Quaternary International 322-323 (2014) 66–77

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Paleosol diversity in the Olduvai Basin, Tanzania: Effects of geomorphology, parent material, depositional environment, and groundwater on soil development

Gail M. Ashley[a,*], Emily J. Beverly[b], Nancy E. Sikes[c], Steven G. Driese[b]

[a] Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, NJ 08854-8066, United States
[b] Department of Geology, Baylor University, One Bear Place, Waco, TX 76798-7354, United States
[c] Parus Consulting, 1508 Eureka Road, Suite 170, Roseville, CA 95661, United States

ARTICLE INFO

Article history:
Available online 17 January 2014

ABSTRACT

Olduvai Gorge, Tanzania is known for its fossil and cultural record of early hominins. The archaeological records are typically found within pedogenically modified sediments, thus the interpretation of paleosols provides important paleoenvironmental context information. The Gorge contains a rich and diverse record of paleosols that vary spatially and temporally, however the stratigraphy can be divided into time slices using dated tuffs and studied in a paleolandscape context. Sediments were deposited in a semi-arid closed rift basin containing paleo Lake Olduvai, with volcanoes supplying volcaniclastic material to an alluvial fan system on the eastern side and quartzofeldspathic fluvial sediments derived from weathered basement rocks on the western side. The shallow saline-alkaline lake in the basin center and groundwater levels in the surrounding uplands fluctuated with Milankovitch-driven climatic (precession) cycles of ~20,000 years. The rift basin paleolandscape (at ~1.8 Ma) is reconstructed using sedimentology, stratigraphy and paleopedology. Standard field descriptions of physical and biogenic paleosol structures are combined with stable isotope ratios of carbonates, and whole rock geochemistry of sediments, to reveal diversity of paleosols within the basin. There are at least three distinct types of paleosols that record a paleocatena related to both landscape and drainage differences. Red tephra-rich Andisols developed on the volcaniclastic alluvial fan to the east of the paleolake, calcium-carbonate-rich, silty Aridisols developed on the interfluves and floodplain of the fluvial plain on the west, whereas clay-rich paleosols (Vertisols) developed on the lake margin and lake in the center of basin. Variances in geomorphology, depositional environment, parent material, and depth to the water table are reflected in the development of distinctly different soil types that can provide key data needed for high-resolution reconstruction of the landscape known to be utilized by early hominins.

1. Introduction

The Olduvai basin (3°S) in northern Tanzania was formed ~2.3 Ma on the margin of the East African Rift System (E.A.R.S.) in response to extensional tectonics and the growth of the large volcanic complex (Ngorongoro) (Dawson, 2008) (Fig. 1). The Ngorongoro Volcanic Highland is a large imposing massif that reaches >3000 m high and is composed of 8 or more eruptive centers of alkali magmas ranging from olivine basalts and trachyandesites, to nephelinites and carbonatites (Hay, 1976; Dawson, 2008; McHenry et al., 2008; Mollel et al., 2008, 2009). When formed, the basin was wide (~3500 km^2), but shallow (~100 m deep). The earliest Olduvai Basin deposits were laid down on an eastward-sloping undulating surface of metamorphic basement rocks of Precambrian age, on the edge of the Serengeti Plain. The east side of the closed basin was framed by the Ngorongoro Volcanic Highland (Fig. 1). The basin fill is a mixture of volcanics (lavas and pyroclastic deposits, i.e. tuffs) and reworked volcaniclastic sediments sourced from the volcanoes to the east and quartzo-feldspathic detritus from the Serengeti Plain to the west (Hay, 1976; Ashley and Hay, 2002). A lake occupied the center of the basin from ~2.0 to 1.5 Ma and the sedimentary record during this period is composed of fluvial, lacustrine and palustrine sediments. The shallow saline-alkaline lake, paleo Lake Olduvai, in the basin center fluctuated with Milankovitch-driven climatic (precession) cycles of ~20,000 years duration (Hay and Kyser, 2001; Ashley, 2007; Magill et al., 2012a).

* Corresponding author.
E-mail address: gmashley@rci.rutgers.edu (G.M. Ashley).

1040-6182/$ – see front matter © 2014 Elsevier Ltd and INQUA.
http://dx.doi.org/10.1016/j.quaint.2013.12.047

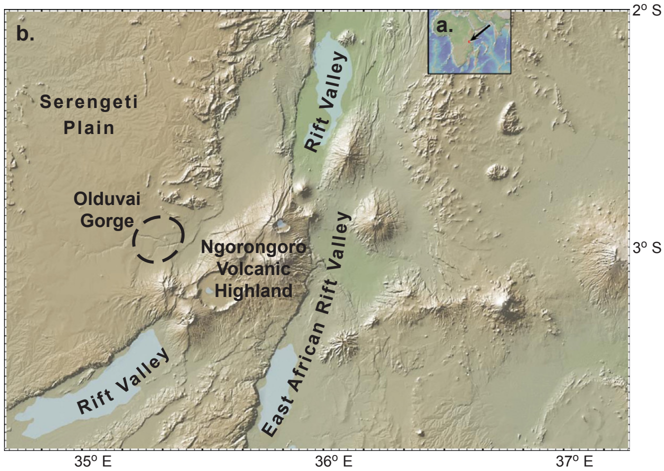

Fig. 1. Location maps. a. Inset shows the study location on the east side of the African continent. b. Olduvai Basin is located in northern Tanzania on the eastern margin of the Serengeti Plain and nestled against the Ngorongoro Volcanic Highland to east and south Metamorphic uplands lie to the north. Ngorongoro Volcanic Highland is situated where the rift splits into two rift valleys at the Northern Tanzanian Divergence (Dawson, 2008). Olduvai Gorge is a 100 m deep incision into a basin filled with Pleistocene sediments.

The investigation of the geology of Olduvai began a hundred years ago, in 1913, with a German expedition led by Reck (1951). A number of other geologists studied the record in the following decades, usually in support of increasing the numbers of fossils and stone tools. The early geological investigations culminated with a comprehensive synthesis of the basin geology by Hay (1976). However, paleosols were not given much attention in these early studies. So, despite the 100 years of geological research the wealth of information that may be archived in the paleosols has gone untapped. The reasons for this may have been that the discipline of paleopedology (study of ancient soils) is a relatively new field and the usefulness of paleosols in terms of providing information on the "Critical Zone" (i.e. the biology, climate and earth surface processes) was not generally appreciated (NRC, 2001; Brantley et al., 2007; Nordt and Driese, 2013). Another impediment could be that many of the Olduvai soils do not display well developed horizonation and strong colors, so they have generally gone unrecognized. Most of the paleosols are immature and not well developed pedogenically because of the dynamic sedimentation processes and attendant geomorphic instability typical in the basin; episodic volcanic eruptions, bimodal monsoon-driven precipitation, seasonal fluvial and colluvial sediment influx, and frequent lake level changes. The paleosols are likely "cumulative" where sedimentation keeps pace with pedogenesis and erosion is minor, resulting in thickened profiles with little or no horizonation (Kraus, 1999).

During the Late Pleistocene extensional tectonics, related to EARS, tilted the region toward the east. The 30 km wide basin was incised by the eastward flowing Olduvai River producing a 100 m deep gorge that exposed exceptionally rich fossil and cultural records (Hay, 1976). The Gorge is known worldwide for its record of early hominins and for the potential to contribute to human origins research (Leakey, 1971; Bunn and Kroll, 1986; Domínguez-Rodrigo et al., 2007). The archaeological records are typically found archived within the sediments between tuffs, many of which have been dated (Deino, 2012), mapped and logged stratigraphically (Hay, 1976) and chemically fingerprinted (McHenry, 2004). This well-dated stratigraphy can be divided into time slices that facilitate high-resolution reconstruction of the paleoenvironmental or paleoclimatic records associated with the fossil and cultural records.

Papers written on Olduvai paleosols reveal a wide range of soils types from paleo-Andisols (Ashley and Driese, 2000) to carbonate-rich paleo-Aridos (Cerling and Hay, 1986; Sikes and Ashley, 2007) to clay-rich paleo-Vertisols (Beverly et al., 2014) despite the relatively small size of the basin. These well-documented studies provide an excellent starting point from which to examine paleosol formation in a semi-arid basin that is well dated and for which the paleoclimatic setting is reasonably well known. The five major factors that most pedologists agree affect soil formation are: (1) parent material, (2) climate (temperature and precipitation), (3) biota (plants and animals), (4) topography (including drainage and hydrology), and (5) time (Jenny, 1941). Paleosols have the potential to retain a record of some, if not all of these Critical Zone factors (NRC, 2001; Brantley et al., 2007; Nordt and Driese, 2013). Thus, Olduvai, a closed basin sourced from differing lithologies and subjected to regular climate fluctuations (wet–dry) climate cycles, makes it an ideal natural lab for examining the relative importance of the 5 factors affecting soil formation. For simplicity, we adapt the terms Andisol, Vertisol and Aridisol, used on modern soils, for these Pleistocene-age paleosols.

1.1. *Objectives*

The objectives of this study are to: (1) characterize the geology (lithology) and hydrology (surface run-off, groundwater, and lake level changes) of this semi-arid basin, and, (2) compare and contrast the three types of paleosols (Andisols, Vertisols and Aridisols) developed within time slices known in the basin and evaluate the relative importance of the five soil forming factors on their formation. The ultimate goal is to utilize the high-resolution record retained in paleosols to better understand the paleoenvironmental or paleoclimatic records associated with the fossil and cultural records in the Olduvai basin.

2. Geologic setting

2.1. *Geology*

The Olduvai basin is a shallow depression between crystalline metamorphic basement rocks that lie beneath the Serengeti Plain (west) and the Ngorongoro Volcanic Highland (east) (Fig. 1). Structurally it is a "rift-platform basin" located on the margin of the Gregory Rift, the eastern branch of the E.A.R.S., and at a point of bifurcation in the rift system (Baker et al., 1972; Frostick, 1997). Geophysical studies reveal that rift valleys (grabens) may be up to 100 km wide and rift parallel faulting may affect up to another 200 km on either side of the main rift valley (Morley, 1999). Olduvai Basin is cut by numerous rift parallel, north–south normal faults (Hay, 1976; Ashley and Hay, 2002).

Infilling of the basin began about two million years ago (Fig. 2). Alluvium was transported from the margins and volcanism contributed both lavas and pyroclastic material episodically (Hay, 1976). A saline-alkaline lake occupied the center of the basin (Hay and Kyser, 2001; Deocampo et al., 2009). Smectitic clays were formed from silicate minerals washed or blown into the lake (Hover and Ashley, 2003). Sandy deltaic sediments interfinger with lake clay deposits on the western margin (Sikes and Ashley, 2007). Wetland sediments (siliceous clays) interfinger with lake clays (Deocampo et al., 2002) and pyroclastic alluvial fan sediments on the east margin (Liutkus and Ashley, 2003). Alluvial fan deposits range from coarse clastics in proximal fan deposits adjacent to the Highland and gradually become finer grained (silts and clays) in the distal area at the lake margin (Hay, 1973; Ashley and Driese, 2000). For simplicity only the oldest part of the basin fill, that deposited during Bed I and Lowermost Bed II time, is shown in Fig. 2.

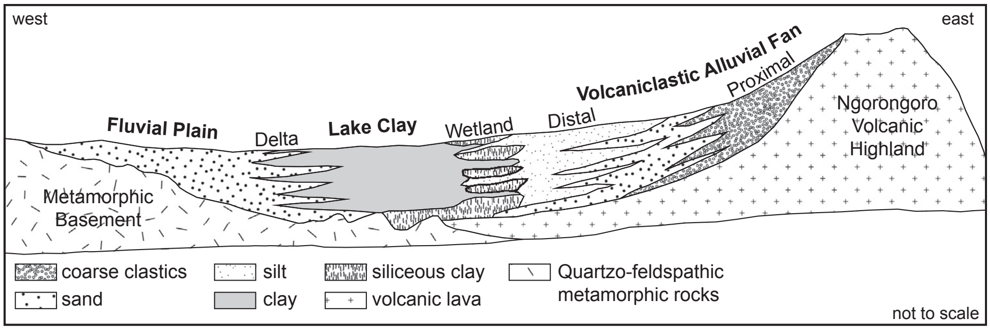

Fig. 2. Cross section of basin fill. A diagrammatic sketch depicts the sediments infilling the Olduvai basin during deposition of Beds I and II (2.0–1.5 Ma). Younger deposits are not shown and thicknesses are not to scale. A volcaniclastic alluvial fan built from the east, sourced from the Ngorongoro Volcanic Highland. These sediments interfinger with wetland deposits and lake sediments in basin center. Quartzo-feldspathic coarse sandy fluvially-transported sediments filled the basin from the west terminating in delta deposits that interfinger with lake sediments in the basin center.

A paleogeographic reconstruction of the basin between 2.0 and 1.5 Ma shows the spatial distribution of key depositional environments, which are fluvial plain, lake, and alluvial fan (Hay, 1976, 1990) (Fig. 3). Stratigraphic sections were chosen for this study of paleosols from three distinctly different depositional environments, each with distinct lithology, namely fluvial plain, lake, and distal alluvial fan. Locations of the sites are indicated in Fig. 3.

2.2. Hydrology

Olduvai is at 3°S latitude in the zone of easterlies and thus is in the rain shadow of the imposing Ngorongoro Volcanic Highland (Fig. 1). Rainfall in the basin has been modeled to be between 250 and 700 mm/y (Magill et al., 2012a), interpreted to be 500–900 mm/y (Sikes and Ashley, 2007) and measured to be 566 mm/y (Hay, 1976), thus it is a semi-arid environment. Precipitation is seasonally bimodal with long rains in March and April and short rains in November and December. The mean annual temperature (MAT) averages 25 °C and the potential evapotranspiration (PET) is 4 times the rainfall (~2000 mm/yr) resulting in a negative hydrologic budget for the year (Dagg et al., 1970).

Given the location and configuration of the basin a hypothetical reconstruction of Olduvai during the study period is proposed in Fig. 4. Moist air transported by easterly winds from the ocean loses moisture on the windward side (Ngorongoro Volcanic Highland), causing the leeward side (Olduvai Basin) to be semi-arid. Modern rainfall on Ngorongoro averages ~1200 mm/yr supporting tropical forest vegetation. Some water runs off, but most infiltrates into the coarse-grained alluvial fan system and moves into the basin as groundwater. Today groundwater exits at the base of the slope at a sump called Olbalbal (Barboni et al., 2007) and it was likely to have been present in the past. Evidence of groundwater discharge in the basin sediments includes copious records of springs and freshwater wetlands on the paleo lake margin (Liutkus and Ashley, 2003;

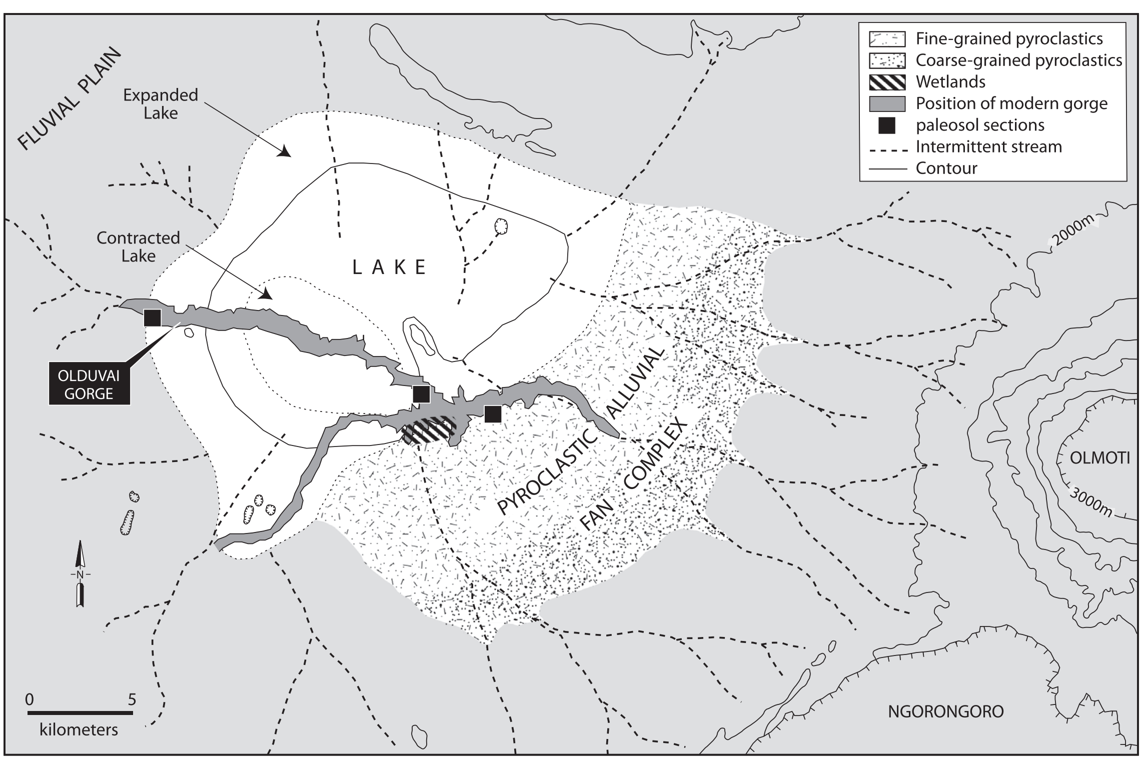

Fig. 3. Paleogeographic map. A reconstruction of the landscape of the Olduvai basin during early Pleistocene time (modified from Hay, 1976). The outline of the modern Olduvai Gorge is shown in gray for reference. The area covered during lake expansions, the location of the wetland, and the fine-grained and coarse-grained facies of the pyroclastic-alluvial fan complex are depicted. Localities of stratigraphic sections of paleosols in Figs. 7–9 are indicated by squares. Figure modified from Ashley and Driese (2000).

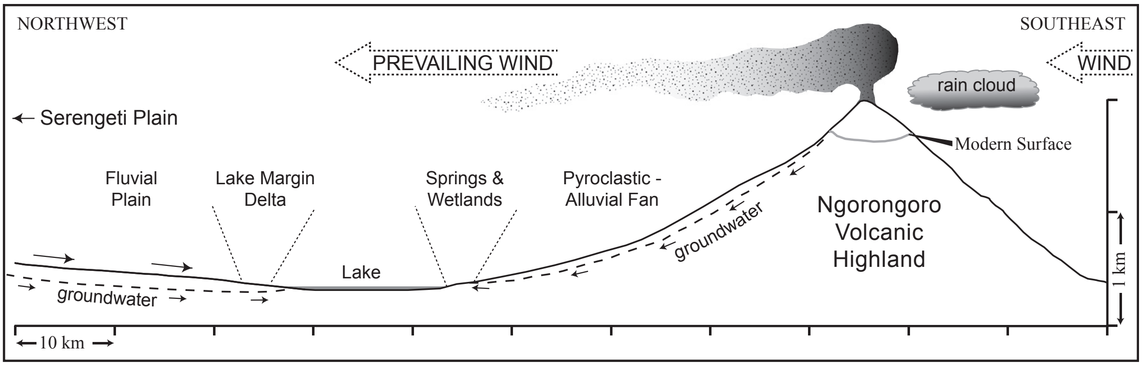

Fig. 4. Early Pleistocene paleogeography. This interpreted landscape shows a 50 km wide paleobasin and an equally wide Ngorongoro Volcanic Highland. The Highland likely provided an orographic barrier to the prevailing easterly trade winds thereby creating a rain shadow in the Olduvai Basin. These winds also carried pyroclastic material supplying eolian sediment and aerosols to the basin. Surface runoff from the Highland likely seeped into the coarse-grained alluvial fan which limited river development on the east side. Rivers on the west were intermittent. Groundwater moved into the basin from higher topography on both margins supporting wet environments at lake margin; deltas (west) and wetlands (east). Topographic relief is >1500 m. (modified from Ashley and Hay, 2002).

Copeland, 2007; Ashley et al., 2010c) (Figs. 2 and 3). There is no direct physical evidence for presence of groundwater on the western side of the basin, but because the basin is closed and the lake is the lowest spot on the landscape, the reconstruction showing groundwater at depth is a reasonable assumption.

A simple groundwater flow model illustrates the likely recharge area (topographic high) and groundwater discharge (GWD) areas for a basin with simple structure (Fig. 5). Flow into a basin will be constrained by the porosity and permeability of the rocks, as well as the structure (folds and faults). Groundwater typically seeps out at base of slope (spring line) or where an aquifer intercepts the surface or exits via a fault. GWD areas are recorded in a variety of palustrine environments as mineral deposits (carbonate or silicates), clay mineral chemistry, plant remains and organic matter (Deocampo et al., 2002; Liutkus and Ashley, 2003; Ashley et al., 2010a,b; Barboni et al., 2010). The locations of the three types of paleosols chosen for study are indicated on the landscape model (Fig. 5).

The position of the water table varies with the topography (and structural geology) and its position is relevant to the formation of soil (Russell and Rhoades, 1956; Retallack, 2001; Ashley et al., 2013) (Fig. 5). The water table separates the upper, vadose zone where there is active leaching and oxidation from the lower, fully saturated phreatic zone where chemical processes are limited. Retallack (2001) logically pointed out that there are three possible situations for a soil with respect to the water table: 1) the soil is entirely above the water table and therefore well-drained, 2) the soil is within a fluctuating water table, and 3) the soil is below the water table and is therefore permanently waterlogged, conditions for a hydric soil.

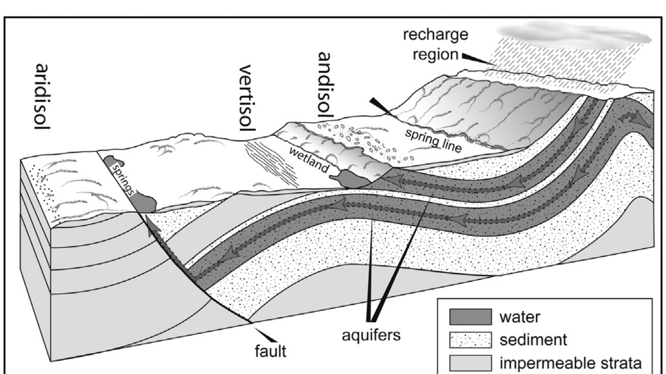

Fig. 5. Hydrology A diagrammatic 3-D model of groundwater flow in a region with folds and a fault. Recharge occurs on a topographic high. Groundwater moves downslope in near surface sediments and exists at base, i.e. the spring line. Groundwater may also move into the basin via aquifers and exit (via wetlands and springs) where beds crop out or a fault plane reaches the surface. Locations of the three of paleosol types in the study are shown (modified from Marshak, 2001).

The paleogeographic reconstruction of the basin environments using basic sedimentology and stratigraphy revealed a lake that fluctuated regularly over a broad, gently sloping lake margin plain (Fig. 3). When examined as a function of time (using dated tuffs and the paleomagnetic record), each lake cycle is about 20,000 ka in duration and there are about 5½ cycles between Tuff IB and Tuff IIA (Ashley, 2007) (Fig. 6). The length of time for each cycle indicates they are Milankovitch precession cycles that are thought to be driven by rhythmic changes of solar insolation reaching a specific spot on the Earth's surface (Ruddiman, 2000). The change in insolation affects the intensity of the summer monsoon rains, i.e. higher insolation leads to higher annual rainfall. Precipitation may increase as much as 50% between wet and dry extremes of the cycle. The duration of the sedimentation record for each paleosol is indicated on the lake cycle graph. The lake clay paleosol record is only one cycle long, the fluvial plain paleosol record is 2½ cycles long and the volcaniclastic fan paleosol record is 3 cycles long.

3. Methods

The paleosols selected for this study have been fully described in previous publications, thus the field and laboratory methods will not be repeated here. See Ashley and Driese (2000) for the Andisol, Beverly (2012) and Beverly et al. (2014) for the Vertisol, and Sikes and Ashley (2009) for the Aridisol.

4. Results

The three paleosols are described and their individual characteristics shown in Figs. 7–10 and their position on the landscape in Fig. 11, a diagrammatic depiction of a paleocatena at ∼1.8 Ma. The paleosols are all composed of horizontal beds of interbedded fine-grained sediments and tuffs. Most of the beds have been pedogenically modified. The paleosols differ in grain size, soil structure, color and the type of carbonate present. The Fluvial Plain Aridisols are waxy and silty waxy clay with occasional very fine sand beds. Carbonate occurs mainly as rhizoliths, nodules and thin calcretes. The Lake Margin Clay Vertisols are waxy (smectitic) clay and stratigraphically associated with a freshwater carbonate (tufa). Carbonate occurs as pedogenic nodules (1–2 cm), precipitated in root traces and concentrated as cemented masses in BK horizons, as

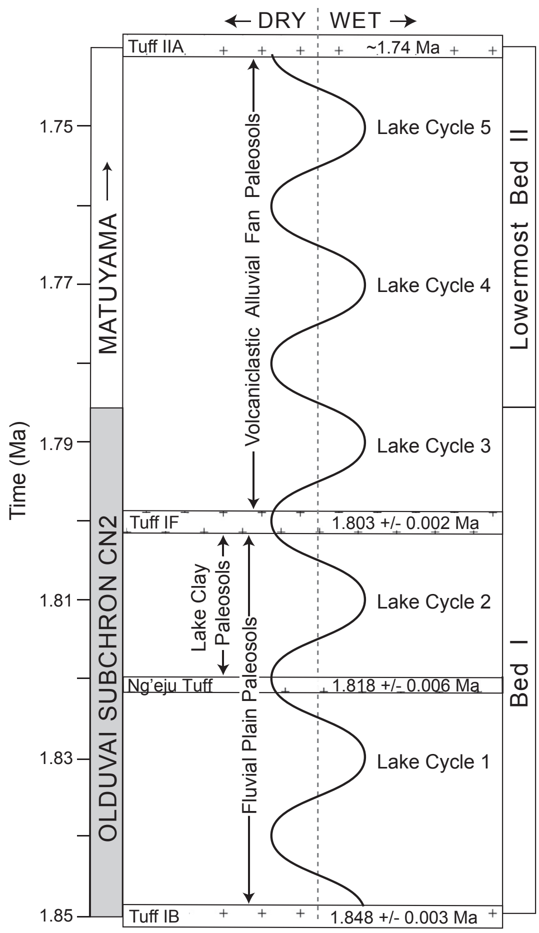

Fig. 6. Lake cycles. The timing of the 5½ precession-driven climate cycles that occurred in the Olduvai Basin between 1.85 and 1.70 Ma is plotted against the available chronology (paleomagnetics and tuff dates) (Ashley, 2007; Magill et al., 2012a,b). Wetter time intervals are to the right and drier times to the left. The time duration of the three paleosol study sequences is indicated. Paleomagnetic data from Berggren et al. (1995). Tuff dates from Deino (2012).

well as groundwater-related concretions (>15 cm). The Volcaniclastic Alluvial Fan Andisol occurs in tuffaceous clay that is interbedded with lake clays. Free carbonate (calcite) occurring as in place pedogenic carbonate was not observed. It is basically non-calcareous except for a few groundwater carbonate concretions near the base of the paleosol and secondary carbonate intergrowths with zeolites (chiefly analcime).

4.1. Fluvial Plain Aridisols

4.1.1. Paleosol description and interpretation

Data used to characterize paleosols from the Fluvial Plain on the western side of the basin (Fig. 2) are from Sikes and Ashley (2007), a study that focused on the use of stable isotopes of pedogenic carbonates as indicators of landscape paleoecology. The reconstructed paleoenvironment consists of a broad, low gradient fluvial system with sandy channels, bordered by floodplains and separated from adjacent drainages by broad silty-clay interfluves. Paleosols developed on the floodplains and interfluves and carbon isotopes were used to determine the relative proportion of C_3 and C_4 plant biomass on the landscape (Cerling, 1984; Cerling and Hay, 1986; Cerling and Quade, 1993). Carbon isotope ratios, $^{12}C/^{13}C$ ($\delta^{13}C$) in carbonate nodules ranged from −12‰ PDB with 0% input from C_4 plants (forest/woodland) to +4‰ PDB with 100% contribution from C_4 terrestrial plants (C_4 grassland). Oxygen isotope ratios, $\delta^{18}O$ ($^{16}O/^{18}O$), were used to identify relative change in local climatic conditions (Quade et al., 1989; Cerling and Quade, 1993). Because temperature does not vary much at this equatorial location, the shift in $\delta^{18}O$ values is interpreted to be caused by fractionation during carbonate precipitation (i.e. more evaporation during drier periods). Here we use the lake level history as a proxy for climate change and wetter vs. drier conditions (Fig. 6).

Detrital sediment was carried to the basin by rivers sourced from Precambrian basement rocks underneath the Serengeti Plain to west and north of the basin providing a quartzofeldspathic-rich parent material (Ashley and Hay, 2002) (Figs. 1 and 3). The sediments comprising the stacked paleosol sequence are best characterized as pedogenically modified silty-waxy clays and waxy clays (Fig. 7).

Unfortunately, because of the landscape approach in Sikes and Ashley (2007), carbonate samples were not collected at close enough intervals to resolve soil profiles using $\delta^{13}C$ of pedogenic carbonate or detect the exact physical boundary of individual paleosols (Cerling, 1984; Quade et al., 1989). Individual paleosols can only be approximated (Fig. 7a). Calcium-rich soils typically show a decrease of $\delta^{13}C$ with (soil) depth indicated a decrease in the ratio of atmospheric CO_2 to plant-derived CO_2 down profile. The decrease in $\delta^{13}C$ reaches an equilibrium at 10–20 cm, or as great as 50 cm below the soil-air interface (Cerling, 1984; Quade et al., 1989; Schaller et al., 2012). This depth can be used to delineate paleosol thickness. Despite the limitation imposed by not being able to identify individual profiles, the pedogenically modified sediments of the Fluvial Plain were analyzed in the context of known climate cycles in the basin (Fig. 7a). Wet/dry cycles were initially interpreted from the lithologic record in the Fluvial Plain area and these interpretations were tested against $\delta^{18}O$ values of the carbonate nodules. A statistically significant correlation was found with $\delta^{18}O$ values of carbonate nodules and wet/dry cycles (Sikes and Ashley, 2007). The $\delta^{18}O$ values of nodules during wet periods were lighter (−4.8‰) and $\delta^{18}O$ values during dry periods were heavier (−4.4‰) suggesting more evaporation involved during calcite precipitation.

A number of subunits with conformable contacts are visible in the pedogenically modified sediments, the color varies from light yellow brown to olive brown (Munsell, 2000). Root and insect traces are common and carbonate nodules abundant, but there is no visible horizonation. This suggests recurring influx of sediment to the site, leaving little time for mature soil development. Continuous deposition with little to no erosion produces weakly developed and over-thickened paleosols termed *cumulative* paleosols (Kraus, 1999). Although the sediment record may at first sight appear unchanging, even monotonous, the well-dated tuffs, Tuff IB and Tuff IF at the bottom and top of the section, respectively, provide a means for correlating the lithology to the independently established lake cycle record attributed to be precession driven (Fig. 6). Except for the instantaneous deposition of Tuff IC, the assumption is made here for more-or-less continuous deposition at ~0.1 mm/yr. This sedimentation rate for non-tuff sedimentation is similar to those rates calculated by Hay and Kyser (2001) and Ashley (2007). The wet/dry climate curve is shown against the stratigraphic section (Fig. 7a). The sediments begin with green waxy clay deposited during a major expansion of the lake that covered the broad area labeled “expanded lake” in Fig. 2 (Hay, 1976). The lake level lowered slightly, thereby receding into the deeper part of the lake basin and the fluvial plain became subaerial. The green clay was pedogenically modified slightly before ash (Tuff IC) blanketed the surface. The 2 m thick silty-waxy clay, including the thin bed of very fine sand above Tuff IC, appears to be a cumulative paleosol (#1) that developed during a dry-to-wet climate

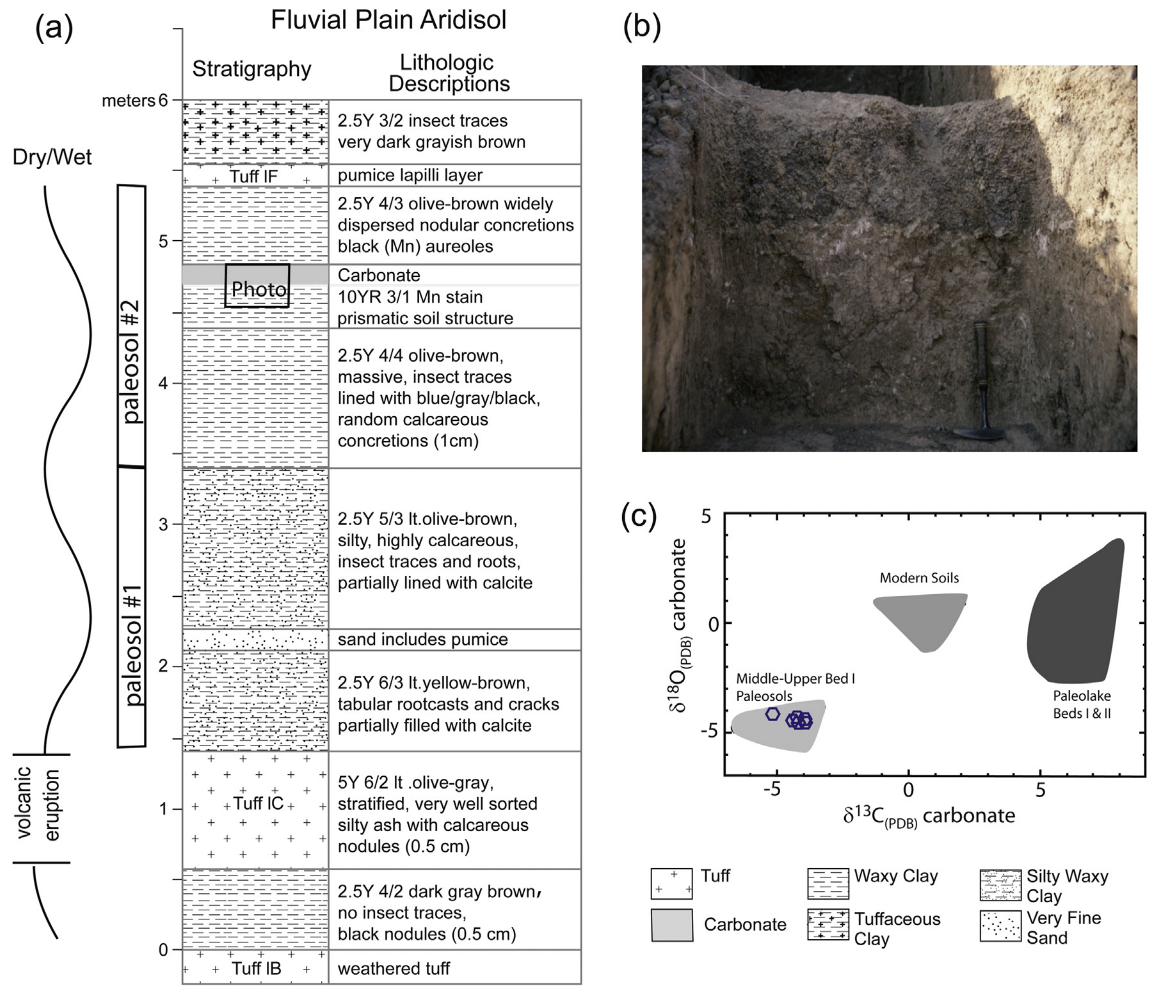

Fig. 7. Fluvial Plain Aridisols. (a). A 6 m thick sequence of olive-brown waxy clays, silty waxy clays and a 0.85 m tuff (Tuff IC) overlie Tuff IB. Detailed description and plot of wet/dry cycles from Fig. 6 are shown alongside the stratigraphic section. Beds with silt and sand were deposited during a drier periods, whereas waxy clays formed during wetter periods. (b) Photo is of dense calcium carbonate concentration (calcrete) overlying waxy clay. Location of photo is shown in (a). (c) $\delta^{13}C$ and $\delta^{18}O$ values from modern soils and calcite precipitated under alkaline, evaporative conditions in the center of paleo Lake Olduvai show a statistically significant separation (Sikes and Ashley, 2007) from carbonates in the Aridisols. The paleosols have a distinct negative signature for both isotopes.

cycle. Sedimentation began with a dry period and ended with a wet period. The color is light yellow brown in the lower portion (drier period) and becomes light olive brown in the upper portion (wetter period). The silty-clay sediment is highly calcareous, with insect traces and copious root traces and cracks filled with calcite. A carbonate sample from the lower portion (dry period) yielded a $\delta^{18}O$ value that is −4.4‰ PDB (Sikes and Ashley, 2007).

The Ng'eju Tuff (Fig. 6), identified as a thin reworked tuff in an outcrop (Loc 64) ~600 m away from the study site by McHenry (2004), does not appear in the sedimentary record at the Fluvial Plain Aridisol site. Either it was not deposited at the site or was not preserved.

Overlying the silty clay paleosol is a 2 m thick olive-brown waxy clay paleosol that has 4 subunits of slightly different color and structure, with calcareous concretions and manganese mottling dispersed randomly throughout. Deposition occurred over one precession-driven climate cycle. Starting with drier conditions it became wetter and then dry again just before the deposition of Tuff IF. The calcrete shown in section (Fig. 7a) and in a photo (Fig. 7b) is a dense, hard, 10 cm thick carbonate unit. It formed as the climate was becoming drier. The more positive $\delta^{18}O$ value of −4.3‰ PDB measured for the calcrete suggests more fractionation and greater water evaporation during carbonate formation as compared to the values for carbonate formed during the wetter time period. Calcretes are thought to form by the dissolution of calcium carbonate ($CaCO_3$) by rainwater and groundwater during wetter periods and then re-precipitation and filling in of interstitial voids with $CaCO_3$ during drier periods (Gile et al., 1966; Wright and Tucker, 1991).

4.1.2. Basin context

Under the semi-arid environment, the source material and the depositional environment in the western portion of the basin produced distinctive soils, Aridisols, with high calcium carbonate (Gile et al., 1966; Staff, 1975, 1998). There was no evidence to link the paleosol to the water table (Figs. 4 and 5), therefore, all pedogenic processes appear to have occurred within the vadose zone. Stable carbon and oxygen isotope values show a statistically significant separation between the paleosols, as well as with modern soil carbonates from the greater Olduvai region (Sikes and Ashley, 2007) and the calcite crystals precipitated under alkaline evaporative conditions in the center of paleo Lake Olduvai during Beds I and II (Hay, 1976; Cerling and Hay, 1986) (Fig. 7c). The $\delta^{13}C$ values of carbonates in the paleosols ranged from −6.6 to −3.3‰ PDB represent an open canopied grassy woodland and wooded grassland setting while the oxygen isotope values range from −4.3‰ PDB for carbonate formed during drier periods to 4.9‰ PDB for

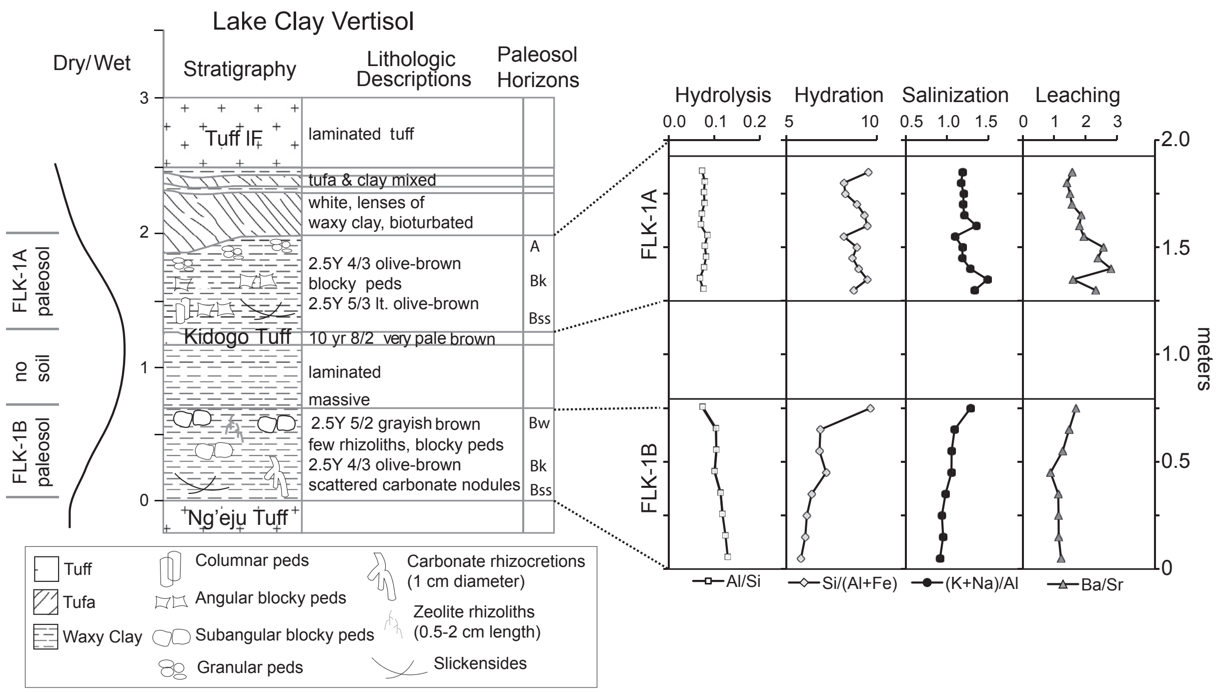

Fig. 8. Lake clay Vertisols. A detailed sediment description is shown adjacent to a 2½ m stratigraphic section sediments between the Ng'eju Tuff and Tuff IF. The sediment is waxy (smectitic) clay with intercalated tufa and a thin tuff. Two paleosols were identified at FLK-1A and FLK-1B and are separated by a non-pedogenic section. A plot of the Lake Cycle 2 graph from Fig. 6 reveals that the paleosols developed during the drier parts of the cycle and the non pedogenic portion during the wettest time. Molecular weathering ratios were calculated for the two soils and are plotted against the section.

carbonate formed during wetter periods. Overall, the data indicate a generally wetter climate and higher proportion of woody C_3 plants during Bed I time than exist under today's semi-arid climate.

4.2. Lake clay Vertisols

4.2.1. Paleosol description and interpretation

Data used to characterize the paleosols developed on lake clay in the center of the basin (Fig. 2) are from Beverly (2012) and Beverly et al. (2014) (Fig. 8). The study used basic pedological field descriptions and bulk geochemical analyses to examine soil development and to reconstruct the paleoenvironment and paleoclimate during Upper Bed I time (Fig. 6). The 2 m of clay (excluding tuff and tufa) sediment deposited between Ng'eju Tuff and Tuff IF over 20,000 years, indicates a 0.1 mm/y sedimentation rate similar to that estimated for the Fluvial Plain. Geological mapping by Hay (1976) showed that the playa lake in the basin center expanded and contracted regularly flooding low-gradient lake margin flat. Hay and Kyser (2001) and Ashley and Hay (2002) linked the lake expansions to Milankovitch cycles. This was supported by additional studies using stable isotopes (Liutkus et al., 2005), lithology (Ashley, 2007), and organic carbon from plants (Magill et al., 2012a) all of which indicated that in addition to these long term cycles, there were also short-term lake fluctuations, occurring on a sub-Milankovitch perhaps even El Niño time scale.

All evidence indicates that the lake flooded frequently across the lake margin, and the flooding frequency and the time the margin was submerged increased as climate became wetter and decreased as climate became drier. A thin veneer of clay was deposited with each flooding event and this clay became the parent material for the Vertisols. Essentially no fluvial drainage reached the lake from the eastern margin. Coarse sediment would have been retained in the alluvial fan as surface run-off infiltrated into the groundwater system before it reached the saline-alkaline lake (Fig. 2). On the western margin, coarse material transported within the river channels was trapped in the delta system. Compositionally, the lake clay is mostly magnesium smectite transformed diagenetically *in situ* from fine-grained silicates (Hay, 1970; Hay and Kyser, 2001; Hover and Ashley, 2003; Deocampo et al., 2009).

The sediments comprising the paleosol sequence are pedogenically modified and the presence of pedogenic slickenside surfaces, wedge-shaped peds, root traces, and the abundance of smectitic clay identify the paleosols as analogous to modern Vertisols (Buol et al., 2003; Southard et al., 2011) that form when the soil expand and contract during repeated wetting and drying cycles (Fig. 8). Pedogenic features identified in clay-rich paleosols at Olduvai indicate precipitation seasonality, as well as seasonal soil moisture deficit (Wilding and Tessier, 1988; Coulombe et al., 1996). The 1.9 m thick clay section is overlain with 0.3 m of carbonate (tufa) and 0.1 m clay and tufa are intercalated at the top (Fig. 8). The basal clay sediments are composed of three conformable units that include a 0.9 m thick lower olive brown paleosol (FLK-1B) and a 0.3 m thick grayish brown bed that is massive at the bottom, weakly laminated at top and lacks pedogenic features. A 0.1 m thick tuff (Kidogo Tuff) separates the middle unit from the 0.7 m thick overlying olive brown paleosol (FLK-1) (Fig. 8).

The oldest unit, the lower paleosol (FLK-IB) has an olive-brown Bss horizon with pedogenic slickensides and fine carbonate nodules (~3 mm diameter) near the bottom and a Bk horizon with subangular blocky peds and both zeolite-and carbonate-filled root traces. The top of the paleosol is grayish brown with a Bw horizon that has abundant zeolite-filled root traces and subangular blocky peds. The upper paleosol (FLK-1A) has a Bss horizon developed near the bottom characterized by angular blocky secondary peds and pedogenic slickensides that developed along columnar peds. In the middle unit, the peds are angular blocky and a concentration of Ca and Sr in the bulk geochemistry indicates a Bk horizon as well as the identification of carbonate rhizoliths (Fig. 8) (Beverly, 2012;

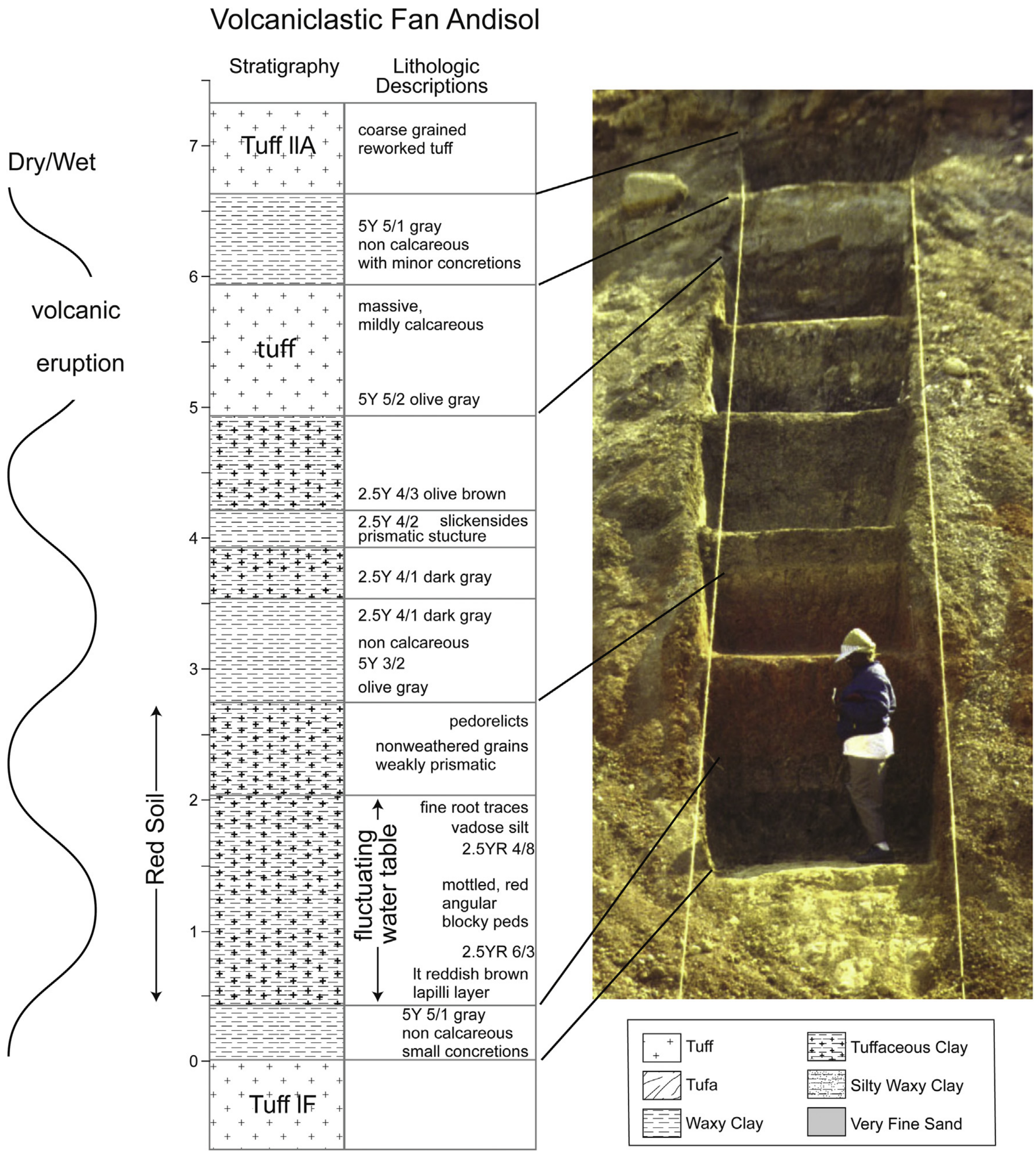

Fig. 9. Pyroclastic Fan Andisol A detailed description of the sediments is shown alongside the 6½ m stratigraphic section consisting of intercalated tuffaceous clay, waxy clay and tuff between Tuff IF and Tuff IIA. A distinctive 1.4 m thick red paleosol occurs near base of section. The lake cycle curve is plotted adjacent to the stratigraphic section and the outcrop photo. Tie lines connect the units in the photo with those depicted in the stratigraphic section.

Beverly et al., 2014). At the top, the A horizon is characterized by granular peds. A more detailed description of the FLK paleo-Vertisols is available (Beverly et al., 2014, see Fig. 3).

One example of the paleo-Vertisol geochemistry from Beverly (2012) is plotted next to the lake cycle curve and stratigraphic section to provide some insights into pedogenic processes that are not visible to the naked eye. Molecular weathering ratios (Retallack, 2001) are used to compare the average chemistry and degrees of weathering and diagenetic alteration of the clays in the two paleosol units. Bulk geochemistry of paleosol samples were analyzed at 10 cm intervals. The molecular weathering ratios are a measure of the amount of hydrolysis (Al/Si), hydration (Si/(Al + Fe)), salinization ((K + Na)/Al), and leaching (Ba/Sr) that occurred during the formation of each soil. The ratios track the relative change in weathering processes through time (Fig. 8).

The overall trends in the geochemical data support the idea that the paleosols are cumulative and that there was insufficient time for differentiation of chemical depth-trends, but the geochemistry does indicate changes in weathering between the lower and upper paleosols (Fig. 8). The climate was dry at the time of the deposition of Nge'ju Tuff and became wetter during formation of Paleosol FLK-1B. The non-pedogenic middle unit accreted during the wettest part of the cycle (when the site was flooded more frequently) and paleosol FLK-1A formed when the climate was drying and more sub-aerially exposed.

Hydrolysis is the reaction of acid with cation-rich mineral grains (usually silicates) which produces clay minerals and free cations (Chesworth, 1973). Hydrolysis (Al/Si) or clay content decreases up section in FLK-1B, and then stays relatively constant in FLK-1A. The other three weathering ratios (hydration, salinization and leaching)

Paleosol Characteristics	Fluvial Plain Paleo-Aridisol	Lake Clay Paleo-Vertisol	Pyroclastic Fan Paleo Andisol
parent material	quartzo-feldspathic sediments	Mg-smectite lake clay with some tephra influence	volcaniclastic sediments and tephra
Texture	Sand and silt	Clay dominant	Very coarse sand to silt
Drainage	well-drained	dominantly well-drained to poorly drained during lake highstands	dominantly well-drained but poorly drained proximal to springs
Calcium Carbonate	High, includes calcrete	Low	Low, except for detrital grains
Zeolites	Generally low	Abundant, filling root pores and channels, replacing tephra grains	Very abundant, replacing tephra grains and filling root pores
Shrink-swell (vertic) features	Absent	Abundant, slickensides and wedge peds	Absent
Redoximorphic features	Absent	Rare	Rare on fan, abundant near springs

Fig. 10. Table comparing characteristics of the three paleosols.

all increase slightly at the top of the section as the climate becomes wetter (FLK-1B), but overall FLK-1B indicates significantly less weathering than the upper paleosol FLK-1A. Molecular weathering ratios for hydration, salinization, and leaching are on average less in the lower paleosol (FLK-1B) and have less variability than in the younger paleosol (FLK-1A). This is due to a higher water table during the wet phase of the precession cycle that enhanced element mobility, but not translocation of elements in paleosol FLK-1B. As the water table dropped, increased pedogenesis was possible and therefore increased hydration, salinization, and leaching in the FLK-1A paleosol. Mass-balance translocations calculated using a parent material and volume change also show increased translocation of elements during the drier upper paleosol FLK-1A (Beverly, 2012; Beverly et al., 2014). During the driest part of the cycle groundwater seeped out and freshwater carbonate (tufa) accumulated on the surface supplying water to the carbonate precipitating wetland (Ashley et al., 2010a).

4.2.2. Basin context

The parent material (lake clays) and the relatively continuous addition of sediment to the surface of this lake margin site produced distinctive clay-rich paleo-Vertisols (Staff, 1975; Sheldon and Tabor, 2009; Southard et al., 2011). The amount of time that the lake margin surface was subaerially exposed decreased up section through FLK-1B and then increased up section through FLK-1A. Molecular weathering ratios and mass-balance calculations support this. Vertisols usually form in low topographic areas where the water table is very near to the surface (Figs. 4 and 5), but there was no evidence of saturation, with attendant anoxic conditions or gleying. Carbonate, in any form, is significantly less than in the fluvial plain environment presumably because of the likelihood of a frequently fluctuating water table (Ashley et al., 2013) (Fig. 10).

4.3. *Volcaniclastic alluvial fan Andisols*

4.3.1. Paleosol description and interpretation

Data used to characterize the paleosol from the Volcaniclastic Alluvial Fan on the eastern side of the basin (Fig. 2) are from Ashley and Driese (2000), a study that focused on the origin of a remarkably intense red paleosol (2.5YR 6/3 to 2.5YR 4/8) and its paleohydrologic and paleoclimatic context. The interpreted paleoenvironment is the fine-grained distal end of an alluvial fan system being sourced from volcanic eruptions in the nearby Ngorongoro Volcanic Highland (Figs. 1–4). The parent material is

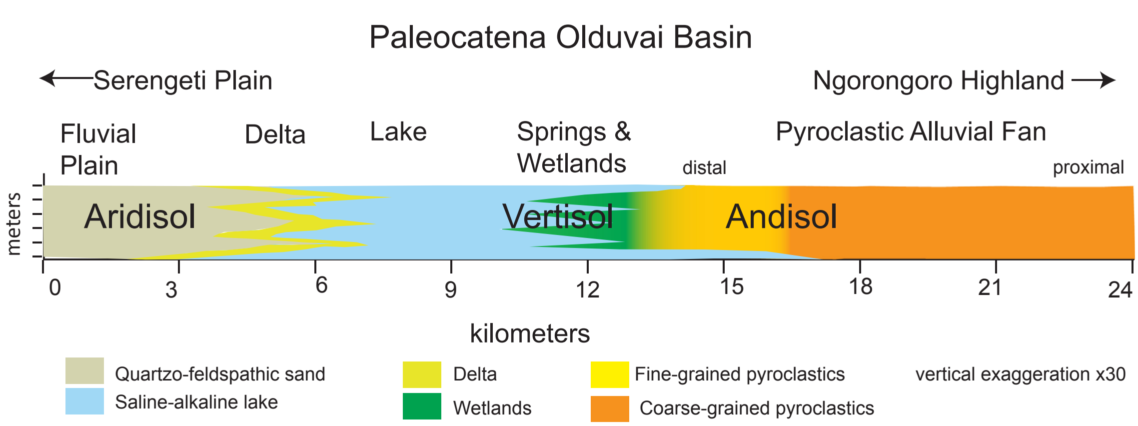

Fig. 11. Paleocatena of Olduvai Gorge. The three paleosol types are placed on a diagrammatic reconstruction of a paleocatena on the Olduvai landscape (alluvial fan, wetland, lake, delta and fluvial plain). Volcaniclastics from Ngorongoro Highland provided parent material for the Andisols on the east of basin. Smectitic clays, formed within the alkaline lake in the center of the basin, provided parent material for the Vertisols. Quartzo-feldspathic sediments sourced from the Serengeti Plain region provided the parent material for the Aridisols on the west side of basin.

pyroclastic ejecta that reached the surface by airfall, debris flows and seasonal run-off (Hay, 1976). Reworked tephra is also added by colluvial or fluvial sheet wash. The volcaniclastic detritus is ultimately sourced from alkaline-rich volcanic rocks of nephelinite and foidite composition (McHenry, 2004).

Tuff IIA is a reworked tuff and its precise age has not been determined by argon/argon dating as have the other tuffs in Bed I. But, a reasonable age estimate is ~1.74, based on the sedimentation range of 0.1 mm/yr established for the basin (Hay and Kyser, 2001) and the age of the Olduvai subchron (1.795 Ma) (Berggren et al., 1995). Using that date, the entire sequence of pedogenically modified silts and clays between Tuff IF and Tuff IIA is ~6.5 m thick and spans ~60,000 years, comprising three lake cycles (Figs. 6 and 9). However, the red paleosol in the lower half of the section is only 1.4 m thick, it is a cumulative soil, and formed during a single climate cycle (Ashley and Driese, 2000). The parent material was volcaniclastic, a tuffaceous clay (with silt), and thus is classified as an Andisol (Staff, 1975; Tan, 1984). The remaining beds in the sequence consist of a 1 m-thick tuff and three intercalated beds of waxy clay of distinctly different color, namely olive gray, dark gray, and gray (Munsell, 2000). These waxy clays are interpreted as lake clays deposited during sustained wet periods when the lake expanded to its fullest extent (Figs. 2 and 6).

The Andisol began to form after the lake expansion above Tuff IF during a period of increased wetness and presumably higher sustained water table and then continued into the following dry period (Fig. 9). Its position on the landscape is interpreted to be a location of highground table or groundwater seepage (Fig. 5). The pedogenic features used to interpret higher water table (and thus impeded drainage) are lack of preserved stratification, strong primary paleosol colors, redoximorphic mottling, coarse and fine Fe segregations and concentrations in matrix and coatings on grains and in pores. The top of the "red soil" formed under drier conditions. Pedogenic features used to interpret improved soil drainage (lower water table) are transported illuviated clay grains and clay pore-coatings. Features used to identify increased drier conditions (lower water table) are the introduction of vadose silt and the formation of zeolites (analcime and natrolite) in soil pores, root pores and cracks (Ashley and Driese, 2000).

The parent material contains both fresh and weathered volcaniclastic minerals that provide a wide range of cations (including Fe, Mn, Cr, Cu Ti, Zr) that can become part of the soil. Geochemical profiles and petrographic analysis identified repeated influxes of volcanic material to the surface and a fluctuating water table that altered the redox potential, thereby producing the intense red-colored soil. The pedology appears to have recorded the climate changes starting with formation of Fe oxide pore linings, followed by illuviated clay coatings, and then lastly by zeolite crystal pore linings (initial wetter conditions with poorer soil drainage, then returning to drier conditions with improved drainage) (Fig. 9). The pedological features in the paleosol between 1.75 and 2.0 m (Fe oxide segregations and pore coatings) indicates a wetter period, whereas features in the overlying beds (2.00–2.75 m) suggest pronounce aridity (vadose silt, reworked zeolite into soil pores). These data support the independently produced lake cycle curve (Figs. 6 and 9).

4.3.2. Basin context

The cation-rich parent material (volcanic tephra) and fluctuating water table during the period of soil formation produced the red paleosol, categorized as an Andisol (Staff, 1975; Tan, 1984). The paleosol interval formed during a full climate cycle during a rising and fluctuating water table. The redoximorphic features in the red paleosol suggest fluctuation of groundwater that could be short-term alternating wet and dry climate phases related to sub-Milankovitch fluctuations within one full precession cycle.

5. Discussion

The Olduvai Basin has a long history of investigations of its geology (~100 years) and archaeology (~50 years), but the paleosol record has escaped the attention of most studies. This paper reviews the published results of three paleosol studies carried out in different parts of the basin. Each study based on records from a relatively short time span (20–100,000 years) to better understand the paleoenvironmental and paleoclimatic context of the fossil and cultural records. The three paleosols are part of a paleocatena extending across the basin from the volcaniclastic-dominated alluvial fan on the east to the quartz-rich fluvial plain on the west (Fig. 11).

The chart in Fig. 10 compares and contrasts a variety of paleosol characteristics (parent material, texture, drainage, $CaCo_3$ zeolite vertic and redoximorphic features) among the three different types of paleosols. The five factors of soil formation (time, climate, biology, topography/hydrology and parent material) were used as a means of comparing and contrasting the paleoenvironmental significance of the three paleosol types: the calcium carbonate-rich Aridisol, the clay-rich Vertisol and the tephra-rich Andisol (Jenny, 1941).

5.1. Soil forming factors

The timeframe of paleosol formation was established using a combination of geochronological records of bracketing tuffs (dated by the $^{40}Ar/^{39}Ar$ single crystal method (Deino, 2012)), the occurrence of well-documented lake cycle records with a rhythmic beat of 20,000 years, and a calculated sedimentation rate of 0.1 mm/yr. There was a good correspondence between known wet and dry periods and soil characteristics. For examples, no pedogenesis at times of high lake level (Lake Clay Vertisol, Fig. 8) and redoximorphic mottling during times of rising and falling limbs of climate cycle (Volcaniclastic Fan Andisol, Fig. 9).

The climate context was interpreted based upon the occurrences of lake cycles that serve as a proxy for increases and decreases in precipitation, associated with astronomically-driven Milankovitch precession cycles (~20 ka). The rainfall in the tropics is seasonal and driven by the Asian monsoon system in response to variation in insolation reaching the Earth's surface (Ruddiman, 2000). Mean annual temperature at the equator remains relatively consistent during these cycles. It is estimated that mean annual precipitation (MAP) in the form of rainfall increases 50% between dry and wet periods. The MAP at Olduvai was modeled to be 250–700 mm/yr (Magill et al., 2012a). It is reasonable to assume that the groundwater storage expands and contracts more-or-less in phase with the rainfall, and that during dry periods it may be an important resource for animals, including humans.

The factor of biology plays an important role in paleosol records. Pedogenic carbonates retain the carbon isotope signature of C3 and C4 vegetation and the imprint on oxygen isotope ratios from meteoric water. The paleosol record is rich in plant remains from trees (Bamford, 2005; Albert et al., 2009; Barboni et al., 2010), localized forests and grassy woodland (Sikes, 1994; Sikes and Ashley, 2007), wooded grassland (Van der Merwe, 2013), and algae in the lake (Magill et al., 2012b) Paleosols have also retained abundant evidence of bioturbation and trampling by large vertebrates (Ashley and Liutkus, 2002). A large biomass at Olduvai is suggested by the tens of thousands of bones found in archaeological sites (Leakey, 1971; Plummer and Bishop, 1994; Domínguez-Rodrigo et al., 2007).

The topography and hydrology (drainage) of soil-forming environments are important; well-developed soils do not form on steep slopes, nor do they form under permanently high water table conditions. The three sites of study at Olduvai are all in areas of low slope and most importantly sites of sediment accumulation: fluvial plain, lake margin, and alluvial fan. Finally, the soil parent materials that strongly influence pedogenic processes were dramatically different (quartzo-feldspathic sediment, clay (both clay minerals and clay size) and pyroclastic detritus of different sizes not surprisingly lead to very different types of paleosols).

5.2. Paleosols in the Paleocatena

Two paleosols formed in the low gradient Fluvial Plain on the western side of the basin where the parent material composition is quartzo-feldspathic. These soils formed on the floodplain and interfluve, both areas of active sedimentation. The lower paleosol (#1) formed during Lake Cycle 1 in silty waxy clay and the other (#2) during Lake Cycle 2 in waxy clay (Figs. 6 and 7). Both are paleo-Andisols with high calcium carbonate content. Temporal variation in pedogenic carbonate oxygen isotope values supports the timing of wet/dry cycles, while the carbon isotope data indicate the vegetation across the paleolandscape supported more woody C_3 plants, at least during the wetter periods, compared to today.

Two paleosols formed in lake-margin sediments during Lake Cycle 2 (Figs. 6, 7, 9). One (FLK-1B) on the rising limb, dry to wet and the other (FLK-1A) during the falling limb, wet to dry and both are identified as paleo-Vertisols. A bed of non-pedogenic massive to laminated clay separates the two paleosols and was deposited during the wettest time of the climate cycle. The subaerial exposure needed for soil formation would have been quite limited during this period. The parent material for the paleosols was clay and the topography a low gradient lake margin, but it was a site that received frequent additions of clay during lake flooding. Carbonate accumulation in any form in the soil itself was minimal. Weathering ratios are weakly expressed and suggest short durations of pedogenesis interrupted by influxes of new parent material during soil development, but an overall average increase in weathering between the lower and upper paleosols tracks a precession cycle.

One Andisol formed in the pyroclastic alluvial distal fan during Lake Cycle 3 (Figs. 6, 7, 10). It is classified as an Andisol because of the volcanic parent material. A second paleosol (not reported on here) formed 1 km upslope in the more proximal part of the fan beyond the limit of the lake during Lake Cycle 4 (Ashley and Driese, 2000). The alluvial fan was a site of steady, slow sedimentation as pedogenesis proceeded. Volcaniclastic material was added to the fan surface via airfall, sheet wash during precipitation events and colluvial processes. The volcanics brought in a rich supply of cations that entered into the soil and become part of the record; in particular Fe^{3+} released from weathering of the volcanic parent material yielded the intense red color when oxidized. The water table was close to the surface and fluctuations of the water table created the environment for alternating oxidation and reduction reactions producing the characteristic mottling (Figs. 5, 9, 10).

6. Conclusions

The archaeological records at Olduvai are typically found within pedogenically modified sediments, thus the interpretation of paleosols provides important high-resolution paleoenvironmental and paleoclimatic context information. Soils formed beneath the ground surface on which early hominins lived were later buried and preserved as paleosols. This study demonstrates that there are clear differences in the types of soils formed within this small semi-arid rift basin during a 100,000 year period. Soil formation was linked to the ~20 ka lake cycles: one soil per cycle on the alluvial fan and fluvial plain; whereas two soils formed in the lake margin clay, one on the rising limb the other on the falling limb. Differences among the paleosols were related to (1) parent material (quartzo-feldspathic fluvial sediment, vs. lacustrine clay vs. volcaniclastic sediment and tephra), (2) climate (wetter vs. drier) and the related secondary effect of lake level change and lake flooding and (3) topography. All paleosol sites were areas of net deposition (accumulation) and the Olduvai soils are overall categorized as cumulative. However, topography or landscape position was particularly important in the pyroclastic alluvial fan, and specifically its proximity to the saline, alkaline lake. Lake level affects the position and fluctuation of the groundwater table and it was the fluctuating water table that provided the change in redox to produce the iron oxides (wetter, lower Eh) and zeolites (drier, higher Eh) that gave the Andisol its distinctive color. In summary, the diversity of paleosols preserved in the basin provides insights on the impact of climate change, lake level and groundwater fluctuations, and volcanic eruptions on the landscape between ~1.85 and 1.74 Ma and adds important information on the environments in which humans evolved. To our knowledge this is the first study in the Pleistocene of East Africa that demonstrates coeval soils of vastly different types in a landscape context that developed under the same climate.

Acknowledgments

Data for the paleo-Vertisol study (EJB) were collected under permits from the Tanzanian Commission for Science and Technology and the Tanzanian Antiquities Department to TOPPP (The Olduvai Paleoanthropology and Paleoecology Project), PIs M. Domínguez-Rodrigo, H.T. Bunn, A.Z.P. Mabulla, and E. Baquedano. We appreciate funding provided by the Spanish Ministry of Education and Science through the European project I+D HUM2007-6381507-63815. Funding from Evolving Earth Foundation, Rutgers University Department of Earth and Planetary Sciences, and Geological Society of America Student Research Grant are also acknowledged by EJB. Appreciation is extended to Michael Siegel for assistance with drafting figures. Discussions with D.M. Deocampo, Carol deWet, Jim Wright and Steven Driese were helpful in reaching our interpretations. We are indebted to the late R.L. Hay for his immense knowledge of the geology of Olduvai Gorge and his generosity in sharing his wisdom during many seasons in the field with GMA and during classes and fieldwork with NES.

References

Albert, R.M., Bamford, M.K., Cabanes, D., 2009. Palaeoecological significance of palms at Olduvai Gorge, Tanzania, based on phytolith remains. Quaternary International 193, 41–48.
Ashley, G.M., 2007. Orbital rhythms, monsoons, and playa lake response, Olduvai Basin, equatorial East Africa (~1.85–1.75). Geology 35, 1091–1094.
Ashley, G.M., Driese, S.G., 2000. Paleopedology and paleohydrology of a volcaniclastic paleosol interval: implications for early Pleistocene stratigraphy and paleoclimate record, Olduvai Gorge, Tanzania. Journal of Sedimentary Research 70, 1065–1080.
Ashley, G.M., Hay, R.L., 2002. Sedimentation patterns in a Plio-Pleistocene volcaniclastic rift-margin basin, Olduvai Gorge, Tanzania. In: Renaut, R.W., Ashley, G.M. (Eds.), Sedimentation in Continental Rifts. SEPM, Tulsa, OK, pp. 107–122.
Ashley, G.M., Liutkus, C.M., 2002. Tracks, trails and trampling by large vertebrates in a rift valley paleo-wetland, lowermost Bed II, Olduvai Gorge, Tanzania. Ichnos 9, 23–32.
Ashley, G.M., Barboni, D., Domínguez-Rodrigo, M., Bunn, H.T., Mabulla, A.Z.P., Diez-Martín, F., Barba, R., Baquedano, E., 2010a. Paleoenvironmental and paleoecological reconstruction of a freshwater oasis in savannah grassland at FLK North, Olduvai Gorge, Tanzania. Quaternary Research 74, 333–343.
Ashley, G.M., Barboni, D., Domínguez-Rodrigo, M., Bunn, H.T., Mabulla, A.Z.P., Diez-Martín, F., Barba, R., Baquedano, E., 2010b. A spring and wooded habitat at FLK Zinj and their relevance to origins of human behavior. Quaternary Research 74, 304–314.

Ashley, G.M., Domínguez-Rodrigo, M., Bunn, H.T., Mabulla, A.Z.P., Baquedano, E., 2010c. Sedimentary geology and human origins: a fresh look at Olduvai Gorge, Tanzania. Journal of Sedimentary Research 80, 703–709.

Ashley, G.M., Deocampo, D.M., Kahmann-Robinson, J., Driese, S.G., 2013. Groundwater-fed wetland sediments and paleosols: it's all about water table. In: Driese, S.G., Nordt, L.C. (Eds.), Paleosols and Soil Surface Analog Systems. SEPM, Tulsa, OK, pp. 47–61.

Baker, B.H., Mohair, P.A., Williams, L.A., 1972. Geology of eastern rift system of Africa. In: Geological Society of America, Special Paper. Geological Society of America, Denver, CO, pp. 1–67.

Bamford, M.K., 2005. Early Pleistocene fossil wood from Olduvai Gorge, Tanzania. Quaternary International 129, 15–22.

Barboni, D., Bremond, L., Bonnefille, R., 2007. Comparative study of modern phytolith assemblages from inter-tropical Africa. Palaeogeography, Palaeoclimatology, Palaeoecology 246, 454–470.

Barboni, D., Ashley, G.M., Domínguez-Rodrigo, M., Bunn, H.T., Mabulla, A.Z.P., Baquedano, E., 2010. Phytoliths infer locally dense and heterogeneous paleovegetation at FLK North and surrounding localities during upper Bed I time, Olduvai Gorge, Tanzania. Quaternary Research 74, 344–354.

Berggren, W.A., Kent, D.V., Swisher III, C.C., Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., Hardenbol, J. (Eds.), Geochronology, Time Scales, and Global Stratigraphic Correlation. SEPM, Tulsa, OK, pp. 129–212.

Beverly, E.J., 2012. High-resolution Paleoenvironmental and Paleoclimatic Reconstruction of a Pleistocene Catena and Climosequence Using Paleopedology and Geochemistry of Lake Margin Paleo-Vertisols, Olduvai Gorge, Tanzania. Rutgers University, MS, USA.

Beverly, E.J., Ashley, G.M., Driese, S.G., 2014. Reconstruction of a Pleistocene paleocatena using micromorphology and geochemistry of lake margin paleo-Vertisols, Olduvai Gorge, Tanzania. In: Diez-Martín, F. (Ed.), Quaternary International. Elsevier, The Netherlands , pp. 78–94.

Brantley, S.L., Goldhaver, M.B., Ragnarsdottir, K.V., 2007. Crossing disciplines and scales to understand the critical zone. Element 3, 307–314.

Bunn, H.T., Kroll, E.M., 1986. Systematic butchery by Plio-Pleistocene hominids at Olduvai Gorge, Tanzania. Current Anthropology 27, 431–452.

Buol, S.W., Southard, R.J., Graham, R.C., McDaniel, P.A., 2003. Vertisols, Shrinking and Swelling Dark Clay Soils. Soil Genesis and Classification. Iowa State University Press, Ames, Iowa.

Cerling, T.E., 1984. The stable isotopic composition of modern soil carbonate and its relation to climate. Earth and Planetary Science Letters 71, 229–240.

Cerling, T.E., Hay, R.L., 1986. An isotopic study of paleosol carbonates from Olduvai Gorge. Quaternary Research 25, 63–78.

Cerling, T.E., Quade, J., 1993. Stable carbon and oxygen isotopes in soil carbonates. In: Swart, P.K., Lohmann, K.C., McKenzie, J., Savin, S. (Eds.), Climate Change in Continental Isotopic Records, pp. 217–231.

Chesworth, W., 1973. The parent rock effect in the genesis of soils. Geoderma 10, 215–225.

Copeland, S.R., 2007. Vegetation and plant food reconstruction of lowermost Bed II, Olduvai Gorge, using modern analogs. Journal of Human Evolution 53, 146–175.

Coulombe, C.E., Dixon, J.B., Wilding, L.P., 1996. Mineralogy and chemistry of Vertisols. In: Ahmad, N., Mermut, A. (Eds.), Vertisols and Technologies for Their Management. Elsevier, New York, pp. 115–200.

Dagg, M., Woodhead, T., Rijks, D.A., 1970. Evaporation in East Africa. International Association of Scientific Hydrology Bulletin 15, 61–67.

Dawson, J.B., 2008. The Gregory Rift Valley and Neogene – Recent Volcanoes of Northern Tanzania. Geological Society, London.

Deino, A.L., 2012. $^{40}Ar/^{39}Ar$ dating of Bed I. Olduvai Gorge, Tanzania, and the chronology of early Pleistocene climate change. Journal of Human Evolution 63, 251–273.

Deocampo, D.M., Blumenschine, R.J., Ashley, G.M., 2002. Wetland diagenesis and traces of early hominids, Olduvai Gorge. Quaternary Research 57, 271–281.

Deocampo, D.M., Cuadros, J., Wing-Dudek, T., Olives, J., Amouric, M., 2009. Saline lake diagenesis as revealed by coupled mineralogy and geochemistry of multiple ultrafine clay phases: Pliocene Olduvai Gorge, Tanzania. American Journal of Science 309, 834–868.

Domínguez-Rodrigo, M., Barba, R., Egeland, C.P., 2007. Deconstructing Olduvai: A Taphonomic Study of the Bed I Sites. Springer, Dordrecht.

Frostick, L.E., 1997. The East African rift basins. In: Selley, R.C. (Ed.), African Basins: Sedimentary Basins of the World. Elsevier Science, Amsterdam, pp. 187–209.

Gile, L.H., Peterson, F.F., Grossman, R.B., 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. Soil Science Society of America Journal 101, 347–360.

Hay, R.L., 1970. Silicate reactions in three lithofacies of a semi-arid basin, Olduvai Gorge, Tanzania. Mineralogical Society of America Special Paper 3, 237–255.

Hay, R.L., 1973. Lithofacies and environments of Bed I, Olduvai Gorge, Tanzania. Quaternary Research 3, 541–560.

Hay, R.L., 1976. Geology of the Olduvai Gorge. University of California Press, Berkeley.

Hay, R.L., 1990. Olduvai Gorge: a case history in the interpretation of hominid paleoenvironments in East Africa. In: Laporte, L.F. (Ed.), Establishment of a Geologic Framework for Paleoanthropology. Geological Society of America, Boulder, Colorado, pp. 23–37.

Hay, R.L., Kyser, T.K., 2001. Chemical sedimentology and paleoenvironmental history of Lake Olduvai, a Pleistocene lake in northern Tanzania. Geological Society America Bulletin 113, 1505–1521.

Hover, V.C., Ashley, G.M., 2003. Geochemical signatures of paleodepositional and diagenetic environments: a STEM/AEM study of authigenic clay minerals from an arid rift basin, Olduvai Gorge, Tanzania. Clays and Clay Minerals 51, 231–251.

Jenny, H.J., 1941. Factors of Soil Formation. McGraw-Hill, New York.

Kraus, M.J., 1999. Paleosols in clastic sedimentary rocks: their geologic applications. Earth-Science Reviews 47, 41–70.

Leakey, M.D., 1971. Olduvai Gorge: Excavations in Beds I and II; 1960–1963. Cambridge University Press, Cambridge, UK.

Liutkus, C.M., Ashley, G.M., 2003. Facies model of a semiarid freshwater wetland, Olduvai Gorge, Tanzania. Journal of Sedimentary Research 73, 691–705.

Liutkus, C.M., Wright, J.D., Ashley, G.M., Sikes, N.E., 2005. Paleoenvironmental interpretation of lake-margin deposits using $\delta^{13}C$ and $\delta^{18}O$ results from Early Pleistocene carbonate rhizoliths, Olduvai Gorge, Tanzania. Geology 33, 377–380.

Magill, C.R., Ashley, G.M., Freeman, K.H., 2012a. Water, plants, and early human habitats in eastern Africa. Proceedings of the National Academy of Sciences of the United States of America 110, 1175–1180.

Magill, C.R., Ashley, G.M., Freeman, K.H., 2012b. Ecosystem variability and early human habitats in eastern Africa. Proceedings of the National Academy of Sciences of the United States of America 110, 1167–1174.

Marshak, S., 2001. Earth: Portrait of a planet. W.W. Norton $ Company, New York.

McHenry, L.J., 2004. Characterization and Correlation of Altered Plio-Pleistocene Tephra Using a "Multiple Technique" Approach: Case Study at Olduvai Gorge, Tanzania (PhD thesis). Rutgers University, USA.

McHenry, L.J., Mollel, G.F., Swisher, C.C., 2008. Compositional and textural correlations between Olduvai Gorge Bed I tephra and volcanic sources in the Ngorongoro Volcanic Highlands, Tanzania. Quaternary International 178, 306–319.

Mollel, G.F., Swisher, C.C.I., Feigenson, M.D., Carr, M.J., 2008. Geochemical evolution of Ngorongoro Caldera, Northern Tanzania: implications for crust–magma interaction. Earth and Planetary Science Letters 271, 337–347.

Mollel, G.F., Swisher, C.C.I., McHenry, L.J., Feigenson, M.D., Carr, M.J., 2009. Petrogenesis of basalt–trachyte lavas from Olmoti Crater, Tanzania. Journal of African Earth Sciences, 127–143.

Morley, C.K., 1999. Basin evolution trends in East Africa. American Association of Petroleum Geologists.

Munsell, 2000. Munsell Soil Color Charts. GretagMacbeth, New Windsor, NY.

NRC, 2001. Basic Research Opportunities in Earth Science. National Research Council, Washington, DC, p. 154.

Nordt, L.C., Driese, S.G., 2013. Application of the critical zone concept to the deep-time sedimentary record. The Sedimentary Record 11, 4–9.

Plummer, T.W., Bishop, L.C., 1994. Hominid paleoecology at Olduvai Gorge, Tanzania as indicated by antelope remains. Journal of Human Evolution 27, 47–75.

Quade, J., Cerling, T.E., Bowman, J.R., 1989. Systematic variations in the carbon and oxygen isotopic composition of pedogenic carbonate along elevation transects in the southern Great basin, United States. Geological Society of America Bulletin 101, 464–475.

Reck, H., 1951. A preliminary survey of the tectonics and stratigraphy of Olduvai. In: Leakey, L.S.B. (Ed.), Olduvai Gorge. Cambridge University Press, London, pp. 5–19.

Retallack, G.J., 2001. Soils of the Past: An Introduction to Paleopedology, second ed. Blackwell Science, Oxford.

Ruddiman, W.F., 2000. Earth's Climate, Past and Future. W.H. Freeman, New York.

Russell, J.S., Rhoades, H.F., 1956. Water table as a factor in soil formation. Soil Science 82, 319–328.

Schaller, M.F., Wright, J.D., Kent, D.V., Olsen, P.E., 2012. Rapid emplacement of the Central Atlantic Magmatic Province as a net sink for CO_2. Earth and Planetary Science Letters 323–324, 27–39.

Sheldon, N.D., Tabor, N.J., 2009. Quantitative paleoenvironmental and paleoclimatic reconstruction using paleosols. Earth-Science Reviews 95, 1–52.

Sikes, N.E., 1994. Early hominid habitat preferences in East Africa: Paleosol carbon isotopic evidence. Journal of Human Evolution 27, 23–45.

Sikes, N.E., Ashley, G.M., 2007. Stable isotopes of pedogenic carbonates as indicators of paleoecology in the Plio-Pleistocene (upper Bed I) western margin of Olduvai Basin, Tanzania. Journal of Human Evolution 53, 574–594.

Southard, R.J., Driese, S.G., Nordt, L.C., 2011. Vertisols. In: Huang, P.M., Li, Y., Sumner, M.E. (Eds.), Handbook of Soil Science: Properties and Processes, second ed. CRC Press, Boca Raton, FL, pp. 33–97.

Staff, S.S., 1975. Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys. In: Agriculture, U.S.D.o. (Ed.), Handbook, p. 754.

Staff, S.S., 1998. Keys to Soil Taxonomy. U.S. Government Printing Office, Washington D.C.

Tan, K.H., 1984. Andosols. Van Nostrand Reinhold, New York.

Van der Merwe, N.J., 2013. Isotopic ecology of fossil fauna from Olduvai Gorge at ca 1.8, compared with modern fauna. South African Journal of Science 109, 1–14.

Wilding, L.P., Tessier, D., 1988. Genesis of Vertisols: shrink–swell phenomena. In: Wilding, L.P., Puentes, R. (Eds.), Vertisols: Their Distribution, Properties, Classification and Management. Texas A&M University Printing Center, College Station, TX, pp. 55–79.

Wright, V.P., Tucker, M.E., 1991. Calcretes: an introduction. In: Wright, V.P., Tucker, M.E. (Eds.), Calcretes. Blackwell Scientific Publications, Oxford, pp. 1–22.