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SEDIMENTARY GEOLOGY AND HUMAN ORIGINS: A FRESH LOOK AT OLDUVAI GORGE, TANZANIA

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ABSTRACT: Recent field work at Olduvai Gorge (Tanzania) using sedimentary geology, in particular high-resolution paleoenvironmental reconstruction and isotope geochemistry, has revealed that freshwater was in proximity to a number of the rich fossil sites in Beds I and II (~ 2.0–1.0 Ma). This paper presents the first geological evidence for springs associated with archaeological sites in this semiarid rift basin. The springs appear to be limited to a small area within the basin and were likely connected to faults that acted as conduits for groundwater. Tufas associated with ten archaeological sites have stable- isotope signatures occurring in a cluster bounded by $\delta^{18}O$ ratios from −6% to +1%, and the $\delta^{13}C$ ratios from −5% to +2%. The $\delta^{18}O$ values cluster around −4%, that of precipitation in the region, indicating a meteoric source. The longevity of the spring record reflects a hydrologic system that apparently persisted for hundreds of thousands of years. Previous landscape reconstructions depicted the archaeological sites on the lake margin of paleo Lake Olduvai, as an alkaline playa. The discovery of springs at or near the archaeological sites provides fresh insights for interpreting hominin behavior during this key time in evolution with respect to procuring food, water, and materials for stone tools, as well as hominin adaptation to climate change and paleoenvironmental change. The idea that spring deposits may be in proximity to archaeological sites could lead to discovery of new sites at other hominin fossil localities in the East African Rift System (EARS).

INTRODUCTION

How, where, and why humans evolved are fundamental questions that capture attention and spark curiosity. A number of recent hominin fossil discoveries as old as 7–5 Ma (Pickford and Senut 2001; Brunet et al. 2002) and advances in DNA research have now documented that humans evolved in Africa and then migrated to other parts of the world starting as early as 1.8 Ma (Gabunia et al. 2000). Geological input into questions about human origins was traditionally restricted to geochronology, as age of the fossil was usually the main question being asked about the context of any new discovery (Leakey 1971). However, evidence of the early exodus of hominins from Africa has raised many other questions. Why did hominins leave the safety of trees (Stanley 1995)? What were the drivers that may have nudged hominins toward bipedalism and led to species that failed, while only one ultimately succeeded (deMenocal 1995)? Were the development of tools and the exodus from Africa a passive or direct response to some paleoenvironmental or climatic stresses (Ashley 2008)? These kinds of questions go far beyond geochronology, as a specialty, and even geology, in general, but sedimentary geology does have a critical role to play in the interdisciplinary research into human origins (Behrensmeyer 1982; Feibel 1997; Ashley 2000; WoldeGabriel et al. 2004; NRC 2010).

Sedimentary deposits are *the* archives of paleoenvironmental and paleoclimate records (Ruddiman 2000). The methods used to reconstruct depositional environments, develop facies models, and track paleoenvironmental changes through time are now being applied to human-origins studies (e.g., Behrensmeyer et al. 2002; Quade et al. 2004; Maslin and Christensen 2007; Trauth et al. 2007). The "sedimentary geology tool kit" includes lithostratigraphy, ichnology, mineralogy, facies analyses, sedimentary petrology, paleontology, as well as paleopedology and isotope geochemistry.

This paper reports on a recent significant discovery of a system of fossil springs in the sedimentary record at Olduvai Gorge, Tanzania, now a World Heritage Site (Fig. 1). Recent field work at Olduvai using sedimentary geology, in particular high-resolution paleoenvironmental reconstruction and isotope geochemistry, has revealed that freshwater was in proximity to most of the rich fossil sites in Beds I and II (~ 2.0–1.0 Ma) (Fig. 2). Those sites are described in Leakey (1971) and Hay (1976) and numerous publications by others over the last three decades.

Starting at approximately 7 million years ago the African continent was undergoing aridification (Cerling et al. 1993). In addition, climate was modulated by astronomically controlled climate change (Ruddiman 2000; Trauth et al. 2005; Ashley 2007; Maslin and Christensen 2007; Trauth et al. 2007). Groundwater-fed springs and wetlands have been recognized as an important lifeline for animals migrating out of Africa during hyperarid periods (Faure et al. 2002; Smith et al. 2004). Thus, this discovery of springs associated with archaeology in the East African Rift, which would have been one of the principal corridors of migration out of Africa, has important implications for our understanding of how hominins might have coped with environmental change (Potts 1996).

The objectives of this paper are to present the first lithological and geochemical analyses of freshwater (spring) deposits from the East

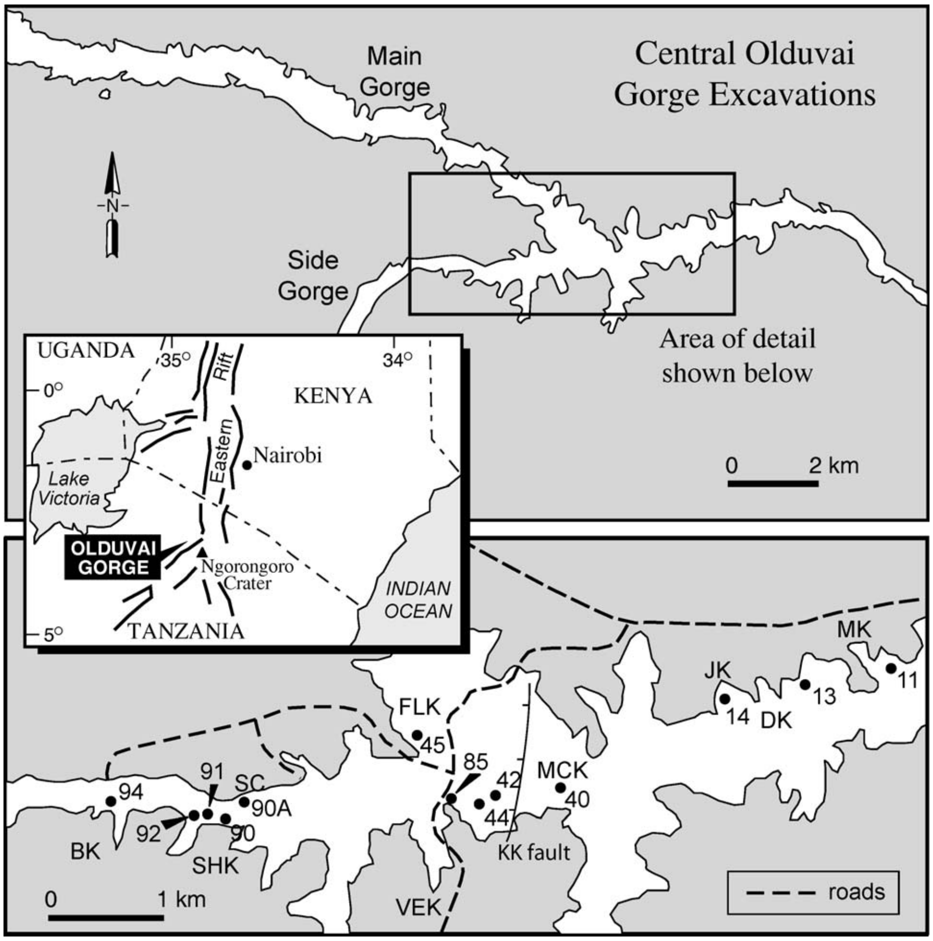

FIG. 1.—Location map of the study area. Inset map depicts Olduvai Gorge adjacent to the East Africa Rift. The open rectangle outlines the junction area covered by the detailed map below. Archaeological areas of the gorge are indicated by letters (e.g., FLK) after Leakey (1971) and numbers refer to the stratigraphic sections from Hay (1976). The location of the KK fault with carbonate deposits is shown.

African Rift that are found in close association with well documented archaeological sites. The time represented is nearly 1 million years long, from ~ 2 Ma to ~ 1Ma (Leakey 1971). The new data are preliminary, but the lithologic descriptions of the deposits are clear and the stable-isotope ratios are unequivocal. These new findings using sedimentary geology are provocative because they provide a viable alternative to the traditional playa-lake environmental model for the archaeological sites and permit new explanations of how hominins coped with survival in these arid settings. The findings provide a small piece of the puzzle of how hominins may have coped with climate change and environmental change during a time of both speciation of hominins and the first migrations from Africa (NRC 2010).

BACKGROUND

Olduvai Basin is in northern Tanzania in the EARS (East Africa Rift System) and exposes a two-million-year-long record of flora and fauna (Leakey 1971) (Fig. 1). Fifty years ago Louis and Mary Leakey drew the world's attention to Olduvai Gorge, by discovering there hominin fossils of both *Zinjanthropus boisei* (now *Australopithecus boisei*) and *Homo habilis* (Leakey 1959). Although there are over an estimated 250 km^2 of fluvial and lacustrine deposits exposed in the basin, most of the archaeologically productive sites are found within in a relatively small area (7 km^2) centered on the junction of the Main Gorge and Side Gorge, representing only a small percentage of the sedimentary outcrop (Fig. 1). Although there is no complete inventory, it is likely there have been at least 10,000 artifacts and even more vertebrate bones, as well as remains of four hominin species recovered in the past 50 years (Fig. 2). The assumption has always been that the high concentration of bones and stone artifacts in this tiny area of Beds I and II (~ 2.0–1.0 Ma) was connected to the presence of paleolake Olduvai, which fluctuated on short (annual) and long (astronomic forcing) timescales (Hay 1976; Peters and Blumenschine 1995; Hay and Kyser 2001; Ashley and Hay 2002) (Fig. 1). Many archaeological sites were interpreted as lake-margin settings (Leakey 1971; Binford 1981; Potts 1984; Blumenschine and Masao 1991). The lake is now viewed as an alkaline playa that desiccated completely during extended dry periods (Hay and Kyser 2001). Analysis of the mineralogy of the lake sediments indicates that the lake water was probably not potable most of the time. Lake sediments contain minerals like celadonite and magadi-type chert that indicates a pH of at least 9.5–10 (Hay and Kyser 2001; Hover and Ashley 2003; Jones and Deocampo 2007; Deocampo et al. 2009). Thus, the lake was a very unlikely source of drinking water for animals, including hominins, creating a paradox that has prevailed on how the apparent abundance of life survived in the context of a playa-lake setting.

GEOLOGY AND HYDROLOGY

The Olduvai basin is located just south of the equator in northern Tanzania immediately adjacent to the Eastern Rift (Gregory) system (Fig. 1). The modern Gorge exposes a two-million-year-long sedimentary record in an incised river valley that drains eastward from the Serengeti Plains. The Gorge cuts across a 50-kilometer-wide rift-platform basin located between Precambrian basement to the west and the Plio-Pleistocene Ngorongoro Volcanic Highland to the east. The basin fill is now disrupted by rift-parallel faults and separated into blocks. The total

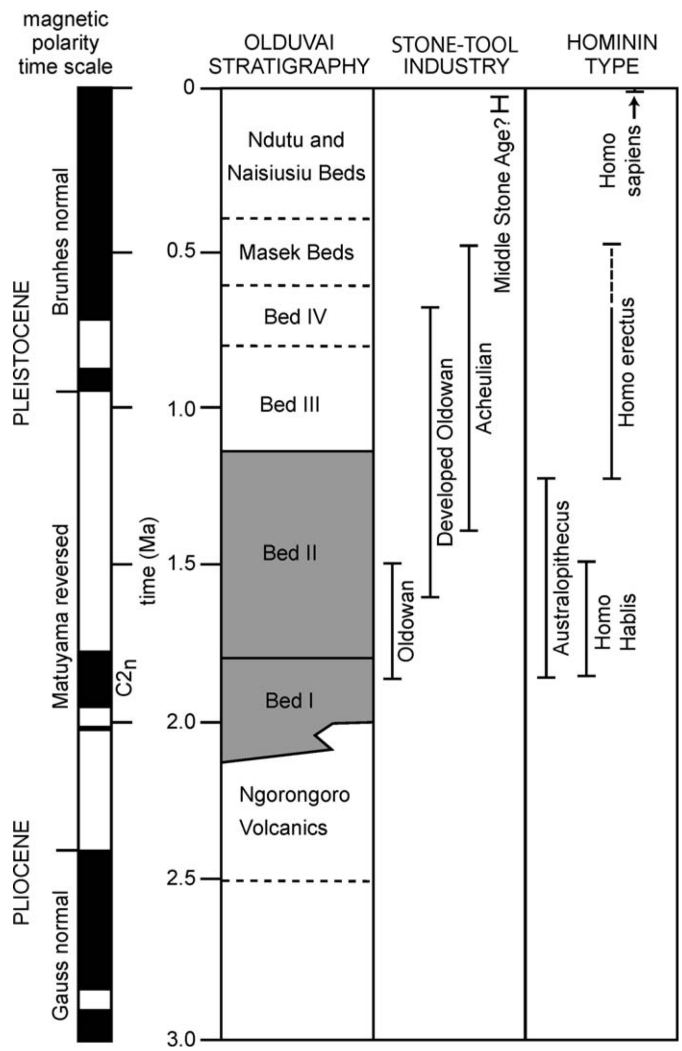

FIG. 2.—Olduvai lithic stratigraphy and magnetic polarity time scale in millions of years. Time period spanned by Bed I and Bed II is shaded. Stone tool industry and type and hominin type found in Olduvai Gorge are shown against time (Ma) and the paleomagnetic timescale (Hay 1976).

sedimentary package (100 m thick) is relatively thin for a rift basin. The record is composed largely of reworked volcaniclastic sediment and air-fall tuffs deposited in a shallow semiarid fluvial lacustrine basin and is divided into a series of six Beds (Fig. 2) (Hay 1976).

Surface water and groundwater flowing into the Olduvai basin from the east and south presumably was sourced from rainfall on the $>$ 3000-m-high Ngorongoro Highland. The Highland today acts as a rain shadow for the predominantly easterly winds from the Indian Ocean (Fig. 3). This situation also would have existed during Bed I and II times, because the atmospheric circulation pattern has not changed significantly (Nicholson 1996; Trauth et al. 2007).

The modern relatively low Ngorongoro Highlands receive ~ 1150 mm a year (Deocampo 2004), whereas Olduvai receives only ~ 550 mm (Hay 1976). Evaporation in Tanzania and Kenya is estimated to be between 2000 and 2500 mm/yr and very few perennial rivers can persist with this highly negative water budget. Groundwater moves toward the basin under gravity and discharges at the base of the slope and along fault lines, or in sites where it rises to the surface upon encountering buried impermeable rocks (Ashley and Hay 2002). Dense, massive basalt was exposed in the junction area during late Pleistocene incision by the Olduvai River. The generally impervious basalt, lying just below the surface during Bed I and Bed II time, was in a favorable position to deflect groundwater to the surface along fractures. The tufa occurs close to the faults and most of the major archaeological sites. Carbonate deposits are found on the fault surfaces, indicating that the faults acted as conduits for groundwater (Fig. 3).

Recent geological fieldwork in the Gorge has revealed abundant evidence for freshwater (springs, seeps, and groundwater-fed wetlands) associated with most of the major archeological sites in Bed I (FLK, FLK-N, FLK-NN, MK, DK, and possibly JK) and in Bed II (VEK, HWK, MCK, BK, SHK, and SC) (Fig. 1). A site-by-site description goes beyond the scope of this paper, but a general summary of the physical features (bedding, sedimentology), biological remains, stable-isotope geochemistry and photographs helps characterize the groundwater-fed environments: springs and wetlands.

Geologic Records of Freshwater: Springs and Wetlands

Springs.—Springs are localized discharges of groundwater disgorging at a point source. Groundwater may also exit along "spring lines" as broad, diffuse seeps that produce permanently wet ground (wet meadows) and standing-water wetlands (Quade et al. 1995; Deocampo 1997; Liutkus and Ashley 2003; Owen et al. 2009). The only physical records of a paleosprings are mineral precipitates, usually some form of carbonate, such as calcite ($CaCO_3$) and associated biology, such as diatoms, chrysophytes, and ostracods (Ashley et al. 2008; Johnson et al. 2009). Freshwater carbonate is called *tufa* or *travertine*. It is formed at low temperatures from calcium-rich water by both physiochemical and biologically mediated precipitation (Deocampo 2010). The calcium is initially derived from weathering of local trachytic and basaltic rocks and becomes dissolved in the groundwater. It is readily available for the formation of carbonate-rich soils or the precipitation of tufa when water flows onto the surface. Degassing of dissolved CO_2 from groundwater may initiate mineral precipitation. Carbonate precipitation is commonly assisted by microbial mats of cyanobacteria (Riding 2002; Deocampo 2010). However, there are many different types and origins of carbonate deposits other than tufa, such as calcrete, soil nodules, concretions, lacustrine limestone, and stromatolites. The identification of a specific type is based on a number of lines of evidence: their geologic context, geomorphology of deposit, crystal habit, and stable-isotope signature (O and C).

The deposits at Olduvai have a wide variety of morphologies ranging from small (a few m^2), irregularly shaped and localized deposits to large more elongate (~ 35 m) mounds (Figs. 4A, 4B). Carbonate also occurs as encrusted root mats and plant stems (rhizoliths) (Fig. 4C) and rarely as tufa beds or as sheets that accumulate in standing or slow moving water. Bedding in tufas is rare, but occasionally thin clay lenses and laminae within the carbonate occur. The texture ranges from dense travertine limestone (rare) to the more common mix of nodules and friable, spongy carbonate. The mound-like form strongly suggests subaerial exposure, and some mounds in the tufa were draped by airfall tuffs (Fig. 3). Other evidence that freshwater was on the former land surface and available to animals (including hominins) is the bioturbation and trampling of the associated wetland deposits by large animals (Ashley and Liutkus 2002). Some tufas appear to be isolated carbonate accumulations, whereas others occur along a line, suggesting that they are related to bedrock fractures.

Oxygen isotope signatures reflect the effects of both the starting ratio in the rainfall to the area and subsequent fractionation due to evaporation. The $\delta^{18}O$ of meteoric water reaching the tropical East Africa is -4.0%, supporting the interpretation that the tufas are sourced by rainfall (deMenocal et al. 2000) (Fig. 5). Atmospheric carbon is -6% (pre-industrial atmosphere) (Cerling and Hay 1986). Carbon values in the tufa, however, reflect both the initial value from the atmosphere and the effects

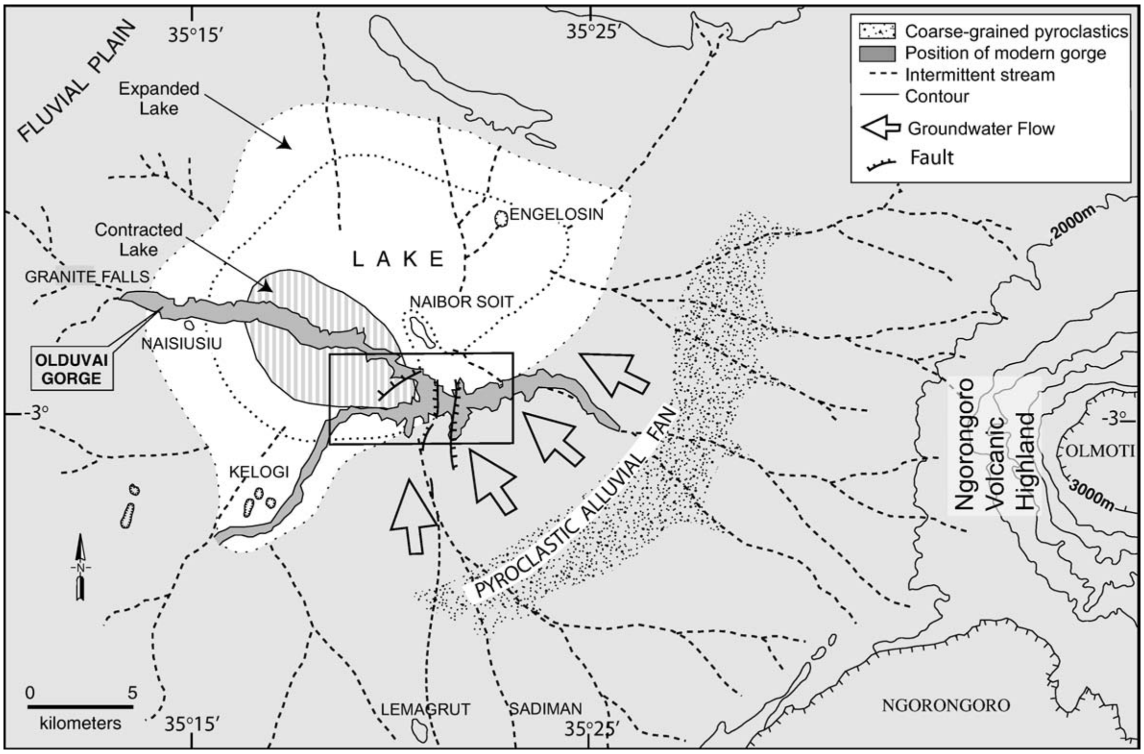

FIG. 3.—Paleogeographic reconstruction of Olduvai Basin during Bed I and II time showing location of the Ngorongoro Volcanic Highland, a pyroclastic alluvial fan building into the basin, the proposed direction of regional groundwater flow, and outline of shorelines during expanded and contracted lake phases in dotted lines. Faults mapped by Hay are depicted. The box outlines the area of study in Figure 1. (modified from Ashley et al. in review).

of biological fractionation by C3 and C4 plants and animals in the soil zone. Figure 5 depicts the isotope signature of carbonate samples from ten fossil-rich sites (Fig. 1). Each of the sites has its own unique isotope signature, but as a group the spring deposits are in a tight cluster bounded by δ^{18}O values that range between -6‰ and +1‰, and the δ^{13}C values that range between -5‰ to +2‰. The spectrum of oxygen ratios reflects the fractionation due to evaporation (Benison et al. 1996; Liutkus et al. 2005). The hydrologic system sourcing the springs apparently persisted during most of Bed I and II time.

Figure 6 compares stable-isotope ratios from a variety of carbonates in the basin: paleolake Olduvai, modern soils, and two selected tufa examples from Middle and Upper Bed I that are equivalent to archaeological sites found in FLK and FLK-N, respectively. Tufas have a distinct stable-isotope signature separate from calcium-rich soils (Cerling and Hay 1986; Sikes and Ashley 2007) and lake sediments from the same basin (Hay and Kyser 2001; Sikes and Ashley 2007). Carbonate minerals lining the fault surfaces have isotope values near the light-isotope end of the tufa fractionation array (e.g., δ^{13}C -3.6‰ and δ^{18}O -5.6‰; δ^{13}C -3.1‰ and δ^{18}O -4.8‰) and thus suggest strongly that the faults were likely pathways for groundwater inasmuch as they represent minimal evaporative fractionation (Fig. 6).

Wetlands.—Spring deposits typically cover a small area (tens of square meters), but wetlands that fringe the springs may be much more extensive (square kilometers). Thus, wetlands can be a direct indication of a groundwater source even if there is no mineral or biological record of the spring. Wetland deposits are composed of clay particles that are either washed in or airborne, as well as aquatic plants and water-tolerant fauna (Liutkus and Ashley 2003). The sedimentary deposit formed in perennial wetlands is "siliceous earthy clay" a term coined by Hay (1976) and developed by Deocampo (2002) and Liutkus and Ashley (2003). The silica comes from the weathering of volcanic rocks and is then taken up by plants (Deocampo and Ashley 1999).

Deposits in Beds I and II can be traced laterally for hundreds of meters wherein changes in grain size, bedding and sedimentary structures are interpreted to record sub-environments within the wetland (Ashley and Liutkus 2002; Liutkus and Ashley 2003; Ashley and Liutkus 2004; Liutkus et al. 2005). Siliceous earthy clay is composed of clay minerals, phytoliths, chrysophytes, diatoms, and vascular plant remains (Hay 1976). Wetland plant remains are commonly preserved by silica (Fig. 4D). Phytoliths and diatoms are also siliceous and are excellent indicators of depositional environment. Phytoliths vary in size and shape depending on the plant taxon and plant part (stem, leaf, root) in which they occur and thus record the vegetation present (Albert et al. 2006; Bamford et al. 2008). Diatom species found in wetlands vary systematically with the water chemistry and are biological indicators of permanently wet ground (Owen et al. 2004; Owen et al. 2009). Bioturbation on different scales is common, ranging from admixing by large-hooved vertebrates or distinct trackways likely created by hippopotami (Ashley and Liutkus 2002). In summary, wetland deposits are corroboration of the presence of a groundwater-fed water supply, even when the carbonate deposits are not exposed, or perhaps were never deposited.

DISCUSSION

The carbonate (tufa) deposits found associated with the archaeological records have a variety of textures and morphologies, but they produce a tight cluster of isotope signatures that are consistent with the interpretation that all were sourced by meteoric water (Figs. 4, 5, 6). Carbonate with isotope ratios similar to the tufas and precipitated on the fault plane of KK fault indicates that fractures functioned as conduits bringing groundwater to the surface (Figs. 1, 6).

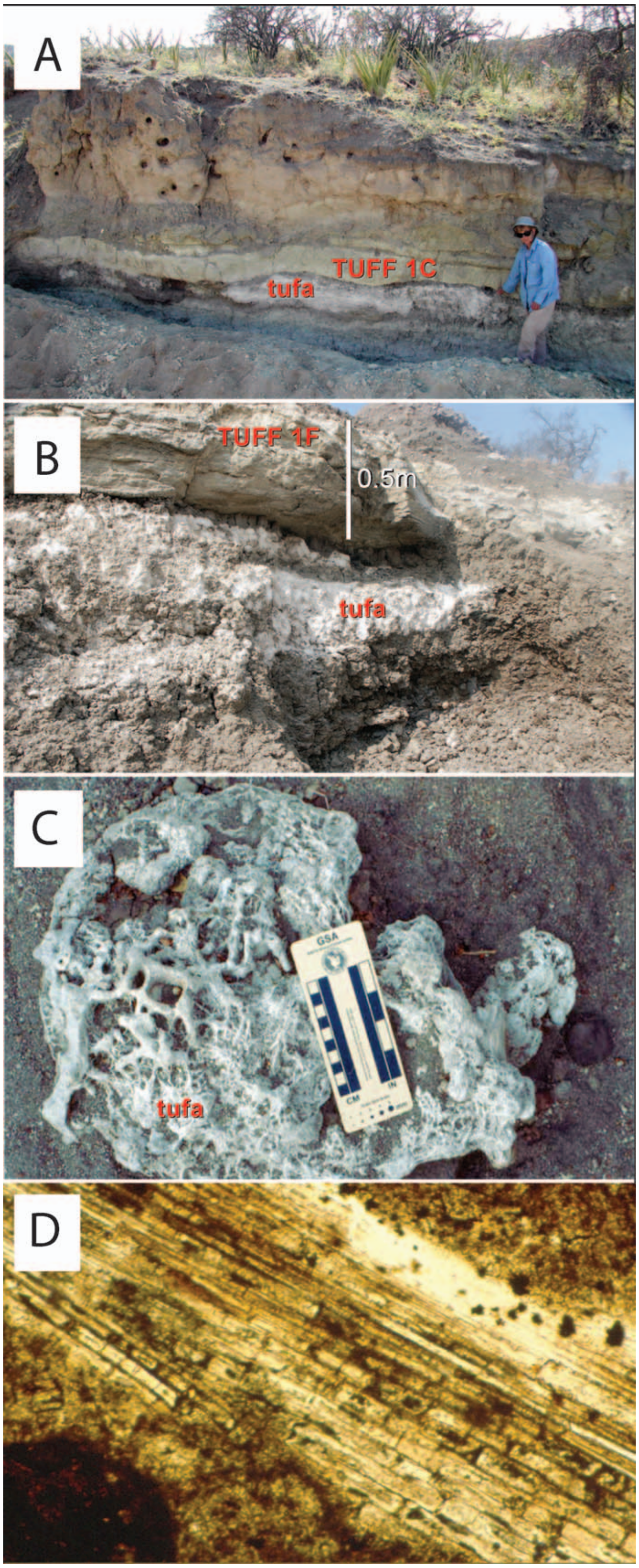

FIG. 4.—Photos. Locations shown on Figure 1. **A)** Middle Bed I—Photo of a tufa equivalent in age to Level 22 at FLK, the layer in which the Zinj fossil was found. **B)** Upper Bed I—A thick tufa equivalent to Level 1, 2 at FLK-N (just north of FLK). **C)** Lowermost Bed II—Open network of tufa with some encrusted plant ← material at VEK. **D)** Photograph of thin section of silicified plant material from the wetland facies (near 44). Width of photo is 1.9 mm (Ashley 2000).

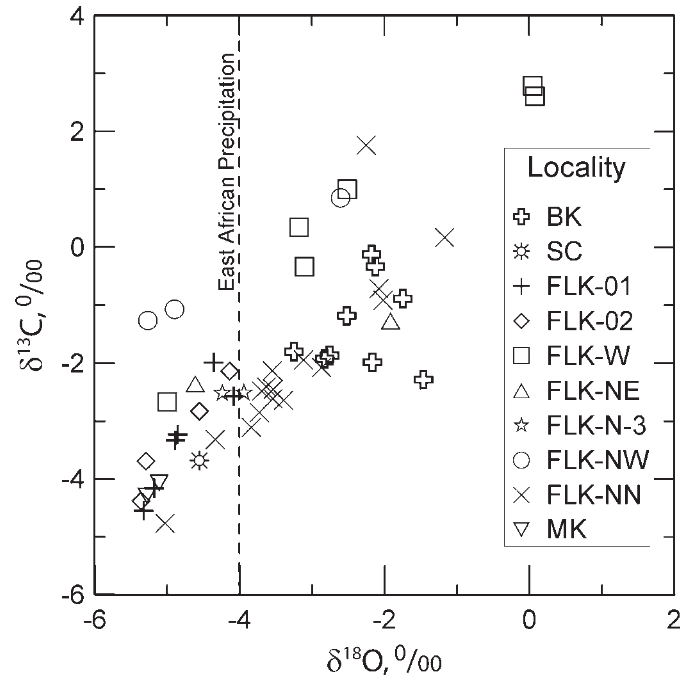

FIG. 5.—Bivariant plot of stable-isotopes of tufas collected at 10 sites shown in Figure 1 reveals a cluster of ratios bounded by $\delta^{18}O$ values between −6% and +1%, and the $\delta^{13}C$ values between −5% to +2%. Each tufa is represented by two or more samples. Each tufa is unique, and the plots show different histories of varying extents of isotope fractionation. The value of the meteoric $\delta^{18}O$ in the region (−4%) is indicated.

The correlation of spring deposits with fossil concentrations must be carefully assessed at Olduvai Gorge on a site-by-site basis in order to determine the link between water source and the hominins and other animals using it. Permanent freshwater sources would likely have affected food-procurement strategies and may have influenced the likelihood of scavenging versus hunting behavior, or vice versa (Potts 1982; Bunn and Kroll 1986; Blumenschine 1987; Potts 1988; Dominguez-Rodrigo et al. 2007).

Although freshwater resources would seem logical, even likely with so much evidence for vertebrate life, the paleoenvironmental reconstructions and hominin behavioral models for essentially all sites in the East Africa Rift System have been either lake margin or fluvial. Both of these types of water sources have limitations in arid settings; during dry periods lakes may become toxic and disappear, and rivers are often ephemeral. Neither would have provided the continuity and dependability needed to support the localized, high concentrations of life and hominin activity evidenced by the archaeological sites. There is a consensus that the climate in East Africa has become more arid over the last 7 million years, and the superimposed Milankovitch-driven climate cycles created "wet" and "dry" periods. Thus, the recognition of dependable freshwater sources during this period of climate instability provides a fresh view on how hominins may have coped with environmental change (NRC 2010).

Other paleoenvironmental reconstructions suggest grassland (Bamford et al. 2008) or a range of habitats from open to closed (Plummer and Bishop 1994). However, like the lake-margin scenarios, these also do not

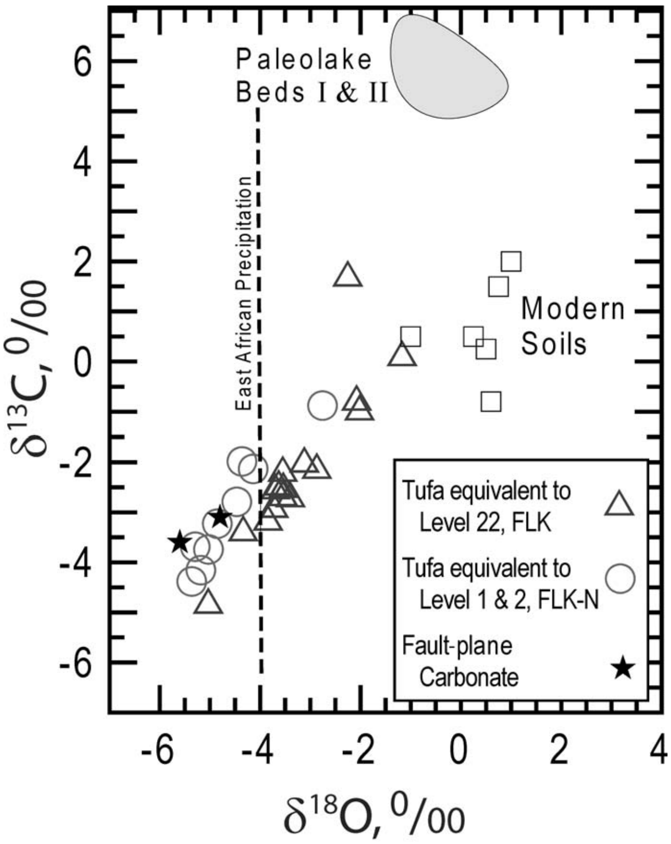

FIG. 6.—Bivariant plot of stable-isotope ratios $\delta^{13}C$ and $\delta^{18}O$ permil of modern soil carbonates from the greater Olduvai region and calcite precipitated under evaporative conditions in the center of paleo-Lake Olduvai during Bed I and Bed II (Sikes and Ashley 2007). Analyses of the tufa equivalent to the archaeological site of *Zinjanthropus* at FLK (Level 22), Middle Bed I (Fig. 4B), and the tufa equivalent to the archaeological site at FLK-N (Level 1,2), Upper Bed I (Fig. 4A) are nearly identical. The isotope signature of the carbonate samples from the fault surface of KK fault (Fig. 1) supports the idea that fractures served as conduits for groundwater. The value of meteoric water $\delta^{18}O$ in the region (−4‰) is indicated.

address the important question of access to potable water. The correlation of spring deposits with dense concentrations of bones demands specific models that attempt to explain the connection between the two records.

CONCLUSIONS

(1) Sedimentary geology is crucial in acquiring information in human-origins research with regards to paleoenvironmental, paleoclimate, and paleoecological contexts.
(2) Freshwater carbonates (tufas) were found associated with many fossil- and artifact-rich sites in Beds I and II. The groundwater-fed springs and wetlands appear to have been sourced via faults that transect the basin.
(3) The springs apparently persisted during Bed I and Bed II time, reflecting an impressively persistent hydrologic system.
(4) The tufas are the first spring deposits associated with human origins sites within the East African (Gregory) Rift System to be identified geochemically. This paleoecological association may hold for other rift basins, and thus Olduvai provides an example that could be used to guide the search for other similar settings.
(5) The documentation of springs deposits at Olduvai Gorge has important implications for our understanding of how hominins might have coped with environmental change (Potts 1996; NRC 2010).

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REFERENCES

ALBERT, R.M., BAMFORD, M.K., AND CABANES, D., 2006, Taphonomy of phytoliths and macroplants in different soils from Olduvai Gorge (Tanzania) and the application to Plio-Pleistocene palaeoanthropological samples: Quaternary International, v. 148, p. 78–94.

ASHLEY, G.M., 2000, Geologists probe hominid environments: GSA Today, v. 102, p. 24–29.

ASHLEY, G.M., 2007, Orbital rhythms, monsoons, and playa lake response, Olduvai Basin, equatorial East Africa (~ 1.85–1.75): Geology, v. 35, p. 1091–1094.

ASHLEY, G.M., 2008, Human evolution and climate change, *in* Gornitz, V., ed., Encyclopedia of Paleoclimatology and Ancient Environments: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 446–450.

ASHLEY, G.M., AND HAY, R.L., 2002, Sedimentation patterns in a Plio-Pleistocene volcaniclastic rift-margin basin, Olduvai Gorge, Tanzania, *in* Renaut, R.W., and Ashley, G.M., eds., Sedimentation in Continental Rifts: SEPM, Special Publication 73, p. 107–122.

ASHLEY, G.M., AND LIUTKUS, C.M., 2002, Tracks, trails and trampling by large vertebrates in a rift valley paleo-wetland, lowermost Bed II, Olduvai Gorge, Tanzania: Ichnos, v. 9, p. 23–32.

ASHLEY, G.M., TACTIKOS, J.C., AND OWEN, R.B., 2008, Hominin use of springs and wetlands: paleoclimate and archaeological records from Olduvai Gorge (1.79–1.74 Ma): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 272, p. 1–16.

BAMFORD, M.K., STANISTREET, I.G., STOLLHOFEN, H., AND ALBERT, R.M., 2008, Late Pliocene grassland from Olduvai Gorge, Tanzania: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 257, p. 280–293.

BEHRENSMEYER, A.K., 1982, The geological context of human evolution: Annual Review of Earth and Planetary Sciences, v. 10, p. 39–60.

BEHRENSMEYER, A.K., POTTS, R., DEINO, A., AND DITCHFIELD, P.W., 2002, Olorgesailie, Kenya: A million years in the life of a rift basin, *in* Renaut, R.W., and Ashley, G.M., eds., Sedimentation in Continental Rifts: SEPM, Special Publication 73, p. 97–106.

BENSON, L., WHITE, L.D., AND RYE, R., 1996, Carbonate deposition, Pyramid Lake subbasin, Nevada: 4, Comparison of the stable isotope values of carbonate deposits (tufas) and the Lahontan lake-level record: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 122, p. 45–76.

BINFORD, L.R., 1981. Bones: Ancient Men, Modern Myths: New York, Academic Press, 320 + xxvii p.

BLUMENSCHINE, R.J., 1987, Characteristics of an early hominid scavenging niche: Current Anthropology, v. 28, p. 383–407.

BLUMENSCHINE, R.J., AND MASAO, F.T., 1991, Living sites at Olduvai Gorge, Tanzania? Preliminary landscape archaeology results in the basal Bed II lake-margin zone: Journal of Human Evolution, v. 21, p. 451–462.

BRUNET, M., GUY, F., PILBEAN, D., AND OTHERS, 2002, A new hominid from the Upper Miocene of Chad, Central Africa: Nature, v. 418, p. 145–151.

BUNN, H.T., AND KROLL, E.M., 1986, Systematic butchery by Plio-Pleistocene hominids at Olduvai Gorge, Tanzania: Current Anthropology, v. 27, p. 431–452.

CERLING, T.E., AND HAY, R.L., 1986, An isotopic study of paleosol carbonates from Olduvai Gorge: Quaternary Research, v. 25, p. 63–78.

CERLING, T.E., WANG, Y., AND QUADE, J., 1993, Global ecological change in the late Miocene: expansion of C4 ecosystems: Nature, v. 361, p. 344–345.

DEMENOCAL, P.B., 1995, Plio-Pleistocene African climate: Science, v. 270, p. 53–59.

DEMENOCAL, P.B., ORTIZ, J., GUILDERSON, T., AND SARNTHEIN, M., 2000, Coherent high- and low-latitude climate variability during the Holocene Warm Period: Science, v. 288, p. 2198–2202.

DEOCAMPO, D.M., 1997, Modern sedimentation and geochemistry of freshwater springs: Ngorongoro Crater, Tanzania [Masters Thesis]: Rutgers University, New Brunswick, New Jersey, 140 p.

Deocampo, D.M., 2002, Sedimentary processes and lithofacies in lake-margin groundwater-fed wetlands in East Africa, *in* Renaut, R.W., and Ashley, G.M., eds., Sedimentation in Continental Rifts: SEPM, Special Publication 73, p. 295–308.

Deocampo, D.M., 2004, Hydrogeochemistry in the Ngorongoro Crater, Tanzania, and implications for land use in a World Heritage Site: Applied Geochemistry, v. 19, p. 755–767.

Deocampo, D.M., 2010, The geochemistry of continental carbonates, *in* Alonso-Zarza, A.M., and Tanner, L.H., eds., Carbonates in Continental Settings: Geochemistry, Diagenesis and Applications: Developments in Sedimentology: Amsterdam, Elsevier, p. 1–59.

Deocampo, D.M., and Ashley, G.M., 1999, Siliceous islands in a carbonate sea: modern and Pleistocene spring-fed wetlands in Ngorongoro Crater and Oldupai Gorge, Tanzania: Journal of Sedimentary Research, v. 69, p. 974–979.

Deocampo, D.M., Cuadros, J., Wing-Dudek, T., Olives, J., and 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, v. 309, p. 834–868.

Dominguez-Rodrigo, M., Barba, R., and Egelund, C.P., 2007. Deconstructing Olduvai; A Taphonomic study of the Bed I sites, Vertebrate Paleobiology and Paleoanthropology Series: Dordrecht, The Netherlands, Springer, 337 + xvi p.

Faure, H., Walter, R.C., and Grant, D.R., 2002, The coastal oasis: ice age springs on emerged continental shelves: Global and Planetary Change, v. 33, p. 47–56.

Feibel, C.S., 1997, Debating the environmental factors in hominid evolution: GSA Today, v. 7, no. 3, p. 1–7.

Gabunia, L., Vekua, A., Lordkipanidze, D., Swisher, C.C., Ferring, R., Justus, A., Nioradze, M., Tvsatchretidze, M., Anton, S.C., Bosinski, G., Joris, O., Lumtey, M., Majsuradze, G., and Mouskhelishvili, A., 2000, Earliest Pleistocene hominid cranial remains from Dmanisi, Republic of Georgia: Taxonomy, geological setting, and age: Science, v. 288, p. 1019–1025.

Hay, R.L., 1976. Geology of the Olduvai Gorge: Berkeley, California, University of California Press, 203 p.

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

Hover, V.C., and 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, v. 51, p. 231–251.

Johnson, C.R., Ashley, G.M., De Wet, C.B., Dvoretsky, R., Park, L., Hover, V.C., Owen, R.B., and McBrearty, S., 2009, Tufa as a record of perennial fresh water in a semi-arid rift basin, Kapthurin Formation, Kenya: Sedimentology, v. 56, p. 1115–1137.

Jones, B.F., and Deocampo, D.M., 2007. Geochemistry of Saline Lakes: Amsterdam, Elsevier, Treatise on Geochemistry, p. 393–424.

Leakey, L.S.B., 1959, A new fossil skull from Olduvai: Nature, v. 184, p. 491–493.

Leakey, M.G., 1971. Olduvai Gorge: Excavations in Beds I and II; 1960–1963: Cambridge, U.K., Cambridge University Press, 309 p.

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

Liutkus, C.M., Wright, J.D., Ashley, G.M., and 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, v. 33, p. 377–380.

Maslin, M., and Christensen, B., 2007, Tectonics, orbital forcing, global climate change, and human evolution in Africa: introduction to the African paleoclimate special volume: Journal of Human Evolution, v. 53, p. 443–464.

Nicholson, S., 1996, A review of climate dynamics and climate variability in eastern Africa, *in* Johnson, T.C., and Odada, E.O., eds., The Limnology, Climatology and Paleoclimatology of the East African Lakes: Amsterdam, Gordon & Breach Publishers, p. 25–56.

NRC, 2010, Understanding Climate's Influence on Human Evolution, *in* National Research Council, ed., Washington, DC, The National Academy Press, 115 + xii p.

Owen, R.B., Renaut, R.W., Hover, V.C., Ashley, G.M., and Muasya, A.M., 2004, Swamps, springs, and diatoms: wetlands regions of the semi-arid Bogoria–Baringo rift, Kenya: Hydrobiologia, v. 518, p. 59–78.

Owen, R.B., Renaut, R.W., Scott, J.J., Potts, R., and Behrensmeyer, A.K., 2009, Wetland sedimentation and associated diatoms in the Pleistocene Olorgesailie Basin, southern Kenya Rift Valley: Sedimentary Geology, v. 222, p. 124–137.

Peters, C.R., and Blumenschine, R.J., 1995, Landscape perspectives on possible land use patterns for Early Pleistocene hominids in the Olduvai Basin, Tanzania: Journal of Human Evolution, v. 29, p. 321–362.

Pickford, M., and Senut, B., 2001, The geological and faunal context of Late Miocene hominid remains from Lukeino, Kenya: Earth and Planetary Science Letters, v. 332, p. 145–152.

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

Potts, R., 1982. Lower Pleistocene site formation and hominid activities at Olduvai Gorge, Tanzania [PhD dissertation]: Harvard University: Cambridge, Massachusetts, 494 p.

Potts, R., 1984, Home bases and early hominids: American Scientist, v. 72, p. 338–347.

Potts, R., 1988. Early hominid activities at Olduvai: New York, Aldine de Gruyter, 396 p.

Potts, R., 1996, Evolution and climate variability: Science, v. 273, p. 922–923.

Quade, J., Mifflin, M.D., Pratt, W.L., McCoy, W., and Burckle, L., 1995, Fossil spring deposits in the southern Great Basin and their implications for changes in water table levels near Yucca Mountain, Nevada during Quaternary time: Geological Society of America, Bulletin, v. 107, p. 213–230.

Quade, J., Levin, N., Semaw, S., Stout, D., Renne, P.R., Rogers, M., and Simpson, S., 2004, Paleoenvironments of the earliest stone toolmakers, Gona, Ethiopia: Geological Society of America, Bulletin, v. 116, p. 1529–1544.

Riding, R., 2002, Microbial carbonates: the geological record of calcified bacterial algal mats and biofilms: Sedimentology, v. 47, p. 179–214.

Ruddiman, W.F., 2000. Earth's Climate, Past and Future: New York, W.H. Freeman and Co., 388 p.

Sikes, N.E., and Ashley, G.M., 2007, Stable isotopic signatures of pedogenic carbonates as indicators of paleoecology in the Plio-Pleistocene (upper Bed I) western margin of Olduvai Basin, Tanzania: Journal of Human Evolution., v. 53, no. 5, p. 574–594.

Smith, J.R., Giegengack, R., Schwarcz, H.P., McDonald, M.M.A., Kleindienst, M.R., Hawkins, A.L., and Churcher, C.S., 2004, A reconstruction of Quaternary pluvial environments and human occupations using stratigraphy and geochronology of fossil-spring tufas, Kharga Oasis, Egypt: Geoarchaeology: an International Journal, v. 19, p. 407–439.

Stanley, S.M., 1995, Climatic forcing and the origin of the human genus, *in* National Research Council, eds., Effects of Past Global Change in Life: Washington, DC, National Academy Press, Studies in Geophysics, p. 233–243.

Trauth, M.H., Maslin, M.A., Deino, A., and Strecker, M.R., 2005, Late Cenozoic moisture history of East Africa: Science, v. 309, p. 2051–2053.

Trauth, M.H., Maslin, M.A., Deino, A.L., Strecker, M.R., Bergner, A.G.N., and Duhnforth, M., 2007, High- and low-latitude forcing of Plio-Pleistocene East Africa climate and human evolution: Journal of Human Evolution, v. 53, p. 475–486.

Woldegabriel, G., Renne, P.R., Hart, W.K., Ambrose, S., Asfaw, B., and White, T.D., 2004, Geoscience methods lead to paleo-anthropological discoveries in Afar Rift, Ethiopia: EOS, Transactions, American Geophysical Union, v. 85, p. 273–276.

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