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Paleoenvironmental context of the Pliocene A.L. 333 “First Family” hominin locality, Hadar Formation, Ethiopia

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ABSTRACT

Detailed lateral study of strata associated with the A.L. (Afar Locality) 333 hominin locality provides paleoenvironmental information at geographic scales of hundreds of meters to kilometers as well as insights regarding alluvial deposition and pedogenesis in the middle Denen Dora Member of the Hadar Formation. A.L. 333 is dated at ca. 3.2 Ma and has produced over 260 surface and excavated specimens of *Australopithecus afarensis*. It represents an unusual source of high-resolution information about the paleoenvironmental context of this hominin. The *in situ* hominin fossils are associated with the final stages of filling of a paleochannel and were buried prior to the formation of overlying paleosols. Preserved bedding structures in the fine-grained hominin-producing strata provide evidence that the abandoned channel continued to aggrade prior to the onset of sustained pedogenesis. Pedogenic carbonates associated with the hominin level thus postdate the death and burial of the hominins, possibly by centuries to millennia. The reconstructed paleodrainage of the DD-2 sandstone (DD-2s) is oriented south to north and consists of a trunk channel, ~40 m wide and 3–5 m deep, connecting a tributary system south of A.L. 333 to a distributary system to the north, which likely ended on the deltaic plain associated with the basin’s depocenter. The hominin concentration occurs in the upper part of the fill of the trunk channel. The burial of the hominin remains involved fine-grained deposition indicating low-energy, seasonal flood events, and there is no sedimentological evidence for a high-energy, catastrophic flood that could have caused the demise of the hominins.

Keywords: Ethiopia, Pliocene, hominin, Hadar, paleoenvironment.

INTRODUCTION

This research focuses on the fluvio-lacustrine architecture and paleogeography of the Denen Dora Member of the Hadar Formation, Afar Depression, Ethiopia, in the vicinity of the unique fossil occurrence known as A.L. (Afar Locality) 333 or the “First Family” locality, which is preserved within this

interval. Over 260 hominin specimens representing at least 17 individuals (Harmon et al., 2003; Behrensmeyer et al., 2003) occur at A.L. 333, making it arguably one of the most important and enigmatic concentrations of early hominin remains ever found. The Denen Dora Member represents a transition from lacustrine to fluvial environments between 3.26 and 3.20 Ma (Aronson and Taieb, 1981; Walter, 1994; Campisano and Feibel, this volume, Chapter 6; Campisano and Feibel, this volume, Chapter 8). The depositional history of A.L. 333

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has been debated since the locality was first discovered and specimens were collected in 1975–1976 (Johanson et al., 1978, 1982; White and Johanson, 1989).

Geological research targeting the sedimentary context of fossil concentrations such as A.L. 333 can address differing spatial and temporal scales, each of which provides information relating to depositional processes that contributed to the preservation of the fossil concentration. Studies of regional stratigraphy typically focus on placing fossil localities within an overall stratigraphic context over lateral scales of tens to hundreds of square kilometers, while the geologic setting of individual archaeological and paleontological sites may be documented at centimeter to meter scale. It is the purpose of this article to use intermediate scales of tens of meters to kilometers to reconstruct the fluvial architecture and paleoenvironments of the middle Denen Dora Member. This will provide a basis for interpreting the paleogeography of the physical landscape inhabited by *Australopithecus afarensis* and associated fauna at a well-constrained point of time. Research on the taphonomy and finer-scale microstratigraphy of this locality by the author and Elizabeth L. Harmon is continuing and will be published elsewhere.

BACKGROUND

The Hadar area of the northern Awash Basin in Ethiopia consists of an ~100 km² region centered on the Kada Hadar drainage at ~11°06'N, 40°35'E (Fig. 1); this region is well known for its fossil vertebrates, including many specimens of the hominin *Australopithecus afarensis* (Taieb et al., 1972; Johanson et al., 1978; Kimbel et al., 1994). The first reports of paleoenvironments of the Denen Dora (DD) Member were part of an overall assessment of the depositional context of the vertebrate faunal record throughout the Hadar Formation (Figs. 2 and 3). The Denen Dora Member was described as 30–40 m thick, with shallow-water lacustrine to deltaic plain deposits in the lower submember (DD-1) overlain by swamp and floodplain deposits (DD-2–3) (Gray, 1980; Aronson and Taieb, 1981; Johanson et al. 1982). The DD-2 submember represents a regressive phase of the paleolake and consists of the DD-2s (s = sandstone) and overlying fine-grained fluvial deposits with pedogenically modified units, CaCO₃ nodules, and root casts. The DD-3 submember is a major sand-dominated unit with abundant vertebrate fossils, interpreted originally as a network of distributary channels and floodplains (Aronson and Taieb, 1981). The paleogeographic reconstruction of the Denen Dora Member based on this earlier work posited high-energy streams from the highlands to the west that spread out into distributary networks upon entering the lower-gradient areas of the rift floor, forming marshes and small deltas (Johanson et al., 1982). Based on further field research, the lower part of the Denen Dora Member is now interpreted as regressive lake to lake-margin deposits, and DD-3s is interpreted as a single, large-scale meandering fluvial system that eroded into the upper part of the DD-2 submember and aggraded laterally over a wide area (Yemane, 1997; Campisano, 2007).

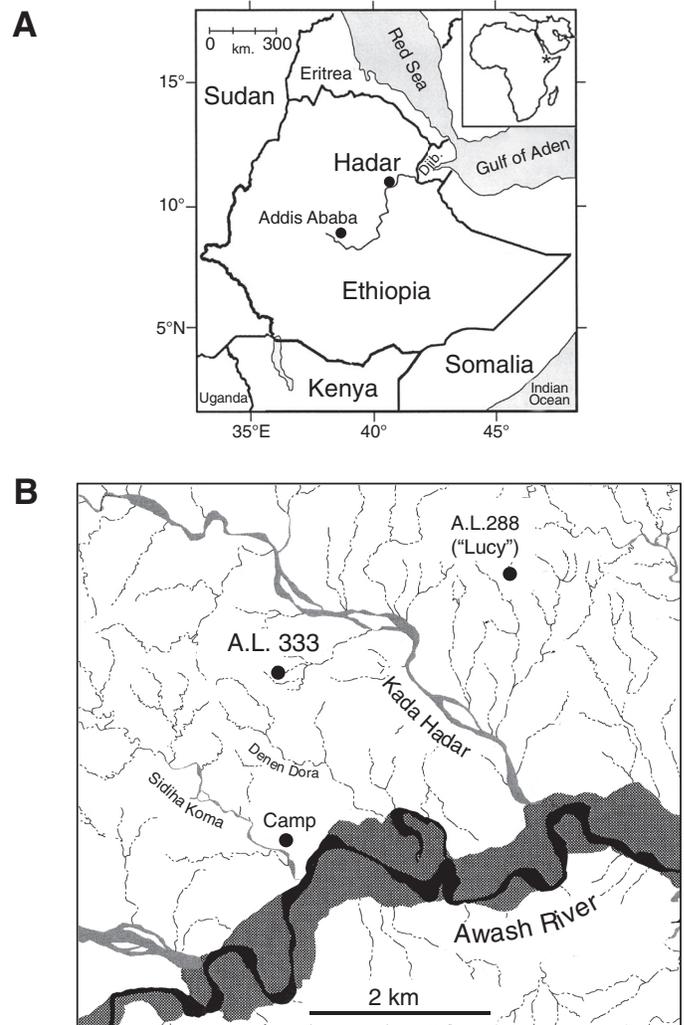


Figure 1. Maps showing the geographic location of (A) the Hadar area in Ethiopia, and (B) the A.L. 333 locality in relation to major drainages at Hadar, the Awash River, and A.L. 288, the fossil locality where the associated partial skeleton known as “Lucy” was found (map in B was modified from Eck, 2002). North is up on both maps; latitude and longitude reference points are shown on the perimeter of A.

In 1975–1976, large numbers of hominin specimens were discovered on the outcrop surfaces in a restricted area designated as A.L. 333, and 19 *in situ* hominin remains were subsequently excavated from carbonate-rich clayey silts near the base of a thick paleosol in the middle part of the Denen Dora Member (Johanson et al., 1982), below DD-3s (Figs. 2 and 3). The locality lies between the TT-4 (Triple Tuff 4), originally dated to 3.22 ± 0.01 Ma (Walter, 1994) and recently recalculated to ca. 3.24 ± 0.01 based on the revised age for the Fish Canyon sanidine standard (Table 5.19 in Campisano, 2007), and the overlying KHT (Kada Hadar Tuff) (3.18 ± 0.01 Ma; recalculated to 3.20 ± 0.01 Ma; Table 5.19 in Campisano, 2007). Recent analyses by Campisano (2007) indicate a slightly older date for TT-4 of 3.256 ± 0.016 , but this will require further work to be confirmed.

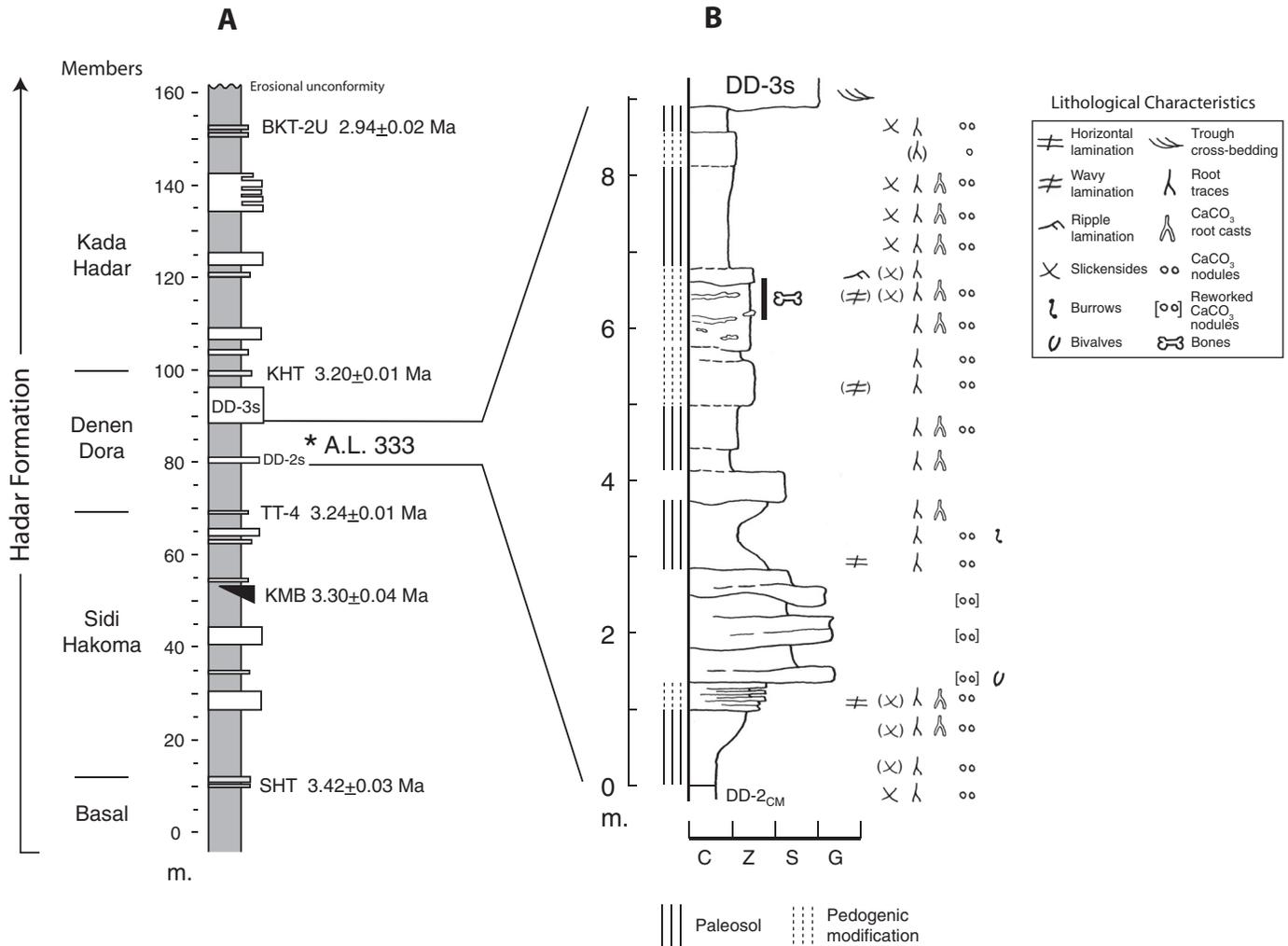


Figure 2. (A) Hadar Formation generalized stratigraphy, showing the major units with revised and recalculated dates based on Campisano (2007). Vertical scale in meters from base; BKT—Bouroukie Tuff, KHT—Kada Hadar Tuff, KMB—Kadada Moumou Basalt, SHT—Sidi Hakoma Tuff, TT-4—Triple Tuff 4. (B) Expansion of the portion of the Denen Dora Member that includes A.L. 333. Detailed section log (section 01/01) was measured at the main A.L. 333 excavation site and extends from the carbonate marker (DD-2_{CM}) into the base of the DD-3 sandstone (DD-3s). Lithologies and sedimentary structures show that the fossiliferous interval occurs in pedogenically altered clayey silts near the top of a fining-upward sequence associated with the DD-2 sandstone (DD-2s), a laterally discontinuous channel deposit. Solid vertical lines indicate well-developed paleosol features (slickensides, root traces, ped structure, calcium carbonate nodules, and root casts); dashed vertical lines indicate units with less-developed pedogenic features and relict bedding. Key to lithology scales below section logs: C—clay, Z—silt, S—sand, G—gravel.

The age of the A.L. 333 fossil locality thus is ca. 3.2 Ma. Most of the hominin fossils were collected along with other faunal remains from an area of ~40 m × 80 m (~3200 m²) on steep slopes and in small ravines up to the stratigraphic level of the excavated specimens. It has long been assumed that the surface hominin fossils were derived from the same sedimentary unit as the *in situ* remains (Aronson and Taieb, 1981).

The geological context of A.L. 333 has been described by a number of researchers, both at the scale of the locality itself (i.e., tens of meters) and within the overall lithostratigraphy of this area (Aronson and Taieb, 1981; Radosevich et al., 1992; Campisano, 2007). The Denen Dora Member is composed predominantly of clays and silty clays but includes three notable fluvial sandstone

units (Campisano, 2007). The site occurs between the upper two of these, DD-2s and DD-3s. The DD-2s originally was characterized as a discontinuous but laterally persistent unit above a series of pedogenically modified mudstones (Fig. 2B) in the middle part of the Denen Dora Member (Aronson and Taieb, 1981). Where present, DD-2s is up to 5 m thick and internally complex, generally fining upward from basal, cross-stratified sands with intra-clast conglomerates to well-sorted sandy and clayey silts. DD-3s is usually ~5.0 m in thickness but can reach 10 m locally and is a cross-stratified, multistoried sandstone with lateral accretion surfaces and an irregular, often deeply erosional base (Campisano, 2007). It is composed predominantly of coarse sand with lenses of allochthonous volcanic pebbles and cobbles, and it grades

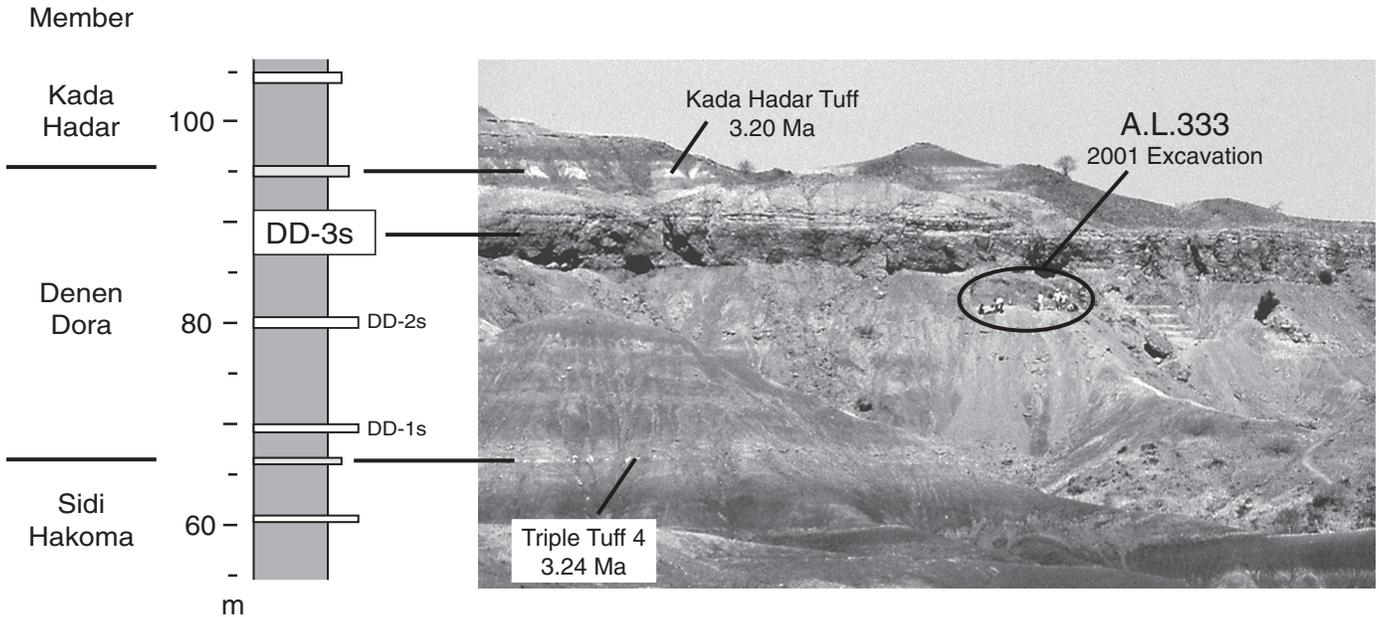


Figure 3. Photograph of outcrops associated with the A.L. 333 locality showing its position relative to the dated tuffs and DD-3s, a laterally extensive, 3–10-m-thick sheet sandstone. The *in situ* hominins were excavated from sediments 2.3–2.85 m below the local base of DD-3s, and surface fossils were collected on both sides of the low ridge and in the drainages below the excavation. Vertical scale shows meters above the base of the Hadar Formation (Campisano, 2007; Campisano and Feibel, 2008, this volume, Chapter 6); DD-1s and DD-2s are two lower, discontinuous sand bodies within the Denen Dora Member. Dates are based on Walter (1994) and Campisano (2007). For scale of photograph, note human figures at excavation (circled) and vertical stratigraphic scale to left.

upward to finer sands and silts below the KHT (see Aronson and Taieb [1981] and Campisano [2007] for further details). DD-3s forms a prominent, indurated sheet sand body throughout the areas of outcrop of the Denen Dora Member, and this helps to create steep slopes and good exposures of the underlying finer-grained DD-2 submember.

METHODS

The area targeted in this study is ~800 m wide (east-west) and ~2.5 km long (north-south), centered on A.L. 333 (Fig. 1). The locality occurs in an amphitheater of steeply sloping sediments extending from below TT-4 to DD-3s, which caps the local ridge top (over 30 m of relief); similar excellent exposures are present throughout the study area. Thirteen geological trenches were dug to document lithostratigraphy over an area of 300 × 500 m lateral to the main hominin-producing areas targeted by the 1976–1977 and 2000–2001 excavations. These, plus the walls of the two excavated areas, made it possible to describe vertical and lateral lithofacies patterns at decimeter scale vertically and 10²–10⁵ m scale laterally (Figs. 3 and 4; see also Supplementary Materials DR1¹). Four additional trenches

and two detailed stratigraphic logs provided documentation of the DD-2 channel and adjacent strata over a broader area (Figs. 5 and 6; Supplementary Materials DR1 [see footnote 1]); the farthest logged section was near A.L. 288—the site of the hominin fossil known as “Lucy”—which occurs at a higher stratigraphic level above DD-3s and just above the KHT.

The DD-2s unit was mapped throughout the study area, following the complex but roughly north-south orientation of the exposures (Fig. 7). Good exposures of the DD-2 submember occur under the continuous ridge-forming DD-3s, and it is straightforward to determine whether the DD-2s is present or not in these exposures. Where DD-2s is absent, there usually are slightly coarser, silty facies at the same level (e.g., sections 01/06 and 01/07 in Fig. 4), indicating overbank deposition from this channel. Abrupt lateral termination of DD-2s provides direct evidence of channel edges, which can be quite steep (Figs. 4–6). Mapping of these channel edges combined with the orientation of internal sedimentary structures indicate where a continuing channel should project onto adjacent outcrops; these predictions were tested by direct observation, trenching, and additional section logs (Figs. 4–7; section logs in Data Repository [see footnote 1]).

The panel diagrams (Figs. 4–6) provide cross-sectional views of the fluvio-lacustrine architecture at three different scales. These were constructed based on stratigraphic correlations between marker beds and unique sequences of beds. Correlation was straightforward over a distance of ~150 m in the A.L. 333

¹GSA Data Repository item 2008196, consisting of scans of the author’s original field logs documenting the stratigraphic context of the A.L. 333 locality, is available at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org. Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

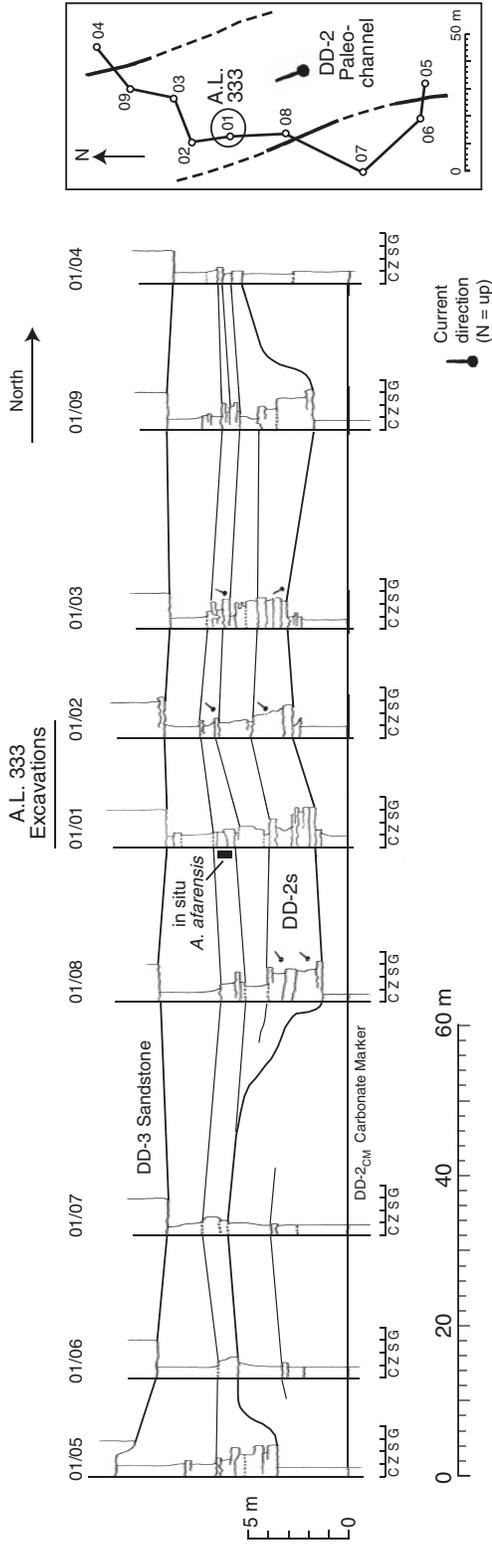


Figure 4. Two-dimensional panel showing the context of A.L. 333 within ~150 m of lateral exposures, based on geological step trenches and excavation walls. The top of a carbonate-rich unit in the Denen Dora Member, the carbonate marker (DD-2_{CM}), is the horizontal datum. Inset box shows the plan view of the section logs and the reconstructed boundaries of the DD-2 channel segment in the vicinity of A.L. 333; solid lines are documented channel margins, and dashed lines are reconstructed channel margins. Cross-stratification indicates a dominantly N to NE current direction. Key to lithology scales below section logs: C—clay, Z—silt, S—sand, G—gravel.

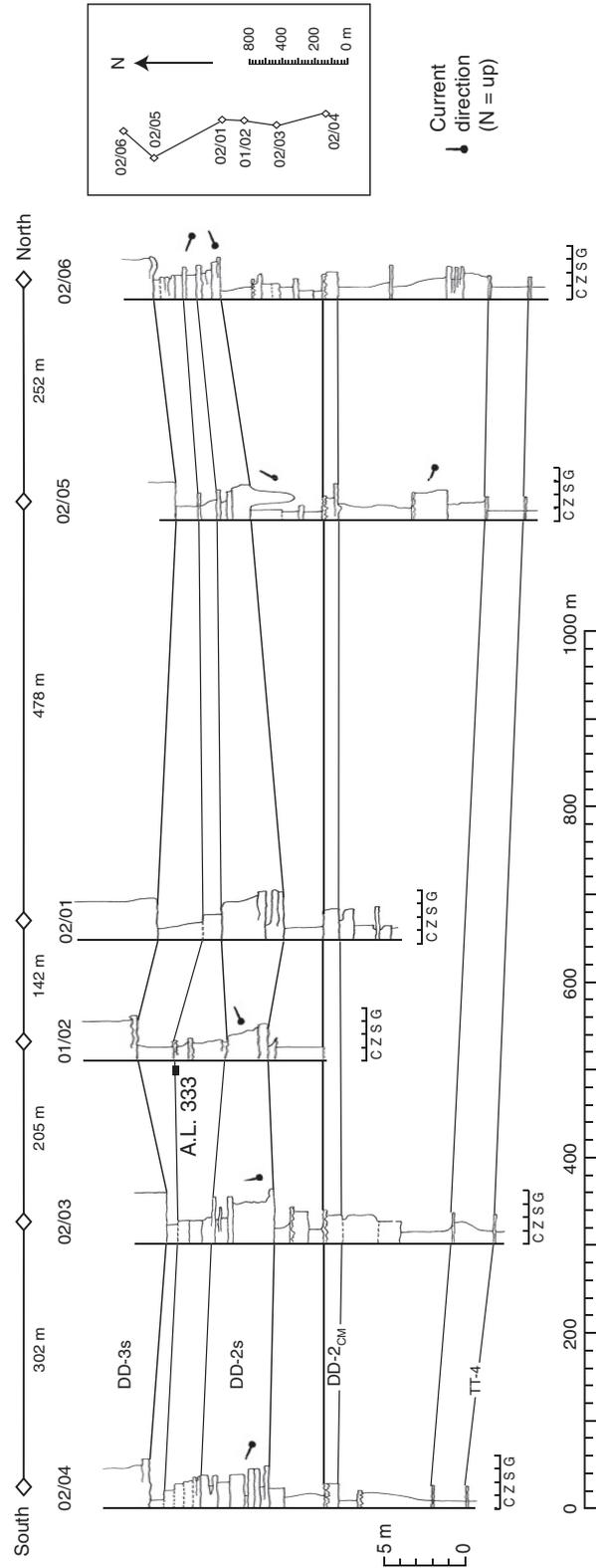


Figure 5. The context of A.L. 333 within the broader-scale fluvioacustrine architecture of the Denen Dora Member from TT-4 to the base of DD-3s. The panel represents a south-to-north cross section over ~1400 lateral meters (sections 02/04–02/06). Horizontal datum is the carbonate marker (CM). Inset box shows plan view of section positions. Key to lithology scales below section logs: C—clay, Z—silt, S—sand, G—gravel.

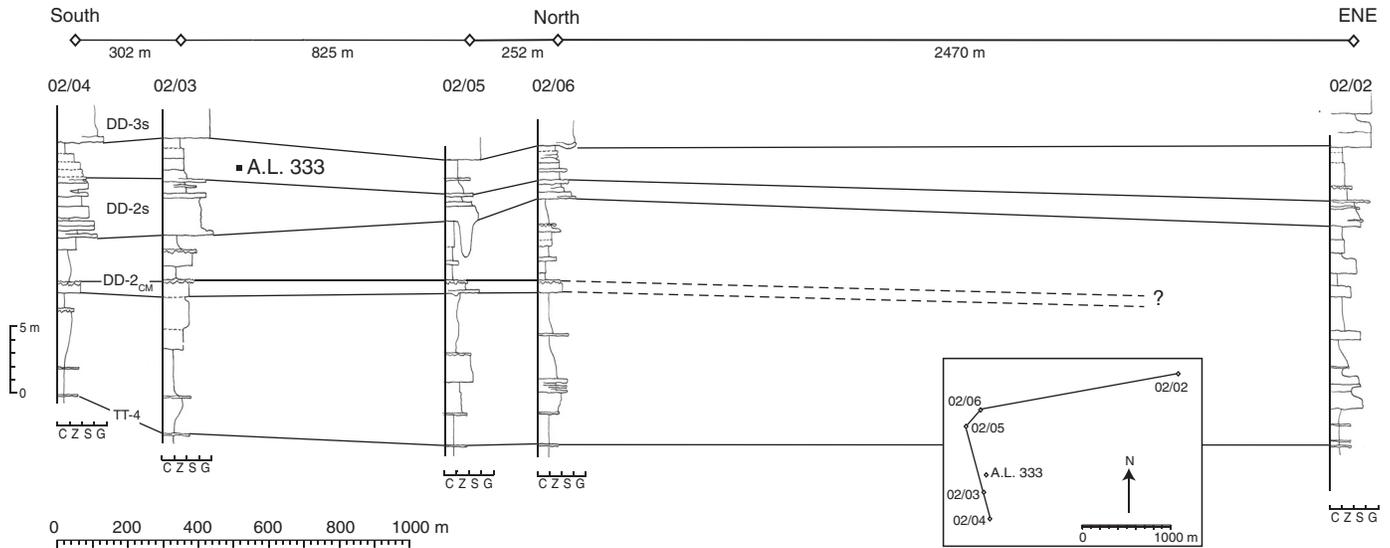


Figure 6. Panel diagram correlating Denen Dora Member strata from the area documented in Figure 5 to strata near the A.L. 288 “Lucy” site to the ENE. Total length of panel is ~4 km. Horizontal datum is the carbonate marker (CM), except between 02/06 and 02/02, where it is TT-4. Inset box shows plan view of section positions and A.L. 333 site. Key to lithology scales below section logs: C—clay, Z—silt, S—sand, G—gravel.

amphitheater, as individual beds could be traced along continuous outcrops (Figs. 3–4). The top of a prominent white-weathering, carbonate-rich claystone (see also Campisano, 2007), designated here as the DD-2 carbonate marker (DD-2_{CM}), was used as the horizontal datum in this area. The larger-scale panels also use this datum except between 02/06 and 02/02 (Fig. 6), where TT-4 is used because the correlation of DD-2_{CM} is no longer clear. Lateral correlations in Figure 5 are based on 1380 m of mostly continuous outcrops, and they show that DD-2s occurs throughout the study area. This scale oversimplifies the configuration of the channel system, however, which can be locally absent, as shown in Figure 4. There is marked thickening of the interval between TT-4 and DD-2s from south to north, indicating deepening of the basin in this direction. The nearly 4-km-long panel in Figure 6 extends the correlations to the vicinity of the A.L. 288 “Lucy” locality to the east, based on stratigraphic matching and marker units, including DD-3s and TT-4. This panel shows a consistent thickness of strata between TT-4 and DD-2s from A.L. 333 to A.L. 288, several kilometers to the ENE, suggesting that the basin was not deeper in that direction during the deposition of the clays and Vertisols of the DD-1 submember. This supports increased subsidence of the northern Ethiopian Rift basin toward the north between 3.8 and 2.9 Ma (Wynn et al., 2006) but is at odds with reconstructions of Hadar paleogeography during Denen Dora time (Yemane, 1997; Campisano, 2007), which suggest that the paleolake lay east of Hadar.

The Denen Dora Member is the most productive in terms of numbers of vertebrate fossils in the Hadar Formation (Taieb et al., 1976; Campisano, 2007), and most of these fossils occur in the DD-2 and DD-3 submembers. At A.L. 333, as well as elsewhere along the outcrops below DD-3s, many fossils found on the slopes of the DD-2 submember are clearly derived from over-

lying DD-3 strata based on adhering coarse sand matrix. Careful surface surveys of the DD-2 submember throughout the study area turned up few fossils that could be clearly associated with the A.L. 333 level (mainly fish, one crocodile tooth, a bovid horn core, an elephant mandible *in situ*). However, this may be in part because of previous intensive collecting in the Denen Dora Member near A.L. 333; farther north across the Kada Hadar drainage, the DD-2 channel sandstone becomes more fossiliferous where it broadens into a sheet sand body.

RESULTS

Strata between TT-4 and DD-3s support earlier interpretations of lake regression and the development of an emergent lake-margin plain (Taieb et al., 1976; Tiercelin, 1986; Aronson and Taieb, 1981; Campisano, 2007). Relatively pure, finely laminated clays at the level of TT-4 represent lacustrine sedimentation, and the upward increase in pedogenic features, including soil carbonate and well-developed slickensides, indicates wetlands that became progressively drier seasonally. These were incised by a paleochannel, the deposits of which formed the DD-2s submember. Continuing alluvial floodplain aggradation combined with a marked interval of paleosol formation followed the end of DD-2 channel deposition.

The DD-2 sand body is a ribbon sandstone (Friend et al., 1979), representing a paleochannel system that was oriented roughly south to north across the study area. It is well exposed in the A.L. 333 amphitheater (Figs. 2–4 and 7) and forms a prominent feature in the deposits of the emergent fluvial-deltaic plain. At A.L. 333, the channel deposit is ~40 m wide, 2–3 m deep, and extends north through the ridge that forms the amphitheater; its edges can be clearly seen on the ridge’s northwest face (Figs. 2

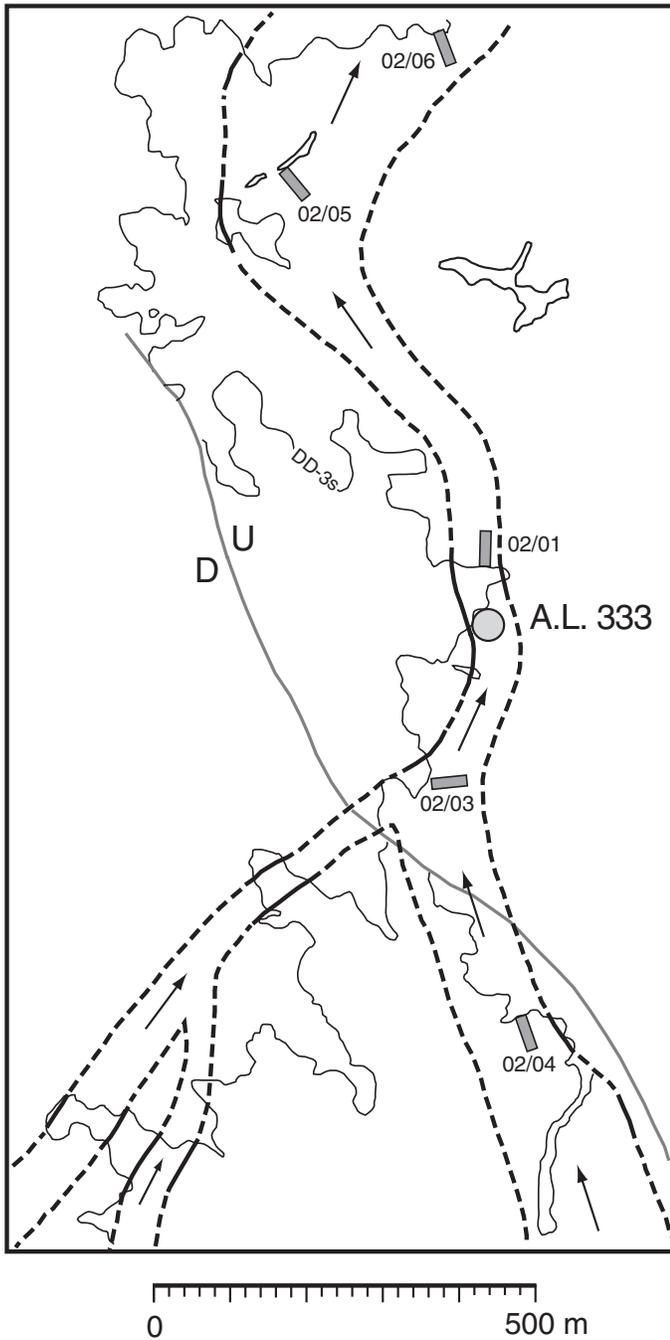


Figure 7. Reconstructed DD-2 channel system, based on documented channel facies and edges (solid line segments), current indicators within the channel, and intervening areas where channel deposits were absent. Thin irregular line marks the outcrop edge of DD-3s; all of the exposures under this sandstone were examined for the presence or absence of DD-2s. Gray rectangles show positions of geological trenches; north is up on the diagram. Normal fault (gray line) does not significantly affect exposures of the Denen Dora Member in this area.

and 4). The basal contact of the channel is irregular, with poorly sorted, locally derived mud and carbonate clasts generally less than 1 cm diameter and occasional articulated bivalves. The lower part of the channel has a sharp cutbank on its northwest edge just south of the excavation area (Fig. 4). Section 01/05 documents another, upstream portion of this same channel to the south (Fig. 4, inset plan view). Farther south (Figs. 5 and 7), exposures of channel segments at the same stratigraphic level are reconstructed as two branches feeding into the single channel at A.L. 333. Two parallel, shallower, and narrower U-shaped channel sand bodies toward the southwest (based on thickness and width of fill) are reconstructed as two smaller tributaries (Fig. 7). Toward the north, DD-2s broadens into a more sheet-like sand body, but internal features including current indicators are consistent with the continuation of the DD-2 channel system. The reconstructed channel in the vicinity of A.L. 333 is sinuous but not meandering, and it did not cut laterally to form a sheet sand. This is evidence that the channel was incised into the alluvial plain and then filled and abandoned in a relatively short period of time without cutting laterally into preexisting floodplain sediments (in contrast to DD-3s).

Aronson and Taieb (1981) described some channels in the Hadar Formation as U-shaped and noted that this implied pauses in sediment accumulation with intervals of channelized erosion into preexisting alluvium. The DD-2 channel provides evidence of such localized incision. In addition to the channel cut-and-fill documented at A.L. 333 (Fig. 4), three steep-sided, 2.5-m-deep “runnel” features at the base of DD-2s north of A.L. 333 (two at the 02/05 trench and one documented across the Kada Hadar drainage to the north) indicate marked erosional incision followed by rapid channel filling (Fig. 5). This suggests either temporary regression of the paleolake and headward erosion from the north, or tectonically controlled variability in local subsidence rates, e.g., local syndepositional flexure or faulting that caused some areas of the depositional basin to be slightly uplifted relative to others and subject to greater fluvial downcutting (Aronson and Taieb, 1981). Short-term climate cycling also could have affected the erosive power of flow into the lake, e.g., if the alluvial substrate was stabilized by vegetation, thereby reducing sediment load in the A.L. 333 channel and increasing its tendency to erode downward rather than expand laterally.

The DD-2 channel fill at A.L. 333 is sand and fine gravel at the base but includes interbedded sand and pedogenically modified sandy silts; these were regarded as separate small channels by Aronson and Taieb (1981), but they actually form parts of the fill of the larger channel feature shown in Figure 4. Deposits of silty clay with CaCO_3 root casts and pedogenic nodules cap the lower part of the channel fill (Fig. 2B, meters 2.8–3.7, Fig. 4). This represents an intermediate phase of fine-grained channel fill when flow energy had temporarily decreased. Above this paleosol, 40 cm silty sand indicate reactivated channel flow, followed by ~2.5 m of silts with variable degrees of pedogenic modification. The top of this sequence is formed by ~1.0 m of well-sorted gray silt, which extends throughout the exposures of the channel in the

A.L. 333 amphitheater at this level but is thickest in the vicinity of the main hominin excavation. Based on original maps, stratigraphic logs, and photographs from the 1976–1977 excavations, reexcavation of the locality in 2000–2001 by W.H. Kimbel (2001, personal commun.), and the author's personal experience at the site, the upper part of this gray clayey silt is the stratum in which the *in situ* hominin remains were originally found. Relative to the horizontal datum provided by DD-2_{CM} (Figs. 4 and 5), the channel underlying these silts forms a slight depression in the area where the hominins were concentrated, and the gray silt unit also is thickest there. This implies that the hominin remains were buried during the final infilling of a shallow (≤ -0.5 m), abandoned channel swale, with deposition overlapping onto the adjacent floodplain.

Radosevich et al. (1992) noted that carbonate precipitation at the A.L. 333 site may have occurred in loose substrates shortly after burial as well as during subsequent soil formation. Some of the hominin remains found on the surface up to the level of the excavation had thick CaCO_3 encrustations and also matrix consisting of medium-grained sand and reworked CaCO_3 nodules (Aronson and Taieb, 1981). The latter suggests that some of the fossil remains were buried by moderately high-energy flow and that these coarser facies of the original hominin-bearing deposit have been lost to erosion. The channel swale could have been temporarily reactivated during a wet-season flooding event, depositing coarser sediment along with the hominin remains as well as finer silts and clays prior to its final abandonment. Alternatively, the surface-collected hominins at A.L. 333 may be derived from successive strata representing different depositional events that combined to form the upper portions of the DD-2 sand body.

The gray silts at the excavated hominin level are cross-stratified at section 01/02, and current directions are oriented 50° east, similar to the current indicators in the lower, sandier DD-2 channel deposits. This suggests that the flow that buried the hominin remains was partly constrained and directed by the linear swale provided by the preexisting channel. The fact that cross-bedding and horizontal stratification are preserved in this unit implies that the silt deposit was a one time event, or part of a succession of events that were thick enough to protect some of the stratified sediments from later bioturbation and other homogenizing processes of pedogenesis associated with the overlying, well-developed clayey Vertisol. This 1.3 m Vertisol has abundant CaCO_3 nodules and root casts (Fig. 2). The soil's parent material accumulated during overbank sedimentation that preceded or was partially contemporaneous with pedogenesis (i.e., an accretionary soil). All of the sediments above the gray silts postdate the burial of the hominin remains, and it is possible that some (though probably not all) of the carbonate precipitation and nodule formation associated with the hominin bones occurred in the subsurface as the Vertisol was forming above the clayey silts. Regardless of the precise timing of the carbonate precipitation, the Vertisol near the top of the DD-2 submember postdates the hominin burial event.

The geological history of the interval between TT-4 and DD-3s, summarized next, is based on documentation of strata in the vicinity of A.L. 333 and is in general agreement with that

of Aronson and Taieb (1981) as well as Campisano (2007); it provides additional details regarding the DD-2 channel and its relationship to the hominin remains at A.L. 333. This history can be separated into 14 stages:

1. lacustrine sedimentation (laminated beds) in a relatively deep lake with clay-grade clastic input plus occasional air-fall tuffs (Triple Tuff sequence);
2. shallowing of the lake, with localized influxes of silts and sands, likely from distributary lobes of a nearby delta;
3. development of lake-margin wetlands with continuing lake regression, seasonal emergence, and pedogenesis;
4. increased development of pedogenic carbonate, indicating more pronounced periods of emergence; continuing lake regression;
5. continuing fluctuation of fine-grained clastic deposition and paleosol formation; more pronounced carbonates (Soil Carbonate Stage 2 of Gile et al., 1966);
6. formation of drainage channel (DD-2) in the study area and variable but locally pronounced downcutting resulting in narrow basal erosion gullies incised into earlier fine-grained deposits;
7. filling of first channel phase, up to approximately the level of the initial erosional incision;
8. temporary cessation of sand-grade clastic deposition and evidence of inactive channel and paleosol formation on the initial channel fill;
9. channel reactivation, with sand followed by silt deposition gradually filling in the channel and aggrading laterally beyond the margins of the earlier incised channel;
10. deposition of hominin remains in a shallow swale near the top of DD-2 channel fill;
11. final phase of deposition in the channel, burying the A.L. 333 hominin assemblage;
12. continued fine-grained deposition on an alluvial plain, where the DD-2 channel system had died or avulsed away from the study area; calcium carbonate precipitation in and around some of the hominin remains and other buried organic materials;
13. formation of a clay-rich accretionary Vertisol, with occasional influxes of fine silt and sand-grade sediment; pronounced development of pedogenic carbonate and prismatic ped structure indicating marked seasonal water-table fluctuations; and
14. erosion of the DD-3 channel system into the upper part of DD-2 submember, including the capping Vertisol, and deposition of a multistoried sheet sand over the area.

DISCUSSION

The DD-2s, although mostly below the level of the excavated hominins, provides the paleoenvironmental context for strata at the excavation site and a rationale for the depositional events that buried the hominin remains. All of the DD-2 channel

fill deposits are similar in lithology, bedding features, and current direction, and this evidence plus the consistent stratigraphic position above a widespread green, CaCO₃-rich clay (DD-2_{CM}) and below DD-3s support the interpretation that this was single-channel system that flowed across a flat, emergent plain toward the Hadar paleolake to the north. This reconstructed channel system, which can be traced as a single entity over ~1.5 km along its axis (Figs. 5 and 7), is north-directed and has a variable preserved width (40–80 m) with smaller and shallower tributaries feeding in from the south. Near the modern Kada Hadar drainage and across it to the north, the channel is well defined but wider and appears to diverge into multiple channels to form a braided distributary system.

The excavated hominin fossils occurred in clayey silt at the top of the channel fill and below a well-developed Vertisol. Preservation of vertebrate remains in the upper parts of abandoned channel fills is common in the terrestrial fossil record (Behrensmeyer, 1988). Previous work by Radosevich et al. (1992) has provided a thorough characterization of paleosols associated with the original A.L. 333 excavation area, based on samples collected by M. Taieb and analyzed by S. Radosevich and G. Retallack. The designation on their Figure 2 (Radosevich et al., 1992, p. 22) indicating “Hominids in Place” at 1.1–1.2 m below DD-3s, however, is in error, based on 1970s diagrams and photographs (W. Kimbel, 2004, personal commun.), relocation of the hominin-bearing level in 2000, and Figure 6 in Aronson and Taieb (1981, p. 188). The actual level is 2.3–2.85 m below DD-3s. Diagrams and measurements of Radosevich et al. (1992) show that all paleosol samples analyzed were above the hominin level except the lowest sample, F-2, at 2.45 m below the base of DD-3s. Thus, their inferences regarding the paleoenvironmental context of the hominin remains, based on the analysis of the paleosols at A.L. 333, relate to environmental conditions that postdate the time of hominin death and burial. The upper part of the hominin-bearing level is in the base of the “Type Fo” paleosol, which Radosevich et al. (1992) characterized as very weakly developed. The F-2 sample is dominantly clay, with ~16% silt and sand, and it differs from most other samples in having relatively more organic carbon and strontium, suggesting unique features of this layer.

As noted by Radosevich et al. (1992), the A.L. 333 hominin remains could have been buried with the parent material or incorporated into the sediment during a subsequent period of pedogenesis. They suggested a catastrophic flood event as a cause of the death and burial of the hominins, supporting the first alternative and implying that paleosol development was subsequent to the burial event. Aronson and Taieb (1981) also attributed the hominin concentration to mass death during a flood event. The results of the 2002–2003 research provide support for burial of the remains during a fluvial depositional event and later pedogenesis superimposed on the original parent sediment. Given the context within the top of a dying channel, however, in a gently sloping swale that was ≤0.5 m deep, as well as the fragmentary nature of the buried hominin remains, it is unlikely that this depositional event—i.e., a flood—also caused their death. Hominin

body parts or individual bones could have been affected by this flow, but the fine grain size of the enclosing sediment and lack of basal erosion features indicate that the depositional event was primarily aggradational, gently covering rather than scouring pre-existing sediment and organic remains, at least at the site of the excavated hominins. Possible transport of the hominin remains from upstream in the channel swale or from a wider scatter on the adjacent floodplain can be tested using the hominin fossils themselves; taphonomic study bearing on such hypotheses will be presented in subsequent publications.

Although there is no direct record of vegetation at the A.L. 333 site, other than root casts associated with pedogenesis, palynological research in the lower Denen Dora Member (DD-1 submember) indicates that the regional habitat was predominantly a dry grassland (Bonnefille et al., 2004). Gray (1980) noted that, locally, fossils of the genus *Kobus* (waterbuck) and other reduncines are common in the Denen Dora Member, which indicates moist substrates with “fresh grass” forage (Reed, 1998). Recent detailed analysis of the depositional environments and mammalian fauna of the Hadar Formation by Campisano (2007) shows paleogeographic differences in the DD-2 submember, with edaphic grasslands and marshy conditions to the north and east of A.L. 333 and more closed bush or woodland habitats in the vicinity of and west of this locality. Stable isotope analyses of pedogenic carbonates at A.L. 333 are in general agreement with Campisano’s faunal evidence, indicating 30%–34% C₄ grassland (Hailemichael, 2000), which is a relatively low proportion of grass compared with other samples from the Denen Dora Member. However, it should be noted that since pedogenic carbonate at the site formed after the burial of the hominin fossils, this habitat signature may not relate to conditions when living hominins were actually present.

The combined evidence indicates that both closed and open habitats were present in the DD-2 submember; the gradient went from more closed to the west to more open, edaphic grasslands to the east (Campisano, 2007). The north-directed DD-2 paleochannel in the immediate area of A.L. 333 likely was one of many drainages that carried water and sediment from the areas to the south and west across the deltaic plain to the north and northeast. The overall landscape that the A.L. 333 hominins inhabited, or perhaps occasionally traversed, would have been a relatively featureless, seasonally dry, grass-dominated plain (on a scale of kilometers) where the slight depression created by the dying channel may have hosted a different type of vegetation, including bushes or trees that were able to grow under conditions of more stable soil moisture (available to plant roots in the silty and sandy channel deposits underlying the channel swale). It is possible that hominins and other animals moved along such linear depressions left by old channels when they ventured into the more open grassland environments or used such areas as sheltering places. The scale of root casts in the brown paleosols lateral to the DD-2 channel indicates grass or small shrubs, and the root casts in the silts and clays in the upper channel fill indicate grass, shrubs, and bushes, but probably not large trees. The immediate vicinity of

the A.L. 333 excavation site has some of the densest concentrations of CaCO_3 root casts and nodules in the upper DD-2 channel deposit, suggesting seasonal fluctuations in moisture (i.e., due to seasonally elevated periods of soil evaporation and plant evapotranspiration) relating to more intense biological activity in this particular spot. The narrow channel between the tributary and distributary systems (Fig. 7) could have provided increased groundwater availability in the underlying channel sands, thus helping to focus more plant growth and deeper root systems in this linear paleogeographic feature.

Although estimates of the time represented by deposition versus pedogenesis versus erosional hiatuses are problematic at the scale of individual geological strata, the DD-2 submember provides an unusual opportunity to examine depositional history between two well-dated tuffs that are close in absolute age. The total amount of elapsed time, based on revised and recalculated dates for the TT-4 and KHT (Walter, 1994; Campisano, 2007) indicates that the ~30 m of strata represent ~40 k.y. (Fig. 2A) for a sediment accumulation rate of 75 cm/k.y., which corresponds in time to a period of increased basin subsidence between 3.4 and 3.2 Ma (Walter, 1994; Dupont-Nivet et al., this volume). The deposits of this interval include DD-3s, which is up to 10 m thick with a deeply erosional base. It seems unlikely that this sheet sand body could have been emplaced in less than 10,000 yr, leaving ~30 k.y. for the ~20 m below DD-3. There are at least eight paleosols in the DD-2 submember, for an average maximum of ~4000 yr per paleosol. The Vertisol above the DD-2 channel is thicker, more internally complex, and more extensively developed than earlier clay-rich soils, and it likely represents a relatively longer period of time, perhaps on the order of 5000 yr. The period of DD-2s channel incision and filling itself should represent no less than several thousand years and likely is closer to 5000 yr, particularly since it includes at least one period of inactive flow and soil formation. This leaves an estimated remaining time span of 20 k.y. below DD-2 for deposition of seven distinct intervals of fine-grained lacustrine to wetland sediments and their subsequent modification by pedogenesis, or ~3000 yr per interval. If Campisano's date of 3.256 ± 0.016 Ma for TT-4 (Campisano, 2007) is used, the total interval would increase from 40 k.y. to 56 k.y., increasing these estimates by ~30%. In spite of the uncertainty of the time estimates, it is clear that the DD-2 submember preserves a high-resolution history of short-term environmental change on a scale of millennia, superimposed on the longer period of lake regression that spanned tens of thousands of years. Against this backdrop of change in the physical environment, the final burial of the concentration of hominin remains at A.L. 333 occurred over much shorter period of time, perhaps in minutes or hours but likely no more than a few years, based on the geological evidence.

Among the East African localities where *A. afarensis* has been documented, only two provide high-resolution temporal and spatial information about the geological and paleoenvironmental context of this species, Hadar and Laetoli. The hominin trackway at Laetoli in Tanzania and the numerous autochthonous

fossil bones and teeth from hominins and associated fauna preserved in volcanoclastic silts and paleosols at 3.5–3.8 Ma indicate bush, woodland, and open habitats (Leakey and Harris, 1987; Agnew et al., 1996; Kappelman et al., 1997; Su and Harrison, 2007). The *in situ* hominin remains at A.L. 333 can be related to a death—and likely life—association of multiple hominin individuals with an abandoned channel swale that crossed a flat, extensive alluvial plain several kilometers from a paleolake to the north. The “Lucy” skeleton and other *A. afarensis* specimens from throughout the Hadar Formation are derived from fluvial and lake-margin deposits but lack more detailed evidence concerning sedimentary context, mainly because most are surface finds. Other East African localities with *A. afarensis* provide only general spatial and temporal information regarding its association with particular habitats. The Dikika *A. afarensis* child from deposits east of Hadar was found in a sandstone block associated with channel sandstones (Alemseged et al., 2006), and the remains may have been transported by fluvial processes prior to final burial in this sand. Teeth and other surface remains from Turkana Basin localities in Kenya are generally associated with fluvial or fluvial-deltaic deposits or are not complete enough to be certainly identified as *A. afarensis* (Feibel et al., 1989; Leakey and Harris, 2003; Campisano et al., 2004). Thus, the A.L. 333 *in situ* hominins and the Laetoli footprints provide the highest resolution contextual evidence for *A. afarensis* ecology currently available and indicate that this hominin occupied a mix of open and closed habitats in aggrading rift basin fluvial plains (Hadar) as well as more “upland” volcanoclastic terrain (Laetoli).

CONCLUSIONS

The study of the paleoenvironmental context of the A.L. 333 locality presented in this paper involves spatial and temporal scales ranging from those of the excavated site itself to decimeter to kilometer cross sections of the aggrading fluvial-deltaic system of the Denen Dora Member of the Hadar Formation. Each scale of inquiry provides information bearing on the depositional history of the locality itself as well as the adjacent strata.

The *in situ* hominin concentration at A.L. 333 is associated with the final stages of filling of the DD-2 paleochannel, and remains were buried prior to the formation of the overlying Vertisol. The burial event(s) that interred the hominin remains at the top of the channel likely occurred during seasonal flooding, and the resulting sediment was subsequently modified by pedogenic processes over centuries to millennia. Preserved bedding structures in the hominin-producing strata suggest that the immediate area of the excavated site continued to aggrade for some time prior to the development of the overlying paleosol(s). Thus, although pedogenic carbonates occur in the hominin level and the fossils have been described as occurring in a paleosol (Aronson and Taieb, 1981; Radosevich et al., 1992), the evidence presented here shows that they were buried by alluvial parent sediment that was later modified by pedogenic processes, not incorporated into the paleosol after it had begun to form.

The reconstructed DD-2 paleodrainage in the study area consists of a trunk channel connecting a tributary system within ~0.5 km to the south of A.L. 333 with a distributary system ~0.5 km to the north; the latter continued northeast for at least several kilometers and likely fed the deltaic plain formed by the retreating paleolake to the north. The hominin concentration is associated with the relatively narrow single channel between the branching distributary and tributary portions of the drainage system, which raises the possibility of a behavioral as well as a taphonomic cause for the paleogeographic position of A.L. 333, i.e., hominins and other animals frequenting a narrow strip of habitat formed by the abandoned channel fill. This channel may have been one of many of similar scale that combined to form the discontinuous sandstone outcrops of DD-2s across the broader extent of the Denen Dora Member. The burial of the excavated hominin remains involved fine-grained deposition, probably due to a shallow, seasonal flood event, and there is no sedimentological evidence for a high-energy, catastrophic flood that could have caused the demise of the hominins.

Based on revised age dates for the TT-4 and KHT, the DD-2 channel system is estimated to have formed and filled in ~5000 yr, and the overlying fine-grained floodplain sediments and Vertisol development may represent ~10,000 yr. The preservation of the hominins occurred during an interval of overall rapid aggradation of the Hadar Formation (5.5 m in 5 k.y. or ~110 cm/1000 yr for the DD-2 channel fill based on section 01/01). The link between well-preserved vertebrate fossils and high rates of sediment accumulation has been previously noted (Campisano et al., 2004) and underscores the paleontological importance of tectonic subsidence in the Afar Depression rift system during the mid-Pliocene. Correlations of sections in the area surrounding A.L. 333 indicate that the depocenter of the Hadar Formation during Denen Dora Member time was toward the north, but faunal gradients (Campisano, 2007) appear to have been transverse rather than parallel to this direction. This suggests that rift-margin climatic gradients could have interacted with axial river and lake systems in complex ways to create habitat variability over scales of tens of kilometers in the Pliocene Ethiopian Rift. Channel systems such as that represented by the DD-2s could have been important as corridors for animals moving among the different habitats and utilizing diverse resources on the Pliocene paleolandscape, as well as providing taphonomically favorable sites for fossil preservation.

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