couvering & Miller 1969; J.A. Van Couvering 1972; Pickford 1984, 1986; Drake *et al.* 1988). The Rusinga Group consists of fluvial, pyroclastic, and lacustrine strata, and the Kisingiri Group consists of debris flow deposits, nephelinite lava flows and tuff breccia. The whole Miocene sequence associated with the Kisingiri volcano forms a coarsening upwards sequence from fine to coarse-grained alluvial and pyroclastic airfall deposits in the older, Rusinga Group to very coarse-grained debris flow conglomerates and nephelinite lava flows in the younger, Kisingiri Group. From bottom to top the sequence represents progradation from distal to proximal volcanic facies with the building of the Kisingiri volcano (Pickford 1986; Thackray & Bestland 1988; Thackray 1989).

The Rusinga Group contains, in stratigraphical order, the Wayondo Formation, an arkosic conglomeratic unit, the Kiahera Formation, consisting of grits and silts of alluvial origin and airfall tuffs, the Rusinga Agglomerate, an ijolite tuff-breccia sheet, the Kulu Formation, consisting of fan-delta and lacustrine deposits (Bestland 1991), and the Hiwegi Formation, consisting of silts and grits of alluvial origin and airfall tuffs.

Drake *et al.* (1988) have produced a revised chronology of the Rusinga Group based on 29 new K-Ar age determinations from samples of the Kiahera Formation, Rusinga Agglomerate, and Hiwegi Formation. The most reliable of these dates, as determined by Drake *et al.* (1988), together with the mammalian fauna, constrain the age of the Rusinga Group to the later part of the early Miocene, some 17–18 million years old.

Kiahera Formation

The Kiahera Formation is near the base of the Rusinga Group and is the lowermost unit of the group that contains abundant pyroclastic detritus. Along with the underlying Wayondo Formation, it is extensively exposed over the western two-thirds of Rusinga Island, particularly in the

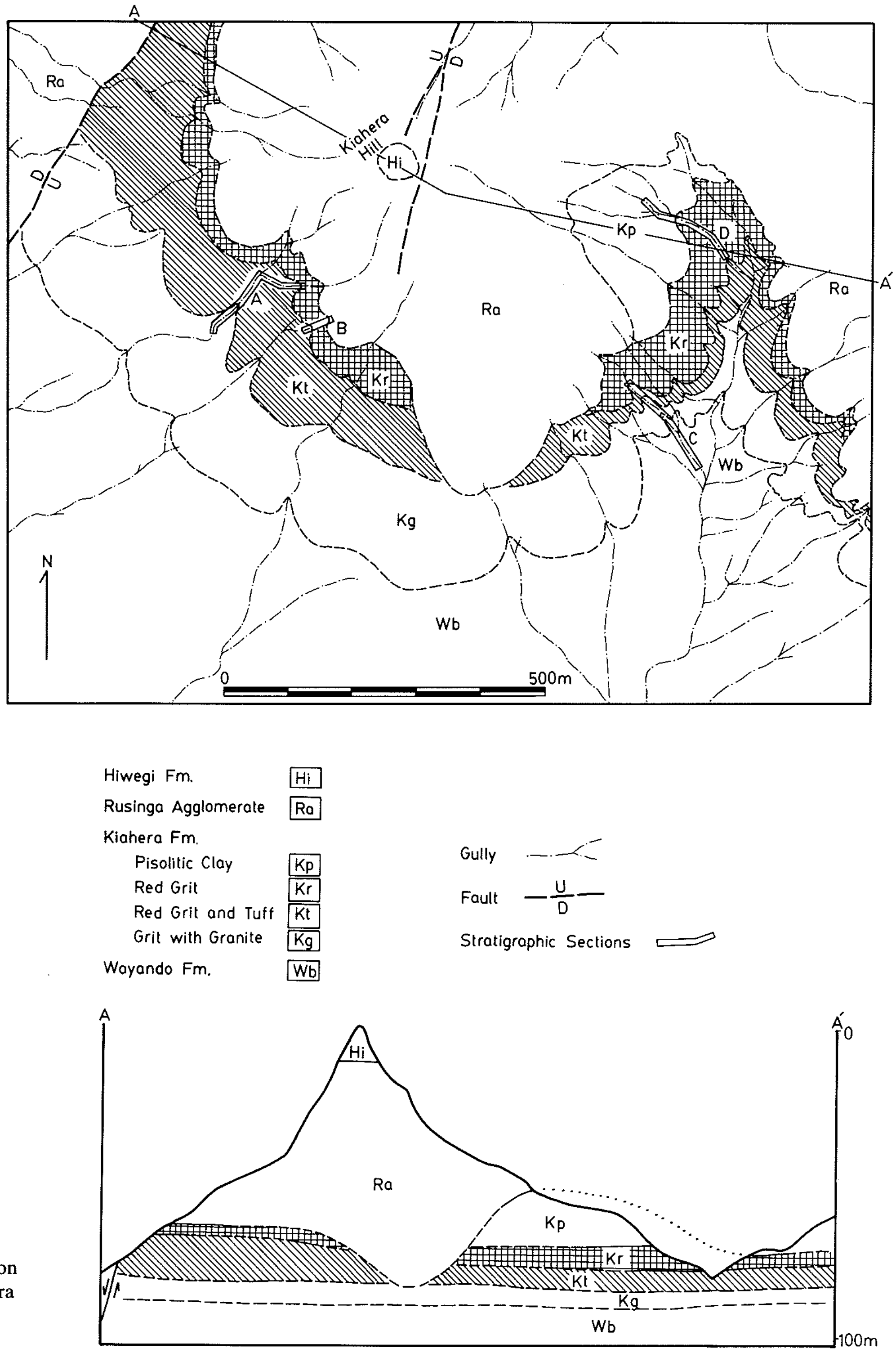

Fig. 2. Geological map and cross-section of the Kiahera Formation in the Kiahera Hill area (modified from Shackleton 1951).

areas of Kiahera Hill, Gumba Hill and the Wayondo Arch area. Lithologically distinct units have been distinguished in the Kiahera Formation by Shackleton (1951) and Van Couvering (1972), and are well exposed in gullies to the south and east of Kiahera Hill (Fig. 2). Lithological units originally defined and described by Shackleton (1951, plate XXVIII) have been refined by Bestland (1990) as fining-upward sequences. The lithologies in the Kiahera Formation are of particular interest here because the ashes, sands and silts were the parent materials of the palaeosols.

Fining-upward sequences

Laterally continuous, ledge-forming strata greatly aided the remapping of Shackleton's (1951) original members. Most of the ledge-forming outcrops in the Kiahera Formation result from the preferential erosion of clayey palaeosols that underlie more resistant pebbly sandstone beds. Such palaeosol-sandstone sequences are well developed in the upper part of unit Kt (Fig. 3), at the 5 m level in Section A (unit Kt), and at the 10 m level in Section C (unit Kr).

At the base of these fining-upward sequences are thickly bedded pebbly sandstones, conglomerates, and tuffs of the sandstone and tuff facies (Fig. 4). Tuffs and accretionary tuffs of airfall origin are interbedded with the coarse sandstones. Low-angle cross-beds are common in the coarse-grained, lower parts of the fining-upward sequences. These cross-beds are inclined 5° to 20° and characterized by bedding thicknesses of under 1 m and commonly 20–50 cm thick, and horizontal lengths of 0.5 m to 3 m. Low-angle cross-beds of similar type and dimensions have been described in gravel of Holocene age and have been interpreted as the products of lateral accretion of gravel point bars (Ori 1982; Arche 1983).

In the upper parts of the sandstone and tuff facies, sandstones are finer grained and thinner bedded and

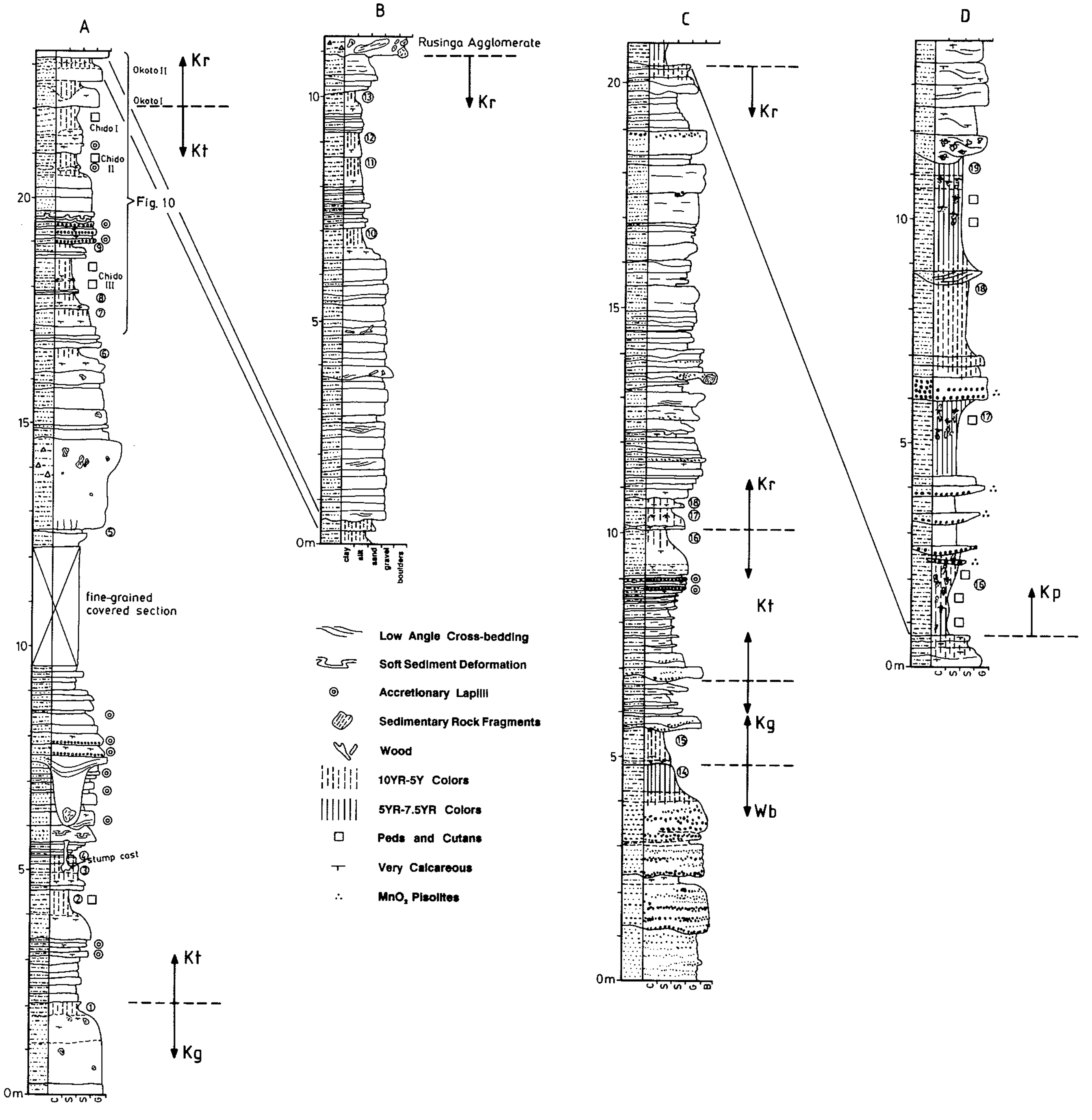

Fig. 3. Stratigraphical sections of the Kiahera and Wayondo formations in the Kiahera Hill area. Sections keyed to Fig. 2.

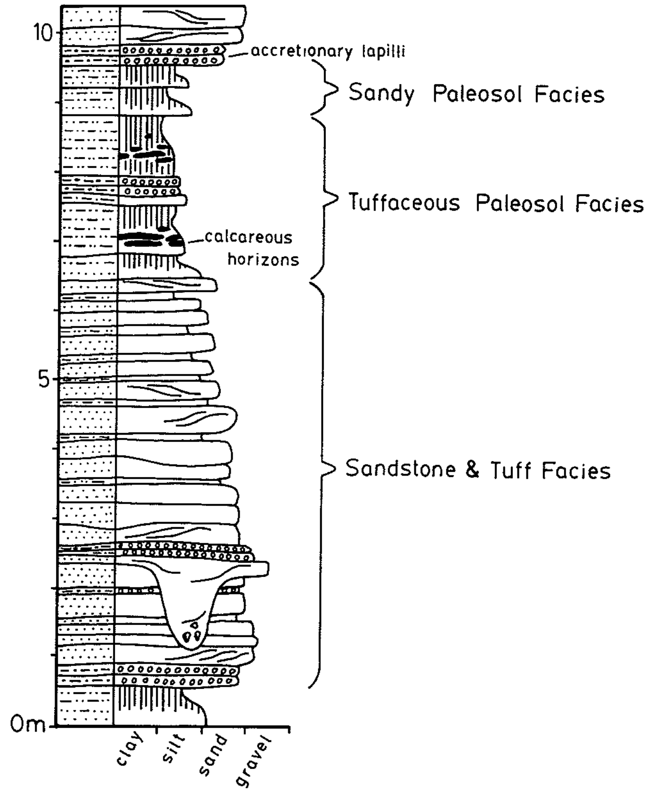

Fig. 4. Composite fining-upward sequence in the Kiahera Formation.

alternate with thin- to medium-bedded silty sandstones and sandy siltstones. The sandy siltstones are both planar laminated and cross-bedded. Cross sets are 5–10 cm thick and lenticular with the lenses defined by low-angle scour surfaces. Individual cross-bed sets rarely extend laterally more than 0.5 m to 1.0 m. These lenticular, cross-bedded strata are interpreted as sheetflood deposits like those described from alluvial fans (Bull 1972; Gloppen & Steel 1981) and from volcanically influenced alluvial plains (Smith 1987). They are interpreted to have resulted from shallow, rapid flow over broad areas.

Above the coarse-grained sandstone and tuff facies is the tuffaceous palaeosol facies consisting of stacked palaeosols and airfall tuffs. This facies contains predominantly Chido palaeosols, described in the following sections.

Above the tuffaceous palaeosol facies is a sandy palaeosol facies which consists of sandstones of feldspar grains and nephelinite rock fragments and sandy Okoto palaeosols, also described in the following sections.

Sandstones

Sandstones and siltstones of the Kiahera Formation are inferred to have originated almost entirely as scoriaceous nephelinitic detritus variously altered during transport, deposition, and initial weathering. A nephelinite composition is indicated by the following observations. (1) The rock fragments have the mineral assemblage and texture of nephelinites: that is, mafic lava flow and scoriaceous fragments rich in pyroxene, opaque Ti–Fe oxides, zeolites, and pseudomorphs and cavities after nepheline grains. (2) The Kisingiri volcano is known to be a nephelinite volcano based on field and geochemical work by McCall (1958), Le Bas (1977, 1987) and Van Couvering (1972). (3) The bulk rock chemical analyses of these sandstones (Bestland 1990) are best identified and grouped into the broad category of nephelinites and compare relatively well to bulk rock analyses of Kisingiri nephelinites (Le Bas 1977, 1987).

Two groups of sandstones are recognized: (1) sandstones consisting of vesicular rock fragments with few feldspar grains, referred to as vesicular rock fragment sandstones, and (2) sandstones consisting of subequal amounts of volcanic rock fragments and feldspar grains, referred to as feldspar and rock fragment sandstones. Sandstones at the base of Red Grit and Tuff and Red Grit units, both in conglomeratic channel complexes at the base of fining-upward sequences, consist largely of volcanic rock fragments that are vesicular, largely non-porphyritic, and zeolite rich (Fig. 5).

Geochemically, the vesicular rock fragment sandstones are distinguished by very high concentrations of Ba (5000–11 000 ppm) and Sr (1600–1800 ppm) when compared with other analyzed sandstones (Ba, 400–600 ppm; Sr, 800–900 ppm) and with nephelinite lavas from Kisingiri (Ba, 1100–1800 ppm; Sr, 1400–3100 ppm). The vesicular rock fragment sandstones also contain a largely non-porphyritic rock fragment population and have low values of Na (0.45–0.61 wt%), probably reflecting lack of feldspars containing Na. The high degree of angularity of the vesicular rock fragments and the relatively homogeneous clast type are strong indications that these sandstones consist of fresh pyroclastic ejecta (scoria) that have been minimally reworked. The high concentrations of barium and strontium in the vesicular rock fragment sandstones most likely reflects the nephelinite–carbonatite parent material composition. The vesicular rock fragment sandstones may represent immediate flooding of the alluvial system following scoriaceous eruptions.

The rock-fragment-and-feldspar sandstones are generally better sorted and rounded than the vesicular-rock-fragment sandstones. These sandstones also have a greater variety of rock fragment clast types, including non-volcanic granitic fragments and twinned and perthitic K-feldspar grains. The rock-fragment-and-feldspar sandstones are distinguished chemically by their high concentrations of sodium, following the high percentage of Na-rich feldspar grains and feldspar phenocrysts in the volcanic rock fragments. Other elemental concentrations of these sandstones are not greatly different than in tuffs and palaeosols. The rock fragment and feldspar sandstones however, include material derived from local Precambrian basement rocks.

Tuffs

Nephelinitic crystal vitric tuffs account for approximately 30% of the strata in the Kiahera Formation. At the base of thick tuff sequences, bedded tuffs with soft sediment deformation are common. Field tests show the tuffs to be highly calcareous. Accretionary lapilli (Reimer 1983) are very common and are visible on both weathered and freshly broken surfaces. Tangentially arranged biotite flakes enhance the concentric lapilli shells. Their tuffaceous matrix has been altered to clays (smectite), Fe-oxides, and micrite. The accretionary lapilli consists of tuff matrix with tangentially arranged biotite flakes, pyroxenes, and long,

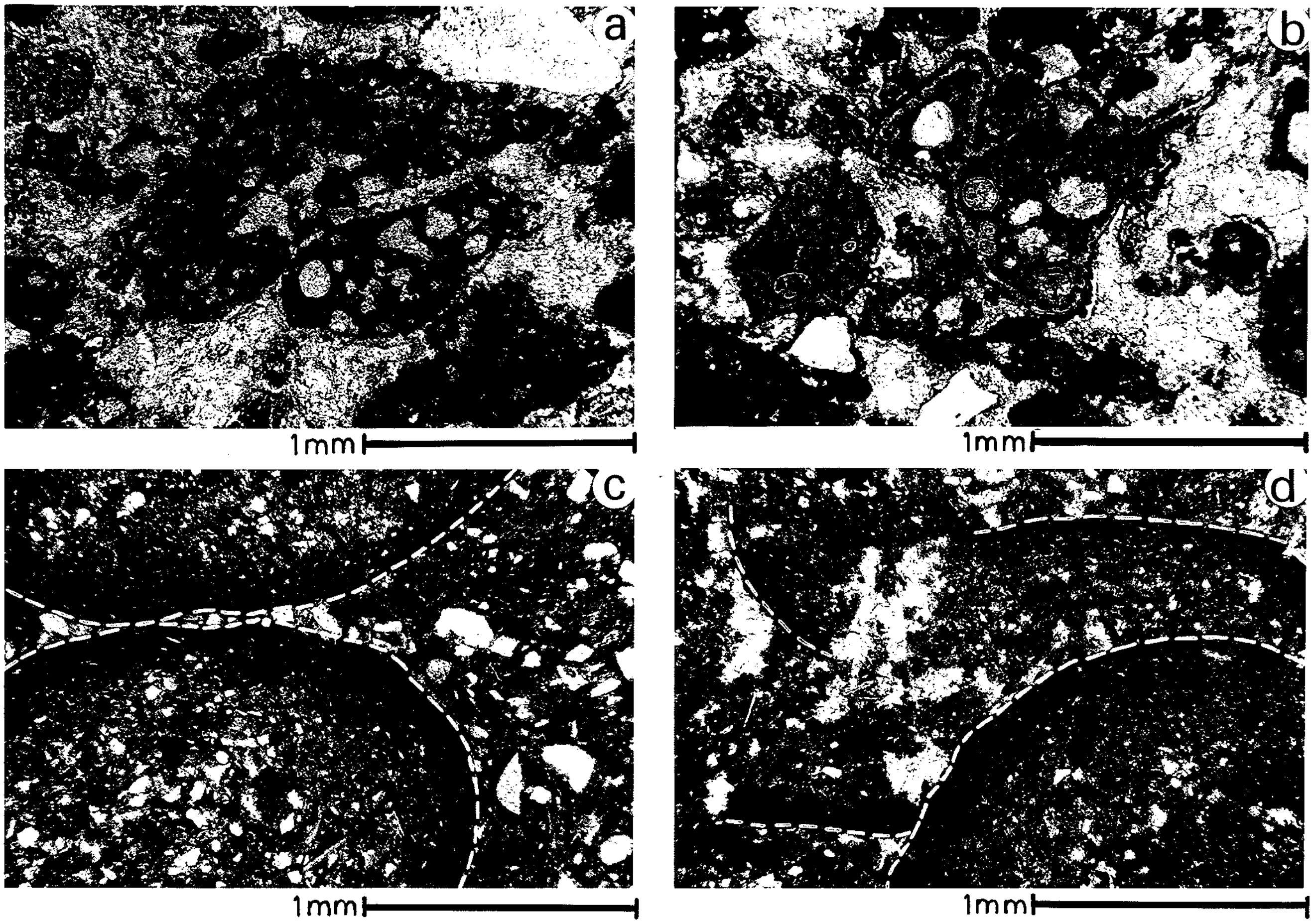

Fig. 5. Photomicrographs of pyroclastic and epiclastic sedimentary rocks from the Kiahera Formation. (**a** & **b**) Vesicular rock fragments in epiclastic sandstones at the base of unit Kr. (**c** & **d**) Accretionary lapilli from pyroclastic airfall beds in unit Kt.

slender calcite crystals. These calcite crystals commonly have thin phyllosilicate grains in the centre. The long calcite crystals could be interpreted as replaced melilite or nyerereite or as primary magmatic calcite. Primary magmatic calcite is the preferred interpretation because of the very clear appearance, sharp and straight boundary with tuff matrix, and long and clear boundary with the phyllosilicate. Long prism-ended and lath shaped crystals in some tuffs are similar to calcite grains from carbonatite deposits described by Deans & Roberts (1984) and Hay (1986). Feldspar and pyroxene crystals are also abundant. Much of the tuff has a calcite and micrite-supported fabric.

Most tuffs in the Kiahera Formation are petrographically and chemically nephelinitic. Na and K abundances are low compared to nephelinitic flows, but, these elements are easily leached from tuffaceous matrix. Several tuffs have high contents of CaO (24–28 wt%) and MgO (9–13 wt%). These tuffs contain abundant suspect grains, either calcite pseudomorphs after melilite or primary carbonate crystals and carbonate globules, and compare best petrographically and chemically with melilitite tuffs described by Hay (1978).

Carbonatite tuff. Evidence for minor amounts of carbonatite tuff in the Kiahera Formation is indirect. Distinctive euhedral grains of calcite common in many highly alkaline tuffs and lavas are now known to be pseudomorphs of natrocarbonatite minerals such as nyerereite and gregoryite (Dawson 1962; Dawson *et al.* 1987; Hay 1978, 1983; Hay & O'Neil 1983; Deans & Roberts 1984). In the Kiahera tuffs, carbonatite or natrocarbonatite ash is indicated in some tuffs by abundant calcite spar and micrite textures similar to textures reported by Deans & Roberts (1984). Some calcite grains have the acicular habit of melilite (common) and prismatic habit of nyerereite (rare). Also seen were carbonate globules, like those in natrocarbonatite ash described by Keller (1981) and Hay (1978), and in some cases these appear to be the nuclei of accretionary lapilli.

Fossil fauna and flora

The vertebrate fauna of the Kiahera Formation is best known from a pipe-like structure in a palaeochannel, interpreted as a fossil stump that decayed and formed a natural trap for a variety of hyraxes, monkey-apes, rabbits, cane rats, mole rats, creodont carnivores, pigs, anthracotheres and chevrotains (Walker *et al.* 1985). The mammalian fauna lacks antelope and zebra of later Miocene open-grassland faunas, but includes some possible open-country elements (mole rats, rabbits), along with a variety of woodland and forest forms (monkey-apes, creodont carnivore, pigs, anthracotheres and extinct chevrotains (Andrews & Van Couvering 1975).

Additional evidence for palaeosols is contained in the fossil fauna of the Kiahera Formation: spiders, insects, millipedes, land snails, lizards, snakes and mammals, with only a few likely aquatic elements (river crabs, crocodiles and flamingos). In the area of the palaeosols studied here, Pickford (1984) has reported mygalomorph spiders, insect cocoons, millipede exuviae, shells of land snails (*Maizania lugubroides, Burtoa nilotica* and Subulinidae indet), and indeterminate mammal bones. Snail shells and ellipsoidal internal casts, some 12–17 mm long by 4–6 mm wide, of insect cocoons were very common in some of these palaeosols (Bestland 1990). No bone was seen. Palaeosols of the Kiahera Formation are not as fossiliferous as other Miocene palaeosols in southwestern Kenya (Retallack 1991*a*).

A small assemblage of fruits and seeds has been found in the Kiahera Formation northwest of Kiahera Hill (locality R126 of Pickford 1984). This assemblage was very similar to fossil floras better known in the Hiwegi Formation (Chester 1957; Collinson 1983).

Features of the palaeosols

A variety of features were used in the field to recognize palaeosols in the Kiahera Formation. These features, supported by a variety of laboratory studies have implications for the palaeoenvironmental interpretation of the palaeosols (Figs 6 & 7).

Most palaeosols in the Kiahera Formation, fall into two groups: sandy palaeosols of the Okoto Series and tuffaceous, clayey palaeosols of the Chido Series. The palaeosols of the Kiahera Formation are here classified into named series after the system used by Retallack (1983*a, b*) which is based on standard soil-mapping units of the US Department of Agriculture (Soil Survey Staff 1951, 1962). A palaeosol series consists of a single type of fossil soil with a definite set of characteristics induced by its particular age and environment. It does not refer to a complete land surface as does the term 'geosol' (Morrison 1968; North American Commission on Stratigraphic Nomenclature 1983). Nor does it refer to sequences of palaeosols considered as a kind of depositional facies, like the pedofacies of Bown & Kraus (1987). Nor should it be confused with chronostratigraphic units (North American Commission on Stratigraphic Nomenclature 1983). Chido and Okoto palaeosols are distinctive and consistently recognizable kinds of palaeosols. They are named from the local Dholuo language; Chido meaning mud and Okoto meaning grit. These are field names independent of genetic classifications of soils.

The alteration of palaeosols during burial and diagenesis can seriously compromise their recognition and interpretation (Retallack 1990, 1991*b*). Especially problematic are changes that occur soon after burial, when the palaeosol is still subject to the influence of surficial processes (Retallack 1991*b*). Burial affects are also discussed in the following sections.

Clayey surface horizons

All the palaeosols recognized in the Kiahera Formation have massive, dark brown, clayey surface horizons that are commonly sharply overlain or truncated above by thick tuff deposits or sandy fluvial deposits (Figs 6 & 7). In both

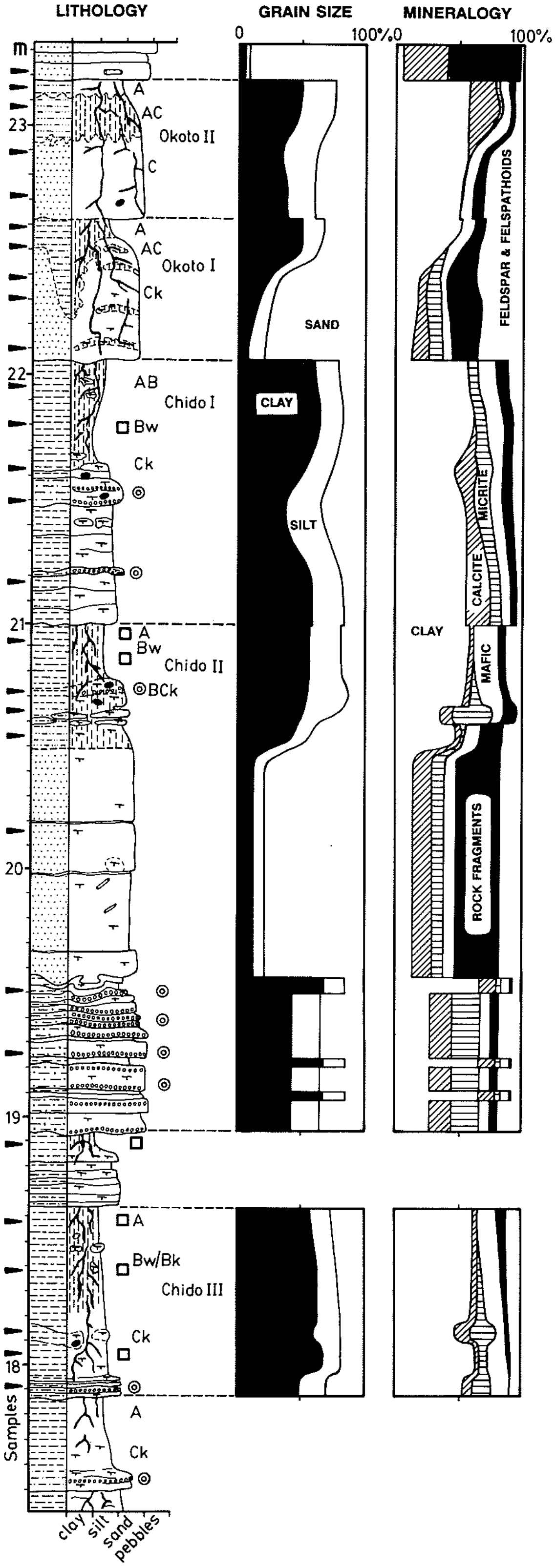

Fig. 6. Columnar lithological section of palaeosols in the upper third of unit Kt (Section A of Fig. 3) from the Kiahera Formation. Grain size and mineralogy determined by thin-section point counting under high power (500 points). Symbols are the same as Fig. 3.

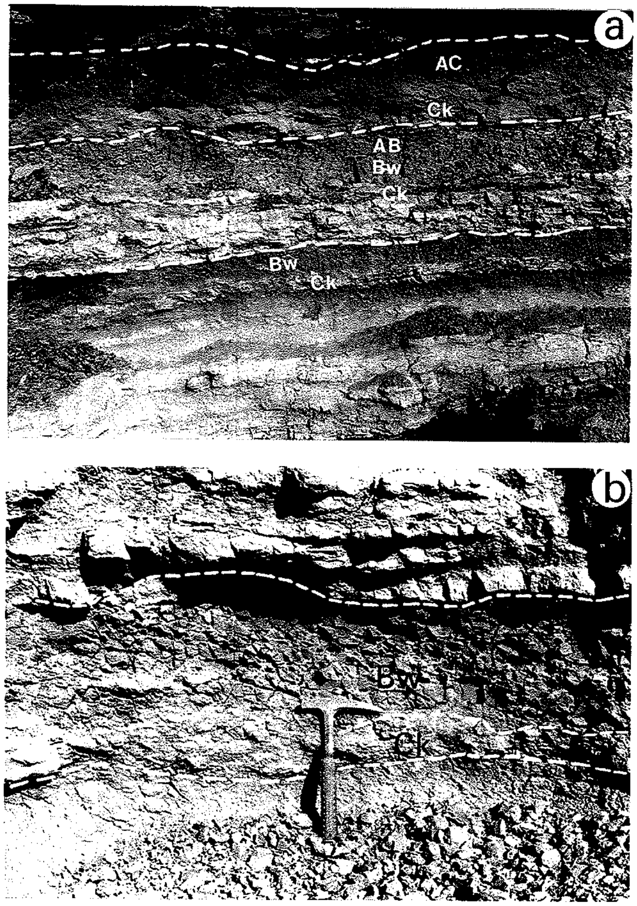

Fig. 7. Calcareous palaeosols in the upper part of unit Kt of the Kiahera Formation. (**a**) These three palaeosols with labelled horizons correspond to the upper half of the columnar section in Fig. 6. (**b**) Rock hammer rests on lenticular calcareous horizons (simide horizons) at the base of the Bw horizon in Chido I palaeosol. Lentil shaped peds are pervasive in Bw horizon of Chido II palaeosol.

Okoto and Chido palaeosols, the clayey surface horizons are brown coloured, Chido palaeosols are dark greyish brown (2.5Y–10YR, Munsell Color 1975) and Okoto palaeosols are dark reddish brown (5YR–10YR). Calcareous root traces are abundant in the surface horizons of both palaeosol types. The upper section of the surface horizons have a fine subangular blocky structure which grades downward into a coarser subangular blocky structure. The lower contacts of Okoto clayey surface horizons are gradational down into bedded calcareous sandstone. These clayey surface horizons are regarded as A horizons in soil terminology.

All the clayey surface horizons examined lack microscopically visible organic matter. Surface horizons of modern soil equivalents contain upwards of 2–3% organic matter and therefore the Kiahera Formation palaeosols are probably much lighter in colour than their precursor soil. Studies of Quaternary palaeosols and equivalent surface soils have shown that soon after burial, soils lose up to an order of magnitude of organic carbon (Stevenson 1969).

In some Okoto palaeosols, there are drab-coloured clayey surface horizons of a greenish grey or bluish grey colour. These drab-coloured layers may reflect areas reduced in association with anaerobic decay of organic matter buried in the palaeosol. Burial gleization is widespread in both palaeosols (Retallack 1976, 1983*a*, 1988, 1990, 1991*b*) and sediments (Allen 1986).

To some extent these clayey surface horizons in Okoto palaeosols may represent the deposits of waning floods, but this cannot be the whole answer considering their abundant root traces, calcareous rhizoconcretions, cocoons, soil-like patterns of cracking and veining, micromorphology and variation with depth of chemical and mineralogical composition. With admixtures of ash and silt, Okoto palaeosols grade into palaeosols more like Chido palaeosols.

Chido palaeosols have an additional horizon of lighter brown (greyish brown, 10YR–2.5Y), blocky-structured silty claystone below the surface clayey horizon. This lower clayey layer contains moderately developed argillans (clay skins) and penetrating ped structure (intersecting planes defined by thin clay skins). These clayey horizons are not enriched in clay to the extent that it could be regarded as an argillic horizon, and have been identified as Bw (cambic) horizons. Cambic horizons contain soil structures such as root traces and clay skins but do not have significant clay enrichment (10%) when compared to the surface or A horizon.

The Chido palaeosols and to a lesser extent the Okoto palaeosols have dull brown colours. Most are in the range of 10YR to 5Y (dark reddish brown to dark greyish brown). These are not diagnostic colours of either strong oxidation or burial reddening, nor of gleization during soil formation or burial. A widespread effect of burial of palaeosols is the dehydration of ferric hydroxide minerals such as goethite to oxide minerals such as hematite (Walker 1967). These changes result in a change of colour from yellow or brown to reddish brown and red in only a few tens to hundreds of thousands of years (Simonson 1941; Ruhe 1969).

Micromorphology of clayey matrix.

Clayey fabrics in Chido palaeosols consists of skeleton grains (mineral grains and rock fragments) in an anisotropic matrix. The clayey matrix largely lacks preferred orientation of clay. However, oriented clay pellets (2–4 μm in diameter) and oriented micro-fractures are present in some Bw horizons. The majority of the Bw and A horizons of the Chido palaeosols consists of floating skeleton grains of feldspar, pyroxene, rock fragments and biotite in a matrix of largely opaque clay. Distributed throughout the clay matrix are numerous opaque iron-oxide grains on the order of 1 to 1/10 μm. The percentage of clay matrix, as determined by thin-section point counting (Fig. 6), is probably overestimated compared with standard sieve analysis and clay aggregation during sieving (Murphy & Kemp 1984).

Calcareous rhizoconcretions and nodules

Calcareous rhizoconcretions are very abundant in palaeosols of the Kiahera Formation. Some calcareous rhizoconcretions have plant cell structure defined by micrite (Fig. 8a). Nodules that are elongate, circular in cross-section (Fig. 8b), and have branching, root-like morphologies are interpreted as calcareous rhizoconcretions (Klappa 1980).

Calcareous nodules are common throughout the clayey surface horizons and are both orthic (diffuse boundaries, in

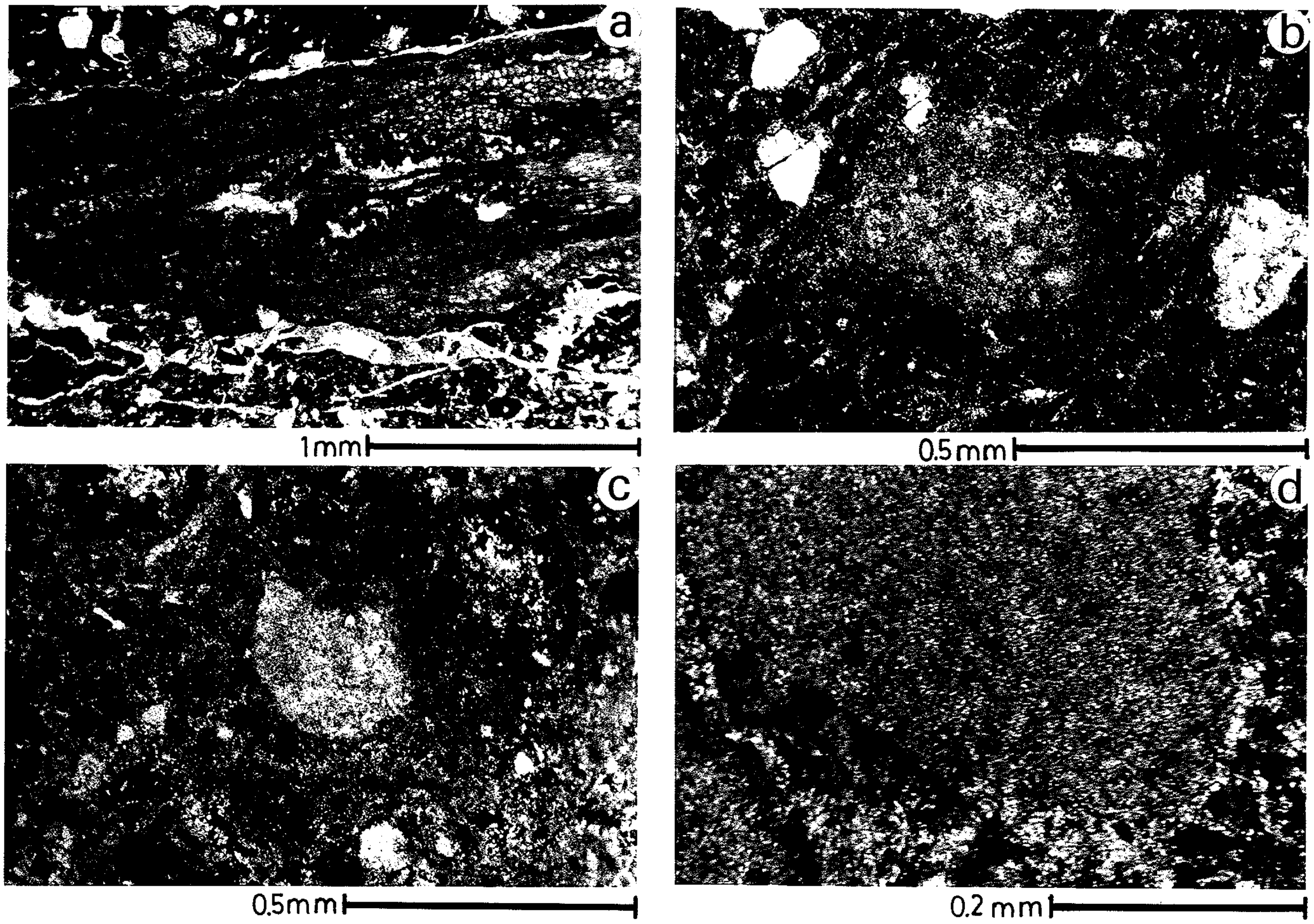

Fig. 8. Photomicrographs of calcareous micromorphology under cross polarized light. (**a**) Calcareous rhizoconcretion with well preserved cell structure. (**b**) An orthic calcareous nodule interpreted as a calcareous rhizoconcretion. (**c**) A disorthic calcareous nodule. (**d**) Calcareous nodule under high power showing mix of bright clay and fine-grained carbonate (25X).

situ growth) and disorthic (distinct boundaries, not in growth position) using terminology of Wieder & Yaalon (1974) and from Brewer (1976). Both kinds of nodules contain a relatively homogeneous mix of carbonate microspar and bright clay forming a fabric where individual crystals of microspar and clay can be discerned under high power objective. Nodules of similar character are common and have been described extensively from calcareous loessal soils by Wieder & Yaalon (1974, 1982). These modern soils are very similar to the Chido palaeosols in that they are calcareous clayey silts and lack extensive areas of large sparry calcite. Wieder & Yaalon (1974) found that the abundance of disseminated clay mineral content was inversely related to the size of microcalcites; more abundant clay corresponded to finer-grained microspar. A similar relationship is found in the Kiahera Formation palaeosols.

Calcareous subsurface horizons

Calcareous horizons in some Chido palaeosols are weather-resistant, continuous and very calcareous, but do not have the massive to nodular morphology common to most soil Bk horizons (Gile *et al.* 1966; Machette 1985; Blodgett 1988). Nor do they show replacive micrite or displacive sparry calcite seen in thin sections of soil Bk horizons described by Wieder & Yaalon (1974). Calcrete structures and fabrics such as carbonate lamellae, coated intraclasts and ooids, common to calcretes (Gile *et al.* 1966; James 1972; Siesser 1973; Machette 1985) were *not* found in the Kiahera palaeosols. Instead the calcareous horizons are 15–25 cm thick and have a lenticular to bedded appearance with gradational boundaries (Fig. 7), resembling the hardpans that form during early weathering of carbonatite–nephelinite ash on the active volcano Oldoinyo Lengai and Plio-Pleistocene Laetoli Beds (Hay 1978). These hardpans are responsible for preservation of footprints and insect fossils in some of these ashes (Hay & Leakey 1982; Hay 1986). We have informally labelled these distinctive calcareous lenses as simide horizons, from the Dholuo term for cement, and regard them as Ck horizons in soil terminology (Birkeland 1984). Thick and well-developed palaeosols in the Kiahera Formation, particularly in unit Kp, lack these simide horizons, or have only relicts of them penetrated by roots or cracks. In such palaeosols the subsurface horizons have much less conspicuous relict bedding. Their micritic, nodular calcareous horizons are indistinguishable in the field and in thin section from those of dryland modern soils.

Depth of calcareous horizons. The preburial depth of calcareous horizons in the Kiahera Formation palaeosols were estimated and compared to calcareous horizon depths of modern soils that are well known from various semi-arid parts of the world (Fig. 9; Jenny 1941; Arkley 1963; Sehgal *et al.* 1968; Sehgal & Stoops 1972; de Wit 1978; Jager 1982; Anderson & Talbot 1965; Anderson & Herlocker 1973; Ruhe 1984). Compaction of the palaeosols is estimated from the depth of burial for the Kiahera Formation which is 1100 m based on the reconstruction of the Kisingiri volcano (Le Bas, 1977; Van Couvering 1972). This amount of burial generates a compaction of 44% for the Kiahera Formation based on Baldwin's (1971) and Baldwin & Butler's (1985) compaction curves for shale. Depth to calcareous horizon was measured in the field (Figs 3 & 6).

Recent studies have demonstrated that the depth to calcareous horizons is related also to dust flux, organic content and soil CO_2 content, evapotranspiration, and base saturation and its effect on the thickness of clayey B horizon (McFadden & Tinsley 1985; Marion *et al.* 1985; Ruhe 1984). These factors explain the spread in the data and limit the interpretation of former precipitation to only a broad range.

The morphology and depth estimates of calcareous horizons in Chido palaeosols compare well with modern calcareous horizons of 'soft' calcareous pan (weakly cemented calcic horizon) found in de Wit's (1978) intermediate grassland, or B landscape type of the Serengeti Plains. Landscape type B supports intermediate length grasslands which receive approximately 550–750 mm of annual rainfall. Soils of landscape type A3 of de Wit (1978) also have calcareous horizons at a similar depth to that reconstructed for Kiahera Formation palaeosols. Landscape A3 is the wetter of the short grassland landscape types, is proximal to the wooded grasslands, and receives approximately 500 mm to 600 mm annual rainfall (de Wit 1978). These soils of de Wit's (1978) correspond to Anderson & Talbot's (1965) 'calcimorphic vertisols with a soft calcareous pan' found on well-drained gentle slopes of Ngorongoro Crater just to the southeast of the Serengeti Plain. Another landscape and soil type of Anderson & Herlocker (1973) which compare well with Chido palaeosols are 'vertisols/brown calcareous soils'. Both these soil types described by Anderson & Herlocker (1973) form on moderate slopes, support medium height grasses, and receive approximately 750–800 mm annual rainfall.

Vertic features

Vertisols and vertic properties are found in soils with at least 30% clay (Soil Survey Staff 1975), dominated by smectite, expandable clays. They commonly form in warm climates with a pronounced dry season (Buol, *et al.* 1980; Soil Survey Staff 1975). Shrinking and cracking of the clayey soil during the dry season and expansion and swelling during the wet season produces movement within the soil, especially the upper half, which tends to mix the soil to varying degrees and commonly produces angular peds, slickensided cutans, and dark coloured soils from the mixing of organic material (Krishna & Perumal 1948; Buol *et al.* 1980). Parent materials that produce smectitic clays with swelling properties are argillaceous limestones, marine clays, mafic igneous rocks and mafic volcanic ash. Vertisols and the parent material of Vertisols are alkaline to highly alkaline and have abundant Ca and Mg as exchangeable cations (Borchardt 1977; Buol *et al.* 1980) and also commonly contain pedogenic carbonate (Blockhuis *et al.* 1969).

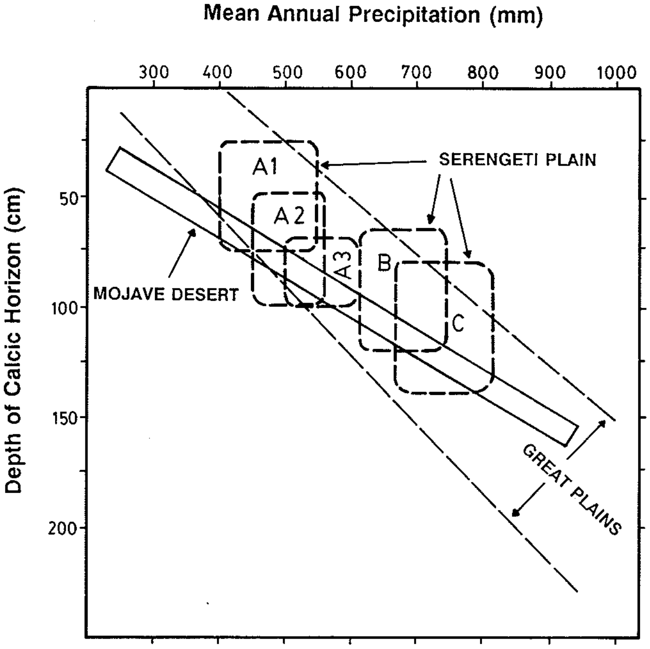

Fig. 9. The depth of calcic horizon in soils formed under different regimes of mean annual rainfall in postglacial loess soils of the Great Plains of North America (after Jenny 1941), Mojave Desert (after Arkley 1963), and from the Serengeti Plain, Tanzania (after de Wit 1978). Dashed boxes represent depths to calcic and petrocalcic horizons from landscape types of short grasslands (A1–A3), intermediate grasslands (B), and long grasslands (C) in the Serengeti Plain (from de Wit 1978).

Chido II palaeosol contains abundant and well developed lentil shaped peds with slickensided cutan surfaces (Fig. 6b). These lentil shaped peds have a long axis oriented roughly horizontal and have long axis dimensions up to 20 cm (Fig. 7b). These peds are very similar to horizontally oriented lentil peds described by Blockhuis *et al.* (1969) from Vertisols in the Sudan. The slickensided cutans are at angles between 30° and 60° from horizontal and indicate that a principal component of stress was lateral, a common feature in expansive vertic soils.

Other vertic properties in the Chido palaeosols include relatively homogenous clay content in the upper two thirds of the profile, poorly developed horizonation, lack of significant leaching between top and bottom of B horizon, angular peds with slickensided cutans, and dull, dark brown, high value, low chroma colours.

In addition, the Chido palaeosols in the Kiahera Formation have mainly smectite clay minerals. Evidence of smectite for the Chido Series is provided by 17–18 Å peaks from Mg-saturated, glycolated clay samples. A minor amount of kaolinite is indicated for sample K-11 by 7 Å XRD peak which disappears when the sample is heated to 550 °C. The presence of vermiculite is strongly suspected, however, definitive XRD peaks are difficult to discern from smectite peaks (Douglas 1977). A broad scatter of 10 Å to 14 Å peaks may reflect illite with interlayered vermiculite and smectite (Douglas 1977; Barnhisel 1977). Illite also is indicated by small peaks at 5.0 Å and 4.4 Å.

A possible type of burial alteration of the Kiahera clayey palaeosols is transformation of smectite to illite by transfer of potassium from groundwater during diagenesis. Illitization of smectite may occur to a limited extent during shrink–swell behavior of swelling clay soils (Robinson &

Wright 1987). Both these clay mineral groups are present in the Kiahera palaeosols, but smectite is much more abundant (Bestland 1990).

Okoto I palaeosol has pseudoanticlinal distortion of otherwise horizontally stratified sands in the C horizon (Fig. 10a & b). Displacive carbonate cement is abundant in cracks within the pseudoanticlines. Pseudoanticlines are relatively common in calcareous soils (Jennings & Sweeting 1961; Blank & Tynes 1965; Reeves 1976; Watts 1977). In Okoto I palaeosol, the pseudoanticlines are very similar to Watt's (1977) 'Type 1 folds' which are postulated to have resulted from the development of vertical cracks extending into the undeformed sandstone. The development of calcareous nodules and falling of loose material into the cracks causes expansion resulting in arching (Watts 1977). Precipitation of carbonate in the up-arched areas may enhance this process (Watts 1977). Another explanation for the folds is that material is being dissolved from the areas of the AC horizon which protrude into the Ck horizon, however, the abundance of calcareous nodules in the AC and C horizon indicate that carbonate has been added to the horizon.

Chemical depth functions

The bulk rock chemical analyses and microprobe analyses in weight percent oxides were converted to atomic percent by normalizing the atomic proportion of cations to 100%. This conversion is a modification of the commonly used molecular weathering ratios (Retallack 1990, 1991*a*) and made to display more accurately the elemental changes in palaeosol profiles by removing the distortion imparted by the differing molecular weight of oxides, thereby comparing atom to atom (Figs 11, 12 & 13). Variation in these ratios can reveal the direction if not the magnitude of weathering trends, especially in cases where refractory Al is included in the ratios. This approach is especially useful in cases of mixed volcanic and sedimentary parent materials where the exact parent material can not be identified.

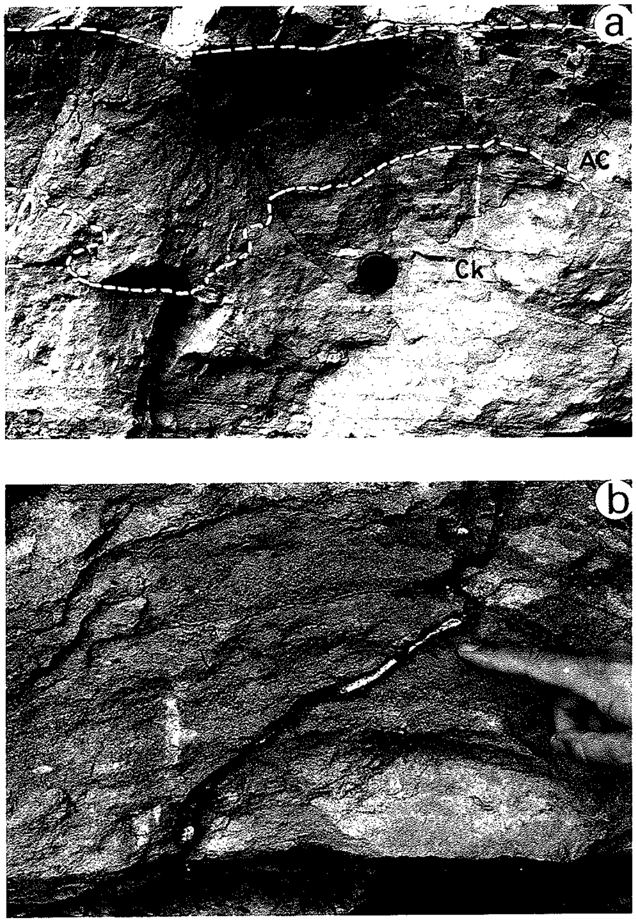

Fig. 10. Photographs of root traces and pseudoanticlines in Okoto I palaeosol. (**a**) Calcareous root traces in the AC and Ck horizons and pseudoanticlines in the Ck horizon. (**b**) Fossil root curves around a calcareous nodule just above finger.

Okoto palaeosols. Bulk rock chemical profiles of both Okoto I and Okoto II palaeosols (Fig. 11) indicate slight leaching and moderate oxidation. The decrease in Na toward the top of the profile is especially pronounced and is well expressed in Okoto I by the reversal of K and Na values from Na greater than K in the C horizon to K greater than Na in the AC and A horizons. The K trend in Okoto I palaeosol reflects, at least in part, an increase in the percentage of biotite (containing 6–8% wt% K) from 1–2% in the C horizon to 4–6% in the AC and A horizons. The Na trend is also affected by the decrease in abundance of feldspar crystals (containing Na) toward the top of the profile. Increased oxidation of Fe is apparent from declining ferrous/ferric iron ratios toward the A horizon. Al content in the AC and A horizons is higher than in the C horizon and corresponds to the higher clay content in the AC and A horizons, as determined from point counting. This up-profile increase in clay is also reflected in an increased Al/Si ratio toward the top of the palaeosol. The Al/K, Al/Na, Na/K and Ba/Sr ratios all show a weak leaching trend from the Ck to the AC and A horizons.

Chido palaeosols. In Chido palaeosols, abundant micrite and microspar in the clayey tuff matrix accounts for high bulk rock CaO values. Apart from the high CaO values, the palaeosols have much the same bulk rock composition as the tuffs, and probably had a tuffaceous nephelinite parent material (Fig. 12). One important deviation from the composition of Okoto I is the low Na values of the Chido samples. Na is contained in feldspars, nepheline, melilite, as well as in clayey matrix. The modal abundance of these minerals in Chido palaeosols is much less than that of Kiahera sandstones and Okoto palaeosols and is the primary reason for this difference.

Bulk rock atomic percentages generally show an absence or slight reversal of a normal leaching trend of easily leached elements such as Na and K. The accumulation of Ca in the Ck horizon is strong and leaching of Ca in the B horizons is moderate. Slight leaching to neutral trends are indicated by Al/Na, Al/K, and Ba/Sr ratios. Moderate oxidation (from Fe^{+}/Fe^{3+}) toward the top of the palaeosol is also indicated. Taken together these trends indicate weak weathering of the AB and Bw horizons and moderate calcification of the Bk/Ck horizons.

Chido I and II both have slight increases in the abundance of sodium and potassium in the AB horizons relative to the Bw and Ck horizons. The abundance of feldspar as well as biotite crystals increases slightly from the lower Bw horizon to top surface and may be the cause of this sodium and potassium increase. Salinization, or Na- and K-rich ash addition are also possible causes for the Na and

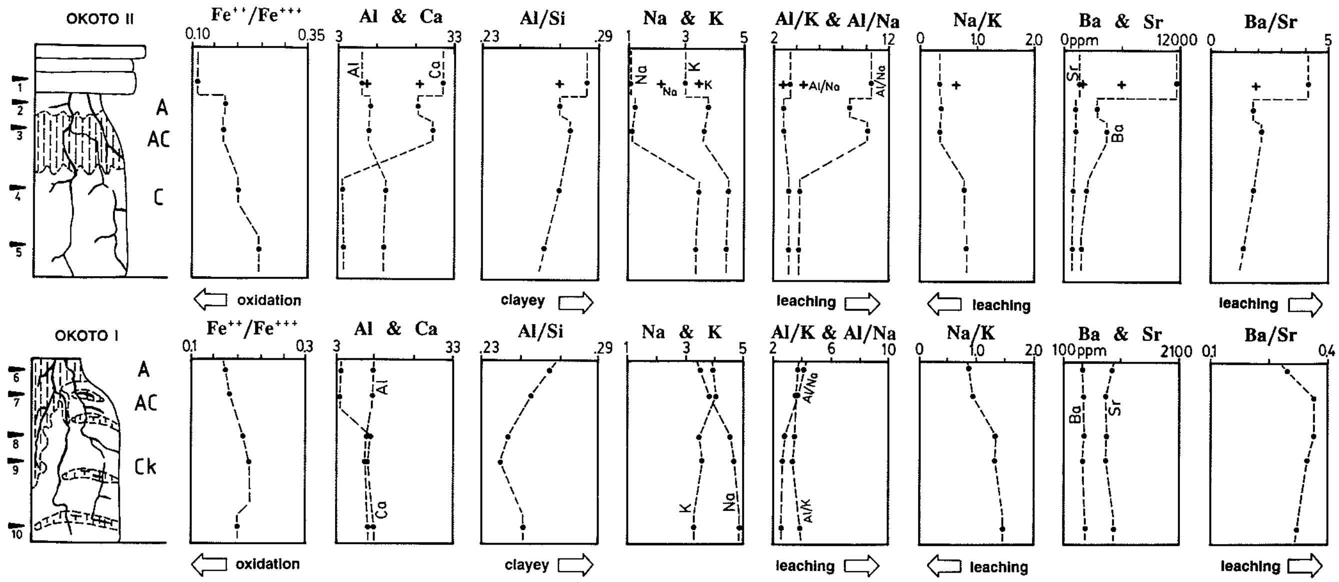

Fig. 11. Bulk rock atomic abundances, atomic ratios, and soil horizon interpretations of Okoto I and II palaeosols.

K increase. Domed-columnar peds indicative of salinization (Northcote & Shene 1972) are absent; instead, there are slickensided, horizontally oriented, lentil-shaped peds, more characteristic of vertic than salinized soils. Microprobe data discussed below point to a combination of rejuvenation and feldspar and biotite mode increase in the AB horizon to explain these sodium and potassium trends.

Weathering trends of clayey matrix. Microprobe analysis of clayey matrix was undertaken to determine what weathering trends exist in the clayey matrix of Chido I palaeosol. Bulk rock analyses include mineral grains such as feldspar, pyroxene, biotite, and calcite, and the observed abundance of these minerals changes vertically through the profiles.

The clayey matrix in samples from the clayey tuffaceous palaeosol, Chido I, were analysed with ARL-EMX and Cameca SX-50 microanalyzers using a 15–20 μm diameter beam and 15 to 20 kV beam current. The grain size of the clayey matrix is on the order of 1–3 μm, and thus the microprobe analyses are treated as bulk analyses of the matrix and not specifically as clay mineral analyses, although they resemble high magnesium smectite clays (Bestland 1990). Very fine-grained opaque grains (on the order of 1 to 1/10 μm in size), of Fe–Ti-oxide, are distributed throughout the clayey matrix with a density of about one grain every one or two microns. These grains account for high Fe and Ti values in these analyses. Additionally, micrite is also distributed throughout the clayey matrix to varying degrees. Many microprobe points have high Ca values and are a mix of clayey matrix and micrite and are not reported here. Clayey matrix analyses with totals above 75% and that have CaO values of under 20% were taken to be most accurate. Only samples from the clayey Bw horizon (sample K-12) and A horizon (sample K-11 and K-11nc) produced analyses that did not contain abundant micrite (Fig. 13). Analyses in weight percent were converted to atomic percent and plotted. Feldspars were also analysed so that their contribution to the bulk rock alkali trend could be evaluated; but these results can be found elsewhere (Bestland 1990).

In all, three different samples were analysed by microprobe: one of the surface clayey horizon, one of clay in a micrite–clay nodule in the surface horizon, and one from subsurface clayey horizon. The trends in Fig. 13a–d are most easily understood as a reflection of the leaching of alkali and alkaline earths from volcanic ash of melilitite composition, together with hydrolysis of biotite and pyroxene to form smectite clays and Fe and Ti oxides and hydroxides. Such weathering would cause the observed Na and Na/K decrease with increasing Al and decreasing Ca content. Similar weathering trends have been documented for surface soils developed on carbonatite–nephelinite ash in the Serengeti Plain of Tanzania (Hay & Reeder 1978; Hay 1978, 1983). Palaeosols of the Kiahera Formation also have similar Si/Al and Al/K ratios to the Tanzanian soils. These trends and the continuous spread of values between different parts of the clayey matrix (microprobe data) are more like features of weathering than of deposition or of alteration after burial.

Also notable are divergent trends in potassium, which is more abundant in the more decalcified parts of the AB horizon (Sample K11) compared to the Bw horizon (Sample K12). Without additional data on interlayering and crystal size of clay minerals, this trend could be due either to illitization of smectite or vermiculite in a seasonally dry climate (as reported by Robert & Trocme 1980; Barshad & Kishk 1970) or by Ostwald ripening of illite crystals during deep burial (Eberl *et al.* 1990).

Na has a straighter trend in the Bw horizon than in the AB horizon, and both Na and K are much more abundant in the calcareous nodules. One interpretation of these trends is that the AB horizon contains fresher ash and hence the Na and K values are higher and more scattered than more weathered parts of the profile. The original alkaline composition of the ash may have been preserved from soil leaching by early carbonate cementation in the calcareous clayey nodules. Na shows little variation with increasing Ca and Al for the non-calcareous samples from the AB and Bw horizon and probably indicate that enough weathering had taken place in these horizons to homogenize these values.

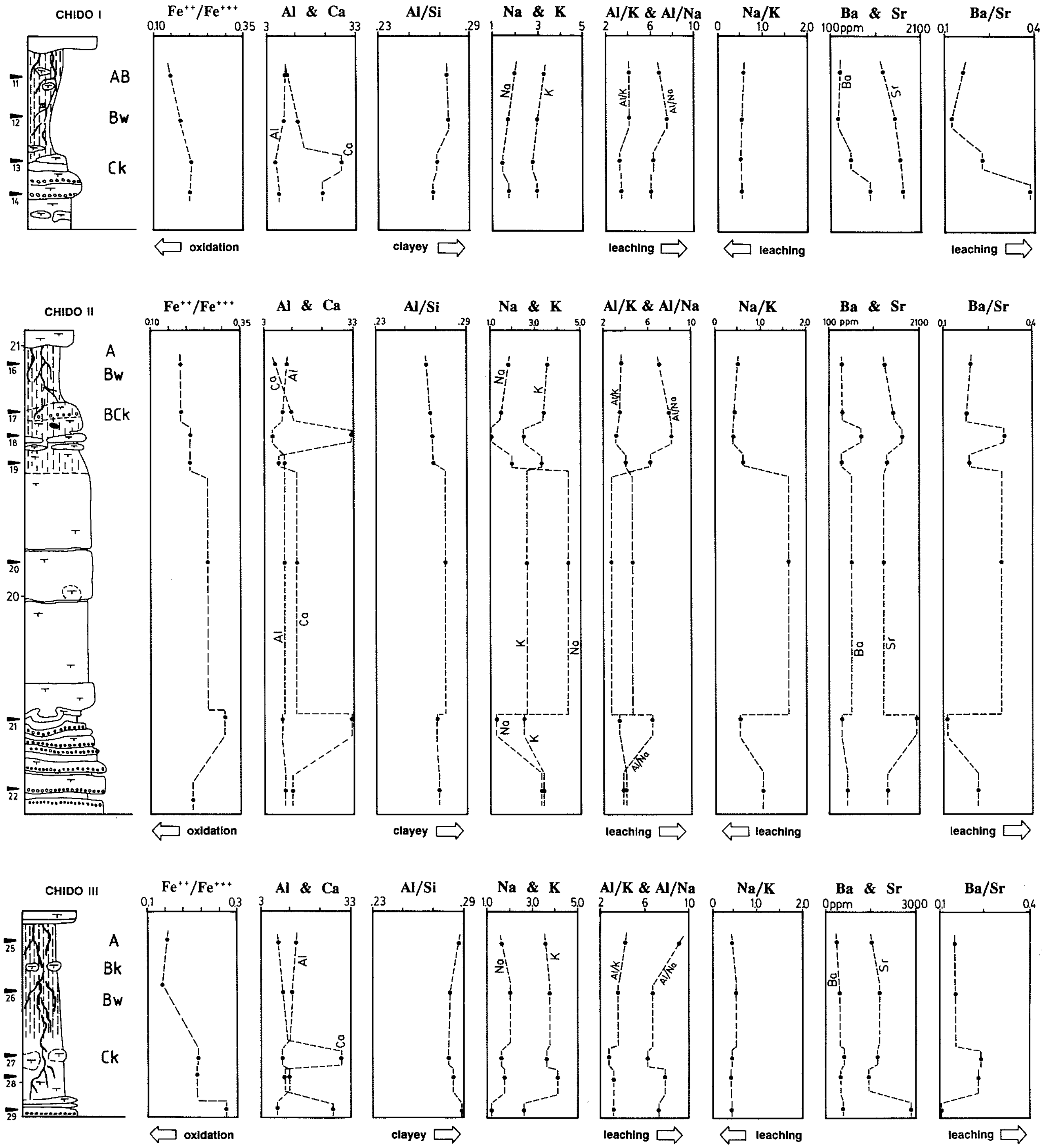

Fig. 12. Bulk rock atomic abundances, atomic ratios, and soil horizon interpretations of Chido I, II, and III palaeosols and associated sedimentary and pyroclastic strata.

Reconstructed palaeosols and their environment

Palaeoenvironmental interpretations of palaeosols are based on the comparison of palaeosol morphology with modern soil analogues and on associated fossil evidence. General palaeoenvironmental interpretations have been made for the Kiahera Formation based on fossil fauna and flora and indicate a tropical woodland palaeoenvironment (Pickford 1984; Chesters 1957). Palaeosol interpretations extend and refine these palaeontologically based interpretations because palaeosols are trace fossils of an entire ecosystem and as such they represent the dominant imprint of climate, vegetation and fauna.

Okoto palaeosols

The Okoto palaeosols are weakly to moderately developed with dark reddish brown silty, clayey A and AC horizons,

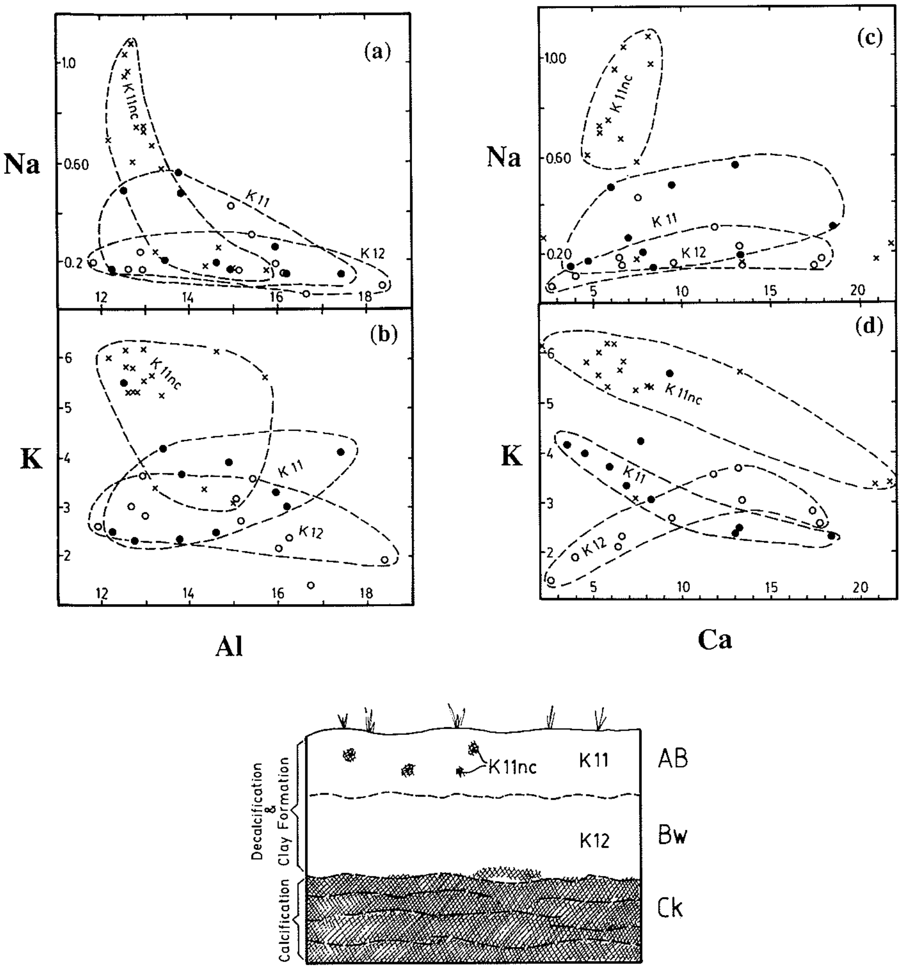

Fig. 13. Scatter plots of atomic abundances and ratios of electron microprobe data from Chido I palaeosol.

sandy, calcareous C horizons with prominent relict bedding, and abundant calcareous rhizoconcretions both small and large that extend deep into the profile. Okoto palaeosols contain abundant fine (mm) and medium-sized (up to 2 cm diameter) calcareous root traces which are probably the traces of low shrubs, forbs, grasses and trees. The deeply penetrating root traces, moderately oxidized colours and good horizon development are all indications of moderate to good drainage.

Okoto palaeosols can be classified as Inceptisols (Soil Survey Staff 1975) because of their weak development regardless of whether their subsurface horizon is interpreted as an AC or Bw (cambic) horizon (Table 1). According to FAO (1971–1981) soil classification, the Okoto palaeosols are intermediate between Fluvisols and Cambisols because they are more developed than Fluvisols with an A-C profile, but not developed to the point of an obvious cambic horizon. Classification of Fluventic Ustropept or Calcaric Fluvisol would be the best considering the calcareousness, tropical climate and fluvial origin of the parent material of these palaeosols. Okoto palaeosols may have formed on overbank sands and silts near streams.

Chido palaeosols

Chido palaeosols are thick, weak- to moderately-developed palaeosols with dark greyish brown clayey A and Bw horizons with prominent lentil-shaped peds, and silty nodular Ck horizons and abundant calcareous rhizoconcretions of fine (mm) to moderate (3–4 cm diameter). These

Table 1. *Summary of palaeosol characteristics and interpretations*

Palaeosol series	Lithology	Diagnostic soil horizons	Diagnostic soil structures	Soil classification	Depositional facies	Landscape position & vegetation
Okoto	Clayey, silty sandstone	AC, Ck	Stout penetrating root traces	Calcic Inceptisol	Channel & levee sands & silts	Riverine gallery woodland
Chido	Silty claystone	Bw, Ck	Lentil-shaped peds Calcareous root traces	Vertic Inceptisol	Floodplain mud and ash	Wooded floodplain

rhizoconcretions are probably the traces of shrubs and small trees. Herbaceous ground cover was, however, not so thick as to create granular soil-structure or other features of Mollisols.

Chido palaeosols show consistent indications of imperfect drainage; these being homogeneous and somewhat dull brown colours (10YR to 2.5Y) throughout the A and B horizons. However, features such as MnO_2 and Fe nodules with reduced colour mottles are largely absent indicating that waterlogging was not prolonged. The Chido palaeosols probably formed on the interfluves between streams where imperfect drainage caused waterlogging during heavy rains, much like similar modern soils on the Serengeti Plain (Jager 1982).

Chido palaeosols are classified as Inceptisols because of their weak to moderate development, Bw (cambic horizon), and Ck horizon (Table 1). They are probably not Mollisols (grassland soils) because the A horizon generally lacks the fine granular texture and abundant root traces indicative of a mollic epipedon. Using the FAO (UNESCO) classification, the Chido Series are Cambisols, and probably Vertic Cambisols. Using the knowledge that these palaeosols formed in a tropical climate and probably under an ustic moisture regime (from rainfall estimates), the suborder Tropept, group Ustropept best fit the Chido Series. Vertic Ustropepts or Vertic Calciustropepts would be appropriate.

Landscape reconstruction

The following discussion is an interpretive summary of the landscapes and depositional processes that produced the Kiahera Formation. Chido and Okoto palaeosols developed on the alluvial apron of Kisingiri volcano (Fig. 14). A landscape model is envisaged in which immature, fluvially influenced soils occur proximal to stream channels and more mature clayey and tuffaceous soils occur distal to streams, as is common in fluvial systems. For example, Bown & Kraus (1987) and Kraus (1987) found in the Eocene Willwood Formation of Wyoming that palaeosol maturity varied in

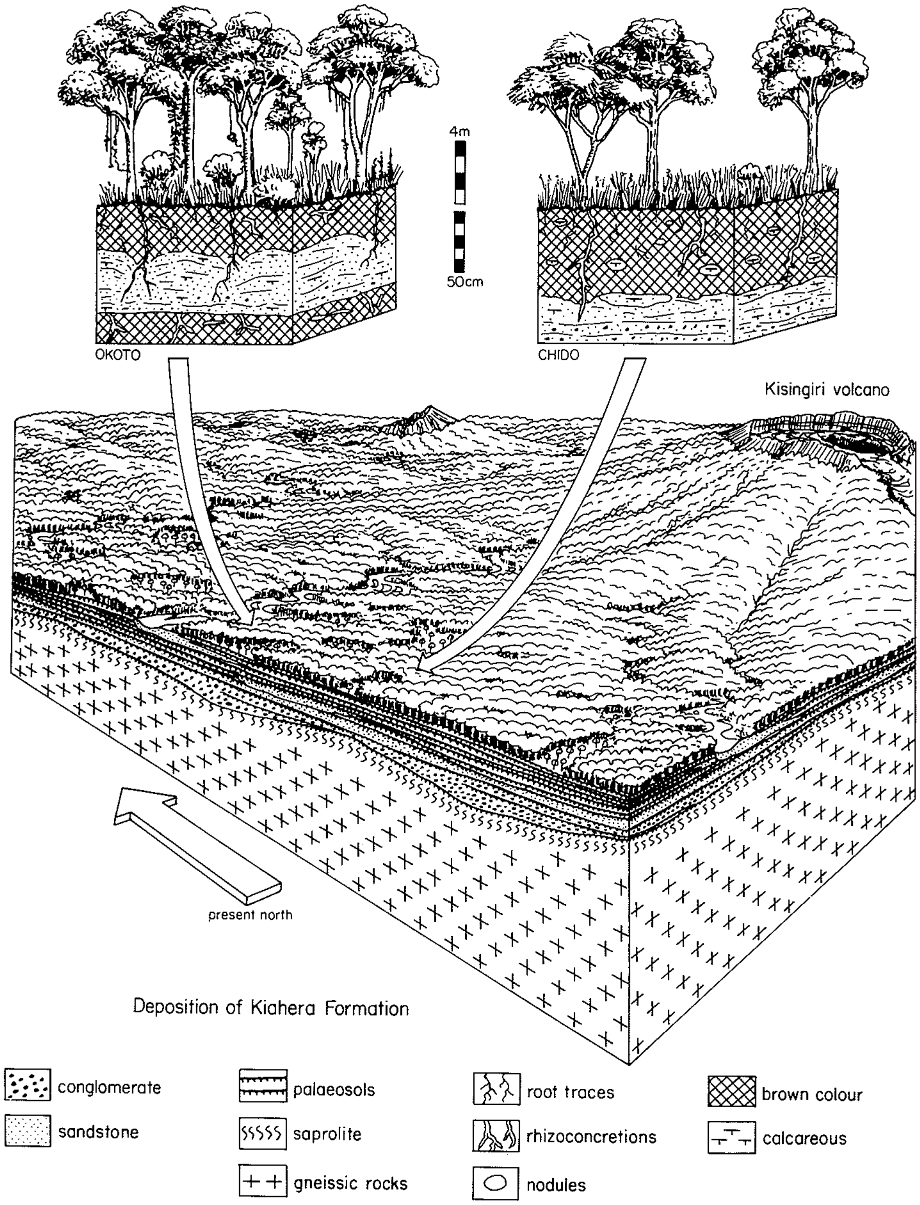

Fig. 14. Mid-Miocene palaeoenvironment of the Kiahera Formation. A landscape of stream-side gallery woodlands with large trees and climbing vines is interpreted for the Okoto palaeosols and a more open grassy woodland environment is interpreted for the Chido palaeosols.

relation to floodplain setting. Proximal to river channels, relatively immature palaeosols are present, and distal to river channels, where both sedimentation rates and disturbance by fluvial reworking were less, relatively mature palaeosols are present. In the Kiahera Formation, however, areas distal from stream channels received substantial increments of ash fall deposits, thus rejuvenating the soils. Furthermore, landscape aggradation by catastrophic events, such as large pyroclastic airfall events and volcanically induced fluvial aggradation, occasionally affected the entire landscape.

Rapid landscape aggradation during Kiahera times is strongly indicated by the presence of numerous thick, coarse-grained channel deposits at the base of fining-upward sequences. These sandstones contain abundant, vesicular volcanic rock fragments. These channel complexes are interpreted to represent fluvial aggradation during and immediately following major eruptive phases of the Kisingiri volcano. Aggradation probably took place over much of the alluvial apron and produced the laterally continuous, ledge-forming sandstone units, common in both the Kiahera and Hiwegi formations.

During periods of relative volcanic hiatus, streams reworked the sand and gravel in channels and in the proximal overbank stream deposits. The weakly developed Okoto palaeosols (sandy Inceptisols) formed on sandy overbank deposits and on abandoned channel sands. Farther away from the effects of stream floods and reworking, ash from small ash eruptions, and perhaps from wind blown sources, accumulated and became incorporated into the soil, forming the moderately developed Chido palaeosols (vertic Inceptisols).

During deposition of the Kiahera Formation, the Kisingiri volcano probably had only modest relief. This interpretation is based on the almost total lack of debris flow deposits in the Kiahera Formation. Debris flows are exceedingly common in many modern and ancient terrestrial volcanogenic deposits when there is a modest to large relief volcano nearby (Vessel & Davies 1981; Smith 1987; Scott 1988). Exceptions occur where there is a large and long alluvial plain stretching far from the volcano (Vessel & Davies 1981). The centre of the Kisingiri volcano, as estimated from the Rangwa intrusive complex and the centre of the Precambrian dome, lies 15–17 km from where the Kiahera Formation is now exposed on Rusinga Island. According to studies of recent eruptions of the Fuego volcano, 4000 m high in Guatemala, the alluvial/fluvial deposits at this distance are dominated by debris flows and pyroclastic flows containing boulder-sized clasts (Vessel & Davies 1981). Sandy and silty alluvium accumulated at distances of more than 30 km. In the Kiahera Formation, sandy and gravel-rich fluvial flood deposits, some of them hyperconcentrated flood-flow type (Smith 1986), are common and indicate that high energy sand and gravel floods were a common mode of fluvial deposition. The presence of thinly bedded sandy silt beds, interpreted as sheetflood deposits, although not a dominant component to the formation, indicate that overbank flooding of moderate intensity also occurred.

Chido and Okoto palaeosols are morphologically, mineralogically, and chemically similar to surface soils on the Serengeti Plain of northern Tanzania (Anderson & Talbot 1965; Anderson & Herlocker 1973; de Wit 1978; Jager 1982). The Serengeti Plain supports woodland in the north and west (Jager 1982) to desert scrub in the east (de Wit 1978), with most of the plain consisting of grasslands of various heights. The active volcano of Oldoinyo Lengai, a nephelinite-carbonatite centre, has contributed ash to the plain during the last 100 000 years (Hay 1989). Other nearby nephelinite volcanoes were active during the Pleistocene and include Ngorongoro Crater, Kerimasi and others. Consequently, much of the Serengeti Plain is underlain by considerable thicknesses of ash and therefore, the soils have only small admixtures of quartz-feldspar-mica from the Precambrian basement rocks. The Serengeti Plains differ from the landscape envisaged for Kiahera palaeosols in their less mafic parent material, and the lack of large braided sandy fluvial systems on the Serengeti Plain. The Serengeti Plain is a site of airfall ash accumulation around inselbergs of Precambrian gneiss that has been dissected into a gently rolling plain with gullies. Chido palaeosols compare well with de Wit's (1978) vertic Mollisols (landscape B, intermediate grassland) of the Serengeti Plain in terms of depth of calcareous horizons, morphology of calcareous features, and structure of B horizon. However, Chido palaeosols lacks a mollic epipedon so well developed in de Wit's Mollisols. Mollic epipedons are distinctive and recognizable in similar Miocene palaeosols at nearby Fort Ternan, Kenya (Retallack *et al.* 1990). The lack of mollic epipedons and the abundant stout root traces in the Kiahera palaeosols indicate that the palaeosols supported dry woodland or grassy, shrubby woodland. Vegetation akin to the grassy woodland landscape types of the Serengeti Plain described by Jager (1982) is our preferred interpretation. The Okoto palaeosols are interpreted to have been more densely wooded because it has abundant medium and large root traces, some of which penetrate deeply into underlying strata. A landscape with a woodland along stream corridors is envisaged for the Okoto Series and grassy woodland for the Chido Series.

The floristic affinities of these grassy woodland type palaeosols were with Zambezian woodlands of southern Africa (of White 1983). Such an interpretation also is compatible with the evidence of fossil snails (Verdcourt 1972), cocoons and other insect remains, and mammals (Pickford 1984) from the Kiahera Formation. The fossil soils, plants and animals of the Kiahera Formation indicate a drier climate and more open vegetation than can be documented from similar lines of evidence some 20 million years old in southwestern Kenya (Retallack 1991*a*), but there was not yet evidence of Mollisols, grasses and antelope that had appeared by 14 million years ago (Retallack *et al.* 1990).

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