Subtle signatures of seeps: Record of groundwater in a Dryland, DK, Olduvai Gorge, Tanzania

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ABSTRACT

Few proxies exist to identify aridity in the depositional record, although drylands cover ca 30% of the modern continental surface. New exposures in a siliciclastic and carbonate sequence in an arid to hyperarid basin at Olduvai Gorge, Tanzania provide a unique multi-proxy record of a 1.85 Ma landscape that was exploited by early humans. The 2 m thick sequence of clastics and carbonates that are exposed along a 450 m outcrop records climate change over a single precession (dry-wet-dry) cycle. Siliciclastic data (sedimentary structures, grain size, mineralogy) and biological data are combined with data for a 10 to 35 cm thick limestone (stable isotopes, elemental geochemistry, petrography) to generate a depositional facies model for a site DK (Douglass Korongo) on this dry rift basin landscape. This site was situated on a low gradient, distal portion of a volcaniclastic alluvial fan. The clastics are intercalated distal alluvial fan sandy silts and lake clays that accumulated in a low energy environment. Groundwater discharge and the alkaline springs and seeps during wet-to-dry change in climate made a freshwater carbonate-rich environment. Bedded lithofacies (a lime mudstone with fossils) were deposited in shallow standing (spring-fed) pools, while nodular lithofacies with calcite spherulites indicate permanently saturated ground (seeps). Both environments experienced similar diagenesis, that is, the precipitation of authigenic barite from supersaturated groundwater, desiccation and pedogenesis, and late-stage calcite precipitation. Compositional and isotopic data suggest that a fresh groundwater-fed system was available to early humans even during dry intervals of the precession cycle.

INTRODUCTION

Drylands account for ca 30% of the modern Earth’s surface. They occur where moisture-bearing weather systems are prevented from reaching an area, such as the interior of a continent, the distal sides of a topographic high (rain shadow), and within high-pressure climate zones (global circulation easterlies). Areas receiving precipitation amounts of <25, 25 to 200 and 200 to 500 mm yr⁻¹ are considered hyperarid, arid and semi-arid respectively (Grove, 1977). The geological record indicates that there were times when the Earth was much drier on average than today, such as the Late Permian to Early Jurassic (Blakey et al., 1988) and the Messenian Crisis in the Late Miocene. However, interpreting the rock record of arid lands requires the use of proxies to estimate ‘dryness’. Aridity is the net result of a limited moisture supply (precipitation, P) and moisture losses (evaporation, E, and transpiration from plants, T). Examples of physical proxies for ‘aridity’ commonly used by palaeoclimatologists are thick accumulations of evaporites, extensive sand dune and loess deposits (Parrish, 1998) and desert soils, such as Aridisols (Mack et al., 1993; Retallack, 2001). In addition, speleothems provide robust records of aridity from evidence of variable carbonate precipitation rate and changes in both δ¹³C and δ¹⁸O (Burns et al., 1998; McDermott, 2004).

Sedimentation is typically discontinuous in drylands and this presents a major challenge in interpreting the depositional record. Lakes are often playas that contract...
and dry up, and rivers are ephemeral, fluctuating between high discharge episodes and periods of inactivity. Eolian reworking may dominate the landscape during persistent interludes of negative hydrologic budget (Patton & Schumm, 1981; Gierlowski-Kordesch & Rust, 1994; Goudie, 2013). Consequently, clastic sedimentation rates in drylands are typically low and episodic, and may be biased by infrequent flooding events. Chemical sediments such as limestones or evaporites may retain important information on the palaeoclimate, including seasonal records of evaporites (Arakel & Hongjun, 1994) and microbes and water droplets that were sealed inside salt crystals (Satterfield et al., 2005). The combination of information from both clastic and chemical sedimentary deposits can provide a more complete understanding of the facies reflecting dryland processes than either source on its own.

The East African Rift System (EARS) traverses the broad zone (30°N to 30°S) of tropical easterlies and has a mainly arid climate (Fig. 1A and B). There is considerable regional variation caused by topography. Uplifted rift flanks and volcanoes are >3000 m high and trap precipitation on the highlands (>2000 mm yr\(^{-1}\)) but create rain shadow effects in the rift valley bottom which typically receives <500 mm yr\(^{-1}\) (Nicholson, 1996). The EARS is composed of discrete sedimentary basins along the elongate rift valley (Frostick, 1997) with sedimentary fill that may date back to the Early Miocene (23 Ma), although the oldest rocks at the surface are <10 Ma. Geological studies in these basins were fuelled by the quest for evidence of early hominins and information on the palaeoenvironmental and palaeoclimatic conditions under which they evolved. The area has been termed the ‘Cradle of Mankind’.

The modern Olduvai Basin in northern Tanzania (ca 3° S) has a semi-arid climate. This basin has been studied for over 60 years and yielded a rich palaeontological and cultural record, as well as three species of hominins (Leakey, 1971; Hay, 1976; Domínguez-Rodrigo et al., 2012). Initial lithostratigraphic research focused on volcaniclastic sediments and interbedded tuffs (Hay, 1976; Ashley & Hay, 2002) (Fig. 2). More recent studies focused on geochemical processes (Hay & Kyser, 2001; Deocampo, 2004b), the sedimentology of limestones (Ashley et al., 2014b) and general palaeohydrology of the Olduvai Basin (Ashley et al., 2010c; Cuthbert & Ashley, 2014). Groundwater rather than surface water was identified as the major source of water to the basin. Excavations starting in 2012 at locality DK (Douglass Korongo) revealed a thick limestone with intercalated fine-grained clastics (Fig. 3A). At the base of the section above a basalt, the sediments archive a dense concentration of artefacts (an archaeological site, DK) in addition to vertebrate fossils (ca 3000) and stone tools (ca 1000) (Leakey, 1971; Egeland, 2007, 2008). A crushed hominin cranium of Homo habilis (H 24) has also been recovered from DK (Leakey, 1971).

Data from the DK outcrops could inform reconstructions of the landscapes used by ancient humans and provide additional sedimentary proxies to identify dryland sedimentary records. The objectives of this paper are (i) to describe the depositional record at DK; (ii) interpret the role of groundwater discharge in this dryland; and (iii) assess the likely persistence of the water and the potential of groundwater to be a freshwater water source for hominins.

**METHODS**

**Field**

Ten 1 m wide trenches were excavated in a ca 450 m exposure along the Olduvai River (Fig. 3B). Data are presented from seven trenches considered representative of the clastics and carbonates in outcrop. When logistically possible, trenches were positioned between Tuff IB (top) and the undulating surface of basalt (bottom). The trenches ranged between 1-5 and 1-65 m in height and were sampled at 10 cm intervals. Geo Trench #9 was 3-5 m thick, but the bottom 2 m is tuff and reworked tuff. These sediments were not included in our analyses. Trenches were located with a handheld GPS.
Laboratory

Grain size analysis

Thirty-three representative samples were analysed. Fifty grams of sediment were disaggregated in deionized water and wet sieved through a 63 μm sieve. The filtered grains were dried and weighed and dry sieved.

Petrography

Hand samples and thin sections (stained with potassium ferricyanide and alizarin red-S (Dickson, 1966) were described. Scanning electron microscopy (SEM) and energy dispersive spectrometry were conducted at Franklin & Marshall College for detailed study of depositional and diagenetic textures. The SEM analysis included imaging, backscatter compositional imaging, and qualitative mineral microanalysis.

X-ray diffraction (XRD)

Microsamples of carbonate micrite, sparry calcite, and barite crystals were obtained using a Dremel microdrill at low rpms. Each sample was microdrilled under a magnifying glass to avoid visibly different constituents, although the small size of the barite crystals meant that some micrite was inevitably incorporated into the same powder. Samples were run at Franklin & Marshall College on a PANalytical X’pert Pro PW3040 X-ray diffraction spectrometer using Cu K Alpha radiation, an automated diffraction slit and a X’Celerator detector, according to standard procedures (scans from 6 to 70 degrees 2 theta and a NIST traceable Si metal used to check goniometers accuracy).

Inductively coupled argon plasma spectroscopy (ICP)

Limestones were microsampled (0.05 g of carbonate) using a Dremel microdrill, were dissolved in 10% nitric acid, and analysed at Franklin & Marshall College on a SPECTROBLUE inductively coupled plasma optical emission spectrometer (ICP-OES), with 750 mm focal length,
a Paschen-Runge optical system, and 15 linear CCD array detectors. Each sample was referenced to the petrography by pairing with the appropriate thin section. Calibrations were made to seven standards, diluted to appropriate concentrations, from Specpure commercial stock solutions. Results are reported in ppm.

**Scanning electron microscopy (SEM)**

Samples were examined using an Evex Global Mini SEM, Model SX-3000, with an energy dispersive X-ray spectrometer (EDX) (Evex Global Nano Analysis, Platinum). Working conditions were 20 kV accelerating voltage, 93 nA beam current. Images were obtained using the back scatter detector and the secondary detector.

**Stable isotope analysis**

Samples of 550 μm to 900 μm were ground to fine powder. Carbonate δ13C and δ18O values were measured in the stable isotope laboratory at Rutgers University (Department of Earth and Planetary Sciences) with a multiprep device coupled to a Micromass Optima mass spectrometer. Carbonates were exposed to o-phosphoric acid for 800 s at 90°C. Stable isotope values are reported in standard per mil (‰) notation relative to the Vienna Pee Dee Belemnite standard (VPDB) through the analysis of an internal laboratory standard that is routinely measured with NBS-19 calcite using reference values of 1-95‰ and −2.20‰ for δ13C and δ18O, respectively (Coplen et al., 1983). Internal long-term internal standard deviations equal ∼0.05‰ and ∼0.08‰ for δ13C and δ18O, respectively.

**GEOLOGY**

The Olduvai Basin is located on the western margin of the EARS at a split in the rift called the Northern Tanzanian Divergence Zone (NTDZ) where the central valley bifurcates around the Ngorongoro Volcanic Highland (Ebinger et al., 1997; Dawson, 2008) (Fig. 1A). Volcanism occurred episodically in the NTDZ from the late Miocene to Recent (Mano et al., 2015). The large volcanic complex has a number of volcanoes that erupted periodically over the last 5 myr. Most are dormant, although one, Ol Doinyo Lengai, is currently active (Dawson, 2008; Deino, 2012). Extensional tectonics and volcanism are part of a regional response to the ongoing development of the EARS (Foster et al., 1997; Dawson, 2008; Le Gall et al., 2008; Mollel & Swisher, 2012). When formed, the Olduvai Basin was surprisingly shallow (100 m) despite its approximate diameter of ca 50 km. Olduvai Gorge was incised in the Late Pleistocene by a river system that now drains eastward towards the Highlands. The basin’s well-dated tuffs allow basin-wide correlation of widely separated outcrops and dating of archaeological sites (Hay, 1976; Blumenschine et al., 2003; McHenry, 2005; Deino, 2012; Domínguez-Rodrigo et al., 2012). Rift-related extensional tectonics segmented the Olduvai stratigraphy into blocks separated mainly by normal faults (Hay, 1976). Similar to other rift basin localities: Mesozoic, eastern North American rift basins (Binney de Wet & Hubert, 1989; de Wet et al., 2002) and Plio-Pleistocene, southern Rio Grande Rift, USA (Mack et al., 2000), bedrock, faults, and magmatic sources influence groundwater composition and flow patterns at Olduvai (Ashley & Hay, 2002; Cuthbert & Ashley, 2014).

**CLIMATE AND HYDROLOGY**

Precipitation in tropical East Africa varies with season and location (Nicholson, 2000), as well as with long-term orbital influences of climate (Trauth et al., 2007). Estimates of precipitation in the Gorge vary from less than 250 mm yr⁻¹ in drier periods of the precession cycle to about 700 mm yr⁻¹ in wetter periods (Magill et al., 2012a). Today, mean annual temperature (MAT) averages 25°C and is not likely to have varied significantly in the past (Ruddiman, 2000).

Potential evapotranspiration (PET) of ca 2000 to 2500 mm yr⁻¹, exceeds the annual (250 to 700 mm yr⁻¹) average rainfall by a factor of 4 to 5 resulting in a seriously negative annual hydrologic budget (Dagg et al., 1970). Few if any perennial rivers can persist with this strongly negative water budget, and all rivers draining into the basin were probably intermittent and ephemeral (Hay, 1976; Ashley & Hay, 2002) despite a study suggesting perennial rivers with riparian corridors may have existed (Blumenschine & Peters, 1998). The adjacent Ngorongoro Volcanic Highland (>3000 m high) traps moisture-laden easterly winds blowing from the Arabian Sea that creates a rain shadow over Olduvai Gorge to the west (Fig. 1B). Modern average rainfall at Ngorongoro is 1150 mm yr⁻¹ (Deocampo, 2004a) and was perhaps twice that during precession wet periods. Some rainfall runs off in ephemeral surface streams, but most infiltrates into the porous volcanlastic deposits of the Highland and moves westward in the subsurface into the Olduvai Basin (Cuthbert & Ashley, 2014). Today groundwater exits at the base of the slope creating a lake/swamp called Obalbal. The scenario was probably similar during the Pleistocene, at which time the Ngorongoro Highland was even higher (Cuthbert & Ashley, 2014). This scenario is, apparently, a common scenario along the EARS as Olago et al. (2000, 2009) noted that in the Central Kenya Rift, groundwater in the basins is derived from rainfall on the valley’s
upland flanks. High-resolution studies of palaeoclimate and palaeoenvironmental reconstruction at Olduvai have revealed a number of springs and wetlands associated with archaeological sites in Middle Bed I (Ashley et al., 2010a), Upper Bed I (Ashley et al., 2010b) and Lowermost Bed II (Liutkus & Ashley, 2003; Ashley et al., 2009; Deocampo & Tactikos, 2010).

ARCHAEOLOGY

The DK site is one of the earliest fossiliferous and tool-bearing deposits in the gorge. M. D. Leakey discovered the archaeological site at the base of the sedimentary section and excavations in 1962 to 1963 revealed a stone circle interpreted as a ‘living floor’, abundant fossils, and stone tools. A Homo habilis cranium was found on the surface in 1968. The interpretation of the archaeological site by Leakey was that it was a record of hominin behaviour (Leakey, 1971). A recent analysis of the record found little evidence of hominin modification (i.e. butchery) to the bones despite an abundance of stone flakes used to skin and disarticulate carcasses (Egeland, 2007).

Egeland thought that the site was a palimpsest, a collection of artefacts that accumulated over a time, and hence the stone tools and cut-marked bones may not be directly related. He hypothesized that the DK site was more likely a carnivore kill site. It is possible that the carcasses were disarticulated and transported by hominins to a place of safety for butchering and consumption. No dense archaeological accumulations have been found higher in the sedimentary sequence, although dispersed fossils and Oldowan tools have been noted by Egeland (2007).

RESULTS

Stratigraphy and sedimentology

The sedimentary infill of the Olduvai Basin is composed of intercalated pyroclastics (tuffs), minor lava flows (basalts), and weathered volcaniclastic detritus transported from the basin margin by ephemeral rivers and authigenic Mg-rich clays produced in the lake (Hay, 1976; Hay & Kysers, 2001; Hover & Ashley, 2003; Deocampo et al., 2009). Volcaniclastics derived from the Ngorongoro Volcanic Highland dominate the east side of the basin, whereas siliciclastics occur on the west side where metamorphics (gneiss and schist) are the primary detrital source (Ashley & Hay, 2002; Ashley et al., 2014a). The study site, DK area, is on the east side of the Olduvai Basin and is situated on the lower slopes of an alluvial fan (Fig. 3A). The fan is composed of clastics sourced from the adjacent Ngorongoro Highland. During palaeo Lake Olduvai highstands the toe of the alluvial fan was submerged, therefore, sedimentary deposits at site DK consist of terrestrial transported volcanioclastic material, in situ carbonate deposition, and palaeo Lake Olduvai shoreline sediments (Fig. 3A).

The DK outcrop is exposed at the very base of a 25 m bluff, on the north side of the Olduvai River (Fig. 3). Vesicular olivine basalt with an undulating surface (presumably a surface of erosion), is at the base of the section. Relief on the basalt is 2 to 3 m and the lows are filled in with tuff and reworked tuff. Field conditions prevented excavation down to the basalt in all trenches. The sedimentary sequence (ca 1-65 m thick) that overlies the basalt is composed of horizontally bedded clastics and a 10 to 30 cm thick carbonate bed. A thin clay layer underlies Tuff IB at the top (Figs 4 and 5). Tuff IB is a trachyandesite and has recently dated at 1-848 ± 0-003 Ma (Deino, 2012; McHenry, 2012).

The siliciclastic sediments are silty claystones interbedded with claystones and have variable amounts of fine sand (2% to 32%) (Fig. 4). Geo Trench #2 differs from the others in that is coarser grained throughout and contains dispersed clasts (0.5 to 2 cm in diameter). Except for the carbonate and thin clay at the top, the sediments are mainly silts (with 2 to 32% sand and locally dispersed basalt) and minor calcareous silts. Excluding Geo Trench #2, the overall pattern up section is an increase in percent sand and then a decrease in percent sand. The carbonate bed is persistent over the 450 m of the curved outcrop and varies between 10 and 35 cm thick. It is a tabular, sheet-like body (not a mound form) and varies from a soft friable carbonate to a more nodular and crystalline texture.

Carbonate petrography

Depositional features

The DK carbonates are divided into two lithofacies endmembers; (i) bedded limestone consisting of lime mudstone or wackestone and (ii) nodular limestone consisting of calcite spherulites in a micrite-smeectite-rich matrix. The two carbonate endmember lithofacies grade laterally and vertically into each other, with variable proportions of each endmember, from nodular limestone packed with spherulites to ostracod-rich wackestone.

The bedded lime mudstone and wackestone lithofacies contain peloids, ostracod and gastropod fossils, possible Chara remains, and burrows in a micrite matrix (Fig. 6A and B). Fine sand to silt-sized quartz, feldspar, volcanic glass shards and detrital igneous minerals are common. Pockets and lenses of smectite-rich clay are also present within the lime muds. Geo Trenches #2, #10 display this lithofacies endmember (Figs 3 and 5).
Geo Trench #5 stratigraphy and photograph. Excavation was 1·3 m high and 1 m wide. Basalt is estimated to be 0·30 m below base. Section starts with 0·10 m of clay (with 5% sand) overlain with silty clay (0·8 m thick) that contains 23% sand and dispersed basalt clasts. Above the silty clay is a 0·15 m clay bed (with 12% sand), a white carbonate (0·30 m thick and 0% sand), a 3 to 10 cm thick clay that has minor sand and a sharp upper contact with Tuff IB. Stratigraphy of Geo Trench #5 also shown in Fig. 5.

Fig. 5. Geo Trench #5 stratigraphy and photograph. Excavation was 1·3 m high and 1 m wide. Basalt is estimated to be 0·30 m below base. Section starts with 0·10 m of clay (with 5% sand) overlain with silty clay (0·8 m thick) that contains 23% sand and dispersed basalt clasts. Above the silty clay is a 0·15 m clay bed (with 12% sand), a white carbonate (0·30 m thick and 0% sand), a 3 to 10 cm thick clay that has minor sand and a sharp upper contact with Tuff IB. Stratigraphy of Geo Trench #5 also shown in Fig. 5.
The nodular limestone lithofacies consists of closely packed calcite microspherulites (approximately 1 mm diameter) (Fig. 6C and D) and, less abundant large calcite spherulites (ca 1 cm diameter). The millimetre-scale microspherulites form an interlocking groundmass. The matrix surrounding the microspherulites and spherulites consists of detrital sand to silt-sized grains of quartz, feldspar, igneous lithic fragments, and volcanic glass shards in smectite-rich clay (yellow-brown colour) and/or lime mudstone (pink-brown colour in stained thin sections) (Fig. 6C and D). Crystal growth generally pushed the fine-grained matrix material into inter-microspherulite spaces, concentrating it between the microspherulites, although some larger detrital grains were incorporated into the microspherulites, trapped between the elongate calcite crystals (Fig. 6C and D). Rarely, calcite fans are nucleated on clay clumps, indicating that the clays were present in the depositional environment.

Spherulites and microspherulites have a radial internal structure with two or more generations of calcite spar precipitated around a central core (Fig. 6C), yielding a rosette form. For simplicity, both microspherulites and the larger spherulites are referred to as rosettes since they share the same external form and internal structure. Rosette layers are composed of multiple generations of acicular to fibrous calcite crystals, defined by thin, dark, inclusion-rich zones sandwiched between layers of lighter coloured calcites (Fig. 6C and D). Under crossed nichols, the rosettes exhibit pseudo uniaxial crosses. Rosette cores consist of blocky calcite, micritic peloidal clusters or a small micritic clump, with acicular to fibrous calcite crystals radiating outwards (Fig. 6C). Rarely, single radiating crystals attain millimetre size and these larger crystals often have a zone of microborings and inclusions at their outer edges (Fig. 6D).

**Diagenetic features**

Thin sections of limestones from all trenches exhibit some degree of pedogenic overprinting, such as circumgranular cracks, vuggy pores, clay-filled pockets, ped and chalky textures. Desiccation cracks and vugs are generally filled...
with sparry calcite cement and are closely associated with black dendrites of Mn and Fe oxides that precipitated along crack margins and around vuggy pores. Both the sparry cement and dendrites are interpreted as having precipitated from groundwater.

Slender prismatic barite crystals, often exhibiting twinning, with prismatic cleavage and low birefringence, occur within and between the calcite rosettes (Fig. 7A and B). They also occur more rarely as clusters within bedded limestone micrite. The crystals generally have sharp margins and good crystal form, indicating authigenic growth in situ. Rarely, some crystals exhibit ragged margins, indicating incipient dissolution by later fluids (Fig. 6D). The prismatic barite crystals are usually small, ca 200 to 300 μm long and ca 20 to 40 μm wide, but may reach dimensions as large as 600 μm by 100 μm.

Mineralogy

The detritus retained on the 63 μm sieve is mainly fine to very fine sand (63 to 250 μm) composed of quartz, volcanic glass shards, mafic minerals, feldspar and occasional barite rosettes (micro nodules) ca 1 to 2 mm in width.

Initial petrographic study suggested that the prismatic crystals might have been gypsum, but this was not borne out by XRD or SEM EDX results. No calcium sulphate minerals (gypsum or anhydrite) were identified. The XRD results for both the bedded and nodular limestones yield calcite and, less commonly, Mg-rich calcite. No aragonite was found. The XRD on the nodular limestones indicated calcite for the rosettes, with an indeterminate result for barite (one primary peak, but secondary peaks, if present, were masked by calcite peaks). Alkali feldspar and quartz occur in all samples.

Inductively Coupled Plasma spectrometry was used to assess whether the two types of limestone (bedded and nodular) had different geochemical signatures although their original water source was probably similar. The ICP results show that the bedded limestone contains micrite with the highest iron, magnesium, and manganese concentrations, relative to the nodular calcite, but overall the bedded limestone values are quite variable. The nodular calcite values are, however, more tightly clustered, particularly in Mg concentrations (Table 1 and Fig. 8). The Mn values for both limestones are low (below detection limit to <600 ppm, with a single outlier at 875 ppm) (Table 1). Strontium concentrations are also variable (trace to 2382 ppm), with the highest values occurring in samples from bedded limestone in Geo Trench # 2 (sample GA-03-14) that contains ostracod shells and is extensively bioturbated (Fig. 6A).

An SEM with Energy Dispersive X-ray was employed to confirm the mineralogy of the prismatic crystals within the calcite rosettes. BaO concentrations of up to 65.9 weight per cent and 30.4 wt % SO₃ in spot analyses of single prismatic crystals confirmed them as barite [with minor contributions of SrO (1.7 wt%) and CaO (2.0 wt %)] (Fig. 9). Backscatter imaging showed barite as very bright in contrast to duller calcite due to barite’s higher atomic number (Fig. 9). The barite composition of the small nodules (ca 2 mm) found during wet sieving of the clastics from just below the limestone was confirmed by EDS (energy dispersive spectroscopy) at Rutgers University.

Carbon and oxygen isotope results

Stable isotope values for δ¹³C and δ¹⁸O are quite clustered, ranging from −2.6 to −4.4‰ and from −4.2 to 5.5‰ respectively (Fig. 10 and Table 1). The δ¹⁸O value of average modern rainfall approximately equals −4.0‰ (V-SMOW) for northern Tanzania (Bowen, 2010). Therefore, CaCO₃ δ¹⁸O values will be precipitated in isotopic equilibrium with this unmodified water, that is, −4.0‰ (V-SMOW). Combination of the V-SMOW to V-PDB conversion factor, with the 25°C ambient temperature frac-

![Fig. 7. Photomicrographs are of stained thin sections, non-polarized light. (A) Nodular limestone lithofacies with a group of three prismatic twinned barite crystals growing authigenically within a calcite rosette core. (B) Nodular limestone lithofacies with a cluster of slender prismatic barite crystals within a calcite rosette.](image-url)
Interpretation and discussion
Depositional environment
Siliciclastic record

The DK site is on the distal portion (toe) of a volcaniclastic alluvial fan, a feature first recognized by Hay (1976) (Fig. 3A). It is an area where groundwater seepage would be expected, that is, the base of the slope (Quade et al., 1995; Springer & Stevens, 2009). Publications on Olduvai since Hay’s study have documented groundwater discharge as an important factor in forming soils (Ashley & Driese, 2000; Ashley et al., 2014a), in the distribution of plants (Copeland, 2007; Ashley et al., 2010b; Barboni et al., 2010), creating wetlands and affecting land use by hominins (Blumenschine & Peters, 1998; Deocampo et al., 2002; Ashley et al., 2009).

The DK site was also situated near the outer edge of palaeo Lake Olduvai, when the playa was at its maximum expansion (Fig. 3A). The sediments, in general, are a monotonous sequence of silty clays interbedded with clays. All sediments have variable amounts of fine to very fine sand (2 to 32%) (Fig. 5). Flooding of the site during lake-level highs is inferred from the smectitic clay layers in the sedimentary sequence. Smectites are authigenic clay minerals that form in alkaline lake water from detrital feldspar washed or blown into the lake (Hay, 1976; Hay & Kyser, 2001; Hover & Ashley, 2003; Deocampo et al., 2010).

### Table 1. Geochemical and stable isotope results

| Sample name | Geo-Trench # | Fe (ppm) | Mg (ppm) | Mn (ppm) | Sr (ppm) | $\delta^{18}O$ %PDB | $\delta^{13}O$ %PDB |
|-------------|--------------|----------|----------|----------|----------|---------------------|---------------------|
| SEEPS       |              |          |          |          |          |                     |                     |
| GA-62-12    | 1            | 1945     | 6269     | 229      | 996      | –4.76               | –2.95               |
| GA-47-12    | 7            | 306      | 6110     | 117      | 388      | –4.45               | –2.99               |
| GA-7A-14    | 7            | 2215     | 7386     | 303      | 418      | –4.28               | –2.79               |
| GA-7B-14*   | 7            | –        | –        | –        | –        | –4.94               | –4.08               |
| GA-8-14     | 7            | 2746     | 6256     | 209      | 323      | –4.77               | –3.38               |
| GA-55-14    | 8            | 878      | 5823     | 481      | 366      | –5.38               | –4.1                |
| GA-97B-12   | 8            | 4999     | 10 227   | nd       | 932      | –4.60               | –3.21               |
| GA-11-14    | 9            | 403      | 2810     | nd       | 1694     | –4.36               | –2.82               |
| GA-12-13    | 9            | 1550     | 5488     | 93       | 2095     | –4.59               | –2.99               |
| GA-12-13*   | 9            | 2624     | 6654     | 119      | 1445     | –          | –                   |
| GA-12-14    | 9            | 800      | 4786     | 150      | 1        | –4.59               | –2.99               |
| GA-53-13    | 9            | 486      | 8241     | 185      | 1349     | –4.42               | –2.94               |
| GA-53-13*   | 9            | 1252     | 5424     | 36       | 1945     | –          | –                   |
| GA-04-12    | –            | –        | –        | –        | –        | –4.65               | –3.8                |
| GA-05-12    | –            | –        | –        | –        | –        | –4.89               | –4.19               |
| GA-07-12    | –            | –        | –        | –        | –        | –3.46               | –2.28               |
| GA-09-12    | –            | –        | –        | –        | –        | –4.23               | –2.42               |
| GA-13-12    | –            | –        | –        | –        | –        | –4.07               | –2.82               |
| Mean        | –            | –        | –        | –        | –        | –5.13               | –4.33               |
| SD          | –            | –        | –        | –        | –        | 1347               | 1826               |
| PONDED      |              |          |          |          |          |                     |                     |
| GA-02-12    | –            | –        | –        | –        | –        | –5.13               | –4.33               |
| GA-3-14     | 2            | 4213     | 18 866   | 875      | 776      | –4.32               | –2.85               |
| GA-4-14     | 2            | 6958     | 23 527   | 322      | 938      | –4.22               | –2.62               |
| GA-7-12     | 2            | 2087     | 4173     | 160      | 487      | –5.06               | –4.34               |
| GA-17-12    | 2            | 5469     | 14 851   | nd       | 1 441    | –          | –                   |
| GA-50-14    | 10           | 903      | 7750     | nd       | 2 382    | –4.38               | –2.33               |
| GA-50-14    | 10           | 791      | 2744     | 264      | 546      | –4.38               | –2.33               |
| GA-51-14    | 10           | 3153     | 12 471   | nd       | 2 112    | –5.48               | –4.44               |
| Mean        | –            | –        | –        | –        | –        | –5.31               | –3.32               |
| SD          | –            | –        | –        | –        | –        | 3368               | 7674               |
Radiometric dates on the 1.7 m thick stratigraphic section are 1.877 ± 0.013 Ma (on basalt) at the bottom and 1.848 ± 0.003 Ma (on Tuff IB) at the top, thus the time interval represented by the section is <29 000 years (Deino, 2012). However, the undulating basalt surface indicates an erosional hiatus. The average sedimentation rate for the entire basin, based on total thickness of the sediments (not including volcanics), between dated tuffs is 0.1 to 0.2 mm yr⁻¹ (Hay, 1976; Ashley, 2007). Applying these average sedimentation rates to the 1.7 m thick section indicates a time duration of approximately 17 500 to 21 000 years for the sedimentary sequence at DK to accumulate between the basalt and Tuff IB.

Excluding Geo Trench #2, the overall pattern up section is an increase in per cent sand and then a decrease in per cent sand. The systematic change in per cent sand could reflect a change in surface processes caused by changes in precipitation. Specifically, the increase and decrease in per cent sand suggests a change in climate from dry to wet to dry up-section (Fig. 5). During drier periods the per cent sand is lower due to reduced activity of surface transport under a negative hydrologic budget. During wetter periods the per cent sand is higher due to increased precipitation and more runoff and sheet wash events. The estimated time span of ca 20 000 years for...
the sequence matches that of a precession cycle that is considered to be the dominant factor of East African climate dynamics (Magill et al., 2012a).

The DK limestones, which require a persistent source of fresh water, occur in the upper part of the sequence, at a time we propose is going from a wet to dry climate. We note that other freshwater carbonates at Olduvai are also associated with changing climate regimes, that is, Milankovitch period transitions (Ashley et al., 2014b). In general, groundwater flow rates are slow (metres/year) and thus would lag behind rainfall in the basin and adjacent topographic highs (Fig. 1B) (Springer & Stevens, 2009; Cuthbert & Ashley, 2014). Groundwater-fed discharge systems typically lag behind recharge associated with an increase in precipitation (Freeze & Cherry, 1979). This lag leads to a potential offset in the stratigraphic record between the more rapid basin response to an increase in precipitation, such as rising lake level, and the onset of significant groundwater flow that could support appreciable carbonate accumulation.

The interpreted climate fluctuation of dry/wet/dry is corroborated by analyses of soil organic matter ($\delta^{13}$C values) from samples in Geo Trench #9. Associated $\delta^{13}$C values indicate vegetation changed from a community dominated by C4 grasses (1.9 m), to a mixed C3/C4 community (1.55 m) with (semi)aquatic macrophytes (1.3 m) before changing again to a community with drought-tolerant C4 grasses, C3 forbs and trees or shrubs (0.8 m and 0.10 m). These vegetation reconstructions and our interpretation of the grain-size data are also supported by a phytoliths and diatom spectra of the same sequence (Albert et al., 2015). The evidence strongly suggests a precession-driven climate cycle at DK, an idea to be tested with further work.

**Carbonate record**

The bedded limestone lithofacies represents carbonate deposition in a shallow ponded-water setting where ostracods, gastropods, and probably Charaphytes attest to the presence of standing water for at least one wet season in a monsoonal climate (Liutkus & Ashley, 2003). The thickness of the limestone (10 to 35 cm) suggests, however, that wetter conditions were likely to have persisted for tens to hundreds of years, but the exact timeframe cannot be determined. The lime muds probably represent both abiotic (physico-chemical) precipitation of calcium carbonate and biologically precipitated calcite by cyanobacterial or algal blooms in quiet shallow water (Flügel, 2004; Pedley, 2009; Pedley & Rogerson, 2010). The muds are bioturbated, indicating an active infauna and generally oxygenated sediments. Detrital sands and silts may have been wind-blown, transported by colluvial processes, or surface run-off.

The nodular limestone lithofacies, composed of millimetre and centimetre-scale calcite rosettes is interpreted as a syndepositional fabric where calcite crystallization was focused in nucleation centres, either clay clumps, peloidal micrite clots or another allochem replaced by sparry calcite. Anhydrite, barite, and possible celestite may precipitate as rosettes within the sediment (Scholle & Schluger, 1979; Hanor, 2000) and calcite may take on nodular forms within deltaic sands (Garrison et al., 1979), or during pedogenesis (Bennett et al., 2012). The DK rosettes have some characteristics typical of anhydrite, barite or celestite stellate forms, but are composed of calcite, with the exception of the prismatic barite crystal clusters within them (Fig. 7). However, prismatic barite crystal clusters also occur outside of the rosettes, and within the bedded limestone sediments. This phenomenon suggests that the rosettes did not form originally as barite, and as no calcium-sulphates were detected using XRD or SEM EDX techniques, it is unlikely, although not impossible, that the rosettes were first deposited as either gypsum or anhydrite, and subsequently replaced by calcite. The simplest explanation, however, based on the evidence available, is that rosettes precipitated as syndepositional calcite. Albert et al. (2015) also interpret DK beds as representative of a high water table with periods of surface water, consistent with our interpretation that the rosettes represent precipitation from groundwater seeps associated with a high and fluctuating water table (Fig. 11).

The oxygenisotope ratios for both lithofacies are very close to present East African meteoric values of ca $\delta^{18}$O (6-0‰) and are tightly clustered. The strongly negative values indicate very little fractionation took place during deposition from the groundwater in either the areas of seeps or in ponded water. Compared to other limestones in the Olduvai Basin, Fig. 10 shows that the DK limestone resembles the Upper Bed I limestone most closely. Upper Bed I limestone is interpreted as a fault-sourced spring site, not associated with a wetland, whereas Middle Bed I and Upper Bed II, characterized by a broad range of $\delta^{18}$O and $\delta^{13}$C values. These carbonates did have large siliceous wetlands associated with them (Ashley et al., 2014b).

Our XRD and ICP data indicate that different depositional conditions for the bedded and nodular limestones resulted in slightly different limestone compositions. Although many freshwater limestones consist only of low-Mg calcite (Wetzel, 1983), our XRD results show that the DK bedded limestones have minor amounts of high-Mg calcite. The bedded limestones also have more variable calcite chemistries than the nodular limestones, suggesting that biological effects (i.e. Sr-rich aragonite gastropod
The prismatic barite crystal clusters occur both within and outside the rosettes. This condition strongly suggests that the prismatic barite crystal clusters are diagenetic features associated with shallow burial and fluctuating shells, bioturbation) may have influenced carbonate geochemistry.

Typically, freshwater is enriched in Mn and Fe, relative to sea water but these elements must be in their divalent states to be incorporated into calcite (Veizer, 1983). The presence of Mn and Fe in the DK limestones (Fig. 8) indicates that there must have been periods of time when calcite was forming in suboxic to anoxic porewater. In ponded water, such as characterizes the DK bedded limestone setting, oxygen minimum zones may be present seasonally and sediment porewaters may become dysoxic/anoxic because of water stratification or macrophyte decomposition in eutrophic environments (Wetzel, 1983). In the nodular limestones, suboxic conditions may reflect water table stagnation, reducing Fe and Mn to divalent cations, whereby they were incorporated into the rosette’s calcite crystals. Overall, however, none of the DK limestones exhibit blue or purple colours in response to the staining technique, indicating that iron concentrations are below the threshold needed for stain response (Dickson, 1966).

Sr concentrations in the bedded and nodular DK limestones may reflect Sr derived from celestite and/or barite since celestite (SrSO₄) and barite (BaSO₄) are in solid solution (Hanor, 2000) and both Sr and Ba were detected in our SEM EDX results. Sr is also readily incorporated into calcite (Veizer, 1983) and both the nodular and bedded limestone samples have similar Sr concentrations (Fig. 8). Magnesium values are generally low for the nodular calcites (2810 to 8241 ppm) while some of the bedded limestone samples are significantly enriched in Mg (>14 000 ppm) (Fig. 8), confirming the XRD result indicating the presence of high-Mg calcite in the bedded limestone sediment. Therefore, geochemical data show that the DK carbonates are distinct in both texture (bedded vs. nodular) and composition. The presence of desiccation features indicates that at some point during formation of the limestone the sediments were exposed and dried. Infilling of shrinkage cracks with sparry calcite cement, and associated Mn and Fe dendritic oxides, indicates subsequent meteoric phreatic conditions, probably associated with a fluctuating water table (Fig. 11). Compositional data support this assumption as all of the calcites contain some ferrous iron and manganese. The porewaters were, therefore, anoxic to suboxic for some period of time, as seen in perennial wetlands and deeper regions of freshwater phreatic systems (Mount & Cohen, 1984; Mitsch & Gosselink, 2000; Renaut & Gierlowski-Kordesch, 2010).

There are several lines of evidence that the environment of deposition varied from subaqueous to subaerial consistent with a fluctuating water table. Changing redox conditions and the varying height of the water table within the sediment profile is supported by the multiple generations of acicular to fibrous calcite, defined by darker and lighter layers, within the rosettes. Rosette growth zones are delineated by inclusion-rich bands alternating with inclusion-poor bands indicating fluctuations in porewater conditions during crystal precipitation. Thicker, better developed light coloured layers represent periods of rapid precipitation due to high concentrations of solutes in the porewaters. The darker, inclusion-rich layers may represent slower precipitation rates where microbes and algae had time to bore the crystal surfaces, producing a micrite-envelope-like fabric along the growing calcite crystal tips. This condition is clearly seen in the larger calcite crystals where microborings are apparent (Fig. 6D). The geochemical results show that the rosettes have a fairly tightly constrained composition, relative to the bedded limestones, suggesting that the composition of the porewaters from which they precipitated were relatively homogeneous, which implies a groundwater and/or surface water source area that did not change very much over the time frame of the rosette’s formation. The concentration of solutes in the porewater and/or the rate of rosette precipitation seem to have varied, perhaps seasonally, producing the growth zones within each rosette, but the composition of the fluid remained relatively homogeneous.

Subtle signatures of seeps

\[ \text{Mg} > 14\,000\,\text{ppm} \] (Fig. 8), confirming the XRD result indicating the presence of high-Mg calcite in the bedded limestone sediment. Therefore, geochemical data show that the DK carbonates are distinct in both texture (bedded vs. nodular) and composition. The presence of desiccation features indicates that at some point during formation of the limestone the sediments were exposed and dried. Infilling of shrinkage cracks with sparry calcite cement, and associated Mn and Fe dendritic oxides, indicates subsequent meteoric phreatic conditions, probably associated with a fluctuating water table (Fig. 11). Compositional data support this assumption as all of the calcites contain some ferrous iron and manganese. The porewaters were, therefore, anoxic to suboxic for some period of time, as seen in perennial wetlands and deeper regions of freshwater phreatic systems (Mount & Cohen, 1984; Mitsch & Gosselink, 2000; Renaut & Gierlowski-Kordesch, 2010).

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The prismatic barite crystal clusters occur both within and outside the rosettes. This condition strongly suggests that the prismatic barite crystal clusters are diagenetic features associated with shallow burial and fluctuating...
redox porewaters (Jennings & Driese, 2014; Jennings et al., 2015) (Fig. 11). Jennings & Driese (2014) note that optimal conditions for barite precipitation include warm sediment temperatures, a stable landscape, distinct wet/dry seasonality that enhances water table fluctuations, and a source for barium and sulphur. The abundance of volcanic rocks in the catchment area provides a readily available source of cations and anions in ground and surface water (Schopka & Derry, 2012).

The weathering of K-feldspar, which is abundant in the Ngorongoro source rocks, is usually invoked as the source of Ba for the barite. McHenry determined barium levels in Bed I glasses ranging from 0 to 0.3 BaO wt% oxides and orthoclase feldspars to have 0.1 to 3.5 BaO wt % oxide (McHenry, 2004). Appropriate redox conditions for barite formation are met in the Olduvai Basin tropical setting, where seasonal rainfall variability affects the water table and weathering of local volcanic rocks provides the source for the barium and sulphur, as well as calcium, iron, strontium, manganese, and magnesium (Hay, 1976; Ashley & Driese, 2000; McHenry, 2009) Interestingly, Jennings & Driese (2014) and Jennings et al. (2015) report barite precipitation in association with gypsum in acid-sulphate soils. This mineral association may represent slow formation in acid-sulphur rich soils where sulphur-reducing and sulphur-oxidizing microbes contribute to its development (Hanor, 2000). In the Olduvai DK strata, the association of barite with calcite rather than gypsum suggests alcalic, rather than acidic conditions (Hanor, 2000; Jennings & Driese, 2014). If, however, the calcite rosettes and limestones formed syndepositionally, and the barite precipitated diagenetically, its presence may indicate a change to more acidic porefluids after burial.

As illustrated in Fig. 12, groundwater and surface water sourced from the adjacent Ngorongoro Highlands collected in the DK creating localized ponds and base-of-slope seeps. These settings yielded bedded limestone in the shallow ponds, and nodular limestone where groundwater seeps percolated through porous and permeable sediment. Due to differences in the depositional settings, carbonates formed with different textures and geochemistry, but both environments experienced similar diagene-
suggest that hominins were dry season visitors only at DK (based on a comparison of archaeological records with those of modern Bushman) (Speth & Davis, 1976). The ponded freshwater at the DK area of the Gorge would have been an important resource during the dry season. Although the lake was nearby, mineralogical studies indicate the lake water was saline and alkaline (Hay & Kyser, 2001; Hover & Ashley, 2003) and thus probably undrinkable. The groundwater-fed spring and seep system would have supported a plant community. A recent study by Albert et al. (2015) on plant remains at DK found that the landscape before eruption of Tuff IB, had abundant grasses and a diversity of potentially edible plants, such as fruits, shrubs and starch-rich rhizomes and tubers. The freshwater source would have been a natural attraction for grazing and browsing vertebrates, as well as carnivores that prey on them. Egeland found that of the 63-3% of bones that were modified by humans 7-3% had carnivore damage (Egeland, 2007). Watering holes are known sites of competition among animals seeking food and water, so clearly a mixed blessing.

CONCLUSIONS

The depositional environment of the DK limestone is most consistent with an alkaline aqueous environment. Locally spring-fed ponded water produced a bedded limestone facies containing freshwater fauna, and areas of groundwater discharge (seeps) yielded nodular limestone facies with spherulites. Fluctuations, probably caused by short-term (seasonal?) water table changes, produced calcite rosettes in the nodular facies, with subsequent diagenetic formation of authigenic barite both within and outside the rosettes. Both carbonate facies have abundant textural evidence for dryland processes such as desiccation cracks and later sparry calcite precipitation that indicate exposure and subsequent re-submergence below the water table during diagenesis. The geochemical evidence is subtle. The oxygen isotope signatures of both facies are tightly clustered with relatively little fractionation during precipitation of calcite. Our isotopic and geochemical results show that the porefluids from which the carbonates precipitated were relatively homogeneous in composition, with variations in the composition of ponded-water limestones likely reflecting biological influences associated with micrite precipitation. The isotopic overlap between DK limestones and those from fault-derived porefluids forming carbonates in Upper Bed I (Fig. 10) hints that there may be as-yet-unrecognized fault conduits associated with the DK limestones as well.

The depositional and diagenetic record preserved at DK reveals dryland conditions where water table variations leave subtle signatures in the sediments. The combi-
nation of carbonate and siliciclastic sediments reflects small changes in groundwater-produced features, yielding a nuanced understanding of dryland deposition. For example, an increase in sand content up-section, caused by increased surface transport, indicates wetter conditions and a decrease in per cent sand indicate dry conditions. The formation of limestones near the top of the section and other indicators (grass vegetation and decrease per cent sand) are consistent with the biomarker evidence from the Central Basin at Olдуvai for the drying limb of a precession (Milankovitch) cycle (Magill et al., 2012b). The DK site at Olдуvai Gorge first attracted world attention because it contains an archaeological site at the base of the section that is a record of hominin activity in the basin. The DK limestone, a result of groundwater intersection with topography, provides a record of a potential water source for vertebrates and hominins even during dry periods.

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