FACIES MODEL OF A SEMIARID FRESHWATER WETLAND, OLDUVAI GORGE, TANZANIA

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ABSTRACT: **The sedimentology and stratigraphy of a freshwater wetland in early Pleistocene (~ 1.75 Ma) volcaniclastic deposits, Olduvai Gorge, Tanzania, are characterized using texture, mineralogy, microfossils, and stratigraphic description to create a depositional facies model. The freshwater wetland was located on the margin of a semiarid, closed basin containing a playa lake. The lake-margin deposits are dominated by two distinct lithologies: waxy claystones and earthy sediments. Waxy sediments are olive green, dense claystones that contain authigenic minerals such as trona, and represent a fluctuating saline, alkaline lake (Hay 1976). Earthy sediments are beige, friable siltstones that contain siliceous microfossils, bone fragments, and minor pebbles; they represent the freshwater wetland. Microfossils from the earthy sediments and diatomites indicate freshwater marsh biota with some rare salt-tolerant species. Associated lithofacies are: diatomite, carbonate, and sandstone.**

Interpretation of vertical and lateral lithofacies variations in the 2 km^2 wetland, based on ~ 50 excavations, identified seven distinct subenvironments: spring deposits, perennial marsh, pool, ephemeral wetland, fringing wetland, wetland channel, and ephemeral stream. The stratigraphic sequence, estimated to represent an ~ 40–50 kyr long interval, indicates that persistent (~ 10^3 yr) wet periods prevailed during the deposition of thick waxy clays when the lake expanded and flooded the wetlands, and equally long intervening dry periods caused the lake to contract, allowing the flourishing of wetlands and accretion of earthy sediment. The lithofacies associations in the Olduvai paleowetland provides an important first step in the development of a depositional environmental model for freshwater wetlands that can be tested elsewhere, particularly in arid and semiarid settings.

INTRODUCTION

Wetlands, marshes, and palustrine environments are often studied in combination with other depositional systems like deltas, lakes, or floodplains, rather than being treated as a distinct entity. They are common in cool, humid climates but are a ''neglected'' environment with respect to arid-region studies. As a result, there is a dearth of information in the literature on arid-region wetlands. A major gap exists with respect to understanding processes, deposits, and the resulting geologic record. Given the potential of wetlands as an indicator of wetter vs. drier periods in arid regions, a descriptive sedimentological model focused strictly on wetlands is needed as a guide for interpreting paleoclimate history.

Paleoenvironmental reconstruction of the early Pleistocene landscape at Olduvai Gorge, Tanzania, revealed a closed-basin saline, alkaline lake adjacent to a large active volcanic complex (Hay 1976). Hay noted the presence of ''earthy claystones'' in the southeastern part of the lake margin zone characterized by the presence of > 10% silica and/or biogenic opal within the sediments. Hay's work (1976), along with recent archaeological and anthropological excavations by OLAPP (Olduvai Landscape Paleoanthropology Project) (Blumenschine and Masao 1991; Deocampo et al. 2002), determined that these earthy claystones represent a small (2 km^2) freshwater wetland system (Ashley and Feibel 1995; Ashley 1996; Deocampo 1997; Liutkus 2000; Ashley 2001; Ashley and Liutkus 2002). This freshwater wetland was a dynamic and integral part of the early Pleistocene landscape (Blumenschine et al. 1999; Ashley 2000). During arid periods in the Pleistocene, these wetlands and associated groundwater seeps were a likely source of freshwater for large mammals and hominids in an otherwise inhospitable landscape (Ashley 1996; Blumenschine and Peters 1998; Deocampo et al. 2002). Numerous fossil remains of *Australopithecus boisei* and *Homo habilis,* as well as stone tools, have been found throughout Olduvai in Bed I and lowermost Bed II (Leakey 1971; Hay 1976; Blumenschine and Peters 1998). In lowermost Bed II, a high concentration of these artifacts is found in the eastern lake margin near the wetlands (Ashley 2000; Deocampo et al. 2002).

At present, there are only a few sedimentological studies of arid-region spring-fed wetlands globally (Quade and Pratt 1989; Renaut and Tiercelin 1994; Quade et al. 1995; Deocampo and Ashley 1997; Deocampo and Ashley 1999) and none specifically from a volcaniclastic setting. No sedimentological facies models have been developed for freshwater wetlands as they have for other depositional environments (Walker and James 1992; Reading 1996). This investigation is the first detailed sedimentological study of an arid-region wetland in a volcanic setting. The goals of this paper are to: (1) characterize the subenvironments of a freshwater wetland on the basis of lithology, microfossils, and sedimentary structures, (2) interpret the facies in terms of physical, chemical, and biological processes, and (3) develop a descriptive facies model to provide the definitive characteristics of a freshwater wetland. The following detailed study at Olduvai Gorge, Tanzania, provides a starting point for developing a more generalized facies model for freshwater wetlands in a variety of geological contexts.

GEOLOGIC SETTING

Olduvai Gorge is the result of fluvial incision into a two-million-year-long sedimentary record of the Olduvai basin situated within the East African Rift Zone in northern Tanzania (Fig. 1A). The basin was ~ 50–60 km wide and is located on the rift margin between the Ngorongoro volcanic highland to the east and the Serengeti Plain to the west. The gorge itself exposes a sequence of Plio–Pleistocene and Holocene sediments > 100 m thick.

The Plio–Pleistocene deposits found within the basin thin from east to west because the dominant source of sediment was the pyroclastic material from the Ngorongoro Volcanic Complex (Hay 1976). With the exception of Oldoinyo L'engai to the northeast, the volcanoes in the highlands are presently dormant or extinct, but examination of the tuffs within the stratigraphic section of Olduvai Gorge indicates that these volcanoes were highly active during the Plio–Pleistocene (Walter et al. 1991). These tuffs are intercalated throughout the sediments and are excellent as isochronostratigraphic markers (McHenry 2001).

The exposed sediments at Olduvai Gorge found between Tuffs IF and IIA have been informally labeled ''lowermost Bed II'' (LMB II). Tuff IF is 1.79 Ma (Hay and Kyser 2001). Paleosol development and thick lacustrine claystones suggest that the time span is likely 40–50 kyr (Ashley and Driese 2000; Hay and Kyser 2001) (Fig. 2). Tuffs IF and IIA are laterally continuous and provide unusually good spatial resolution of the stratigraphy between these two isochronostratigraphic layers, particularly in the center of the basin. Using Tuffs IF and IIA as markers, the location and extent of the exposed wetland sediments within this narrow time range have been mapped over a 1.0 by 2.0 km area (Ashley 1996; Blumenschine et al. 1999; Ashley and Hay 2002). Figure 1B shows the study area in relation to the junction between the two main sections of the gorge, as well as the local archaeological area designations (Hay 1976).

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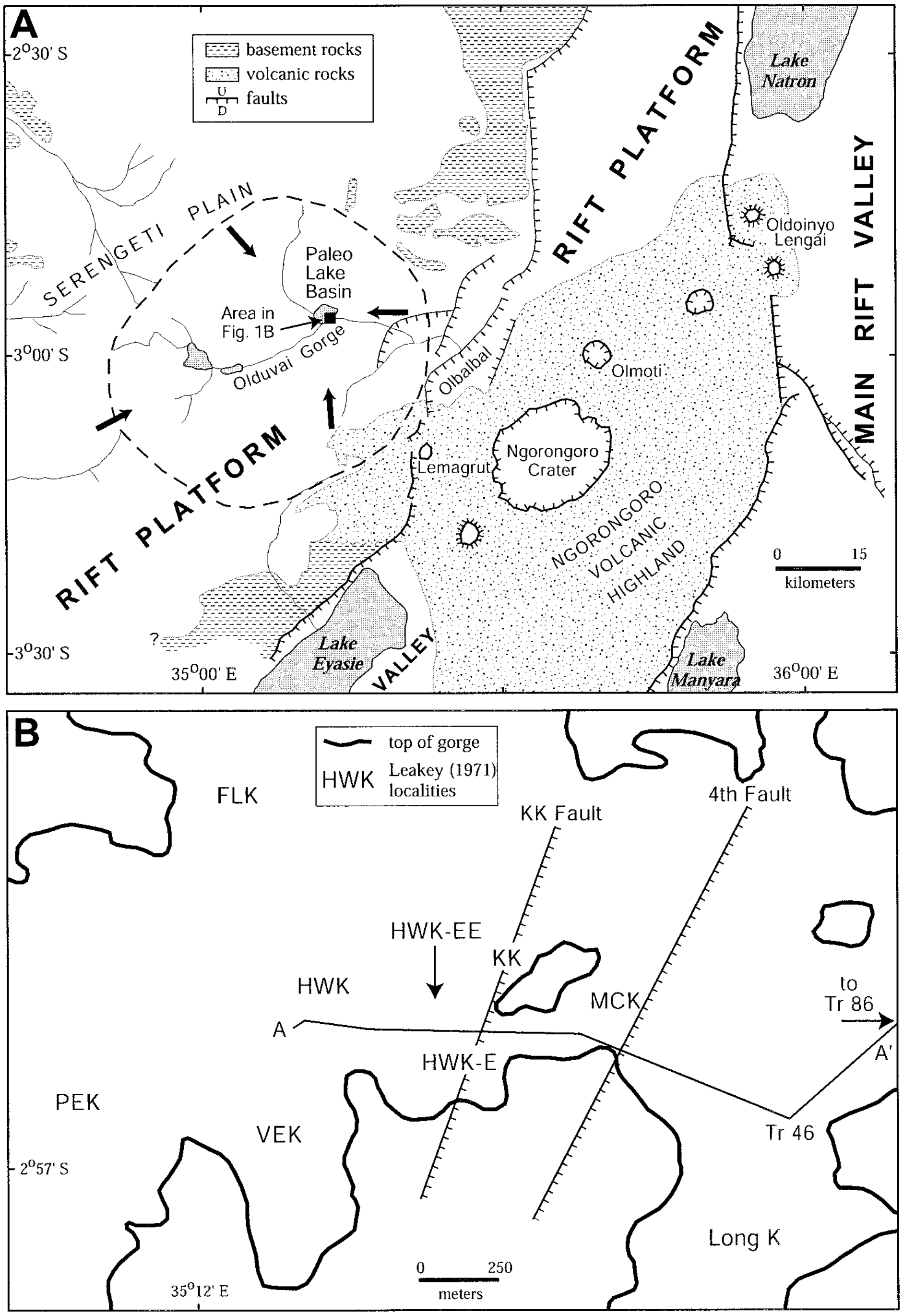


FIG. 1.—Location of the Olduvai paleo-basin in northern Tanzania, East Africa. **A)** Dashed line outlines the location of the paleo-basin. Arrows indicated sediment transport direction. The Ngorongoro Volcanic Highland is to the east and south of the modern gorge. Small black rectangle represents area enlarged in part B. Modified from Ashley and Hay (2002). **B)** Enlarged map of the junction between the two main segments of the Gorge, where the paleo-wetland sediments are concentrated. Location names given by Leakey (1971) are labeled. The heavy black line indicates the modern outline of the gorge. Fault locations are also superimposed on the map (dashed lines). Transect A–A′ is shown in Figure 3.

PALEOLANDSCAPE RECONSTRUCTION

Hay's (1976) interpretation of the Olduvai basin indicated that a saline, alkaline lake was situated in a closed basin to the west of the Ngorongoro volcanic highland. Thick units of green, waxy claystones were interpreted as saline, alkaline lake deposits on the basis of their stable-isotope signature and mineralogy, including minerals such as gaylussite, trona, zeolite, and cherts (altered from a sodium-silicate parent) (Hay 1976; Hay and Kyser 2001). An alluvial fan composed of pyroclastic material and reworked tuffaceous sediment built into the lake basin from the fringing volcanic highlands to the south and east. Precipitation on the volcanic highlands moved into the basin down the alluvial fan both as intermittent, ephemeral runoff and subsurface groundwater flow (Ashley 1996; Liutkus 2000). When the lake level lowered, because of arid conditions, the distal end of the alluvial fan supported a wetland environment that accumulated earthy (siliceous) sediments (Ashley and Feibel 1995; Ashley 1996). Several indicators led to the interpretation of this area as a freshwater region, including freshwater aquatic fauna and flora and spring-related carbonates (Ashley 1996; Deocampo 1997; Liutkus 2000). As climate fluctuated, the ecological response of this small area of the basin to the presence of the wetland and/or the lake produced interbeds of a variety of lithologies (Table 1).

STRATIGRAPHY

The stratigraphy of LMB II is shown in a 5 km fence diagram from the lake basin (west) through the lake margin to the pyroclastic-dominated

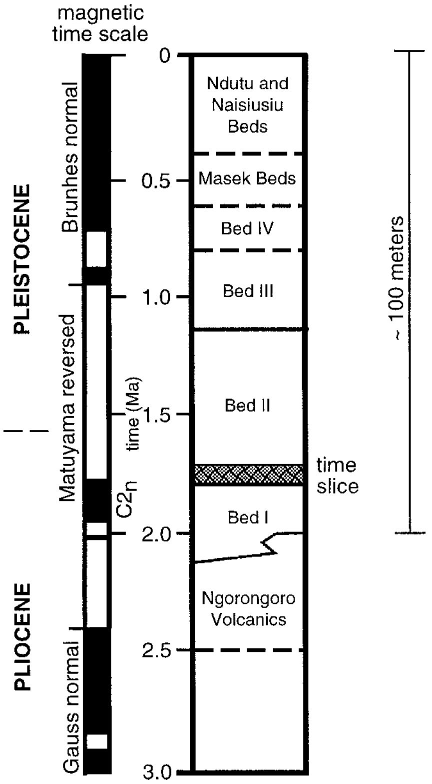


FIG. 2.—The magnetic polarity timescale is shown on the left; C2N is the Olduvai subchron. The stippled area in the stratigraphic column indicates the timeslice discussed in this paper (lowermost Bed II) (modified from Hay 1976).

alluvial fan (east) (Fig. 3). At least three distinct large waxy clay units blanketed the lake margin area during LMB II times. The earthy sediments and tuffaceous claystones interfinger with these lake clays. Closest to the lake, in the west, excavations reveal minor lake-level advances as seen by the thin, alternating waxy and earthy clay units (Figs. 3, 4). An excavation (OLAPP trench 72) shows a small depression in the landscape that was infilled with waxy claystone during a lake highstand (Fig. 3). In most areas, two thick earthy sediment units separate the waxy clays.

Lowermost Bed II begins above Tuff IF. A typical sequence of lithologic units within the lake-margin region in succession is: Tuff IF, waxy clay (called LMB II basal waxy clay), texturally immature sandstone (local), thick earthy clay, thin diatomite (local), intermediate waxy clay, thick siliceous (local) earthy clay, waxy clay (called topmost waxy clay), and Tuff IIA. For correlation, the top of the basal waxy clay unit was used as a datum, assuming that a high lake stand would have blanketed the entire basin with waxy clay and infilled any depressions. Two thick earthy units separate three large waxy clay units, suggesting three large lake expansions during the span of LMB II. During drier periods and lake recession, the wetland emerged and earthy sediments were deposited.

Typically, stratigraphic correlation over large distances (10^1–10^2 meters) is difficult. However, one area (HWK-E) provides unusually good stratigraphic resolution (Fig. 5). Correlation of the waxy and earthy units within HWK-E continues for > 100 m^2. A 20 m^2 deposit of diatomite appears to be completely encapsulated within the earthy sediment unit and is underlain by a lithic wacke sandstone that can be correlated up to ~ 100 m away.

SEDIMENTOLOGY

Five lithologies constitute the lake-margin sediments of LMB II: the primary wetland lithofacies (earthy sediments) and four associated lithofacies (waxy claystones, diatomites, carbonates, and sandstones). Sedimentological descriptions and depositional environments for each of these lithologies were determined from outcrop description, X-ray diffraction and grain size analyses, thin-section microscopy, and microfossil analyses. The key characteristics of each lithology and the interpreted depositional environments are summarized in Table 1. The spatial distribution of the lithologies was used to interpret the location of the marsh, as well as the position of springheads, groundwater seeps, ephemeral streams, and standing pools of freshwater. This information was then used to develop a facies model. Descriptions of the four distinctive lithofacies associated with the earthy claystones are given first.

Associated Lithofacies

Waxy Claystones.—These waxy sediments are dense, olive green (5Y 4/3), massive claystones that have an angular–blocky appearance (Figs. 4, 6A). Minor rootmarks and insect burrows are present as well as minerals such as trona. Basement metamorphic pebbles are found in these clay-

TABLE 1.—*Earthy sediments and associated lithofacies.*

Lithology	Color	Composition	Associated Features	Depositional Environment
Earthy sediments	white to beige to light gray (5Y 7/2)	friable, massive siltstones • smectite • interlayered illite/smectite • discrete illite	siliceous plant and bone fragments, carbonate rootcasts, metamorphic pebbles, diatoms, phytoliths, pollen; abundant artifacts	wetland, marsh
Waxy clay	olive green (5Y 4/3)	dense, massive claystones • smectite • interlayered illite/smectite	associated minerals such as trona; some localized rootmarks, insect burrows; calcite, pyrite, K-spar (Hay 1976); few artifacts	saline, alkaline lake
Diatomite	white (5Y 8/1)	thinly bedded (10–40 cm) powdery siltstones • interlayered illite/smectite • noncalcareous	abundant silica (diatoms, phytoliths, plant fragments), pollen, bone fragments and long bones, crocodile teeth; desiccation cracks; few artifacts	pool
Carbonates	white to pale yellow (2.5Y 8/2)	• thick, vertical slabs of calcium carbonate (20–30 cm high, 1-4 cm thick) • nodules (granule to 10 cm) • tufas (resemble rootmats)	highly localized; vertical carbonates intersect at high angles; nodules meld together to form sheets of carbonate above Tuff IF	springhead or groundwater seep
Sandstone	gray (5Y 5/1)	poorly sorted lithic wacke • texturally and mineralogically immature • noncalcareous but locally cemented	localized, high concentration of volcanic rock fragments, metamorphic pebbles, cobbles, plant and bone fragments, whole longbones, compact scour-and-fill structures, 10 to 20 cm fining-upward sequences, SSW to NNE paleoflow; few artifacts	ephemeral streams off alluvial fan

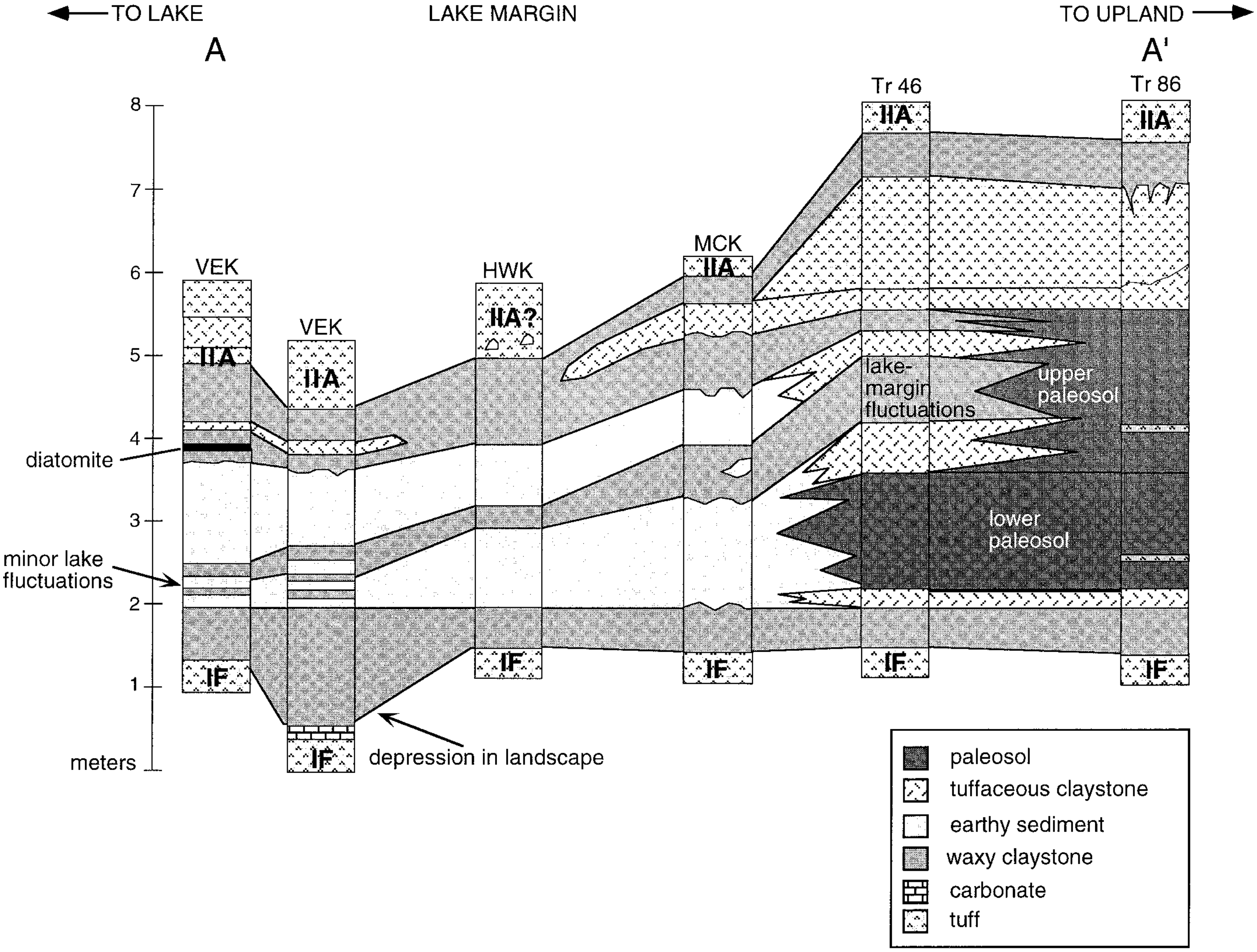


FIG. 3.—Stratigraphic cross section from alluvial fan in the east to the lake margin in the west (~ 2.25 km). Transect A–A′ is shown in Figure 1B. Correlation of OLAPP Trenches 46 and 86 is from Ashley and Driese (2000). Trench 13 (HWK) was excavated by R.L. Hay (unpublished data). In all stratigraphic columns, the top of the basal waxy clay unit was used as a datum.

stones, but other coarse materials are only a minor component. However, Hay and Kyser (2001) note several authigenic minerals such as calcite, trona, pyrite, and K-feldspar in the waxy claystones of the LMB II central lake basin.

Diatomite.—Diatomite layers are rare, highly localized, and difficult to correlate between excavations only a few meters apart (Fig. 5). These thin deposits (10 to 40 cm) of noncalcareous sediments are white, and the material on the surface readily weathers to a soft powder, whereas the unweathered material below is more consolidated. XRD analyses show very low, broad XRD peaks near 4.26 to 4.05Å, indicating amorphous silica. Some deposits show desiccation cracks on the surface. Many whole long bones and bone fragments, representing hippo and elephant, along with crocodile teeth are found within these sediments (Fig. 6B). These sediments have been found interbedded with both earthy and waxy claystone units.

Carbonates.—Highly localized tufa and micritic carbonate deposits occur within the earthy sediments. The tufa resembles carbonate rootmats, composed of large masses of plant stems and roots cemented together. Crack-filling carbonate slabs protrude through *in situ* sediments at high (nearly vertical) angles (Fig. 6C). The slabs are thin (1 to 4 cm wide) and are 20 to 30 cm high. In other areas, layers of massive carbonate immediately overlie Tuff IF. These carbonate layers are localized and appear to be nodules that have been cemented together into a sheet of carbonate, with only a faint remnant outline of the previously spherical nodules. In other areas, discrete spherical carbonate nodules are found distributed unevenly throughout the waxy claystones. The nodules vary in size from pea size to 10 centimeters or more across.

Sandstones.—The sandstones are gray, noncalcareous, texturally and mineralogically immature lithic wackes, with a high concentration of volcanic rock fragments and mafic minerals (Ashley and Hay 2002). Particle sizes range from clay, silt, and sand to small cobbles (*a* axis up to 20 cm long). They contain clasts of earthy and waxy claystone, silicified plant remains, bone fragments, as well as unbroken long bones of birds and other animals, and stone artifacts. The sandstones are bedded in 10 to 20 cm fining-upward sequences and show numerous scour-and-fill structures within a 1.5 m section at HWK-E. The bounding surface between Tuff IF and the overlying sandstone is sharp and erosional. Small-scale crossbedding and stringers of sand- to granule-size material are abundant. If long axes are assumed to be flow parallel, then long bone orientations and long axes of cobbles suggest a paleoflow in HWK-E trending from SSW to NNE (Hanson 1980). In the HWK-E, HWK, and KK areas, this sand is locally cemented with carbonate into small nodules from granule size to 10 cm in diameter.

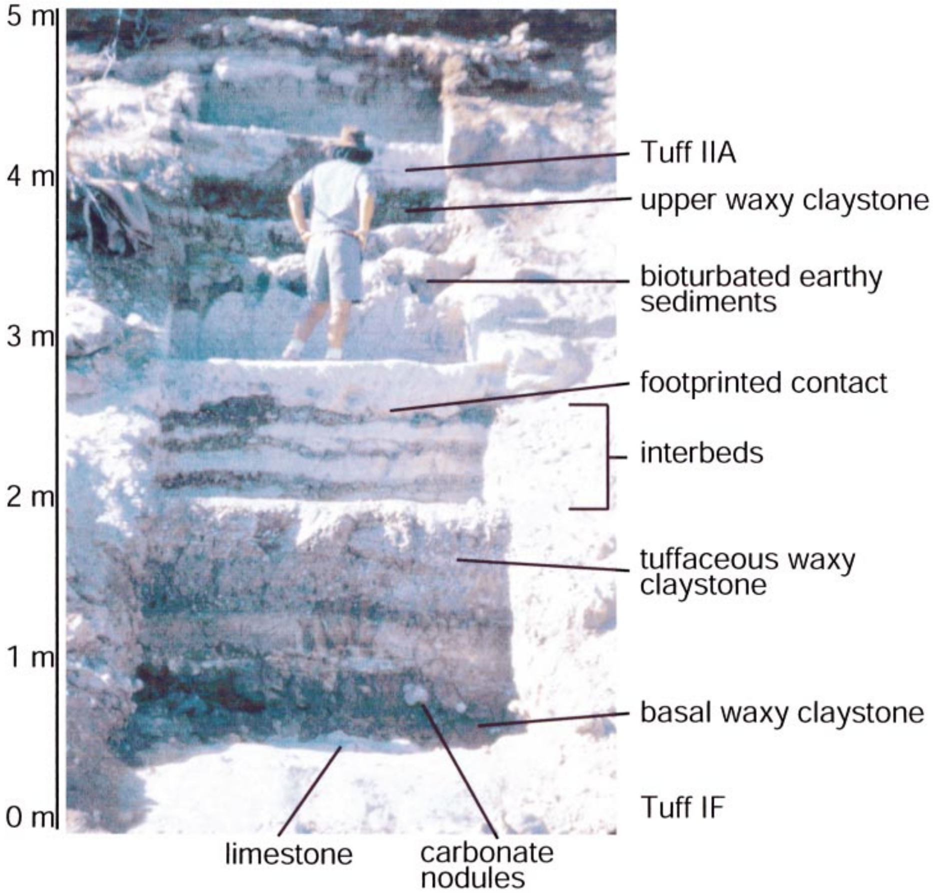


FIG. 4.—Field photograph of a field excavation (VEK) within the lake-margin region at Olduvai. The bounding units of lowermost Bed II (Tuffs IF and IIA) are visible at the bases and tops of the sections, respectively. The basal waxy claystone is clearly visible and contains carbonate nodules. The upper waxy claystone directly underlies Tuff IIA. The middle waxy claystone appears as a series of earthy and waxy claystone interbeds, and the top of this unit is footprinted.

Earthy Sediments

Outcrop Description.—The earthy sediments are characterized by their white to beige to light gray color (~ 5Y 7/2), granular and massive appearance, abundance of siliceous plant fragments (including phytoliths), bone fragments, rhizoliths, and granules of basement metamorphics (Liutkus 2000) (Fig. 6A). Some exposures of earthy sediments have large populations of carbonate root casts and reed casts, whereas other earthy clay units have a large concentration of silicified plant stems with a triangular cross-sectional shape (Fig. 7A, B). The thickness of individual earthy clay units varies from several centimeters to over 2 meters. In highly localized deposits (e.g., HWK-E), some earthy sediments have a more greenish color and clayey texture than typical earthy sediments, and appear to be mixed, most likely bioturbated, with some waxy clay (Ashley and Liutkus 2002). These sediments (''waxy-earthy claystones'') are darker than a typical earthy sediment, and are more consolidated. Small spherules of manganese oxide can be found in these waxy-earthy claystones.

Bedding and Sedimentary Structures.—Earthy sediments are massive and typically interfinger with waxy claystones (Fig. 4). The boundaries between the two are generally sharp, and in some areas the earthy sediments are footprinted (~ 5 to 15 cm deep) and the depressions are infilled with waxy clay (Figs. 4, 6A, 7C). These footprinted surfaces can be traced laterally for up to 10 meters or more (Ashley and Liutkus 2002). Lateral variation within the unit is apparent by changes in mineralization, color, grain size, and minor clay mineralogy. For example, in localized areas, carbonate rhizoliths are preserved and no siliceous material is found, whereas a meter away only siliceous plant material is preserved and carbonate is absent (Fig. 5).

Texture.—Typical earthy sediments are more silty than clayey: approximately 20% sand, 40% silt, and only 22% clay (Fig. 8A, B, C). The remaining 18% is attributed to organic matter removed prior to analysis, soluble salts such as trona, mineral precipitates such as calcite (identified after drying the residual liquid after pipette analysis), and experimental error. These sediments are technically siltstones (Folk 1974), but this study acknowledges the term ''claystone'' given in the field and throughout the literature for consistency (Hay 1976). Waxy-earthy claystones have a higher proportion of clay: 6% sand, 20% silt, and 48% clay. The weight percent of coarse material is higher in the VEK, MCK, and Long-K areas, whereas silts and clays are the dominant materials in HWK-E, HWK-EE, and KK (Fig. 9). Clay-fraction amounts increase in these same areas whereas the sand fraction decreases, but the silt fraction remains high in all samples.

A moderate proportion of clay (> 20%) and a wide variety of grain sizes, compositions, and shapes are apparent in the earthy sediment samples. Clast variation can be seen easily in thin section without magnification (Fig. 8A, B). In some samples, the percentage of sand-size clasts in the finer-grained claystone and siltstone is between 20% and 30%, but it may be as low as 1% to 3% in other samples. The clasts are poorly sorted, and the degree of rounding is variable. These clasts are a variety of colors and textures indicating a variety of compositions (organic matter, clay clasts, silica fragments, and minerals).

Concentrations of subrounded, well-sorted, more densely packed silt grains held together with clay were noted within the otherwise poorly sorted silty–sandy samples (Fig. 8B). There appears to be no preferred orientation to these pockets of finer-grained material. Other samples of earthy clay show a more uniform grain size (silt) (Fig. 8C). The earthy sediments have a low density with void spaces between the particles. In some samples, this interstitial space is infilled with clay, and in other samples this space is filled with micritic calcite.

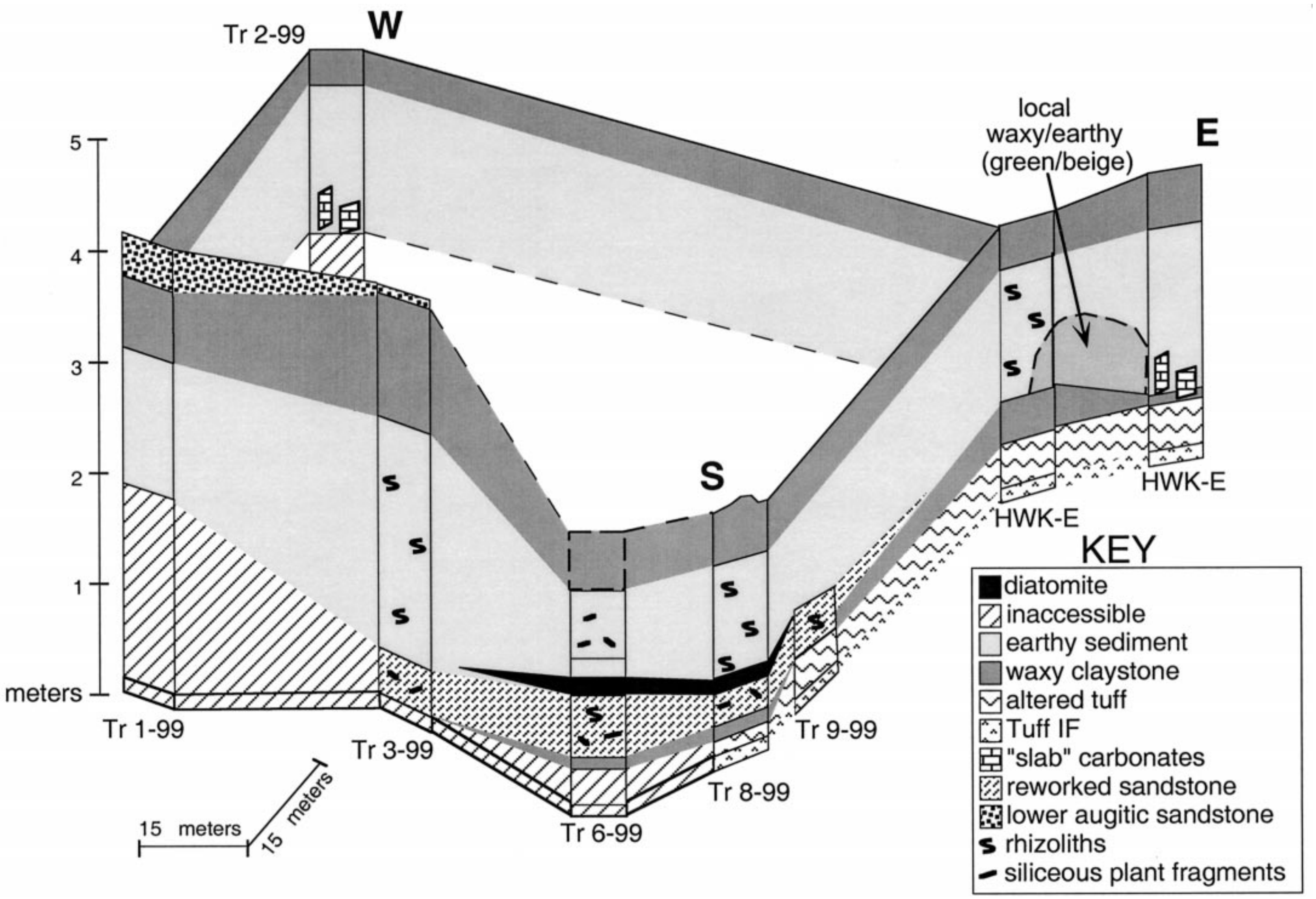


FIG. 5.—Fence diagram of a 100 m^2 region within the wetlands (HWK-E) extrapolated from the exposures seen in the excavated trenches. Trench widths are diagrammatical and are not to scale. Tuff IF is projected for Tr1, Tr2, Tr3, and Tr6; it is not exposed and is assumed to have no topography.

Various volcanic minerals with fresh crystal morphology are easily identified in thin section. Euhedral sanidine crystals and well-formed augite crystals (Fig. 8D) are abundant, and other minerals include amphibole, well-twinned plagioclase and albite feldspar crystals, bright-green olivine, milky quartz, and opaque heavy minerals. Volcanic rock fragments composed of feldspar needles are also abundant. Unaltered glass shards were noted, although dissolution of some of the volcanic grains was evidenced by irregular holes in the middle of the grains.

Clay Mineralogy.—X-ray diffraction patterns obtained for air-dried and glycolated subsamples of earthy clay ($< 63\ \mu$m) indicate a smectite-rich mineralogy, interpreted from the expansion of air-dried clay peaks up to $\sim$ 17 Å after glycolation (e.g., Velde 1995). Three distinct types of clay were noted within earthy sediment samples: smectite, illite, and interstratified illite and smectite. For comparison, a waxy clay sample (Fig. 10A) shows a typical smectite pattern, with the air-dried 001 interplanar spacing expanding from 12.81 Å to 16.99 Å with glycolation. A second suite of clays is indicated by air-dried interplanar spacings between 13.5 Å to 14 Å that expand up to 18.4 Å to 19.9 Å with glycolation. Expansion of the 001 spacing up to and exceeding 17 Å may suggest mixed-layer clays (Webster and Jones 1994; Hay, personal communication) or small grain size. These clays do not indicate discrete illite peaks, nor do they display the typical well-formed and predicted patterns for interstratified illite–smectite peaks. Hay has suggested that only a small amount of illite interstratification is necessary to expand the 001 spacing beyond 17 Å (personal communication 2002). Further evidence for interstratification is the nonrational higher-order reflections. The third type of clay pattern shows discrete illite along with smectite and/or possible small amounts of interstratification of the two. In Figure 10B the smectite 001 spacing is near 13 Å, and this spacing expands upon glycolation to 17.67 Å (indicating little to no interstratification). Once the smectite diffraction peak position shifts to 17 Å or more, a smaller peak emerges at 10.28 Å that indicates discrete illite (Deocampo et al. 2002). Illite does not expand upon glycolation, and therefore its interplanar spacing remains at $\sim$ 10 Å. The smectite air-dried pattern masks the presence of the illite phase until it is shifted to a lower angle upon glycolation. In these samples, expansion of the smectite 001 spacing upon glycolation reveals the illite 10.28 Å peak but the subsequent peaks do not resemble an interstratified illite–smectite pattern (Reynolds 1980). With the exception of the illite interstratification in some of the earthy sediments, the XRD patterns of the waxy clay and earthy sediments are similar (Fig. 10A, B).

Overall, waxy clay samples indicate a strong smectite presence, with strong 001 peaks, and well-formed 002, 003, 004, and 005 peaks (Fig. 10A). Earthy sediments do not show such strong peaks, nor are the patterns as well-defined (Fig. 10B). Diatomite samples, as expected, indicate poorly formed smectite patterns and an extremely broad peak between 5.05 Å and 3.59 Å, encompassing the peaks for quartz (4.26 Å) and cristobalite (4.05 Å).

Microfossils and Bone.—Thin sections of earthy sediment samples revealed various types of plant fragments, including phytoliths. The plant fragments represent hydrophytic plants with large nodes characteristic of

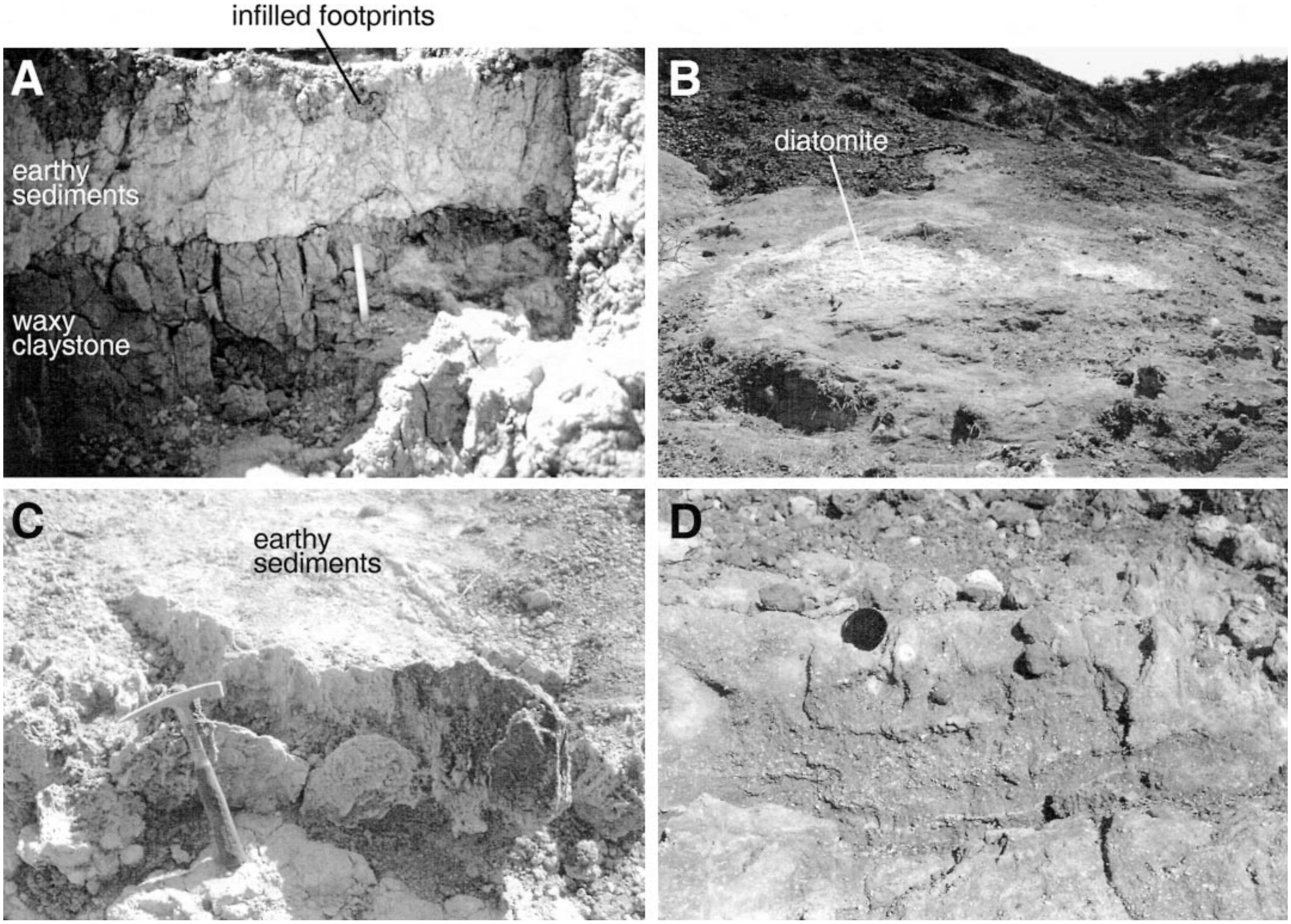


FIG. 6.—Field photographs of the various lithologies associated with the earthy sediments. **A)** Back wall of an excavation. The color difference between the earthy (light) and waxy (dark) sediments is striking, and the bedding contact between the two is usually sharp. Note the discrete footprints at the top of the earthy sediment unit that are infilled with waxy clay. Ruler (30 cm) for scale. **B)** Unexcavated deposit of diatomite at HWK-E. **C)** Vertical ''slab'' carbonates, found locally within LMB II, protrude through earthy sediment units. **D)** Fining-upward sequences in an outcrop of sandstone. Locally, these deposits are cemented into carbonate nodules of sand, plant particles, pebbles, and bone fragments. Lens cap for scale.

aquatic vegetation (McWeeeney, personal communication). Some thin sections indicated leaf epidermis sections, hexagonal cells that are indicative of stem sections, and the tip of a growing root. The fragments in Figure 11A are cross sections of a *Scirpus* sp. stem and sheath. Also, wood fragments were noticed by a characteristic rectangular, elongate cell structure. In addition, some cellular structures did not show typical plant-cell characteristics (Fig. 11B) and are hypothesized to be permineralized animal tissue (Peteet, personal communication). Thin-section microscopy of the earthy sediments also revealed vertebrate bone fragments.

Pollen grains of Cyperaceae, Graminae, and ''Cheno/Ams'' occur in the LMB II wetland sediments. *Cyperus* is a marsh sedge found throughout the modern wetlands of East Africa (Hamilton and Taylor 1986). Grasses are also common around these wetlands in East Africa, mostly on the periphery and on the local savanna grasslands adjacent to these wetland and lake systems. Pollen grains that were LMB II age were commonly damaged and their preservation was less robust than well-preserved modern specimens found within the same samples (Goman, personal communication). The pollen data are consistent with the findings of Bonnefille (1984), whose data from Olduvai Gorge Beds I and II show a high presence of Cyperaceae and Graminae pollen. Phytolith analyses could not provide specific information as to plant types beyond the familial level.

Over 35 diatom species were identified (from both LMB II earthy sediments and diatomites), indicating a variety of subenvironments and water chemistries (Owen, personal communication). Two diatomite samples are dominated heavily by *Fragilaria zeilleri* (a freshwater epiphyte) and showed minor diatom frustule breakage and rare, broken sponge spicules. This suggests that the diatoms were *in situ.* Samples of typical earthy sediments yielded only rare diatoms, with traces of species such as *Anomoeoneis sphaerophora, Cymbella fonticola, C. ventricosa, Fragilaria zeilleri, Navicula* sp., *Synedra* sp., and *Surirella ovalis* that were between 90 to 100% broken. Sponge spicules were present in three samples and rare in all other samples. One sample showed signs of corrosion of diatoms and spicules.

DISCUSSION

Texture and Composition of Earthy Sediments

The earthy sediments are a distinctive lithofacies based on sedimentary structures, color, texture, grain size, clay mineralogy, and microfossils, and are distinctly different from the waxy claystones with which they are interbedded (Table 1; Figs. 4, 6A–D). The earthy sediments are friable, light colored (beige to gray), and contain a large amount of siliceous plant frag-

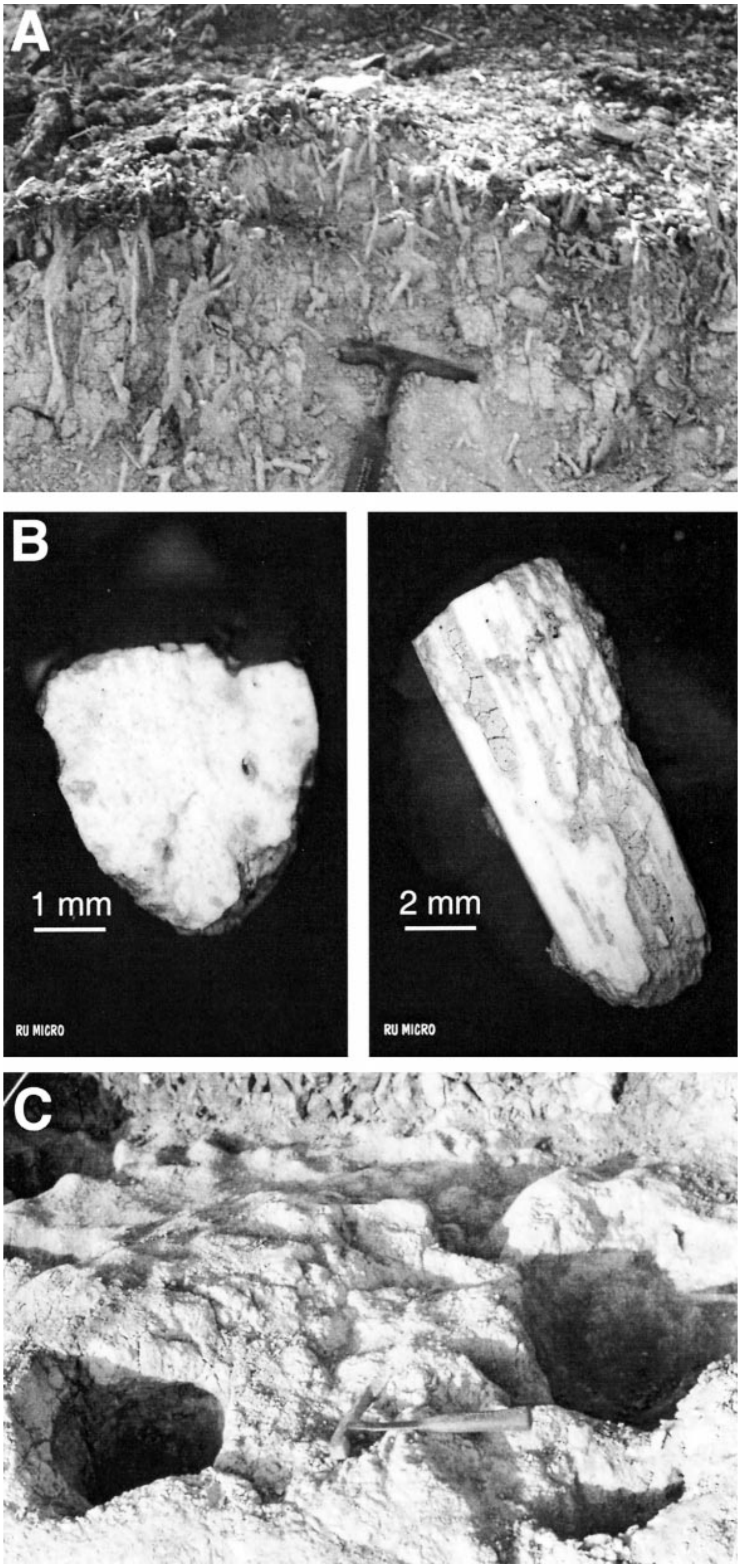


FIG. 7.—**A)** Field photo of carbonate rhizoliths in earthy sediments. **B)** Downshaft and sideways views of a silicified plant stem taken from an earthy sediment sample (HWK). Many of the silicified plant fragments are triangular, and the stems appear to have striations down the long axis, perhaps reflecting plant texture. **C)** View of footprinted horizon of earthy sediment. The infilled waxy claystone has been excavated away, leaving the discrete impressions of large vertebrate ''footprints.'' Hammer for scale.

ments, diatoms, phytoliths, pollen, etc., along with bone and artifact fragments. The waxy claystones are dense, dark green sediments that have a lower concentration of coarse (sand) material. The grain-size data indicate that the earthy sediments are siltstones rather than claystones; however, this characterization does not incorporate the ~ 18% of the sample weight that is attributed to organics, dissolved minerals, and experimental error.

The grain size (% sand) variation in a transect parallel to the lake margin indicates that little coarse material (sand, gravel) entered the central part

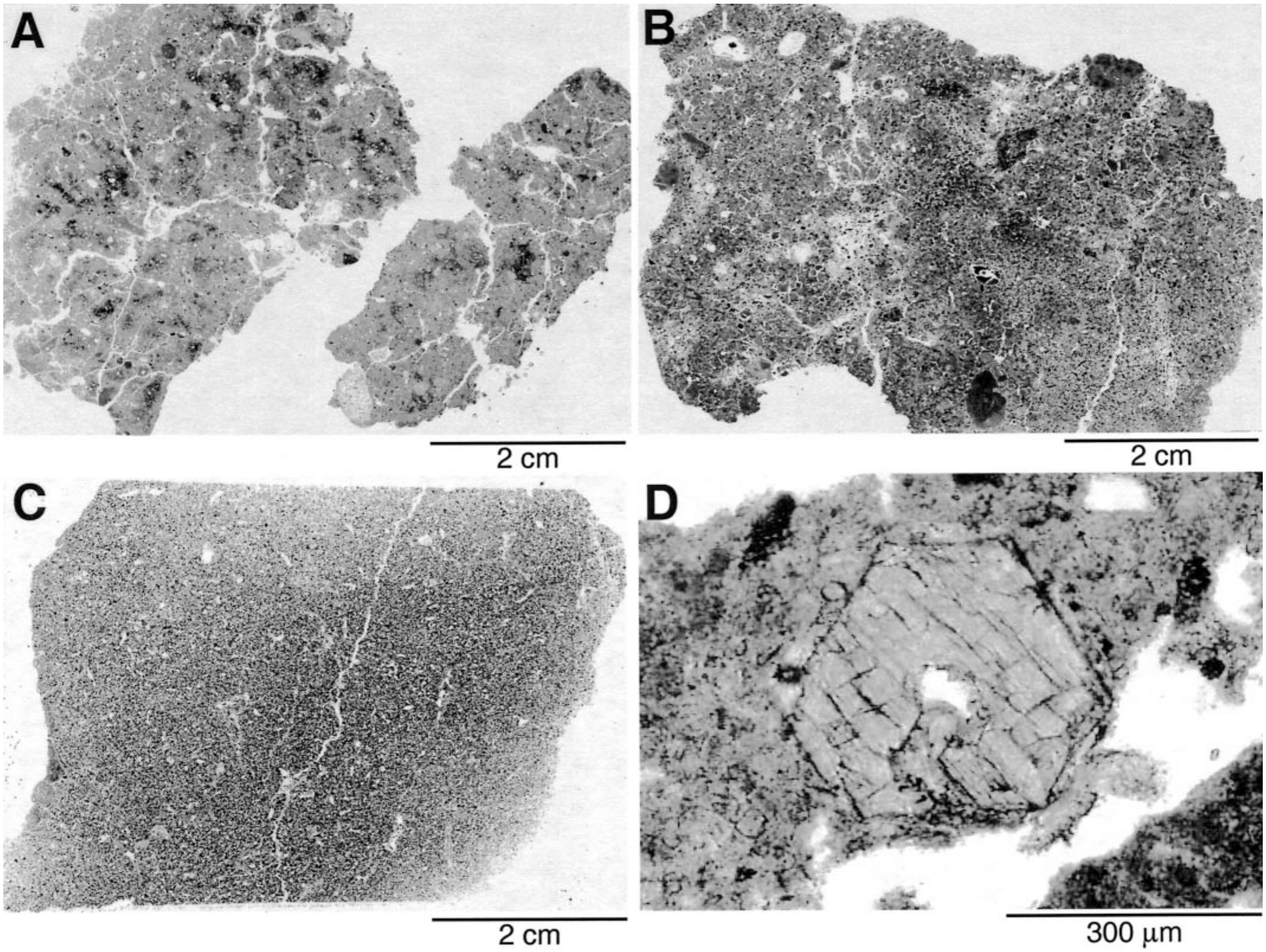


FIG. 8.—Reflected-light, computer-scanned images of thin sections of earthy sediment (A, B, C). **A)** Earthy sediments are particulate, often containing bone fragments, plant fragments, and lithologic clasts that consist of varying amounts of sand, silt, clay, and silicified organic material (seen as lighter material in thin section). **B)** Pockets of finer-grained sediment (centimeters long) are often ''suspended'' in the earthy sediment groundmass, suggesting a mixing of sediment that at one time had some bedding or layering. **C)** Silty claystone with massive and homogeneous texture. **D)** Plane-light microscopic image of a euhedral augite crystal with a dissolved core.

of the Olduvai wetlands, suggesting that sediment was being trapped upslope, perhaps by vegetation (Fig. 9B). The higher proportion of sand on the margins of the wetlands indicates that there was little upslope of these areas to trap sediments carried by surface (sheet?) runoff (Fig. 9A). This grain-size pattern fits well with the Quade et al. (1995) model that predicted that wetlands found at the base of slopes have little coarse sediment input, because of the trapping effect of vegetation upslope. The upslope landscape of a vegetated drainageway at Olduvai is hypothetical, but would be consistent with the rare and localized fluvial sandstones (i.e., ephemeral stream deposits), the relatively low proportion of sand in the wetland sediments directly down slope of the drainageway, and the higher proportion of sand on peripheral areas of the wetlands that are downslope of the less vegetated drainageway margins (Fig. 9B).

The clay mineralogy of the lake and wetland sediments is similar, but XRD peaks from wetland sediments are not as sharp and well-formed as the XRD peaks from lake clays (Fig. 10A, B). This is likely due to grain-size differences; earthy sediments are mainly siltstones, rather than pure claystones. Therefore, an XRD pattern of a sample in the $< 63\ \mu$m fraction would not show as much clay-size material, thereby causing the peaks to be of lower intensity and broader.

A more perplexing question is why two deposits that look different and appear to form in quite different environments have, in most important respects, identical clay mineralogies (Fig. 10). The most reasonable explanation is that the wetland sediments are merely a modification or an alteration product of previously deposited lake clays. Lake expansions during persistent wet periods would deposit Mg-smectite and illite on the lake margin. At times when the wetlands developed on the landscape during lake recession, these underlying lake clays could be altered by extensive bioturbation, dissolution, and the addition of abundant silica (plant fragments, diatoms, phytoliths) and volcanic detritus (Deocampo et al. 2002). The presence of freshwater in the wetlands would not only attract large vertebrates that would increase the bioturbation of the sediments (Deocampo 2002; Ashley and Liutkus 2002) but also promote biological productivity, which could enhance the addition of silica into the earthy sediments (i.e., plant fragments, diatoms, etc.).

In addition to Mg-smectite formation, the periodic desiccation of the wetlands may have fostered illite interlayer formation (Eberl et al. 1986; Hay et al. 1991). The alteration of smectite to illite–smectite involves addition of K^+ and evaporative concentration of the water in which the clays are forming. At Olduvai, weathering of the volcanic bedrock and the resulting altered volcanic feldspars likely provided the potassium for clay alteration. The interaction of unstable K-feldspars (with respect to the stable

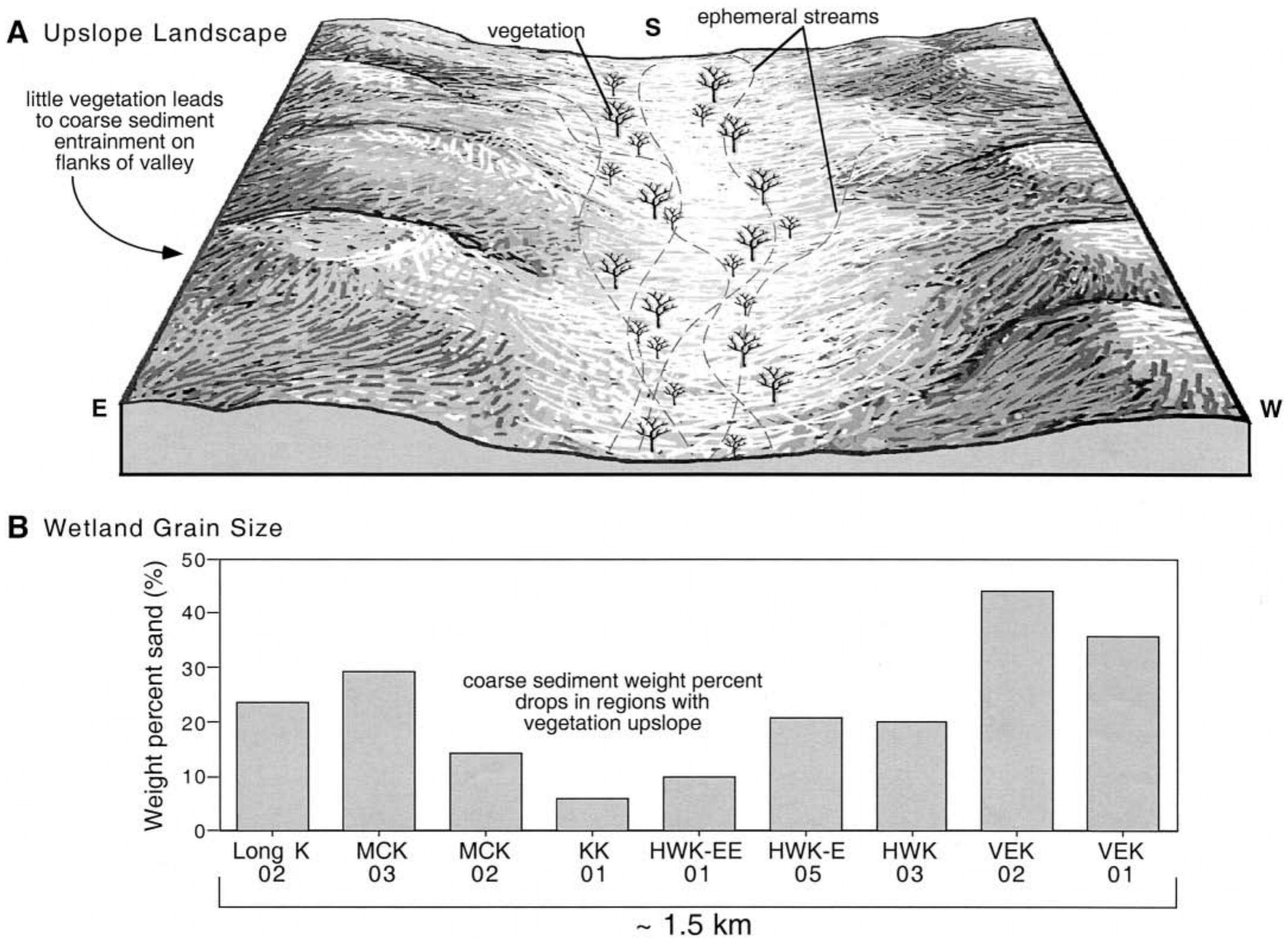


FIG. 9.—**A)** Hypothesized landscape upslope from the wetlands. Thick vegetation in the drainageways in the upslope region traps the coarse sediment, allowing only finer material to enter the wetlands. During high-discharge events, small ephemeral streams (dashed lines) may carry coarse sediment into the wetlands, evidenced in outcrop by localized cross-bedded deposits (e.g., HWK-E, KK). On the flanks of the valley, coarse sediment can easily be incorporated into sheetwash owing to the lack of vegetation. **B)** Histogram of weight percent of sand (from total sample weight) across an ~ 1.5 km wetland transect from Long K (in the east) to VEK in the west (see Fig. 1B for localities). The coarse-fraction weight percent remains high on the wetland periphery, indicating a sparsely vegetated landscape upslope. In the center of the wetland, coarse-fraction weight percent drops significantly.

illite) with undersaturated solutions (with respect to K-feldspar) could release not only the potassium ions needed for the illite formation but also silicon and aluminum ions needed to form the smectitic clays (Velde 1995). During short-term dry spells, between lake-level retreats and wetlands emergence and when salinity was high because of evaporative concentration, potassium could become fixed in the interlayer site of the Mg-smectites. Thus, throughout the period of wetland growth, alteration of the lake clays (via bioturbation and silica addition) occurred in the presence of fresher water, while illite interstratification continued during wetting–drying episodes. In addition to authigenic clay formation, some detrital clay material from the volcanic highlands could have been introduced to the wetlands by stream inflow and eolian transport.

The Wetland Fossil Record

Macrophytes.—The interpretation of the various forms of biogenic silica and plant material found within the earthy sediments helps to delineate the spatial variability of the wetland subenvironments. The presence of hydrophytic plant fragments in the earthy claystones indicates a sustained aquatic environment. A tentative identification of *Scirpus* sp. is likewise consistent with a marshland, because *Scirpus* sp. usually grows in perennial marshes and has a tolerance for increased salinity (Mitsch and Gosselink 2000). Wood fragments suggest that local small trees or shrubs were found within or upslope of the wetland. In modern Lake Eyasi, *Acacia* sp. trees grow along the spring channels and modern marshlands.

Pollen.—The pollen in the earthy clay samples provides information on the surrounding environment. Cyperaceae, Graminae, and Cheno/Am pollen were noted in samples from both the lake and the wetland. All are typical plants near or in wetlands in East Africa (Thompson and Hamilton 1983; Hamilton and Taylor 1986). *Cyperus immensis* and *C. lavigaetus* are common sedges in the modern marshes of East Africa (Hamilton and Taylor 1986). In addition, grasses such as *Cynodon* are present in the ephemeral wetland subenvironments of these modern systems (Deocampo 1997). Interpretation of pollen identification is tentative, inasmuch as pollen grains can be transported several kilometers by wind before being deposited in the lake and wetlands. However, the pollen supports the wetland scenario and previous work by Bonnefille (1984), and does not indicate the presence of atypical or rare vegetation in the area. The pollen grains cannot be identified beyond their families, and therefore provide only general infor-

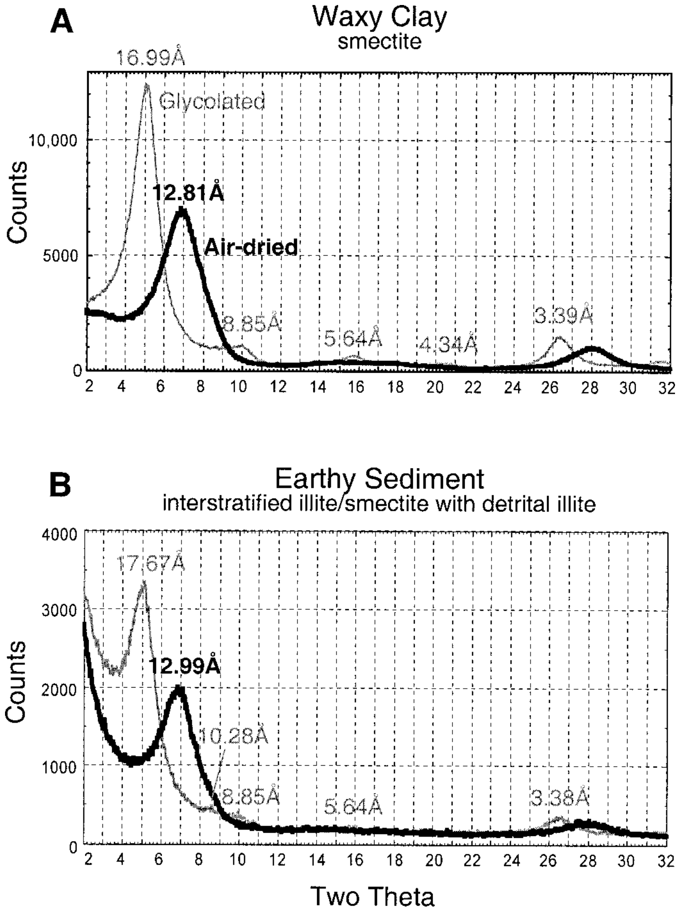


FIG. 10.—X-ray diffractograms from the < 63 μm fraction of a waxy clay [A] and an earthy sediment [B]. Both diffractograms indicate a smectitic composition, although the peaks in the waxy clay are better formed and more intense. Also, some earthy sediments have higher 001 *d* spacing (17.67 Å), indicating interstratification with illite. Detrital illite is also noted by a peak at $\sim$ 10.3 Å that does not shift upon glycolation.

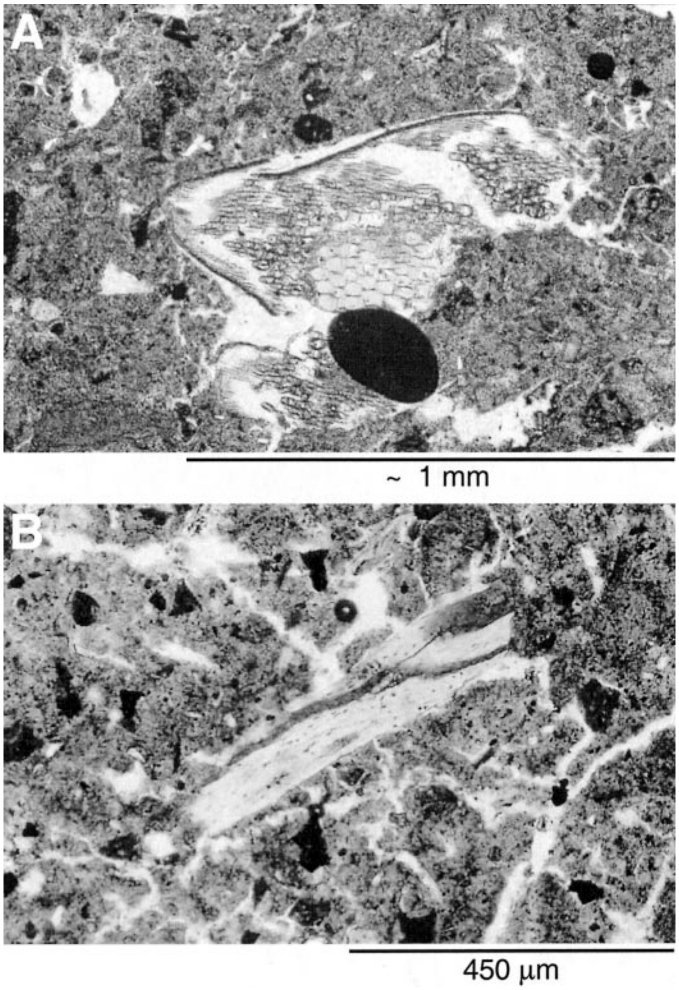


FIG. 11.—**A)** Plane-light image of several plant fragments. Plant fragments are abundant in the earthy sediments. The large, open nodes may indicate that these plants were hydrophytic. **B)** Plane-light image of cellular material (with elongate cells) hypothesized to be mineralized animal tissue.

mation as to the local vegetation. Phytoliths were also observed and add to the silica content of the earthy sediments and provide additional evidence for the presence of vegetation.

Diatoms.—The diatoms in the earthy sediment samples and the diatomites support the claim that both sediment types indicate fresh water. However, the quality of preservation and the specific species found in the assemblages of diatoms from each sediment type suggest some differences in the overall interpretations of the earthy sediments and the diatomites. Earthy claystones preserve few diatoms, and some of those diatom species indicate a tolerance for salinity and high pH (e.g., *Anomoeoneis sphaerophora, Nitzschia latens, N. elliptica, N. elkab*). The low abundance of diatoms preserved in the typical earthy claystones may be a result of (1) competitive exclusion, (2) geochemical exclusion, or (3) dissolution by saline, alkaline lake waters (pH > 9) that affected the sediments postdepositionally as short-term lake level rises flooded the wetlands. One sample showed corrosion of the diatoms, which may support this hypothesis. The influence of saline, alkaline lake waters on the wetland environment potentially explains the presence of salinity- and alkalinity-tolerant diatom species within the earthy claystones. It is also likely that these salt-tolerant species were blown in from more saline puddles on the neighboring mudflats. The fact that the diatoms are broken in most earthy sediment samples may be due to wave action, fish predation, and/or bioturbation by animal hooves.

Conversely, the diatomite layers preserve large assemblages of diatoms, and the abundance of *Fragilaria zeilleri* and other species such as *Cymbella ventricosa, Rhopalodia gracilis,* and *R. vermicularis* indicates an environment with low alkalinity and fresher waters presumably with abundant aquatic plants, because these species are mostly epiphytic. Some of the diatoms present in the diatomite samples are oligohalobous, meaning they can tolerate a wide range of salinities, and therefore do not provide specific salinity indications. In the diatomite samples, both the *presence of diatoms* and the *environmental affinity* of some of these diatoms indicate a freshwater influence, because silica is not well-preserved in high-pH environments. The diatoms found in the diatomites were freshwater floras. Their noncorroded frustules support the hypothesis that diatomites formed in standing pools of fresh water located in depressions within the wetlands (continuously fed by groundwater) and so were only minimally affected by lake advances. In addition, these diatoms were unbroken and the samples showed rare broken sponge spicules, suggesting that these microorganisms were *in situ.*

FACIES MODEL FOR THE OLDUVAI WETLANDS

Subenvironments

Various subenvironments can be inferred for the Olduvai sediments: spring, perennial marsh, pool, ephemeral wetland, fringing wetland, wet-

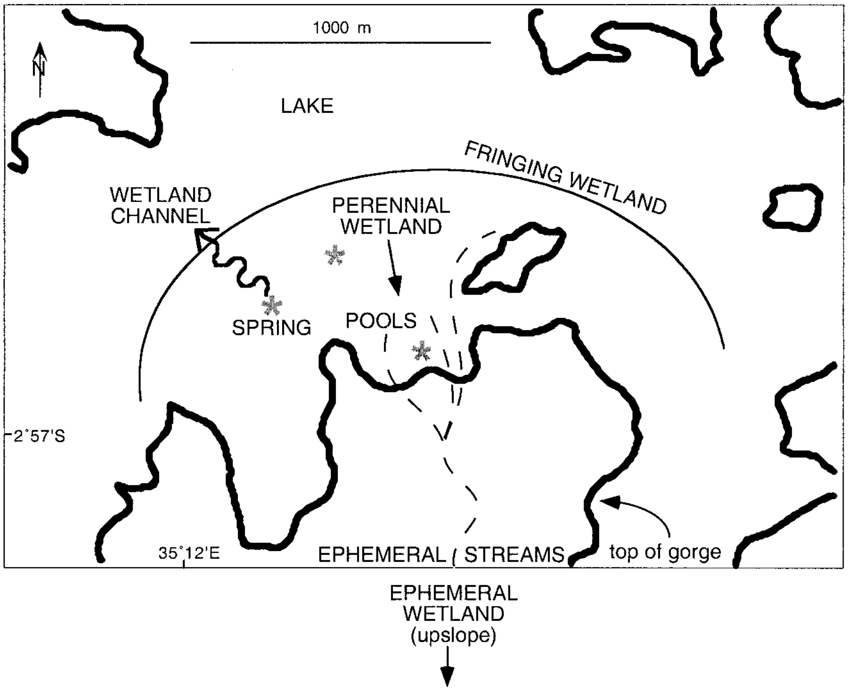


FIG. 12.—Location of subenvironments superimposed on a location map of Olduvai Gorge. The perennial wetlands are located near HWK-E and encompass springs, pools, and ephemeral stream inflow. The * indicate the location where springheads or groundwater seeps are interpreted from the presence of carbonate.

land channel, and ephemeral stream (Fig. 12). A descriptive model for the distribution of subenvironments within the LMB II Olduvai wetlands is developed by integrating information derived from the study of the lithologies and their components as well as the spatial patterning of the deposits (Fig. 13). Information from (1) authigenic mineralization of calcite, silica, and clays, (2) biogenic silica formation and preservation, (3) biological traces, (4) grain-size differences, (5) lithologic changes, and (6) localized sedimentary features is incorporated into the depositional model.

Spring deposits are fenestral carbonates or tufa deposits (Ashley 2000, 2001). Silica is not preserved in these deposits, because the pH needed for calcite supersaturation exceeds that of silica preservation (Deocampo and Ashley 1999). Vertical ''slab'' carbonates indicate exchange of water between the subsurface and the surface environment through desiccation cracks. The carbonate precipitates as groundwaters degas upon equilibrating with the atmosphere (Morel and Herring 1993).

Perennial marsh deposits are laterally continuous (Fig. 5) and are typified by massive earthy sediments, footprinted surfaces, and large animal trails (Deocampo 2002; Ashley and Liutkus 2002) (Fig. 7C). They contain a high percentage of silt and have a smectite and/or illite–smectite clay mineralogy (Fig. 10B). Sand fractions drop below 25% of the total sample weight (Fig. 9B). Silica is readily preserved in the perennial marsh sediments, likely because the organic acids suppressed the pH (Deocampo and Ashley 1999). Thus, silica plant fragments, phytoliths, and pollen are well preserved. Both freshwater and saline, alkaline diatoms are found in these sediments. Carbonates are less common but not absent, and are found near point sources of freshwater seeps. Peats are not preserved in these early Pleistocene sediments; they would be oxidized with any change in lake level or groundwater level.

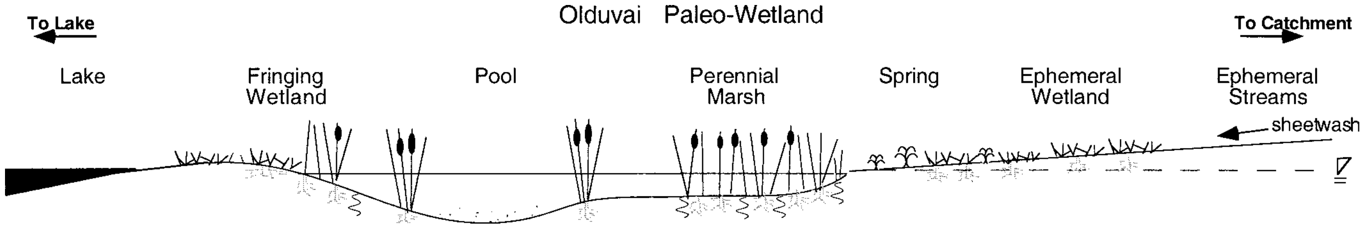
Localized diatomite sediments, with minor detrital silt and sand input, indicate *pools* within the perennial marsh. Abundant freshwater diatoms constitute the sediment, and these diatoms indicate that the pools are likely perennial. Traces of large animals (e.g., crocodile teeth, bones, and artifacts) are often found (Cushing 2002). Silicified pieces of plant material are common and no carbonates occur, suggesting a circumneutral pH that allows silica preservation and carbonate dissolution (Deocampo and Ashley 1999). These pools fill natural depressions in the landscape and, judging by the low component of detrital sediment, are fed by groundwater.

Fringing wetlands and mudflats, such as VEK, MCK, KK, and Long K (Fig. 12) are also characterized by large-animal bioturbation. The individual beds cannot be easily correlated, because of the frequent wetting and drying of the region creating discontinuous lithofacies. Unlike the perennial marsh deposits, the earthy claystones here show an abundance of carbonate rootcasts that may indicate elevated pH necessary for carbonate precipitation. Similarly, the grain size of the sediments is sandy to silty, in contrast to the finer-grained material in the perennial marsh (Fig. 9). Illite is present in these regions either as an interstratified clay or as a discrete phase. XRD data indicate that zeolites are present in the deposits, suggesting alteration by more saline-alkaline waters (i.e., farther from the spring source and closer to the lake).

Ephemeral wetlands exhibit features similar to the fringing wetlands, because both subenvironments have a potential for rapid wetting and drying as the groundwater supply fluctuates. During low water levels, both the fringing and ephemeral wetlands can dry out, allowing for entrainment and deposition of sediments by wind or water. The ephemeral wetland has the potential for being highly vegetated during wet periods (Quade et al. 1995), unlike the fringing wetland, which would be too alkaline to support much vegetation. The large amount of sand, silt, and plant fragments in the ephemeral stream deposits found in HWK-E and KK suggests that an ephemeral wetland environment exists upslope, perhaps unexposed in the south wall of the gorge.

A *wetland channel* is found within the fringing wetlands at VEK, indicated by a small, shallow scour within an earthy sediment unit with a sand and gravel lag. This is the only occurrence of this subenvironment, but we hypothesize that these channels would have drained the wetlands into the lake and the lake margin. Such channels should be different from the ephemeral streams given their location on the periphery of the wetlands, occurrence within an earthy sediment unit, lack of cross-bedding, fining-upward sequences, plant and bone fragments, artifacts, etc., and overall finer grain size (silty sandstone rather than coarse sandstone).

The sandstone units at HWK, HWK-E, and KK represent e*phemeral streams* (Fig. 12). These texturally and mineralogically immature sandstones are concentrated in a few areas and indicate shallow, flashy flows oriented approximately NNE (perpendicular to the lake margin). The sandstones record runoff from an upslope drainageway during high-discharge,



Sedimentology	earthy siltstone with some sand	diatomaceous claystone	siliceous earthy claystone	"slab" carbonate, tufa	silty claystone	lithic wacke
Composition	interlayered illite/ smectite, illite, smectite, zeolite	white, powdery siliceous smectite; plant fragments, diatom frustules	smectite and illite (detrital), some interlayered illite/ smectite; plant fragments; biogenic silica	carbonate	some smectite, illite, and interlayered illite/ smectite	immature, poorly sorted lithic sandstone
Pedogenic/ Physical Features	rootcasts, desiccation cracks, footprinted surfaces, scour-and-fill structures in channels out to lake	desiccation cracks, organic material; few to no carbonates	footprinted surfaces, hippo trails; carbonate tubules, insect burrows	vertical "slab" carbonate	desiccation cracks, footprinted surfaces	scour-and-fill structures, fining-upward sequences, cross-bedding
Sediment Input (origin, amount)	high detrital input from eolian and lacustrine sources,authigenic mineralization of clays and salts	little sedimentation; detrital input of silt/clay; biogenic silica	some silt/sand input from fluvial and eolian transport; eolian input of biogenic silica	authigenic minerals	medium to coarse debris from alluvial fan runoff and ephemeral streams; some eolian transport	wide range of clast size and rounding indicates eolian and fluvial transport from volcanic highland upslope
Biology	*Scirpus*?, low sedges	diatoms, floating algae, sponges, fish; *Typha*?	both fresh and salt-tolerant diatoms; hydrophytic plants (*Typha*, sedges, *Scirpus*)	diatoms, algae	grasses, sedges, and possible woody shrubs	possibly woody shrubs, trees?
Associated Features	salts are found in these sediments; small channels appear to drain the wetland into the lake	these highly localized deposits contain siliceous roots and plant fragments and have a high diatom diversity	these laterally continuous sediments are heavily bioturbated and contain some rootcasts and carbonate nodules	fenestral carbonate resembles root mat	deposits are bioturbated and laterally discontinuous; contain carbonate nodules	deposits are localized and lower bounding surface is sharp and erosional

FIG. 13.—Facies model for the subenvironments in the wetlands interpreted from the earthy sediments of LMB II, Olduvai Gorge. This hypothetical transect runs from the base of the alluvial fan to the south or east (ephemeral stream runoff), through the wetlands, to the lake in the north and west and encompasses sedimentological features, biology found in the sediments, and the origin and amount of sediment input into the subenvironment. The ''wetland channel'' subenvironment is not included in this diagram, because deposits were localized and infrequent.

short-term events (Fig. 9A). The presence of siliceous plant materials, pebbles, carbonate rootcasts, artifacts, bones, waxy clay clasts, etc., indicates that they are eroded and transported materials from an upland source (presumably the ephemeral wetland). The varying degree of clast rounding and the fact that delicate bones are preserved intact indicate either that flow was flashy or that material was constantly incorporated into the flow along its path. The compact size of the scour-and-fill structures along with the fineness of the bedload and the lack of characteristic channel features negates the possibility that such sandstones represent large, perennial channels.

Lithofacies Synthesis

This study is the first detailed sedimentological study of a freshwater wetland in a semiarid environment. Several distinct lithofacies are identified and interpreted within this early Pleistocene ''time slice'': earthy sediment, waxy claystone, diatomite, carbonate, and sandstone. The color, composition, microfossils, and sedimentary structures make each lithology distinctive and useful for delineating subenvironments within the wetland complex (Table 1). The nearby volcanic complex (Ngorongoro) left its signature in the sediments with the ubiquitous Mg-smectitic clays, glass shards, and occasional fresh volcanic minerals. Vertical and lateral lithofacies variations interpreted from stratigraphic sections and a fence diagram reveal seven distinct subenvironments (spring deposits, perennial marshes, pools, ephemeral wetlands, fringing wetlands, wetland channels, and ephemeral streams) that can be placed within a detailed description of the Olduvai paleo wetland (Figs. 13, 14).

The stratigraphy of the lake-margin wetland indicates persistent (~ 10^3 yr) wet periods during which waxy clays accumulated when the lake expanded and flooded the wetlands. During equally long intervening dry periods when the lake contracted, the wetlands flourished, accreting earthy sediments. Springs, groundwater seeps, and ephemeral rivers appear to be the main water sources. The location of the wetland remained fixed regardless of the location of the playa lake (i.e., the wetland did not migrate laterally in response to lake-level fluctuations). Spring deposits appear to be local and are restricted to the southeastern part of the basin (Ashley and Hay 2002). In addition to persistent climate-change influences, the identical Mg-smectite clay mineralogy in the saline-alkaline lake deposits and freshwater wetland deposits suggests that the wetlands may have been inundated periodically for short time periods (a few years) during long periods (thousands of years) of lake contraction.

CONCLUSIONS

This study at Olduvai Gorge documents the spatial and temporal variability of lithology, microfossils, and sedimentary structures in a paleowetland during a narrow window of time. The sedimentary record was interpreted in terms of hydrology (springs, surface runoff, and the lake),

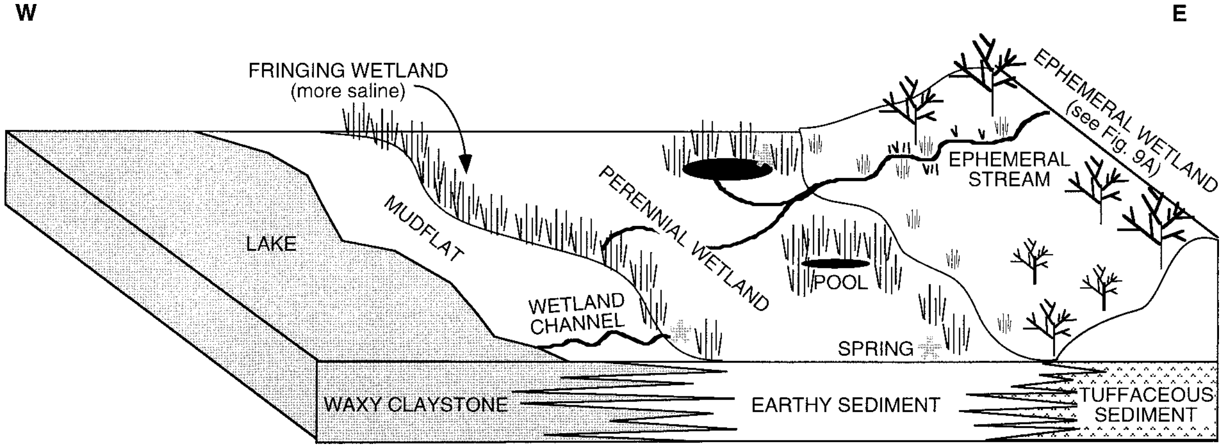


FIG. 14.—Generalized wetland facies model. Waxy claystones underlie the lake waters, and earthy sediments form beneath the wetlands. In the east, tuffaceous claystone underlies the distal end of the alluvial fan. The volcanic highlands would presumably have been upslope, to the east.

wetlands ecology, and associated biota. The extensive data set provides the information base to begin to develop a general sedimentological model of freshwater wetlands that can be applied and tested elsewhere. The Olduvai study provides insight into an ancient landscape and hopefully provides ecological and paleoclimalogical inferences for paleoenvironmental reconstruction elsewhere in the Olduvai basin and other semiarid wetland settings.

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