2013

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Mahaney, W.C.

Elsevier


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Mineralogy and chemistry of Late Pliocene–Early Pleistocene paleosols on Mount Kenya: Weathering indices of relative age and paleoenvironmental reconstruction

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Article info

Keywords:
Fe/Al extracts
Tropical mountain glaciation
Late Pliocene/Early-mid Quaternary paleosols
Early-mid Quaternary paleoclimate

Abstract

Iron and Al extracts as weathering indices in paleosols have been used in many localities to determine relative age, transformation of total chemical element concentrations to secondary forms, translocation of organically-complexed Al and long-standing inundation of soils with groundwater. On Mt. Kenya, a succession of paleosols straddling the Olduvai subchron are here analyzed to determine the degree to which Fe/Al extracts assist paleoenvironmental reconstruction, especially relative age determination, genesis and translocation of alteration products and the effect of paleoclimatic deterioration with the advent of glaciation ca. 2.0 Ma, and possibly before. Warmer/humid climate from the onset of the Plio-Pleistocene to the Olduvai subchron, thereafter reverting to a long episode of oscillating drier/wetter ice age perturbations is written into the profile morphologies, mineralogies and chemistries supporting earlier stratigraphic interpretations.

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1. Introduction

Iron and Al extracts have been used in a number of different latitude belts, on a range of lithologies from equator to pole to reconstruct pedogenic trends related to time and climate (Blume and Schwertmann, 1969; Alexander, 1974; Parfitt and Childs, 1988; Mahaney et al., 1991, 1999; Pai et al., 2004; Mahaney et al., 2006; Schulli-Maurer et al., 2007; Mahaney et al., 2009, 2010, 2012). Over the last four decades, three extracts of Fe and Al including Na-pyrophosphate (Fe2/Al2), acid ammonium oxalate (Fe2/Al2) and Na-dithionite (Fe2/Al2), each have been taken from stratigraphically important suites of soils/paleosols to determine relative age, translocation of organic carbon, reduction in lattice Fe with weathering and relative increases in secondary hematite plus goethite. Originally it was thought that Fe2 approximated organically-complexed Fe (McKeague and Day, 1966), a relationship later shown to be in error (Parfitt and Childs, 1988). Na-pyrophosphate extracts of Al (Al2) long considered an approximation of organically-complexed Al, have been shown (Parfitt and Childs, 1988; Mahaney et al., 2009) to be an accurate proxy for organic carbon translocation in a variety of different environments. Acid ammonium oxalate extracts of both Fe2 and Al2 originally considered to represent amorphous forms of both elements, are now known to approximate the concentration of ferrihydrite (5Fe2O3·9H2O) in paleosols (Parfitt and Childs, 1988). Walker (1983) asserted that soils with high magnetite concentrations are prone to erroneously elevated values of Fe2 due to oxalate–magnetite interactions; however, as discussed later, samples here with high concentrations of magnetite, do not show anomalous values. The Al2 concentration represents a mass of secondary Al products (Mahaney and Fahey, 1988; Birkeland et al., 1989; Mahaney et al., 2009), which when compared with Al2 (Al2 – Alp) yields an approximation of allophane and imogolite (Parfitt and Childs, 1988). Sodium dithionite extracts of Fe2 represent the sum total of secondary Fe – namely, hematite + goethite + ferrihydrite – and for Al2 a partial extract of secondary crystalline Al. Concentrations of Al2 continue to be reported although their importance in stratigraphic work is uncertain and these extract values should be used with caution (Birkeland et al., 1989).

Given the uncertainty and adjustments that have been made with the use of Fe and Al extracts, the work of Parfitt and Childs (1988) established a firm footing for several extracts of both elements. Whereas, Fe2 is of uncertain use, Fe2 and Fe2 concentrations yield approximate values for ferrihydrite (secondary hydroxide) and Fe2, the sum total of extractable crystalline Fe, respectively. Because Fe2 has been known to measure concentrations of secondary Fe since the seminal work of Mehr and Jackson (1960), many workers have concentrated on using
it to measure concentrations of secondary hematite, goethite and ferrihydrite in soils and paleosols. Despite the partial solubility of ferrihydrite, the ratio Fe\textsubscript{ox}/Fe\textsubscript{tot} is often used to approximate the build-up of ferrihydrite against goethite + hematite + ferrihydrite over time. Since Fe\textsubscript{ox} has an affinity for water-saturated conditions, corresponding decreases of Fe\textsubscript{ox} in a section possibly indicate phreatic conditions or a perched water table (Mahaney and Fahey, 1988) at some time in the past rather than reaction with magnetite. Given the variable but low concentrations of magnetite reported here, the Fe\textsubscript{ox} trends should be treated with caution as values may likely be overestimates of Fe\textsubscript{ox} in some horizons. However, to test the possibility of Fe\textsubscript{ox} reactivating with magnetite we ranked Fe\textsubscript{ox} against Fe\textsubscript{ox} (Fe\textsubscript{px}/Fe\textsubscript{ox}) in three sections having a magnetite increase downward to determine if Fe\textsubscript{ox} increased with depth. Despite a gradual increase of magnetite with depth, the ratio Fe\textsubscript{px}/Fe\textsubscript{ox} does not show corresponding or anomalous behavior.

When coupled with total Fe (Fe\textsubscript{tot}), it is possible to calculate the relative age of soil formation using the function Fe\textsubscript{px}/Fe\textsubscript{tot} (Mahaney et al., 1999, 2010) which measures the slow release of goethite + hematite + ferrihydrite with time. Similarly the arithmetic function Fe\textsubscript{px} − Fe\textsubscript{ox}, normally used to calculate the approximate concentration of goethite plus hematite minus ferrihydrite, can be used with certainty in this instance. Lattice Fe (Fe\textsubscript{latt} − Fe\textsubscript{ox}), which diminishes with age, should be inversely related over time barring redox fluctuations caused by a drop in the water table.

Within the Al extract group, the concentration Al\textsubscript{px} acts as a proxy for organic carbon and the ratio Al\textsubscript{px}/Al\textsubscript{tot} may be used to test movement within a section or profile. Thus, increases in Al\textsubscript{px} down-profile are approximated with translocation of organic carbon, which remains one of the principal tests of a spodic horizon in Spodosols (Podzols) (Soil Classification Working Group, 1998; NRCS, 2004). Extracts of Fe and Al are used here, along with other mineral and chemical data, as age and paleoenvironmental indicators for the weathering of sediments in the oldest Early Quaternary moraine complex on Mount Kenya (Fig. 1a location; Fig. 1b topography). These residual chemical parameters also establish relative weathering indices between buried and relict paleosols and test organically-complexed Al as a proxy indicator of movement of organic carbon from surface epipedons for both relict (exposed) and buried profiles into subsurface horizons. Since the arithmetic function Al\textsubscript{px} − Al\textsubscript{ox} is considered a proxy for total allophane and imogolite (Parfit and Childs, 1988), these two common poorly crystalline clay mineral concentrations were monitored down section at the three sites. Because both allophane and imogolite have been shown to undergo high rates of release in tephra-rich sediment (Hiradate et al., 2010), the trend of these common aluminosilicate weathering products from the top (low tephra) to bottom (higher tephra) in the three sections analyzed here, was established to test inferred allophane/imogolite distributions.

Furthermore, given the local stratigraphy and chronology established by Mahaney et al. (2013a), a test of climate and time factors on weathering and their influence on soil/paleosol morphogenesis is attempted.

2. Regional geology

Mount Kenya, part of the Central Plateau of East Africa, is a volcanic center with an intense and complex tectonic history since its inception during the Early Miocene (Baker, 1967; Schluter, 1997). The Eastern Rift valley of Neogene age follows an older Cretaceous rift lineament, with lavas issuing from fractures producing major mountains such as the Aberdares and Mount Kenya with the summit for the latter just over 5100 m asl.

The Mount Kenya massif is a volcanic succession with a thickness of ~6200 m overlying the African basement series (Baker, 1967; Vernacome, 1983; Ries et al., 1992). Outpourings of Late Miocene to Pliocene mafic volcanics, sourced from the mantle (Rogers, 2006; Dawson, 2008), were accompanied by eruption of tuffs and agglomerate in the early phase of mountain building. The mountain entered a major constructive phase by mid-Pliocene time, undergoing a final eruption of the main vent at ~2.71 Ma (Veldkamp et al., 2007), the later event coinciding with net upwarding of the Eastern Rift Valley. Mount Kenya must have been close to its present elevation or higher to allow glaciation to start by ~2.0 Ma or before (Mahaney, 1990). Estimates of erosion of the summit area of the mountain vary from >2000 m (Gregory, 1921) to <1000 m (Mahaney, 1990) but the present valley floors were well incised by the time of the Olduvai Event (~2 Ma). The mountain has been stable since Late Pliocene time with minor faulting showing offsets of only tens of meters (Mahaney et al., 2011).

The history of glaciation on Mt. Kenya is extensive. The oldest glaciations named, from oldest to youngest, Pre-Gorges, Gorges and Lake Ellis [Fig. 1 (Mahaney, 1990; Mahaney et al., 2013a)], are known only from moraines on the eastern (Gorges Valley, Fig. 1a, b) and southeastern flanks of the mountain and are important in the context of this study because they represent the early stage of glacial growth on one of the highest tropical mountains on Earth. Herein, normally magnetized glacialic sediments and bedrock with reversed overprints are, in turn, overlain with either reversed or normal beds/horizons considered to represent the Olдуvai subchron with late Matuyama overprints. The inherent test here involves a correlation of paleomagnetic data (Mahaney et al., 2013a) against characteristics of the paleosol profile and chemical signatures of Fe/Al extracts as indices of weathering and translocation.

Is the long punctuated weathering history of these multistory pedostratigraphic complexes coeval with the paleomagnetic chronology? Are loess-stripping/deflation episodes (Barendregt and Mahaney, 1988; Mahaney et al., 1997) as described in other similar-age profiles from this region recognizable in this paleosol sequence or are they different? These are some of the questions that prompted the analyses described below.

3. Materials and methods

On Mt. Kenya, sample pits were excavated and cleaned back to expose fresh sediment in the oldest terminal moraine system in Gorges Valley (Fig. 1). Of the 26 sections of Gorges-age moraine examined on the eastern flank of the mountain, three (GOR64, 68, 69) were selected in lower Gorges Valley for detailed pedological, petrographical and chemical analyses, as reported here. The soil descriptions used are genetic and follow guidelines set out by the NRCS (2004, and Soil Survey Staff, 2010). Some exceptions in horizon nomenclature apply here insofar as horizon designations follow the Canadian system (i.e. Ah for humus rich A horizons), Cox for oxide-rich C horizons (Birkeland, 1999). The ‘ox’ designation implies a yellow-reddish color stronger than 10YR 5 or so. The designation ‘m’ refers to cemented material (Schonebecker et al., 2002; Soil Survey Staff, 2010). Soil color assessments follow the color chip system of Oyama and Takehara (1970). At least 500 g samples were collected from each horizon in each section to allow for particle size, clay mineral, and geochemical analysis of total Fe and Al. Particle size analysis followed procedures outlined by Day (1965). Samples were wet sieved to separate sands from clay plus silt, the sands subsequently dried and weighed out to the nearest hundredth of a gram. The silt/sand boundary of 63 μm follows the Wentworth scale; the silt/clay division used is 2 μm (NRCS, 2004).

Organic carbon was determined by loss on ignition (LOI) at 400 °C after 15 h following procedures outlined by USDA (NRCS, 2004); while total N was measured by Leco CHN Autoanalyzer. Total C and CEC were cross-checked with organic C to ensure no carbonate was present. Cation exchange capacity (CEC) was determined by the ammonium acetate method of Pfeeh et al. (1947) and Schollenberger and Simon (1945). The pH of the <2 mm fraction was determined by electrode on a 1:5 solution (10 g mass:50 ml distilled H\textsubscript{2}O) and the concentration of total salts by conductivity (Bower and Wilcox, 1965).
The Fe₄ and Al₄ extractions were made from 1 g (<2 mm fraction) subsamples, with sodium dithionite, as well as Na-citrate buffers releasing crystalline, amorphous, and organically-bound forms of Fe and Al, following criteria set out by Coffin (1963). Processed in the dark, to avoid photo-oxidation, acid ammonium oxalate was used to extract ferrihydrite (Parfit and Childs, 1988) following McKeague and Day (1966). Subsequently, concentrations of Fe and Al were determined by atomic absorption spectrophotometry (AAS) using a Perkin Elmer 373 instrument, calibrated with appropriate bracketing standards. Instrumental neutron activation analysis (INAA) followed methods identified by Hancock (1984) to measure total Fe and Al in the <2 mm fraction of the soil samples. XRD analysis of the <2 μm fraction using oriented mounts followed methods outlined by Whittig (1965).

Sediments were sampled for paleomagnetic analysis by pressing plastic cylinders (2.5 cm diameter) into clean vertical faces. Remanent magnetization was measured using a JR-5A spinner magnetometer (Agico, Brno). Stepwise alternating field demagnetization (10–100 mT) proved sufficient to magnetically cleanse the specimens. Viscous normal
overprints were removed by 20 mT demagnetization, following methods outlined in Nelson et al. (2009) and Duk-Rodkin et al. (2010). Data were compiled in Excel spreadsheets that were later exported to Statistica 10.0 for more detailed and precise statistical analyses. After this stage, charts were plotted and correlations attempted.

4. Results

4.1. Stratigraphy

The three pedostratigraphic sections (Fig. 2) consist of two profiles each: one at the surface representing sediment exposed for variable lengths of time following cessation of the Gorges Glaciation at some unspecified time but presumably during or just after the Olduvai Event (ca. 1.8 Ma); the second, a buried suite of paleosols in weathered bedrock or till pre-date the Olduvai Event, the latter referred to as the pre-Gorges Glaciation (ca. 1.8 Ma). Till thicknesses vary from just over a meter to less than 0.5 m and presumably represent a minimum for the original deposits. Truncated boundaries between surface and buried paleosols are considered to represent erosion during glacial oscillations. At one of the sections ([GOR68]) [Fig. 2], a glacial outwash (3Cox horizon) is present, whereas in others it is missing. The magnetostratigraphy of these sections is described in Mahaney et al. (2013a) and the history of glaciations and magnetostratigraphy of glacial/interglacial sediments and paleosols on Mt. Kenya are outlined in Barendregt and Mahaney (1988), Mahaney (1990) and Mahaney et al., 1997).

Within the lower buried profiles, paleomagnetic analysis (Fig. 2) depicts either older Ahb horizons, some with reversed overprints (GOR64 and 69), or one (GOR68) which is normally magnetized and probably dates to the Olduvai subchron of the Matuyama Reversed Chron (~ 1.8 Ma). The lack of a reversed overprint in the surface profile of GOR68 is difficult to explain given the weathered grains resident there but may be related to pervasive deflation or to lower initial Fe content. Despite the lack of an s-shaped curve in particle size curves for the Ahb horizons, their silty compositions (Fig. 3a–c) and lack of pebbles are taken to indicate a largely aeolian origin. Below these uniformly thin Ahb horizons, subsurface horizons are either composed of weathered bedrock (GOR64, GOR69) or weathered till (GOR68), the latter possibly a signature of a pre-Olduvai (Pre-Gorges) glaciation. The lowermost horizon in GOR68 reveals stratification indicating a waterlain till (Fig. 2). Given the fact that paleomagnetic measurements can be readily obtained from these sediments (Barendregt and Mahaney, 1988; Mahaney, 1990; Mahaney et al., 2013a), till deposition must have been of a less viscous nature, perhaps not that of a liquid slurry as evidenced by the sediment character of the 5Coxbm horizon, but certainly with a sufficient water content allowing magnetic grains to become oriented in the earth's ambient field at the time of deposition.

Of primal importance is the presence of Bt horizons in both GOR64 and GOR69, which signals downward translocation of clay during pedogenesis, a process that could only occur with the presence of continuous forest implying a higher timberline and a more humid microclimate than today. The horizons are thin but nevertheless heavy with clay, quite in contrast to GOR68, which carries a buried B horizon complex.
complete with etched and corroded grains but without any evidence of clay movement.

The relative ages of loesses, paleosols, and tills described here were established by paleomagnetic analysis and are shown to range from the early Matuyama (2.6 Ma) for the initial stages of weathering, to the mid-Matuyama for the initiation of major glaciations on the mountain. The Gorges glaciations and associated interglacial deposits range in age from the mid-Matuyama to the early Brunhes Chron (~0.78 Ma). These relative ages can be further tested by examining variations in concentrations of \( \text{Fe}_2/\text{Fe}_3 \), as well as other mineral and chemical trends.

4.2. Profile morphology

The three sections reveal similar stacks of profiles, the surface paleosols consisting of admixtures of aeolian-influxed sediment marked by Ah horizons forming surface pedon epipedons. Below, the B and C horizons are comprised either of till (GOR64 and GOR69), or till and/or outwash (GOR68). Grouped together, the surface profiles represent the bulk of sediment weathered over a period of \(<2.0\) Ma. Below, in the buried units, similar successions of 3Ahb (GOR64 and GOR69) and 4Ahb (GOR68) horizons consist of loess overlying buried B and C horizons of weathered till (GOR68) or weathered bedrock (GOR64 and GOR69). The loessic input in the Ahb horizons is either apparent from higher silt content (GOR64; Fig. 3a, GOR68; Fig. 3b) or from translocation of silt downward into B and C horizons (GOR69).

Surface epipedons (Ah horizons) show considerable complexity with various horizon splits. The particle size analysis (Fig. 3a, GOR64; Fig. 3b, GOR68; Fig. 3c, GOR69) of these horizons shows considerable clay content (4–38% but generally 15–38%) with high organic carbon content of \(~10–12\%\) (detailed in the chemistry subsection below), much of which is inert to attack by 10% HCl, and is presumably lignin rich (Mahaney et al., 2013a). Mean phi calculations of particle size distribution curves (Fig. 3a–c) show various shifts depicting clay movement of different magnitude, sometimes within the Ah horizon group (GOR64; Fig. 3a) and always in the Btb horizons of GOR64 and 69. Otherwise mean particle size centers between 5 and 7 phi (with occasional variations of 1–9 phi) depending on weathering intensity. Soil structures are granular in the Ah horizons but below that any original structure has been destroyed by compaction over a long time interval. The high clay content insures variations of firm moist consistence within this group of samples along with near to full plasticity and slight to very sticky properties. The B horizon group carries the subscript ‘w’ to suggest

Fig. 3. Particle size distributions and mean particle size calculations: a, GOR64; b, GOR68; and c, GOR69. Particle size distributions down-profile in each paleosol provide a measure of clay production per the lower vs. the upper paleosol groups. Trends indicate degrees of aeolian contributions in the Ahb horizon group compared with surface epopedons. Mean particle size calculations and trends in each profile are useful for gauging degrees of clay production and translocation.

Please cite this article as: Mahaney, W.C., et al., Mineralogy and chemistry of Late Pliocene–Early Pleistocene paleosols on Mount Kenya: Weathering indices of relative age and paleo..., Geomorphology (2013), http://dx.doi.org/10.1016/j.geomorph.2013.08.006
In addition to VRFs, volcanic phenocrysts are common with lesser plutonic material being aphanitic volcanic rock fragments (VRFs) and tephra. In preservation of magnetite in these samples, the dominant source is charcoal. Considerable variability exists in the magnetic strength and traces to a few percent of organic matter, partially mineralized in some samples. Calcite is rare and microscopically detected by the occasional faint acid reaction which follows from the chemical analysis carried out on the bulk sample (<2 mm fraction; Table 2A). Clay balls and limonite concretions readily disaggregate or gelatinize and bleed/leach in acid.

The degree of preservation of organic matter is exceptional, especially in the Ahb horizons where recovered specimens are not readily hydrated and show no reaction to HCl. Recognizable fragments of stems, twigs, needles and bark appear as lignin-rich entities very resistant to chemical attack. Some samples might be reworked (down-worked) surficial materials, previously dried out and resistant to microbial degradation or they may have formed in place from long-term weathering in situ.

Within the surface profiles of the three sections, the soil epipedons (Ah group of horizons) are dominated by polycrystalline aphanitic VRFs comprising variable mixes of plagioclase in groundmasses of dark glass with traces of pyroxene and magnetite. Many grains appear as residual phenocrysts weathered away from more reactive glass or finer grained materials. The sands carry 5 to 10% residual, dark carbonized plant matter, an amount similar to what is reported below in the chemical analysis of the bulk fraction. Only a small percentage of detrital grains and VRFs are attracted to a magnet. Aside from somewhat higher Fe-oxide patinas on grains in GOR69, the samples contain a higher proportion of magnetic grains. The sands in the GOR68-Ah group are more highly weathered grains with a greater percentage of clay coatings and detrital quartz is more common along with black woody charcoal.

Analysis of the B/C group of horizons in the upper paleosols reveals variable percentages of magnetic grains and black VRF particles, the majority comprising residual feldspar and quartz. The magnetic fraction includes yellow coated grains with iron oxyhydroxides and traces of carbonized plant matter. In some cases (GOR69) etched sand grains are more common and in the lower Cb horizon grains are more highly etched and corroded. In GOR68, VRF grains are more vesicular than in the other two profiles with linings of clay and opaline silica. Some quartz grains are rounded, partially coated with black Fe/Mn oxyhydroxide rinds but because they are common only to quartz they may represent an admixed pre-weathered component. Rinds on sands carry fine laminar-archival records similar to more robust weathering rinds on surface clasts, many of the latter carrying complex biomineralization (Mahaney et al., 2013b).

The buried Ahb epipedons are a class unto themselves in that they contain abundant dark olive brown sands (GOR64) with many organic coated VRFs and abundant tuff and tephra particles. Because of the dull surface luster of many grains this sample appears more highly weathered compared with the Ah horizon above. GOR64 also contains a high percentage of magnetic grains with less reaction to acid. In contrast the GOR69-3Ahb presents a more vigorous reaction, an observation supported by the Feo concentration reported in Table 3 below. However the degree of release of oxyhydroxides appears similar to GOR64-3Ahb. The GOR68-4Ahb is different again, being comprised largely of volcanic tephra with reddish particles that may have been oxidized, with glass showing appreciable coatings of orange Fe-oxide oxyhydroxides. Quartz is rare and black charcoal comprises less than

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Fig. 3 (continued).

4.3. Sand petrography

Analysis of the sand fraction by petrographic microscope revealed traces to a few percent of organic matter, partially mineralized in some instances with cellulose and lignin, tough protein-sheathed seeds and charcoal. Considerable variability exists in the magnetic strength and preservation of magnetite in these samples, the dominant source material being aphanitic volcanic rock fragments (VRFs) and tephra. In addition to VRFs, volcanic phenocrysts are common with lesser plutonic and metamorphic rock fragments, the latter presumably from the underlying African basement complex. Most of this material might be reduced in size and weathered but is not pervasively altered to clays and residual oxides, at least insofar as clay/oxide coatings exist in the sand fractions. These fractions are fine enough to have been derived from xenoliths which are common in mafic to intermediate tephras. Many grains exhibit variability in their preservation from fresh to weathered, which is the hallmark of reworked weathered sediment mixed with fresh aeolian delivered allochthonous grains and grains with weathered armored surfaces. Calcite is rare and microscopically detected by the occasional faint acid reaction which follows from the chemical analysis carried out on the bulk sample (<2 mm fraction; Table 2A). Clay balls and limonite concretions readily disaggregate or gelatinize and bleed/leach in acid.

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Within the buried B/C horizons, weathered brown to light orange colored sands clustered about the 500 μm grade size (GOR68) are highly oxidized, with glass showing appreciable coatings of orange Fe-oxide oxyhydroxides. Quartz is rare and black charcoal comprises less than

Please cite this article as: Mahaney, W.C., et al., Mineralogy and chemistry of Late Pliocene–Early Pleistocene paleosols on Mount Kenya: Weathering indices of relative age and paleo... Geomorphology (2013), http://dx.doi.org/10.1016/j.geomorph.2013.08.006
4.5. Soil chemistry

The pH of the surface profiles (Table 2A) in the three sections shows some variation down-profile with profiles GOR64 and GOR68 showing strong acidity in the Ah group trending with minor overlap toward moderate acidity with depth to the contact with the buried Ah horizons. GOR69 grades from strong to moderate acidity with depth in the upper epipedon, thereafter with depth becoming strongly acidic. The buried profiles react somewhat differently with depth where the Ahb horizons range from very strongly acid to neutral becoming slightly to moderately acid (GOR64, GOR68) or very strongly to moderately acid (GOR69) with depth. In part, total salt data derived from conductivity analysis supports the pH with slight elevations where fresh organics at the surface are under decomposition, but for the most part, the electrical conductivity indicates a well-leached paleosol succession. Soil color, a common indicator of organic and Fe content, supports the different grades of acidity indicated by the range of pH and the well leached status of the profiles, both surface and buried. What is most apparent from the variation of hue is the stronger reddish color in the surface profile of GOR68 relative to GOR64 and GOR69, which is most probably a reflection of variable soil moisture or plant cover over time. The color intensity and chroma (Oyama and Takehara, 1970) indicate stronger organic inputs in GOR64 and GOR68 compared with GOR69, a trend correlating with organic carbon trends shown below in Table 2B. Color trends in the buried profiles show little relation to pH but hues darken with an increase of organic content.

The chemistry (Table 2B) of the three sections shows relatively high contents of organic carbon in the surface Ah horizons (range ~7–11%), which indicates the total percent organic matter in the soil matrix probably exceeds ~10–15% overall. Interestingly, organic carbon values are also high again in the Ahb horizons suggesting, either that carbon is translocated to depth in the surface profiles replenishing organic compounds in the buried Ahb horizons, or that the original carbon is long-lived, perhaps lignin-rich and extremely robust in the face of weathering energy as indicated in the petrographic analysis. Total C is

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### Table 1

Mineralogy of the clay fraction of the GOR paleosol succession.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>H</th>
<th>I</th>
<th>Q</th>
<th>Gi</th>
<th>He</th>
<th>Go</th>
<th>Ptx</th>
<th>Mt</th>
<th>Pl</th>
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<tbody>
<tr>
<td>GOR64</td>
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<td>n</td>
<td>t</td>
<td>t</td>
<td>n</td>
<td>t</td>
<td>t</td>
<td>n</td>
<td>t</td>
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<tr>
<td>Ah1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>t</td>
<td>t</td>
<td>t</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Ah2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>t</td>
<td>t</td>
<td>t</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2Bw1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>t</td>
<td>t</td>
<td>t</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2Bw2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>t</td>
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<td>t</td>
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<td>t</td>
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<td>x</td>
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<td>2Coxz</td>
<td>t</td>
<td>t</td>
<td>t</td>
<td>t</td>
<td>x</td>
<td>t</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
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<td>t</td>
<td>t</td>
<td>x</td>
<td>t</td>
<td>x</td>
<td>x</td>
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<tr>
<td>4Btb</td>
<td>t</td>
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<td>t</td>
<td>x</td>
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<tr>
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<td>t</td>
<td>t</td>
<td>t</td>
<td>x</td>
<td>t</td>
<td>t</td>
<td>x</td>
<td>x</td>
</tr>
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</table>

### Table 2A

Selected physical characteristics, pH and total salts (EC) in the GOR succession, Mount Kenya.

<table>
<thead>
<tr>
<th>Site</th>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>pH (1:5)</th>
<th>EC’ (mS/cm)</th>
<th>Color</th>
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<tbody>
<tr>
<td>GOR64</td>
<td>Ah1</td>
<td>0–21</td>
<td>5.3</td>
<td>.33</td>
<td>7.5YR 2/1</td>
</tr>
<tr>
<td>Ah2</td>
<td>21–36</td>
<td>5.3</td>
<td>.16</td>
<td>7.5YR 3/1</td>
<td></td>
</tr>
<tr>
<td>Ah3</td>
<td>36–52</td>
<td>5.4</td>
<td>.12</td>
<td>7.5YR 3/2</td>
<td></td>
</tr>
<tr>
<td>Ab4</td>
<td>52–69</td>
<td>5.5</td>
<td>.03</td>
<td>7.5YR 2/2</td>
<td></td>
</tr>
<tr>
<td>2Bw1</td>
<td>69–91</td>
<td>5.5</td>
<td>.02</td>
<td>7.5YR 3/4</td>
<td></td>
</tr>
<tr>
<td>2Bw2</td>
<td>91–107</td>
<td>6.0</td>
<td>.02</td>
<td>7.5YR 4/4</td>
<td></td>
</tr>
<tr>
<td>2Cox1</td>
<td>107–170</td>
<td>6.1</td>
<td>.02</td>
<td>7.5YR 4/3</td>
<td></td>
</tr>
<tr>
<td>2Cox2</td>
<td>170–210</td>
<td>7.2</td>
<td>.02</td>
<td>7.5YR 5/2</td>
<td></td>
</tr>
<tr>
<td>3Abh</td>
<td>210–220</td>
<td>6.3</td>
<td>.02</td>
<td>7.5YR 4/4</td>
<td></td>
</tr>
<tr>
<td>4Btb</td>
<td>220–235</td>
<td>5.9</td>
<td>.03</td>
<td>7.5YR 4/4</td>
<td></td>
</tr>
<tr>
<td>4Cbx</td>
<td>235+</td>
<td>5.7</td>
<td>.02</td>
<td>7.5YR 5/4</td>
<td></td>
</tr>
</tbody>
</table>

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**Notes:**

- Minerals are halloysite (H), illite (I), quartz (Q), gibbsite (Ga), hematite (He), goethite (Go), pyroxene (Px), magnetite (Mt) and plagioclase (Pl). Semi-quantitative mineral amounts are calculated as follows: = nil, tr = trace, x = small amount, xx = medium and xxxx = abundant.

- **Electrical conductivity.**
sometimes up to 1% greater than organic C, possibly the result of carbonatite minerals, as otherwise it is not likely calcite could withstand the acidic pH of the soil microenvironment. Occasionally, it appears that minor instrument error or interference from other volatile elements may be to blame for organic carbon values in slight excess of total carbon. As expected, total N percent tends to follow organic carbon.

The pH trends differ slightly among the three surface profiles, from strongly acidic in the surface horizons becoming moderately acidic with depth. In the older profiles below, the Ahb horizons show considerable variability from very strongly acidic in GOR69 and moderately acidic (GOR68) to slightly acidic (GOR64). The lowermost B and C horizons depict only slight pH variation in GOR64, values rising somewhat in GOR68 and 69.

The down-section CEC data (Table 2B) in each profile depict trends showing higher values in the surface epopedon group (Ah horizons) and in the Ahb horizons reflecting high organic carbon contents. Otherwise, in the surface profiles Bw/C horizons, lower CECs reflect the Si:Al (1:1) clay content of metalhalloysite, values trending higher in the Bwb horizons in response to increased clay content. The standard test of removing the organic carbon influence on CEC (CEC/100 g clay; Birkeland, 1999) would simply reduce all values to <20 supporting the clay mineralogy discussed above. As a weathering index (Martini, 1970), the CEC/clay ratio was not used in this case because of the high organic matter content (Bloesch, 2012) resident in both the surface and buried profiles.

4.6. Fe and Al extracts

The raw data for Fe and Al extracts are given in Table 3. The Feo distributions show relatively low concentrations down the surface profiles with slightly elevated levels in the Ah horizons, increasing into the buried profiles by ~150%. The exact composition of material in the Feo extract is unknown but XRD data on a number of samples establish that crystalline material is part of the load (Mahaney unpublished). The Feo distribution, without adjustment to ferrhydrite, yields lower levels in the surface profile epopedons increasing incrementally into the buried profiles. Because magnetite is thought to react with acid ammonium oxalate (Walker, 1983), and petroglyphic analysis of the sand fraction indicates an increase of magnetite in the lower profiles of all three sections, part of the increase in Feo may result from laboratory preparation or from the flux of perched water over bedrock (GOR64, 69) and the one cemented Coxb horizon (GOR68). However, a portion of the increase in Feo with depth still suggests greater production of ferrhydrite in the lower profiles compared with the surface counterparts, even if the exact concentrations are in doubt. As expected from the Feo trend, Fed tends to follow a similar pattern although with higher concentrations. While the Alo concentrations, taken alone and gauged down-section in all three sites, tend to correspond to nearly uniform distributions of organic carbon or increases of organic carbon in buried Ahb horizons. The real test of Alp translocations can only come from normalizing the values with Alb and comparing the data with the organic carbon database in Table 2B.

The principal function of the Fe extract ratio Fed/Fet (Table 4) is to quantify the relative age of weathered sediment via the slow gradual increase of secondary Fe to total Fe. Correlating Fed values with the twin profiles in each section, it is obvious that age-quotients in the epopedons of the surface profiles have similar values to the understory
horizons extending with depth to the Ahb horizons. There are variations where the quotient drops (GOR64) with depth in the Ah horizon complex, whereas in others (GOR68) it rises, or remains uniform (GOR69).

Within the Bw group of horizons in the surface profiles, Fe₀ while elevated, is seen to remain uniform (GOR64, GOR69), or increase with depth (GOR68), the latter signifying an increase in age. Within the buried profiles, Fe₀ is either elevated (GOR64, GOR69) compared with the surface profiles, or remains relatively the same (GOR68). To some degree the increase in Fe₀ is registered by stronger yellow–red colors (Table 2A) as in GOR64 and 69 while in other cases (GOR68) colors vary somewhat but remain essentially the same throughout.

Taking the paleomagnetic data (Fig. 2) for each of the horizons by groups (Gauss, Olduvai and < Olduvai/Upper Matuyama), as outlined by Mahaney et al. (2013a), and calculating the median value of Fe₀/Fe₀ for each group (Fig. 4), produces a trend line depicting a slow rise from the surface profiles of 0.5 to buried units reaching 0.65. The difference of 0.15 in median quotients represents greater weathering energy during pre-Olduvai time. While the normal magnetization obtained from the surface epipeds (Ah group) of GOR64, and the complete surface profiles of GOR68 and 69 plus the lower 4Ahb horizon, might relate to the Olduvai and any of the younger normal events (Jaramillo, Brunhes), it is placed within the Upper Olduvai on the basis of weathering criteria outlined here. Despite the large range of Fe₀/Fe₀ in the youngest normally magnetized (< Olduvai/Upper Matuyama) group, its close correlation to the median value of the Olduvai group indicates a similar median age, the large range likely a product of recycling of the mobile fine grain material in this highly charged aeolian Afroalpine environment. Interestingly, the range of Fe₀/Fe₀ observations around the median values in the Olduvai and Gauss groups is significantly less, possibly the product of reduced aeolian activity which fits with the expected reduction of preglacial katabatic wind circulation and higher elevation of the timberline.

As a further test of age, the calculated concentration of ferrihydrate (Fe₉₀) (Table 4) shows a staggered increase in GOR64 — lower in the surface epipeds (Ah group), plateau increase of 150% to near 200% in the Bw/Cox group, leveling off in the buried profile (3Ahb/4Bhtub horizons). Again, a similar trend to GOR64 is evident in GOR69. The trend in GOR68 is different, since concentrations decline with depth in the surface profile, increase in the buried profile and decline again in the very bottom horizons. In all, the Fe₉₀ while slightly elevated from extract preparation, tends to follow the distributions of Fe₀ observed in the petrographic analysis of the sand fractions. The distribution of Fe₉₀ parallels that of Fe₀/Fe₀, corroborating two distinct populations of weathered sediment, a group with higher elevated indices comprising the lower profiles and a group with slightly lower indices which is not as weathered in the surface profiles.

A weathering index of the effect of climate and time on Fe release is inherent in the arithmetic relationship of Fe₀ — Fe₉₀, the intent being to measure the amount of lattice Fe remaining in a sample. Since SEM/EDS (Mahaney et al., 2013a) and petrographic investigations of large populations of grains per horizon indicate a near uniform lithology within the upper profiles in each section with a 20–30% increase in Fe minerals with depth, the expectation is that at least in the upper profiles, lattice Fe should reflect leaching/weathering with depth. Overall, lattice Fe in the surface epipeds remains above 2% and is relatively constant in GOR64, GOR69, whereas in GOR68 it greatly declines in Ah1, leveling off in the lower epipeds. Within the Bw/Cox group of surface horizons there are minor variations again in GOR64 and GOR69 as lattice Fe increases relative to the overlying Ah group, which suggests the Ah horizons are not only acid makers but long-lived ones as well. GOR68 stands apart again with lower lattice Fe, presumably since it is more aggressively weathered and leached. Within the buried profiles, Fe₉₀ is higher in GOR64 and 69 reflecting higher Fe in the bedrock compared with GOR68 which comprises a till with a mix of lithologies including additional quartz. Correspondingly, lattice Fe is higher in GOR64 and GOR69 and lower in GOR68 with the exception of the 5Coxbmb horizon.

A measure of the translocation of Al, the ratio Al₉₀/Al₀ shows nearly uniform distributions in the upper profiles with only very slight movement in the epipeds of GOR64. In the buried profiles slight increases in some Ahb horizons may reflect the relatively high organic carbon values (approximately 4–6% or about half the normal values in the Ah1

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**Table 4**

Fe and Al extract functions for pedostratigraphic successions in the Gorges Moraine of Late Pliocene/Early Pleistocene age. Individual extracts are in percent calculated from data in Table 1.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>Fe₀/Fe₉₀</th>
<th>Fe₉₀/Fe₀</th>
<th>Fe₀ – Fe₉₀</th>
<th>Fe₀/Fe₉₀</th>
<th>Al₉₀/Al₀</th>
<th>Al₀ – Al₉₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOR64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ah1</td>
<td>0–21</td>
<td>0.53</td>
<td>0.24</td>
<td>2.14</td>
<td>0.46</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>Ah2</td>
<td>21–36</td>
<td>0.47</td>
<td>0.25</td>
<td>1.92</td>
<td>0.61</td>
<td>0.11</td>
<td>0.01</td>
</tr>
<tr>
<td>Ah3</td>
<td>36–52</td>
<td>0.48</td>
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<td>2.01</td>
<td>0.49</td>
<td>0.13</td>
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</tr>
<tr>
<td>Ah4</td>
<td>52–69</td>
<td>0.47</td>
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<td>0.50</td>
<td>0.10</td>
<td>0.15</td>
</tr>
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<td>0.25</td>
<td>2.96</td>
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<td>0.59</td>
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<td>0.07</td>
<td>0.01</td>
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<td>0.39</td>
<td>2.62</td>
<td>0.63</td>
<td>0.13</td>
<td>0.12</td>
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</table>

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**Fig. 4.** Box plot averaging out medians for three groups of horizons, ages determined partly from weathering criteria and partly from paleomagnetic data. Polynomial regressions of Fe₀/Fe₀ ages, the latter averaged for Gauss (2.6 Ma), Early Olduvai (2.0 Ma), and Late Olduvai (~1.8 Ma). Three groups of horizons in three paleosol sections show average Fe₀/Fe₀ values of between 0.5 and 0.65, as indicated by a trend line, with one outlier (GOR68-Ah1) which must comprise greatly reworked Fe minerals. The wide standard deviation in the younger group of samples is probably partly due to organic dilution in the Ah horizons (less a factor in the older Ahb horizons due to hydrolysis) or to reworking of older weathered sediment.
horizons of the surface paleosols). Movement of organic carbon is not registered in either of the two Bt6 horizons in GOR64 and GOR69 despite the movement of clay. The very low values of Alp likely reflect microbial activity with a nearly stony soil temperature estimated to be about ~8 °C, nearly unvarying throughout the year (Mahaney, 1990).

Concentrations of Alp vary somewhat erratically and tend to increase in the Ahb horizons. Similarly, crystalline AI by – Alp – depicts an erratic trend with depth in the profiles. While Alp was formerly considered to amount to secondary AI oxides (McKeague and Day, 1966) it often exhibits lower values than amorphous AI (Alt). Because the Alp values obtained here often exceed the crystalline AI (Alt) concentrations, only the latter are used in soil classification studies (NRCS, 2004). As reported elsewhere (Parfitt and Childs, 1988; Birkeland et al., 1989; Mahaney, 1990; Mahaney et al., 1999) it appears that Na-dithionite is unable to extract all secondary crystalline AI. However, Parfitt and Childs (1988) consider Alp – Alt to approximate released allophane plus imogolite, two widespread but poorly crystalline aluminosilicate products. While calculations of this arithmetical function appear staggered through the sections (Table 4), depicting nil to 0.3% in the surface paleosol profiles, values increase markedly in the lower buried profiles from nil to 2.2%. The significance of the Al profile variation is that some horizons appear to have been more chemically active than others and also that the older buried profile in GOR64 may, in fact, be younger than GOR88 and GOR95, as suggested somewhat by the topographic displacement of moraine fronts shown in Fig. 1a.

5. Discussion

Unlike other paleosol sequences (Mahaney et al., 1999; Schülli-Maurer et al., 2007) where Feo/Fe values increases with time in a chronosequence, the data presented here show two populations of paleosols in the GOR group: upper and lower, with the upper group containing reworked material from below and from other surrounding well weathered sites. In a two-dimensional sense, reworking of material from below into the upper profiles may be related to deflation prior to the ingress of glacialation, but in a three-dimensional sense, material could be translocated laterally within horizons and in tandem with groundwater fluxes. The increase of Feo in the lower horizons might be partly due to an increased content of Fe-bearing minerals, loss of Si from leaching and/or a more humid and warmer preglacial climate. This trend is paralleled by a sharp increase in Feo in the lower profiles, which is a product of additional ferrhydrite release and/or sample preparation. Spikes in the concentration of Feo with depth (Mahaney and Fahey, 1988) in any of the profiles may well signal strong reducing conditions with perched water at some time in the past and/or fluctuations in maginitic content of the parent materials. The Feo trends in all three sections are only interrupted with ‘spikes’ in the SBwb1 horizon of GOR68, possibly the 3Ahb horizon of GOR69 and the 4Bth horizon of GOR64, all known to have higher magnetite, thus confirming their data could result from sample preparation. Otherwise the Feo trend with depth in all three profiles is one of slow decline with depth away from the acid producing Ah and Ahb horizons followed by an increase in the buried profiles. Clearly this is a situation where length of weathering time (surface pedons >2.0 Ma) comes close to equaling weathering in a buried suite of older paleosols (buried pedons) forming in a warmer and presumably wetter climate over a much shorter time frame (~0.5 Ma).

Variations in lattice Fe (Feo – Feo) may have involved reworking of old grains into younger epipedons (i.e. GOR68-Ah1), whereas in other profiles the surface epipedons are slightly lower in lattice Fe or about the same as compared with the subsurface horizons. The GOR69 profile shows a reduction of lattice Fe in the Ah1 followed by increases below in the upper profile, presumably a response to increased weathering in the surface or incorporation of pre-weathered materials by aeolian influx. Within the lower profiles, lattice Fe shows either a sharp reduction in the Ahb horizons (GOR64, GOR69) compared with the Bt6 horizons below or a slight reduction with a slow increase into the bottom of the profile (i.e. GOR68). In all, considering the greater loss of lattice Fe in the lower group of paleosols, the data argue for well-weathered sediment with high ratios of Feo/Feo, the result of a long and variable weathering trend, first under a warmer and more humid preglacial climate followed by episodic weathering, faster under interglacial climates and slower under glacial ones. Even given increased Feo in the lower profiles, whether straight from bedrock (GOR64, GOR69) or mixed with glacial debris (GOR68), the early and largely pre-Olduvai weathering episode was shorter than the post-Olduvai Event but appears to have been influenced by a more aggressive paleoclimate in the former which supports previous microscopic and chemical (SEM/EDS) investigations of Mahaney et al. (2013a). The Fe data further suggest that some pre-weathered grains in the lower profile found their way into the upper profile either by glacial mixing or by aeolian transport.

The Alp data strongly suggest little release of organically-bound Al which is curious because of the inordinately high Alp throughout. High Al might result from Si leaching, and given the high rate of etching and corrosion (Mahaney et al., 2013a) seen throughout all three sections, it is likely Si removal has increased the concentration of Alp. Little Alp also might be attributed to microbial action over time. Calculations of goethite/goethite + hematite made by Kämpf and Schwertmann (1983) in tropical soils showed that goethite is more responsive to moisture, organic carbon and low pH whereas higher temperature favors the formation of secondary hematite. Analysis of the raw data in the GOR sequence shows that Feo/Feo values increase with depth into the lower profiles in all three sections with some reworking of weathered products from the buried unit into the ground paleosol (upper unit). Presumably, these values are underestimations if one accepts the magnetite/oxalate overestimation of Feo but the data do indicate an excess of hematite over goethite, a trend supported by the XRD analysis of the clay fraction (Table 1). While the 3000 m elevation on Mount Kenya is not inherently a kaolinite-forming climate, XRD analysis of the clay fraction in the GOR group clearly shows an excess of hematite over goethite (Table 1) in the lower profiles, a trend seen elsewhere (Kämpf and Schwertmann, 1983), all of which strongly suggest a stronger (warmer-wetter) climate during the morphogenesis of the buried paleosols.

Similarly, the ratio Feo/Feo, the ‘activity ratio’ of Dormaar and Lutwijk (1983), formerly considered to measure the conversion of amorphous Fe (Feo) to crystalline forms (Feo), is now sometimes used to illustrate a reduction in Feo over time (Mahaney et al., 1999; Schülli-Maurer et al., 2007). This ratio is not readily applicable here given the variability of Feo and lack of trends with depth among all three sections. If there were truly a large scale influx of fresh materials to the surface epipedons in all three profiles, and if Feo/Feo is higher in younger sediment, this ratio should identify the aeolian input.

The wetting depth in paleosols, often marked by the depth of root penetration, here coincides with ~80 cm in GOR68, ~90 cm in GOR64 and ~50 cm in GOR69. While these depths may likely have changed during various glacial episodes, they appear to coincide closely with depletions in Alp (Table 3). Because the paleosols are clay rich, it may be that wetting depths established in the first 100 kyr weathering episode become locked in place with little variation barring a large scale influx of soil water during one or more interglacials. To firm-up estimates of wetting depths from proxy Alp trends one would need to work out field capacities and permanent wilting points of moisture in the profiles.

The presence of an older, buried till in the GOR68 section emphatically demonstrates that a glaciation preceded the Gorges event (Mahaney, 1990; Mahaney et al., 2013a). The question is when and how extensive was it? The presence of glacially-crushed grains in Early Quaternary lahars on the mountain (Mahaney, 1990) may well correlate with till in the lower profile of GOR68. The higher Feo values in the buried unit C, relative to the Gorges till within the surface profiles (unit B), argue for an older age for this lower till. Despite the attempt to
use Fe\textsubscript{0} (Dahms et al., 2012), along with other oxihydroxides as a long-lived (~1 Ma) chronometer in the European Alps and the Rocky Mountains of N. America, we used only the Fe\textsubscript{0}/Fe\textsubscript{0} function, since Fe\textsubscript{0} is partially soluble and subject to unknown rates of solution during interglacial periods and here it is compromised by the prevalence and persistence of primary magnetite.

To understand how and when glaciation began on Mount Kenya it is necessary to understand the exact timing of construction of the massif to an altitude that fostered retention of snow and development of glaciers. Assuming the mountain reached its maximum elevation at the time the plug rock crystalized at 2.71 Ma (Veldkamp et al., 2007), revised from 2.65 Ma (Everden and Curtis, 1965), surfaces must have become stable soon thereafter allowing weathering to ensue in stable sites along with early glaciation. It is this earliest glaciation in the Early Pleistocene, or perhaps series of episodic ice advances, that is central to the discussion here. Late Pliocene/Early Pleistocene paleoclimate reconstructions using global benthic \textsuperscript{18}O trends (Lisiecki and Raymo, 2005) invoke small amplitude climatic oscillations from cool/dry to warm/wet for much of East Africa, reverting after the Olduvai Event to cold/drier climate that probably led to early glaciation on the mountain. This trend is similar to the sequence of a dry climate deduced for the west flank of Mt. Kenya (Mahaney et al., 2011) during the Early Pliocene, reverting to a less dry climate toward the close of the epoch at the boundary with the Pleistocene. In this low elevation grassland environment the first ingress of loess from Pleistocene glaciation led to the development of argillitic (Bt) horizons that may well have developed in conjunction with punctuated humid intervals prior to and across the Olduvai Event (Lisiecki and Raymo, 2005). It is these Bt horizons on the west flank of the mountain that probably correlate with similar weathering records (Btb horizons) in Gorges Valley (Mahaney et al., 2011). The Btb horizons in GORB4 and GORB69 probably formed during the high amplitude climatic intervals of 2.7–2.5 and 1.9–1.7 Ma interbedded with periods of acidification, as determined from detailed analysis of lacustrine records (Trauth et al., 2005).

Assuming the drier intervals in the Early Pleistocene correlate with glaciation, humid intervals with interglacial climates, it is likely that the earliest Pleistocene glaciations (pre-Gorges and Gorges) correlate with the first arid period of 2.5–1.9 Ma, the post-Gorges weathering with a drier interval (<1.7 Ma, Trauth et al., 2005). If this correlation is correct, then the Btb horizons in the GORB4 and GORB69 profiles had for the most part prior to 2.5 Ma, and the inference of expanded forest changing the microclimate at the site is on reasonably firm ground.

In summary, with some variability down profile in all three sections, the petrography shows a mix of weathered/fresh grains with a multitude of xenoliths and preweathered fragments that have likely been extensively reworked by aeolian and glacial processes, some many times over. Other grains appear to have lost armored surfaces, presenting fresh fragments that seem out of place in profiles that have been exposed to the subaerial atmosphere for variable lengths of time since the Gauss Normal Chron.

6. Conclusions

The build-up and distribution of Fe and Al extract concentrations over time present some unexpected twists to what are usually straightforward trends. The usual case on Mount Kenya is for fresh sediment superposed on older tills to yield lower Fe\textsubscript{0} values, the result of deflation during times of severe drought in climate with the advent of ice in the upper catchments. While this occurred in nearby areas (Mahaney, 1990; Mahaney et al., 1997) it does not seem to have affected the three sections described here. What is outstanding is the degree to which old grains are recycled from weathered bedrock and older till bodies into younger tills/outwash and aeolian sediment (surface epiplains) and later subjected to further weathering. While wetting depths are tentatively identified halfway into the surface profiles there is little in the Fe release data to indicate much of a shift in weathering intensity over time.

While problems persist with the precise meaning of Al\textsubscript{0} and Al\textsubscript{0} over time, Al\textsubscript{0} (raw data) shows some variation, partly responding to weathering depth and partly also to presumed microbial action, which with given soil temperatures of +10 °C at 3000 m is likely intense (viz: Mahaney, 1990). The Fe\textsubscript{0}/Fe\textsubscript{0} ratio as a geochronometer yields high ratios with some minor variations in the upper profiles of all three sections indicating a long weathering history, the product of episodic changes in climate from the Olduvai Event to the present. Increases in the ratio at depth in the older suite of paleosols may result partly from increased primary Fe-bearing minerals in the sediments and partly from a climate more ameliorative to weathering. Other Fe extract trends and arithmetic functions tend to support the Fe\textsubscript{0}/Fe\textsubscript{0} interpretations. Variations in Fe\textsubscript{0}/Fe\textsubscript{0} are probably related to partial dissolution of ferrhydrite, with possible reaction to differential ground water invasion and sample preparation.

Acknowledgments

This research was funded by Quaternary Surveys, Toronto. A research grant from the National Scientific and Engineering Research Council of Canada (NSERC) to RWB in support of this work is gratefully acknowledged.

References


