LETTERS

Geological and palaeontological context of a Pliocene juvenile hominin at Dikika, Ethiopia

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Since 1999, the Dikika Research Project (DRP; initiated by Z.A.) has conducted surveys and excavations in badlands that expose Pliocene and Pleistocene sediments south of the Awash River in Ethiopia, between surrounding hominin localities at Hadar[1], Gona[2] and the Middle Awash region[3]. Here we report our geological mapping and stratigraphic measurement of the DRP area, and the context of a remarkably well-preserved skeleton of the earliest known juvenile hominin at the Dikika DIK-1 locality[4]. Our mapping of the DRP area permits a complete definition of the hominin-bearing Hadar Formation and provides a cohesive structural and tectonic framework defining its relationships to adjacent strata. Our findings reveal the basin-scale tectonic, depositional and palaeoenvironmental history of the area, as well as a clear taphonomic and palaeontological context for the juvenile hominin. Such data are crucial for understanding the environmental context of human evolution[5,6], and can be integrated into larger-scale tectonic and palaeoenvironmental studies[7,8]. Our basin-scale approach to palaeoenvironments provides a means to elucidate the complex geological history occurring at the scale of temporally and geographically controlled fossil point localities[3,9–11], which occur within the rich tectonic and depositional history of the Awash Valley.

The DRP area lies southwest of the Tendaho-Goba'ad discontinuity, which separates two tectonic regimes: the southeast-spreading Ethiopian Rift system (ERS) and the northeast-spreading Red Sea Rift system (RSRS)[7,8]. Because the DRP area exposes the entirety of the Hadar Formation (>3.8–2.9 million years (Myr) old) and Busidima Formation (2.7–<0.6 Myr old), our observations of local structure and stratigraphy allow reconstruction of the basin-scale tectonic and depositional history (Fig. 1). We find evidence of the DRP area being influenced by both the RSRS and ERS tectonic regimes during migration of the triple junction northward since 11 Myr ago (ref. 8). During deposition of the Hadar Formation, rapid sedimentation (30–90 cm kyr^{-1}) filled the then-active Hadar Basin. Thickening of the Hadar Formation with increasing representation of lacustrine facies occurs northeastwards across a series of northwest-trending syndepositional faults, indicating that local extension of this basin configuration occurred parallel to RSRS extension at ~N 45° E. Our mapping also provides a definitive lower boundary to the Hadar Formation in contact with the uppermost weathered surface of basalt flows, as originally suspected by a previous study[12]. Although the previous map showed these as the Afar stratoid series basalt (ASSB), we interpret the flows below the Hadar Formation as the Dahla series basalt (DSB). Unlike the DSB, local flows of the ASSB are syndepositional with the Hadar Formation (often showing features of cooling in the Hadar Lake), and do not extend southwest of a series of northwest-trending faults that cut across the DRP (one flow of the ASSB is the Kadada Moumou basalt[1]; another caps Andalee Ridge). The upper surfaces of two DSB-flows visible below the Hadar Formation each have a deeply weathered residual palaeosol, indicating an extended period of non-deposition before formation of the Hadar Basin (Fig. 2, section G). In the southeast DRP, the uppermost palaeosol is overlain by poorly sorted juvenile volcanic-arenitic sands, which interfinger with lacustrine clays of the lower Hadar Formation further basinward (northeast). The presence of the Ikini Tuff (a correlate of the Wargolo Tuff from the Turkana Basin[13]) indicates that the Hadar Formation sediments extend at least to the age of this tuff (3.8 Myr old; ref. 13) and overlie the weathered surface of the DSB.

The Hadar Formation upper boundary is defined by an angular unconformity to the overlying Busidima Formation[2] (Fig. 1b; the Busidima unconformity surface, 2.9–2.7 Myr old; ref. 2). Deposition of the Busidima Formation clearly postdates most of the fault offsets. Thus, later than 2.9 Myr ago, deposition in the Hadar Basin ceased and the Hadar Formation strata were uplifted from a depositional position by normal faults parallel to currently active basin-bounding faults of the Yangudi Basin in the Southern Afar Rift (Fig. 1). This period of uplift and erosion marks a similar change in extension direction in the Main Ethiopian Rift from 135° to 105°, indicated by the onset of similarly oriented faulting in the Adama Basin[8] (Fig. 1). Following 2.7 Myr ago, local sedimentation began in the Busidima Half-graben (filled with sediments of the Busidima Formation), which thickens westwards towards the As Duma border fault. This tectonic setting contrasts strongly with that of the Hadar Basin, and is similar to a series of more recent marginal grabens that extend into the northern Afar along the edge of the western escarpment[7].

Initiation of sediment accumulation in the Hadar Basin is marked by a sharp transition from deep weathering and erosion of the basaltic basement to rapid deposition of lacustrine clays of the Basal Member that thicken northeast from zero to >60 m. Lake shoreline facies, which are represented by two gastropod-bearing bioclastic sandstones (B-g, Basal gastropodite) near the top of the Basal Member, transition to a subaerial lower-delta-plain and delta-channel facies-association that contains the juvenile hominin[4] in the lower Sidi Hakoma Member (DIK-1 locality; Fig. 1). This depositional setting, combined with the remarkable preservation of many articulated faunal remains lacking evidence of preburial weathering, most probably indicates rapid deposition during major flood events, burying many fossils as intact corpses (including the juvenile hominin). We have mapped regional depositional environments during emplacement of the Sidi Hakoma Tuff, from shallow lacustrine in the northeast DRP area, to offshore lacustrine delta at Arbosh, subaqueous delta channel at Gango Akidora, and a mappable upper delta plain fluvial channel in upper Arbosh (Fig. 2). The river-dominated

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delta system in the DIK-1 area transitions to a stable shoreline and lacustrine deposition in the upper Sidi Hakoma through the lower Denen Dora members. The upper Denen Dora through most of the Kada Hadar members shows a return to predominantly fluvial facies, with only brief sedimentological evidence of local transgression of the Hadar Lake, such as that represented by the confetti clay.

The diverse fauna from the excavation site at DIK-1 (ref. 4) were collected from two trough cross-bedded tabular sandstones with basal pebble or grit lags, representing distributary delta-channel facies (Fig. 2). Primates are very rare: in addition to the hominid *Australopithecus afarensis,* only isolated teeth of other primates—*Theropithecus darti* and Cercopithecidae (indeterminate)—were recovered during screening. Carnivores are uncommon except a relatively frequent large otter, *Enhydriodon*. A well-preserved canid cranium may be conspecific with a *Nyctereutes*-like mandible, but is probably not of this genus. A cranium of *Elephas* is more derived than that of *E. ekorensis*, and resembles *E. recki brumpti*. Other molars have similar morphology but fewer plates and are more brachyodont, reminiscent of *E. ekorensis*. Coexistence of these closely related species supports recent views[14] that their evolution is more complex than a single anagenetic lineage. The DIK-1 *Hipparion* is relatively large, but a complete metatarsal is slightly smaller than specimens from Hadar[15]. Lower teeth of *Hipparion* often have a large ectostylid, showing that this feature is not restricted to later Pliocene forms. A hexaprotodont hippo with a wide symphysis has second incisors, similar in size or slightly smaller than the third incisors, that fill a gap between teeth size of the two named species in the Hadar Formation[16]. Despite within-member size variation among suids, clear metric trends can be demonstrated in members of the genera *Kolpochoerus* and *Notochoerus*. *K. afarensis* from the Hadar Formation is larger than *K. deheinzelini* from Aramis, Sagantole and Chad, but specimens from Amado (northeast of Hadar) bridge the size gap between these species. Within the DRP, the size of third molars (and premolars) in *K. afarensis* increases in the Basal Member and the lower Sidi Hakoma Member. The size of third molars of *Notochoerus* does not increase, but a mandible from the DIK-1 locality confirms a previous suggestion that premolars from the base of the Sidi Hakoma Member are still *Nyanzachoerus*-like, whereas those discovered at Denen Dora and Kada Hadar members are significantly reduced[17]. The most common bovid at DIK-1 is an impala, slightly smaller and more primitive according to the weaker lyration of its horn-cores than the *Aepyceros shungurae* from the Shungura Formation[18], but more closely related to an unnamed species there[19]. Horn-cores from the Sidi Hakoma Member are slightly larger but less compressed than those from the Denen Dora Member. They are much shorter and less spiralled than those of the current form, but also than those from Lothagam[20], indicating co-occurrence of two lineages of impalas in the East African Pliocene. A bovid cranium has horn-cores similar to those of *Tragelaphus nakuae* from the Turkana Basin. A similar form from the Denen Dora Member at Hadar was reported[18], but it is also present in the Sidi Hakoma Member. We provisionally refer a single almost straight horn-core to the poorly defined genus *Praedamalis*. It might belong either to the type-species, *P. deturi*, from Laetoli and the Denen Dora Member at Hadar[18] (also found in the Sidi Hakoma Member), or to *P. howelli* from Maka[21]. An alcelaphine, *Damalops sidihakomai*, is represented by a horn-core and teeth of a derived pattern, although its p4 is primitive according to its open lingual valley, as at Maka. Lower molars attributed to *Golunda* from DIK-1

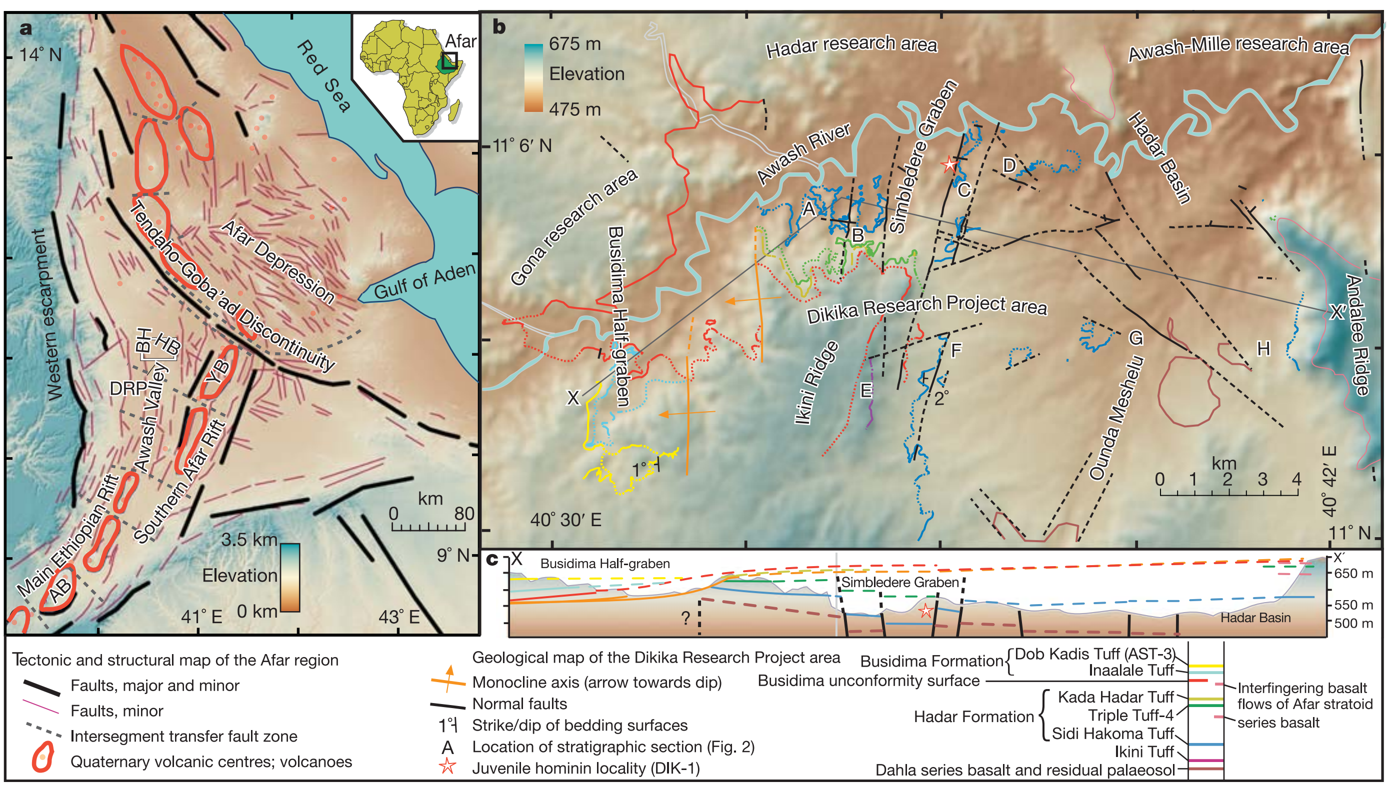

Figure 1 | **Maps of the Afar region and of Dikika Research Project area.** **a**, Tectonic framework of the Afar region. **b**, Geological map of the eastern DRP area. **c**, Cross-section of the DRP area (approximately the white box in **a**). Inactive basins (both shown normal to extension direction) include Hadar Basin (HB) and Busidima Half-graben (BH), and undescribed basins of the Middle Awash Valley. A cross section along the front of badland exposures in the Awash Valley (line, X–X') shows structural relationships between the Hadar Formation (deposited in the Pliocene Hadar Basin; thickening northeastward) and the Busidima Formation (deposited in the Busidima Half-graben), providing a simple structural explanation for the Hadar Formation exposures in the Hadar/Dikika area and for the Busidima Formation exposures in the Gona/Asbole area. YB, Yangudi Basin; AB, Adama Basin; AST-3, Artefact Site Tuff at Gona.

closely resemble *G. gurai*, but the one upper molar series does not show the cusp orientation and elongation that characterizes the extant *G. ellioti* and to a lesser extent the fossil *G. gurai*[22]. This specimen is tentatively referred to a similar genus *Pelomys*, also known from Olduvai and Omo.

The $^{13}C/^{12}C$ ratios ($\delta^{13}C = [\{(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard\ of\ Vienna\ Pee\ Dee\ Belemnite(VPDB)}\} - 1] \times 1{,}000$) of carbon in pedogenic carbonate ($\delta^{13}C_{pc}$; Fig. 2) from Andedo and Gango Akidora (~3.5–3.1 Myr old) indicate a local increase of C_4 plants after ~3.4 Myr ago, a trend that continues through the Busidima Formation at Gona[23]. The sharp contrast between Hadar Formation and Busidima Formation stable isotope values is not unexpected, given the extreme differences in their tectonic and depositional settings described above. A mean $\delta^{13}C_{pc}$ of −9.5‰ from a dark-coloured and clayey, poorly drained palaeosol below sands yielding the juvenile hominin indicates an insignificant contribution from C_4 grasses in a delta plain setting. C_4 grasses, which outcompete C_3 plants in well-drained and seasonally watered aridland soils, increase to nearly one-third of the biomass in the soils developed on delta channel deposits (mean $\delta^{13}C_{pc} \approx -6‰$), and further through the Denen Dora and Kada Hadar members. The abundance of freshwater gastropods, fishes (mostly catfish), hippopotamids, crocodiles and giant tortoises (Table 1) associated with the hominin corroborates the interpretation of a mesic deltaic environment, with nearby permanent water. The DIK-1 fauna includes many species from mesic bush- and tree-associated genera such as *Ugandax*, *Golunda*, and *Millardia*, and possibly *Praomys* and *Pelomys*. This, combined with the absence of open- and xeric-adapted gerbils lends support to wooded

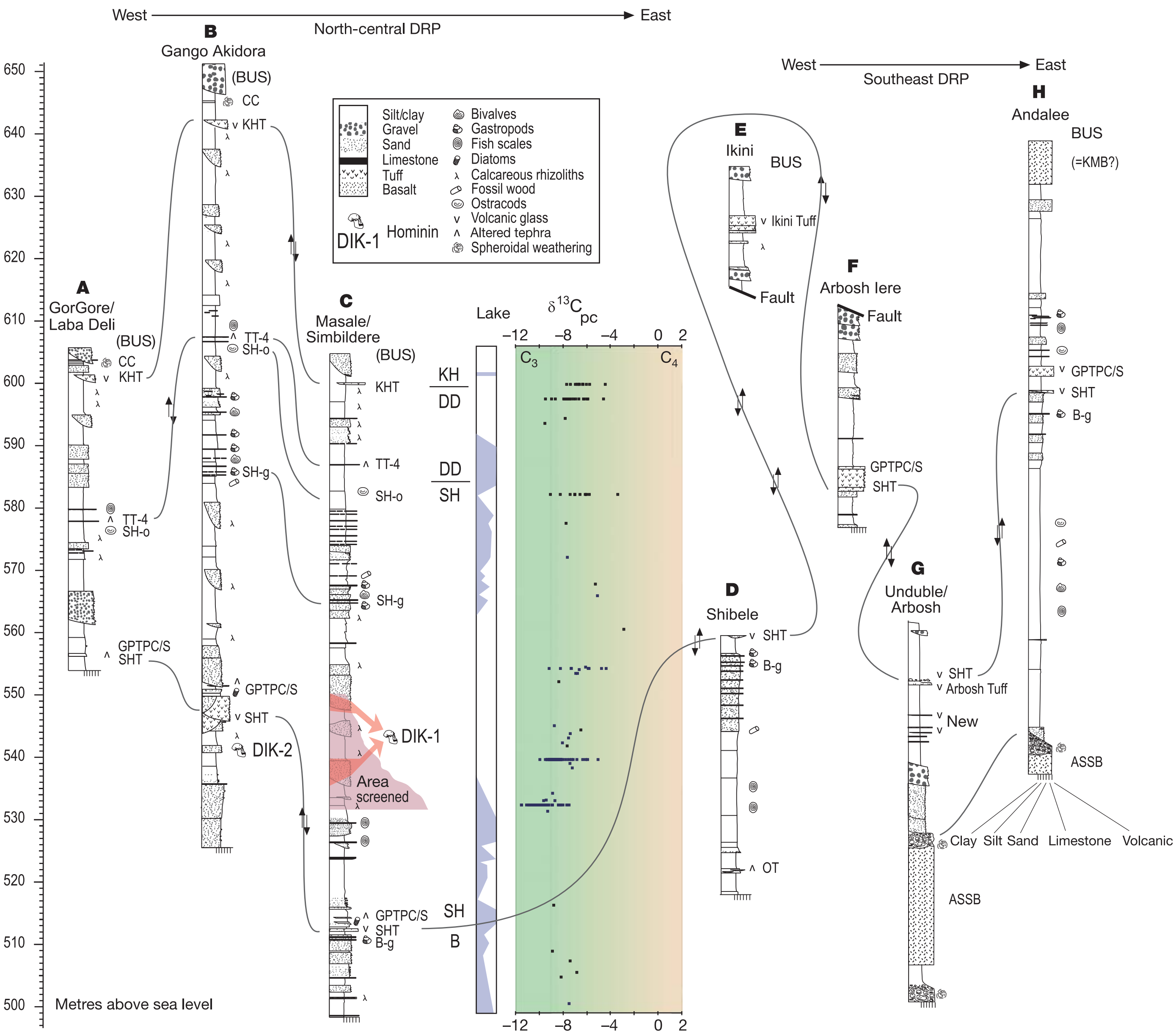

Figure 2 | Stratigraphy of the Hadar Formation in the Dikika Research Project area. Location of sections are shown in Fig. 1. $\delta^{13}C$ of pedogenic carbonate and lacustrine facies are shown from Gango Akidora, Masele, and Simbildere with respect to section C height. In the north-central DRP (sections A–D) the lower Hadar Formation thickens towards the Hadar Basin centre across syndepositional faults (primarily oriented northwest), and is offset by predominantly postdepositional faults forming the Simbildere Graben (north–northeast-trending). In southeastern DRP (sections E–H), the Hadar Formation also thickens northeast, particularly the Basal Member, which is deposited on the local sedimentary basement (weathered surface of Dahla series basalt). See Methods for definitions of the stratigraphic markers.

environments. Impalas are the most common antelopes at DIK-1 and in equivalent levels (SH1 sand, Sidi Hakoma Member) at Hadar, a fact that is consistent with the prevalence of C_3 vegetation. However, the high abundance of Alcelaphini (wildebeest relatives) and of the rhinocerotid genus *Ceratotherium*, in addition to the large number of elephants, indicates that open grasslands were an important part of the palaeolandscape. The vertebrate fauna associated with the juvenile hominin therefore suggests a mosaic of mesic habitats. A greater relative abundance of grazing mammals at DIK-1 indicates palaeoenvironments that were more open than those associated with *Ardipithecus* (5.8–4.4 Myr ago; Adu-Asa and Sagantole Formations, Middle Awash region, Ethiopia)[10,24], *Australopithecus anamensis* (4.2–4.1 Myr ago; Kanapoi Formation, Turkana Basin, Kenya and Sagantole Formation, Middle Awash region, Ethiopia)[9,25] and *Kenyanthropus platyops* (3.5 Myr ago; Nachukui Formation, Turkana Basin, Kenya)[26]. Both the DIK-1 fauna and that from the equivalent interval, SH1, at Hadar indicate mosaic environments. However, the greater proportion of grazing bovids at DIK-1 shows that Dikika had more open habitats than Hadar at that time, probably owing to its depositional position further upstream from the lake. As the fossil vertebrate surveys at Dikika focused on narrow stratigraphic intervals in the lower Sidi Hakoma Member, further work is needed to determine the extent of time-averaging represented by the documented fauna.

Table 1 | **Vertebrate fauna of the DIK-1 hominin locality and surroundings**

Pisces	
	*Clarias sp.** (24)
Reptilia	
	Elapidae cf. *Naja* sp.* (1)
	Crocodylus cf. *niloticus** (13)
	Centrochelys sp.* (24)
Mammalia	
Rodentia* (14 total)	
	Golunda cf. *gurai** (6)
	*Acomys coppensi** (4)
	*Millardia taiebi** (1)
	Pelomys sp.* (1)
	Saidomys cf. *afarensis** (1)
Primates	
	*Australopithecus afarensis** (1)
	Theropithecus darti * (5)
	Cercopithecidae indet.* (3)
Carnivora	
	Herpestidae indet.* (1)
	Canidae indet. aff. *Nyctereutes* sp.*† (6)
	Enhydriodon sp. (1)
Proboscidea	
	Elephas cf. *recki brumpti* *† (several fragments)
	Elephas cf. *ekorensis* (several fragments)
Perissodactyla	
	Ceratotherium mauritanicum * (16)
	'*Hipparion*' cf. *hasumense* * (10)
Artiodactyla	
	*Hexaprotodon afarensis** (91)
	Kolpochoerus afarensis * (8)
	*Notochoerus euilus** (4)
	*Nyanzachoerus kanamensis** (3)
	Giraffa cf. *jumae** (6)
	Sivatherium maurusium (3)
	Tragelaphus aff. *nakuae** (3)
	Ugandax sp.* (5)
	Praedamalis cf. *howelli* *† (2)
	Damalops sp. (10)
	Aepyceros sp.* (17)
	Gazella sp.* (1?)

The list includes fauna from the immediate vicinity of the DIK-1 site between ~510 and 560 m in section C of Fig. 2; this roughly corresponds to the SH1 submember of the Hadar Formation biostratigraphic terminology. Numbers in parentheses indicate the number of specimens identified in a systematic surface survey and by screening at the site by R.B. and D.G. Numbers in parentheses for Rodentia indicate number of specimens identified in systematic screening for micromammals by D.R. cf., confer (similar to); aff., affinis (related to); indet., indeterminata (not determined).
* Taxa most closely associated with the hominin skeleton of DIK-1.
† New occurrence for the Hadar Formation.

METHODS

Field data in Fig. 1 are superimposed on Shuttle Radar Tomography Mission (SRTM) digital elevation data. The geological map of the DRP outlines stratigraphic marker horizons that delimit the Hadar and Busidima Formations and member boundaries of the Hadar Formation. Major structural features of the ERS include transform-fault zones between sub-basins (Fig. 1; tectonics and structure are detailed according to refs. 7, 8). Active rift segments include the Main Ethiopian Rift, Southern Afar Rift and Afar Depression. Depositional sub-basins with active volcanic centres include the Yangudi Basin, and Adama Basin. Local lithostratigraphy (shown in Fig. 2) is based on a definition of the Hadar Formation[27] using which exposures across the Awash River from Dikika were originally mapped[27]. The Busidima Formation is defined from the Gona area[2]. Hadar Formation member names are: B (Basal; base of sediments–Sidi Hakoma Tuff (SHT)), SH (Sidi Hakoma; SHT–Triple Tuff-4), DD (Denen Dora; TT-4–Kada Hadar Tuff (KHT)), and KH (Kada Hadar; KHT–Busidima unconformity surface (BUS)). Stratigraphic framework is based on tephrostratigraphic correlations that allow direct comparisons between the DRP fauna and others of the Awash Valley (see Supplementary Table 1), where considerable effort has been focused on radiometric dating of volcanic strata interfingered with hominin-bearing sediments[3,11]. Altered tephra indicated in Fig. 2 are not analysed due to complete weathering of glass shards. Local to regional stratigraphic markers and the method of determining age are: the surface of uppermost DSB flow (>3.8 Myr old), Ikini Tuff (equivalent to Wargolo; 3.8 Myr old; ref. 13), Ounda Leita Tuff (OT; 3.49 Myr old; stratigraphic scaling and sedimentation rate extrapolated from the SH member), Arbosh Tuff (equivalent to Maka Sand Tuff; 3.40 Myr old; ref. 3), B-g (Basal gastropodite; 3.40 Myr old; sedimentation rate extrapolated from the SH member), SHT (equivalent to Tulu Bor Tuff and B-β Tuff; 3.40 Myr old; ref. 28), GPTPC/S (Green Pumiceous Tuff pebble conglomerate/sand; 3.40 Myr old; stratigraphic scaling), Kada Damoumou Basalt (KMB: 3.28 Myr old; ref. 30), SH-g (Sidi Hakoma gastropodite; 3.28 Myr old; stratigraphic scaling), SH-o (Sidi Hakoma ostracodite; 3.23 Myr old; stratigraphic scaling), TT-4 (3.22 ± 0.01 Myr old; ref. 29), KHT (3.18 Myr old; ref. 29), confetti clay (CC; 3.16 Myr ago, stratigraphic scaling) and BUS (previously referred to as the Major Disconformity Surface at Hadar, but named BUS at Gona; beginning 2.9 Myr ago, but in parentheses in Fig. 2 where there may be post-2.7 Myr erosion; ref. 30). Section elevation is determined from the intersection of a prominent tuff (SHT in most sections) and the digital elevation surface from Fig. 1.

Received 24 April; accepted 6 July 2006.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank J. Haile-Mariam of the Authority for Research and Conservation of Cultural Heritage, and the Afar Regional State for research permission; and G. Assefa and H. Habtemichael for aid in the field. This work would not be possible without the assistance of the many Issa field crew, as well as logistical support from M. Mekonnen, H. Defar, A. Zerihun, A. Takele, A. Kiros. We also thank J.-C. Rage for snake identification, and K. Reed and G. Eck for access to the Hadar catalogue and collections. This research was funded by the National Geographic Society with logistical support from the Institute for Human Origins and the Ministère des Affaires Etrangères. Stable isotope analyses were performed at RSES, Australian National University, Canberra and at FEEA Stable Isotope Laboratory, St. Andrews. Tephrostratigraphic chemical analyses were performed at the University of Oregon Microprobe Laboratory, Eugene, with funds from the Baldwin Memorial Fund.

Author Contributions J.G.W. was the project geologist. D.C.R. did tephrostratigraphy. Fauna were analysed by Z.A. (head of project and palaeoanthropology), R.B. (palaeoenvironments), D.G. (biostratigraphy) and D.R. (micromammals).

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