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Volcanism, tectonism, sedimentation, and the paleoanthropological record in the Ethiopian Rift System

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ABSTRACT

The Ethiopian Rift System consists of basins that are in different stages of evolution. Some of the rift-related basins in southwestern Ethiopia are half-grabens that have not evolved to symmetrical rifts since the initiation of rifting here in the middle Miocene. These basins contain fossiliferous Pliocene–Pleistocene volcaniclastic sediments and volcanic rocks and have been occupied by early hominid populations. The Afar and the Main Ethiopian Rifts are symmetrical, with both margins fully developed. Several paleoanthropological localities, ranging in age from the Quaternary to the Pliocene, were discovered within these rift basins. The discovery of *Australopithecus afarensis* (the "Lucy" species) at Hadar and *Ardipithecus ramidus* and *Australopithecus garhi* in the Middle Awash makes the region the most prolific early hominid area in the world.

Many of the known Pliocene–Pleistocene paleoanthropological localities that have given us information about our ancestors are concentrated in the East African Rift System. This is not a coincidence, because the volcanic and tectonic activities that were responsible for the formation of the rift basins and coeval sedimentation created ideal environments for the proliferation of life and the preservation of faunal and floral remains. Volcanic and tectonic activities created plateaus and mountains; most of the sediments in the basins were derived from these topographic highs located within and outside the rift valleys. Volcaniclastic sediments and volcanic ash were responsible for the quick burial and preservation of fossils during diagenesis. Diagenetic processes involving silicification, calcification, zeolitization, feldspathization, clay formation, and pedogenesis all played roles in fossil preservation in the volcaniclastic sediments. Volcanic rocks interbedded with the fossiliferous sediments also provide temporal information about geologic processes, faunal evolution, paleoenvironment, and early hominid behavior and lithic technology.

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INTRODUCTION

The East African Rift System provides a unique setting for paleontological and archeological investigations of human origins and evolution. Skeletal and cultural remains of hominids have been recovered from many locations within the basins of the East African Rift Systems in Ethiopia, Kenya, Tanzania, Uganda, and Zaire. Important paleoanthropological sites occur within the Ethiopian Rift System in the Omo Basin (Shungura, Usno, and Fejej), Main Ethiopian Rift (Konso-Gardula, Gademotta, Gadeb, Melka Kunturé, and Kesem-Kebena), and the Afar Rift (Middle Awash, Gona, and Hadar) (Fig. 1). Most of these localities occur on the rift floor. Gadeb and Melka Kunturé are located along the eastern rift shoulder and on the western rift margin of the central sector of the Main Ethiopian Rift, respectively. Some of Ethiopia's most important paleontological and archeological localities, such as Fejej, Burji, Konso-Gardula, Bilate, and Kesem-Kebena, were recently discovered by the Paleoanthropology Inventory Project of Ethiopia, between 1988 and 1991 (Asfaw et al., 1991, 1992; WoldeGabriel et al., 1991, 1992a; Suwa et al., 1991). This project was initiated to survey vast, previously unknown areas of the rift basins and inventory their paleoanthropological resources. The survey indicated the tremendous potential of the late Cenozoic volcaniclastic sediments of the Ethiopian Rift System for paleoanthropological research. On the rift floor, topographic barriers created by lava flows, uplift, and faulting created basins and lakes that acted as sediment traps. The volcanic rocks played major roles by providing sediments to the rift basins. The remarkable preservation of faunal and floral remains in the Pliocene–Pleistocene sedimentary rocks was possible because of quick burial by sediments. Moreover, these source rocks for the volcaniclastic sediments and interbedded tuffs provided the necessary chemical components for the preservation of the fossils during diagenesis. There is a strong link between these dynamic processes, rapid sediment deposition, and fossil preservation. The most important primary and contextual data (fossils and artifacts) were embedded and preserved in sedimentary deposits until the recent exposure by tectonic-driven erosional processes. Time-stratigraphic data obtained from tephra interbedded with fossiliferous sedimentary deposits provide an important framework for the study of hominid origins, evolution, adaptations, and cultural changes. Paleoanthropological information from these newly discovered localities is briefly summarized in this chapter.

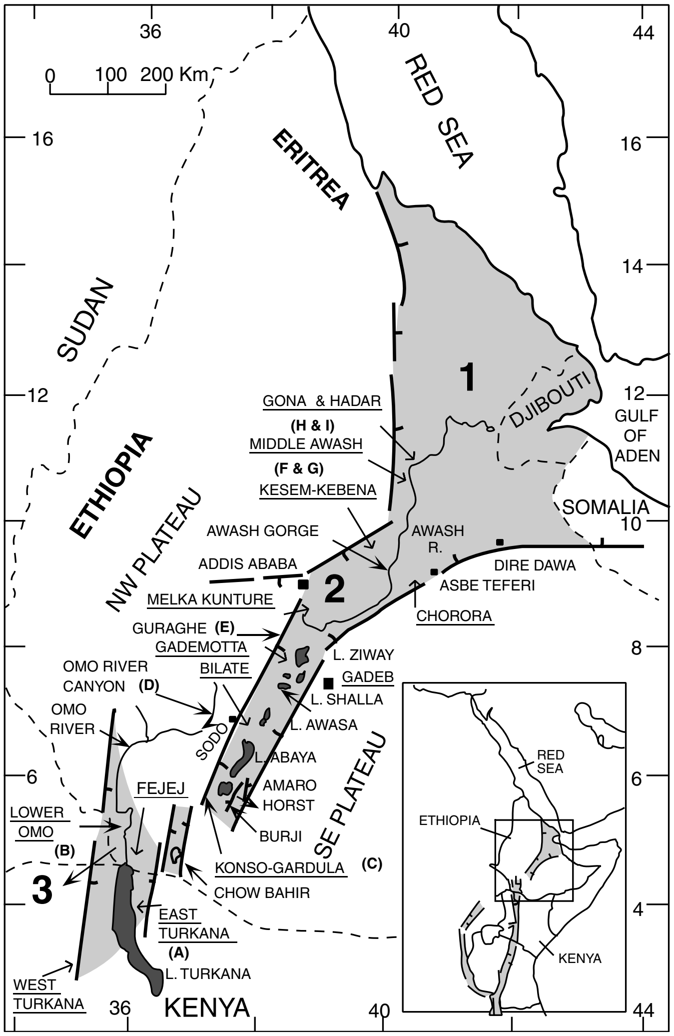

Figure 1. Location of the Ethiopian Rift System. Important paleoanthropological localities are underlined. Stippled and dark areas represent the rift basins and rift valley lakes, respectively. Inset map shows the distribution of the East African Rift System. 1 = Afar Rift, 2 = Main Ethiopian Rift, and 3 = Omo rift zone. Letters in parentheses are tephra sections in Figure 3.

As mentioned above, the paleoanthropological remains are closely associated with sedimentary deposits (often tuffaceous) related to the formation of the volcanic plateau, uplift, and the development of rift basins that began in the middle to late Miocene period (Fig. 2). Moreover, pyroclastic rocks of distal origin are interbedded with these sedimentary deposits; the pyroclastic rocks contribute to fossil preservation and act as chronometric controls. Feldspar phenocrysts, potassium-bearing silicic lavas and tuffs, and mafic lava flows provide temporal constraints for the timing of volcanic and tectonic activities, rift evolution, sedimentation, and the hominid remains and artifacts.

Most of the hominid remains and associated artifacts in the rift system have been found in Pliocene–Pleistocene volcaniclastic sediments, but in most cases older sedimentary deposits are rare in the rift basins because the longer the embedding sediments are emplaced, the more susceptible they are to either erosion or deep burial. The intense volcanic and tectonic activities within the different basins of the Ethiopian Rift System during the Neogene and Quaternary periods not only played important roles in forming the fossil record, they could also destroy it. The erosional-sedimentary cycle has persisted in the rift valley environment for millions of years (Fig. 2). As a result of the interplay between depositional and erosional forces driven by tectonic processes, there are numer-

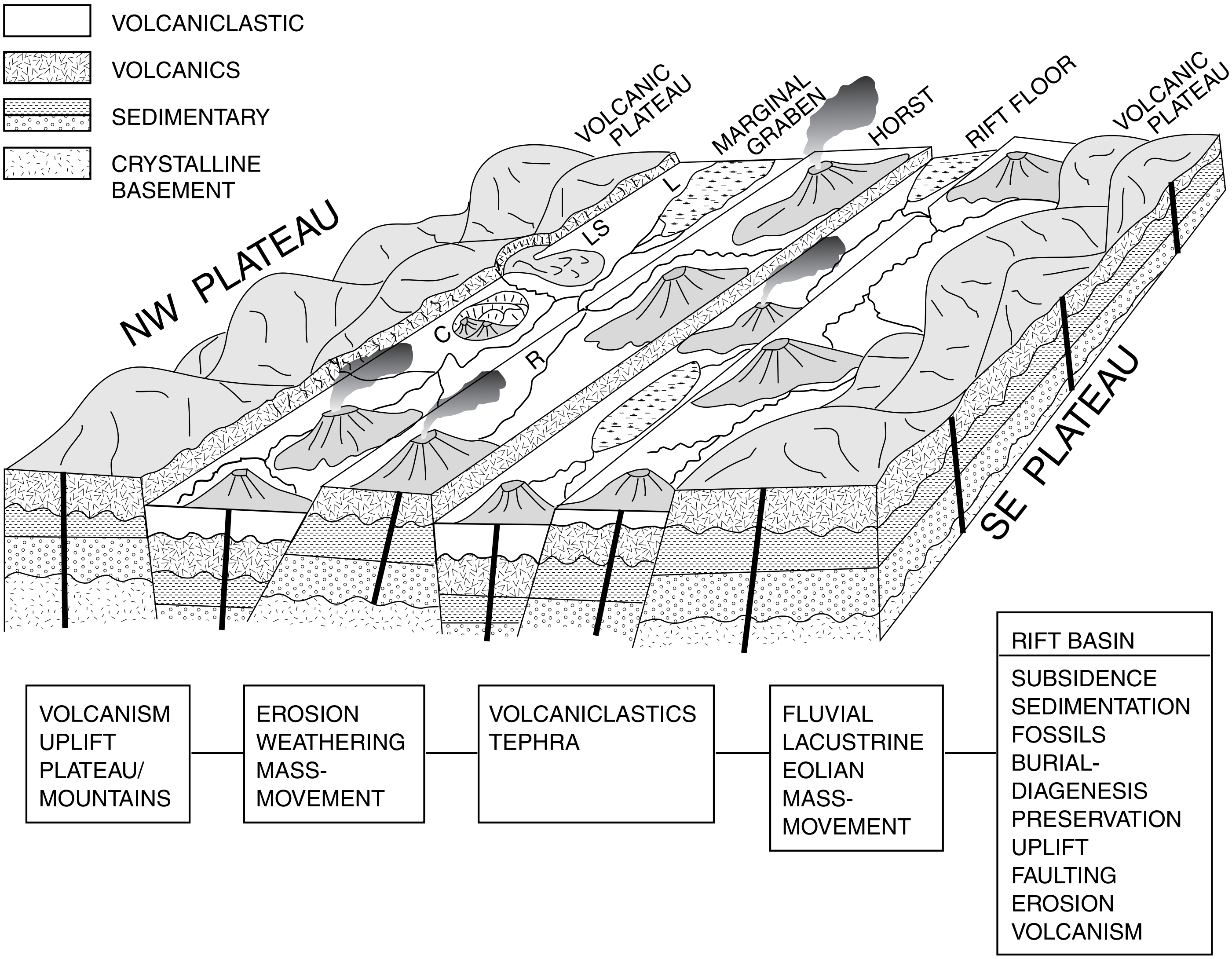

Figure 2. Schematic representation of tectonism, volcanism, and sedimentation processes within the Ethiopian Rift System. Tectonism and volcanism create differences in topographic elevations triggering sediment generations that are washed and deposited in rift basins. The lakes and rivers are foci for deposition of these sediments, and the plants and animals living in and around them are often entombed in the sediments. The bones and wood, once buried, are fossilized and cycle again to the surface as local tectonics elevates the sediments to sustained erosion. In these situations, often the hilly flanks of the rift and uplifted blocks of the floor are exposed by erosion, paleoanthropological resources can be discovered and investigated. This dynamic processes has been taking place since the late Eocene when volcanism started to create the Ethiopian Plateau and the rift basins. Letters represent lakes, swamps, and deltaic environment (L); rivers (R); landslides (LS); calderas and volcanic centers as sources of the voluminous tephra (C).

ous gaps in the fossil record, particularly in the important time period between 10 Ma and 5 Ma, which is pertinent to the understanding of the origin of Hominidae during the late Miocene. A discussion on the history of rifting, volcanism, uplift, erosion, sedimentation, burial, and diagenetic processes is briefly outlined here for the paleoanthropological localities in different parts of the Ethiopian Rift System. This background is necessary to understand the role of these processes on the evolution of Pliocene–Pleistocene flora and fauna, including the hominids.

TECTONICS, VOLCANISM, SEDIMENTATION PROCESSES, AND FOSSIL PRESERVATION

The Cenozoic geological history of Ethiopia is characterized by massive and voluminous Paleogene mafic and silicic volcanism and domal uplift, Neogene rifting and volcanism, and rift-bound Pliocene–Pleistocene rifting and volcanism (Zanettin et al., 1980; Davidson and Rex, 1980; Berhe, 1986; Berhe et al., 1987; Hart et al., 1989; WoldeGabriel et al., 1990, 1991; Ebinger et al., 1993). Another major component of the

Cenozoic volcanic and tectonic processes of the Ethiopian Rift System is the coeval sedimentation that was triggered by volcanic and tectonic activities that altered relief, drainage, and climatic conditions (Fig. 2). The provenance for these sediments is the weathering products of eroding volcanic rocks along rift escarpments and shoulders; faulted and uplifted rift blocks; and volcanic centers, shields, and plateaus within and outside the rift. The Ethiopian Rift System, bounded by adjacent plateaus rising 2,000–3,000 m above the rift floor, consists of a number of half-grabens and symmetrical rift basins. Although rift-related basins started to form during the late Oligocene to early Miocene times, the Afar and the Main Ethiopian Rifts were fully defined by middle to late Miocene time (Berhe 1986; Berhe et al., 1987; WoldeGabriel, et al., 1990, 1991; Ebinger et al., 1993; Chernet et al., 1996). The north-northeast-south-southwest–trending Main Ethiopian Rift (MER) terminates in southern Ethiopia against crystalline basement. However, a 200- to 300-km-wide rift zone, which forms the northern extension of the Kenya Rift, occurs west of the MER (Moore and Davidson, 1978; Davidson, 1983; WoldeGabriel and Aronson, 1987). Rifting in this broad tectonic zone of northern Kenya and southwestern Ethiopia started during the middle Miocene (Moore and Davidson, 1978; Bellieni et al., 1987).

If 'the present is a key to the past," the rift basins provided a unique setting for dynamic ecosystems that were characterized by the proliferation of life, with abundant supplies of food, water, and a favorable climate (e.g., present-day prolific wildlife occurrences along the floor of the East African Rift System in Tanzania, Kenya, and Ethiopia). Rift-related subsidence and coeval sedimentation also created an ideal environment for the accumulation of volcaniclastic sediments, burial, diagenesis, and preservation of organic remains. Because rifts formed after widespread and voluminous volcanism and uplift, the sediments in the rift basins are mostly volcaniclastic and pyroclastic in origin. Following the deposition of the sediments in a rift basin, mechanical compaction creates porewater circulation that may start to interact with the clastic fragments and volcanic glass, leading to dissolution, increased alkalinity of the fluids, and precipitation of new diagenetic mineral phases like clays, zeolites, and carbonates. Thus, water-rock interaction and hydrolysis of volcanic glass provided the necessary components for the replacement, cementation, and preservation of fossils within fluvial and lacustrine volcaniclastic sediments. For instance, in the case of vertebrate fossils, diagenetic minerals infill pore spaces in bone and thus preserve 3-D structure during burial and postburial isomorphic substitution of fluoride for hydroxyl groups in bone apatite, thereby changing bone carbonate hydroxyapatite to the less soluble carbonate fluorapatite (Posner et al., 1984; Lucas and Prevot, 1991). The roles of tectonic, volcanic, and sedimentary processes on fossil preservation in different paleoanthropological localities of the Ethiopian Rift System are briefly highlighted in descriptions of the basins that follow.

Omo Basin of Southwestern Ethiopia

In the Omo Basin, the Kenya Rift bifurcates into a dominant north-south–trending, 200–300-km-wide, rift zone that contains half- and symmetrical-graben systems that terminate against crystalline basement highs and northeast-southwest–trending lineaments in western Ethiopia (Moore and Davidson, 1978; WoldeGabriel and Aronson, 1987). These half-grabens are characterized by broad, westerly tilted fault blocks with high and steep scarps, usually on their eastern sides. These basins are filled with Pliocene–Pleistocene fossiliferous volcaniclastic sediments (Davidson, 1983).

The Omo-Turkana Basin in southern Ethiopia and northern Kenya has provided an unparalleled Pliocene–Pleistocene record of hominid and technological remains when compared with any other paleoanthropological sites within the East African Rift System (de Heinzelin, 1983; Feibel et al., 1989) (Table 1). According to Bellieni et al. (1987), the eastern part of the Turkana Basin begun to subside during the middle Miocene (15 Ma) and a fully defined rift basin was present by ca. 7 Ma. Although middle Miocene basins similar to the Turkana Basin may have existed in the Omo Basin, major rift structures in the region were not fully defined until the late Miocene (<12 Ma) (Davidson and Rex, 1980).

The rift basins in southern and southwestern Ethiopia are filled with fluvial and lacustrine sediments that are classified into major sedimentary groups of Miocene and Pliocene–Pleistocene ages. The Miocene sedimentary rocks exposed along the east and west sides of Lake Turkana have not been as well studied as the Pliocene–Pleistocene deposits of the area (Feibel et al., 1989). The major sedimentary deposits are represented by the Pliocene–Pleistocene Omo and late Pleistocene Turkana Groups (de Heinzelin, 1983). The Omo Group volcaniclastic sediments occur along the northern (Mursi, Shungura, and Usno Formations), eastern (Koobi Fora Formation, Fig. 3A), and western (Nachukui Formation) parts of Lake Turkana (de Heinzelin, 1983; Brown and Feibel, 1986; Harris et al., 1988). The Shungura Formation of the Omo Group is ~760 m thick and occurs north of the modern Omo River delta in Lower Omo (Fig. 1). It consists of lacustrine, fluvial, and deltaic sedimentary deposits, which have been divided into 12 members using interbedded, distal silicic tuffs (Fig. 3B). Most of these distal tuffs were identified using letters, starting with Tuff A at the base of the section, through H and J to L at the top of the stratigraphic sequence (de Heinzelin, 1983). The older tuffs occur within fluvial sequences that are finer grained upwards. In the middle section, the sediments are dominated by lacustrine, siltstone, and claystones, whereas in the upper sequence, both fluvial and lacustrine sediments are present. de Heinzelin (1983) suggested that the Omo ecosystem was characterized by tropical fauna that lived in the same kind of environment as the present ones in the basin and evolved from closed woodland to more open grassland.

About 25–30 km north and upstream from the Omo delta, the type section of the Usno Formation consists of 172 m of flu-

TABLE 1. IMPORTANT PALEOANTHROPOLOGICAL SITES IN THE ETHIOPIAN RIFT SYSTEM

Areas with paleoanthro-pological sites	Location within the rift	Sedimentary environments	Age of tuffs	Number of tuff beds/Ma (preserved)	Tuffs; percentage of stratigraphic section	Percentage of tuffaceous sediments in stratigraphic column	Hominid Species	Hominid Ages	Types of stone tools	Ages of stone tools (Ma)
Shungura Usno Fejej	Omo rift	Lacustrine, fluvial, overbank	4.1–1.39 Ma	13	9	Estimated at 70	A. afarensis A. aethiopicus A. boisei H. habilis H. erectus	4.0–2.9 2.5 2.3–1.2 1.9 1.8	Oldowan-Acheulean	≤1.9
Konso-Gardula	Southern MER	Fluvial	2.0–1.35 Ma	~4	5	95	H. erectus	1.7–1.4	Acheulean	1.7–1.4
Gademota (Middle MSA)	Central MER	Colluvium, paleosol	35–1.81 ka	3	n.d.	n.d.	H. sapiens	0.18–0.03	MSA	0.18–0.03
Gadeb	Eastern rift shoulder, Central MER	Lacustrine, fluvial	2.51–ca. 0.7 Ma	>2	~12	Estimated at 50	H. erectus	1.5	Acheulean	1.5
Melka Kunturè	Central MER	Fluvial	≤1.5 Ma	5	n.d.	n.d.	H. erectus	≥1.5	Oldowan-Acheulean	≥1.5
Kesem-Kebena (K–K6)	Northern MER	Fluvial, overbank, lacustrine	1.04–1.0 Ma	3	38	62	H. erectus	1.0	Acheulean	1.0
Middle Awash	Southern Afar	Fluvial, overbank, lacustrine	4.38–4.29 Ma	>20	5	40	A. ramidus H. erectus A. garhi	4.4 1.0 2.5	MSA Oldowan	<1.0 2.5
Hadar	West-central Afar	Fluvial, overbank, lacustrine	3.4–3.18 Ma	5	<5	Estimated at 40	A. afarensis H. erectus	3.2	Oldowan-Acheulean	2.6 1.0
Gona	West-central Afar	Lacustrine, deltaic, fluvial	2.94–<2.52 Ma	>4	<5	Estimated at 40	None	--	Oldowan (oldest)	2.6–2.5

Abbreviations: MSA= Middle Stone Age; MER = Main Ethiopian Rift

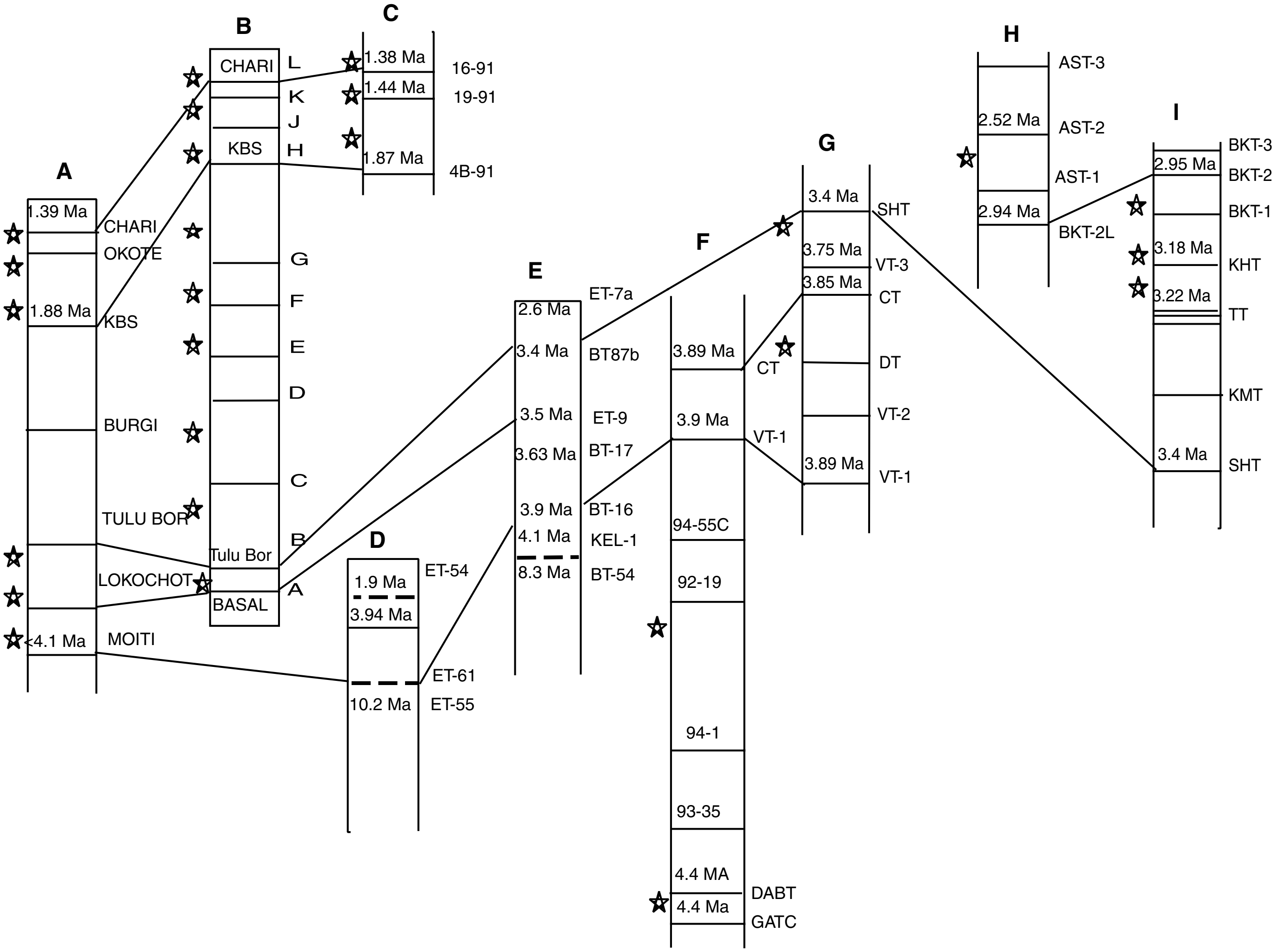

Figure 3. Correlations of tephra interbedded with fluvial and lacustrine volcaniclastic units in the Omo-Turkana Basin (A=Koobi Fora and B=Shungura Formations), Konso-Gardula (C), the Omo River Canyon (D), the western rift margin of the central sector of the Main Ethiopian Rift at the Guraghe Mountains (E), the west (F) and east (G) sides of the Middle Awash, Gona (H), and Hadar (I). Thicknesses of fluvial and lacustrine volcaniclastic sediments and the positions of the tephra layers for the different localities are not to scale. Most of the correlations were established by dating and chemistry (WoldeGabriel et al., 1992a; Brown et al., 1992; Brown, 1994). Thick broken lines indicate unconformity surfaces. Locations of hominds or artifacts at each location are indicated by an asterisk (Feibel et al., 1989; Asfaw et al., 1992, White et al., 1993, 1994; Walter, 1994; Semaw et al., 1996). AST—Artifact Site Tuff, BKT—Bouroukie Tuff, CT—Cindery Tuff, DABT—Daam Aatu Basaltic Tuff, DT—Doublet Tuff, GATC—Gaàla Tuff Complex, KBS—Kay Behrensmeyer Site, KEL—Kella, KHT—Kada Hadar Tuff, KMT—Kada Mahay Tuff, SHT—Sidi Hakoma Tuff, TT—Triple Tuff, VT—Vitric Tuff.

vial sediment, with interbedded coarse conglomerates that contain clasts of metamorphic rock (Brown et al., 1970). The section was divided into 20 members designated by U-1 through U-20, starting from the base of the section. A correlation based on stratigraphic features and tephra was established between the Shungura and Usno Formations (de Heinzelin, 1983; Cerling and Brown, 1982). The Lokochot and Tulu Bor Tuffs, dated at 3.5 Ma and 3.4 Ma, respectively, occur in both the Shungura and Usno Formations (Brown, 1994). The oldest tuff in the Omo Group is the Moiti Tuff, dated at 4.1 Ma, which is exposed east and west of Lake Turkana in northern Kenya (McDougall, 1985). A chemically correlative tuff (VT-1) from the Middle Awash yielded a younger age of ca. 3.9 Ma (White et al., 1993). This tuff was not found in the Shungura and Usno Formations to the north of the lake (de Heinzelin, 1983).

More than 200 km upstream from the Lower Omo, the Omo River Canyon is about 1.2 km deep (Figs. 1 and 3D). Volcanic rocks ranging in age from 17 Ma to 2 Ma are exposed in outer and inner canyon walls (WoldeGabriel and Aronson, 1987). Middle Miocene (16.7–17.0 Ma) rhyolite and trachyte flows are exposed in a narrow inner canyon of the modern river that is less than 5 km wide, whereas the upper part of the outer canyon consists of late Miocene (10.5–10.2 Ma) basalts and hawaiites. The outer canyon is broad, terraced, and 20–30 km wide. The middle Miocene rocks in the inner canyon are unconformably capped by an early Pliocene 20–30 m thick ash fallout that is chemically correlated to the Moiti Tuff, by basalt flows (3.94 Ma) and by a welded crystal-rich tuff that is within the age range of the KBS Tuff of northern Kenya (WoldeGabriel and Aronson, 1987; Hart et al., 1992; WoldeGabriel et al., 1992b). The poorly consolidated ash fallout was deposited in an ancestral valley of the Omo River and was covered soon after its deposition by a 3.94 Ma tholeiitic basalt flow, which protected it from erosion.

According to WoldeGabriel and Aronson (1987), a middle to late Miocene "failed" rift zone initiated the ancestral Omo River, approximately along its present course, at ca. 10 Ma. Thus, the Omo River was flowing southward by late Miocene (=10 Ma) time and was carrying sediment into the Omo-Turkana Basin during the late Miocene and early Pliocene periods. The crystalline basement and the Paleogene and Neogene volcanic plateaus of west-central Ethiopia (Brown et al., 1970; Davidson, 1983; Berhe et al., 1987) were the provenance for most of the thick volcaniclastic sequences of the Omo-Turkana Basin. The absence of pre–Moiti Tuff in the northern part of the Omo-Turkana Basin is consistent with the lack of older tuffs in the Omo Canyon stratigraphic sequence (Fig. 3D). However, silicic tephra centers and deposits of late Miocene to early Pliocene ages are present along the rift shoulder of the western rift margin within the drainage basin of the Omo River (WoldeGabriel et al., 1990). Erosion, burial by younger sediments, reworking, and alteration of tephra may be responsible for the absence of the late Miocene tuffs in the northern part of the basin. Older tuffs (>3.9 Ma) are present in Kanapoi at the southern part of the basin (Leakey et al., 1995).

Despite the occurrence of a Moiti Tuff–equivalent ash fall (20–30 m) in the Omo River Canyon more than 200 km upstream from Lake Turkana, the absence of the Moiti Tuff in the Shungura and Usno sections appears to be erosional. This suggests that deposition occurred south of the Shungura and Usno type localities during early Pliocene time. The Moiti Tuff occurs at the base of the Koobi Fora and Nachukui Formations in east and west Turkana (Figs. 1 and 3A). In the Fejej plain east of the northern end of Lake Turkana, early Pliocene basalts (4.4–3.6 Ma) crop out on top of ~30 m of fossiliferous sandstone, limestone, and claystone, indicating a more extensive proto–Lake Turkana during early Pliocene time (Davidson, 1983; Watkins, 1986; Asfaw et al., 1991; Kappelman et al., 1996).

Early hominids and archeological remains have been collected from the Pliocene–Pleistocene volcaniclastic sediments of the Shungura, Usno, and Fejej localities (Fig. 1, Table 1). Temporal aspects of these paleoanthropological remains within the Omo Basin were established by dating and by geochemical correlations of tephra interbedded with these fossiliferous sediments (Asfaw et al., 1991; Brown, 1994; Kappelman et al., 1996). The discoveries of hominid remains within the sedimentary sequence of the Omo-Turkana Basin spanning the Pliocene–Pleistocene periods (4.2–1.4 Ma) suggest that tectonic, volcanic, and sedimentation processes in the region had minimal impact on the long temporal distribution and survival of hominids, who were able to adapt to the changing environment. Sediments eroded from volcanic, sedimentary, and crystalline basement rocks were responsible for quick burial of fossils in the Omo Basin. Alteration during water-rock interaction in the depositional environment produced secondary mineral phases that were responsible for the cementation and replacement of the organic remains.

Southern Sector of the Main Ethiopian Rift

The southern sector of the Main Ethiopian Rift is divided into two basins by the Amaro Horst (Fig. 1). Geologic sections along both branches of the rift are poorly exposed because of recent sedimentation and vegetation cover. However, the rift-oriented Amaro Horst and both escarpments expose crystalline basement, sandstone of unknown age, and thick sections of Eocene to late Miocene mafic and silicic lavas and tephra (WoldeGabriel et al., 1991; Ebinger et al., 1993). Fieldwork in 1989 at the Burji locality, at the southern part of the Amaro Horst, documented a middle to late Miocene fossiliferous volcaniclastic lacustrine and fluvial sedimentary sequence interbedded with basaltic flows (WoldeGabriel et al., 1991). A primitive species of choerolophodont mastodon and floral remains were discovered within this sedimentary deposit; the biochronological evidence suggested an age of 17–15 Ma for these fossils and for the beginning of rift-related basins in the southern sector of the Main Ethiopian Rift (Suwa et al., 1991; WoldeGabriel et al., 1991).

A new locality with hominid and archeological remains was also discovered in the Konso-Gardula region along the southern end of the northeast-southwest–trending Main Ethiopian Rift in 1991 (Figs. 1 and 3C, Table 1) (Asfaw et al., 1992). Unlike the Omo-Turkana Basin, this fossil locality is small and occurs along the western flanks of the Ganjuli Graben, on the western branch of the southern Main Ethiopian Rift. The Pliocene–Pleistocene (1.9–1.3 Ma) volcaniclastic sediments are ~50 m thick and overlie crystalline basement rocks. These sediments consist of conglomerates, sands, silts, and dark brown clays derived from the adjacent volcanic plateau. Three or more interbedded bentonitic and diatomaceous tuff layers occur in the sequence (Fig. 3C). Two of the tephra layers have been correlated with the late Pliocene KBS (1.88 Ma) and the early Quaternary Chari (1.39 Ma) Tuffs of the Omo-Turkana Basin (Asfaw et al., 1992). Geologic and archeologic evidence suggests hominid habitation along the edge of a lake. However, faulting and subsidence along the axis of the Ganjuli rift basin during the Pleistocene modified the landscape. As a result, the fluvial and lacustrine sedimentary rocks of the Konso-Gardula locality were uplifted and exposed by erosion. Work by an Ethiopian-Japanese team has resulted in additional spectacular fossil discoveries and much more geological and geochronological information (Suwa et al., 1997).

The first African record of the Acheulean stone tool tradition attributed to *Homo erectus* is firmly established between 1.7–1.4 Ma at the Konso-Gardula site (Asfaw et al., 1992). This locality is separated from the Shungura and Usno Formations of the Omo Rift half-grabens by north-south–trending crystalline basement highs and the Chow Bahir Rift. The southern parts of the Main Ethiopian and the Chow Bahir Rifts are connected by the Sagen River valley, a major tributary of the Weyto River that drains into Chow Bahir east of the Lower Omo (Fig. 1). No detailed or comprehensive geological survey has ever been conducted to determine evidence of hominid occupation and migration through the area of the river valley and the adjacent Chow Bahir Rift.

At Burgi in the southern MER, as in other Ethiopian basins, well-preserved terrestrial and aquatic fauna and plant remains are present in the lacustrine and fluvial sediments of the middle Miocene and late Pliocene localities. Diagenesis of tuffs and tuffaceous sediments produced bentonites and other alteration products that were useful for the cementation and preservation of fossils. The volcaniclastic sediments responsible for the preservation of these faunal and floral remains had their provenance in the uplifted rift escarpments and shoulders and the 100-km-long and 70-km-wide Amaro Horst (Fig. 1).

Northward along the rift floor and east of Sodo, the Bilate River and its tributaries expose Pleistocene fluvial and lacustrine (diatomaceous) sediments interbedded with basaltic lavas and ash flows and fallout. These tephra erupted from the Quaternary silicic volcanoes of Duguna east of Sodo and from Corbetti caldera just north of Lake Awasa (Fig. 1). Most of the sediments were transported by the Bilate River that flows between these two major Pliocene–Pleistocene silicic centers. A preliminary survey conducted in the area by the Paleoanthropological Inventory Project of Ethiopia in 1989 indicated widespread stone tool production localities.

Central Sector of the Main Ethiopian Rift

Unlike those in the Omo-Turkana Basin, geologic sections within the central sector of the Main Ethiopian Rift are poorly exposed. Structural and stratigraphic relations of volcanic rocks along both Rift escarpments of the central sector of the Main Ethiopian Rift indicate a two-stage rift development (WoldeGabriel et al., 1990). The early phase started during late Oligocene–early Miocene time and was characterized by a series of alternating and opposed half grabens. The half-grabens evolved into a symmetrical rift during the late Miocene. The western rift margin exposes localized crystalline basement, Mesozoic sedimentary rocks, and Miocene and Pliocene mafic and silicic lavas and tephra. The area was characterized by active rifting during the Pliocene–Pleistocene. For example, Pliocene silicic tephra correlative to those exposed along both sides of the rift escarpments occurs below 1.5–2 km of rift-fill sediments in the adjacent rift floor (WoldeGabriel et al., 1990). The rift floor is covered today by lakes, lacustrine sediments, mafic lavas from fissure eruptions, and silicic tephra from the nearby Quaternary volcanoes of Aluto (0.27–0.021 Ma) along the southern edge of Lake Ziway and the Shalla caldera (0.28–0.18 Ma) (Mohr et al., 1980; EIGS-ELC, 1985; WoldeGabriel et al., 1990).

The rift floor in the central sector is compartmentalized into closed basins, unlike the Omo Basin or the southern sector of the Main Ethiopian Rift. Sediment sources include rift-bound horsts, volcanic centers, and fault scarps as well as both sides of the rift escarpments. Major Neogene silicic, phonolitic, and trachytic volcanoes along the rift shoulder also contributed sediments and tephra to the rift floor. Because of the depth of the basins and their limited catchment areas, most of the exposed volcaniclastic sediments in the central sector are lacustrine. Laminated clays and diatomaceous beds, derived from alteration of volcaniclastic sediments and tephra, are the dominant sedimentary rocks. Fossils are mostly of aquatic organisms. However, a few, mostly relatively young, paleoanthropological sites have been identified and studied within this part of the rift valley. Vertebrate faunal remains are rare in these localities; this may simply be related to a paleoenvironment that was dominated by deep lakes that formed in an actively subsiding basin. The 3.5-Ma crystal-rich tuff of the Butajira Ignimbrite dominates both walls of the rift margin and occurs ~2 km below the present rift floor, suggesting intense subsidence related to voluminous caldera-forming silicic eruption (WoldeGabriel et al., 1990). Such deep basins probably did not support abundant fauna because of inaccessibility. Conversely, the geochemical composition of sediments plays a major role in fossil preservation (Pickford, 1986), and it is not well understood whether the chemistry of the sediments or preburial taphonomic processes were responsible for the scarcity of fossils at the archeological sites described below.

A Middle Stone Age (>35–>180 k.y.) archeological site was discovered in the vicinity of the Gademotta caldera, west of Lake Ziway (Fig. 1) (Laury and Albritton, 1975; Wendrof et al., 1975). According to Laury and Albritton (1975), the Middle Stone Age sites occur within paleosols of the late Pleistocene Gademotta Formation. The Gademotta Formation is underlain by a silicic lava flow, with a K/Ar age of 1.1 Ma (Wendrof et al., 1975). However, subsequent dating of the rhyolitic lava by the same method yielded a somewhat older age of ca. 1.3 Ma (EIGS-ELC, 1985; WoldeGabriel et al., 1990). Water-level fluctuations of Lake Ziway appear to have greatly influenced human habitation in the area during late Pleistocene time (Laury and Albritton, 1975). The continuous occurrences of artifacts in paleosols that are covered by volcanic ashes within the stratigraphic sequence suggest that the occupation of these sites was not disrupted by eruptions and deposition of thin ash beds.

Older paleoanthropological localities were discovered along the eastern rift shoulder (Gadeb) and the western rift margin (Melka Kunturé) of the central sector of the Main Ethiopian Rift (Fig. 1). The availability of water appears to have been a major factor in the occupation of these sites during the early Pleistocene. It is not clear if there were other contemporaneous habitation sites within the rift floor between Melka Kunturé and Gadeb during this time period because the area is covered by recent volcanic flows, volcaniclastic sediments, and lakes. However, widespread volcanism and high lake-level stands in the rift floor during the early Pleistocene appear to have made the rift floor inhospitable and may explain the marginal distribution of occupation sites at that time.

Pliocene–Pleistocene (>1.5 Ma) sediments of the Gadeb plain contain artifacts and evidence for hominid occupation on the plateau of the eastern rift shoulder (Williams et al., 1979; Clark and Kurashina, 1979). The artifact-bearing fluvial sediments of the Gadeb plain occur across from the Gademotta caldera Middle Stone Age sites. The Pliocene–Pleistocene stratigraphic section at Gadeb consists of several tuffs that are interbedded with arkosic sands, gravels, pumiceous mud flows, and diatomites. The scarcity of vertebrate fossils and absence of hominid remains from the Gadeb site may not be due to poor preservation because the sediments are not any different from those of other fossiliferous sites. However, the outcrop size at Gadeb is much smaller, and the area is mantled by recent alluvium and grass, so that exposed fossils are few. Moreover, older diatomaceous beds are locally baked and deformed by Pliocene basalt flows. The early to late Pliocene basalt flows (4.4–2.5 Ma) unconformably overlie middle Miocene (16.5 Ma) trachyte flows exposed along the steep sections of the Wabi Shebele River Canyon (Williams et al., 1979). The eastern rift margin of the central sector is 50–60 km west of the Gadeb archeological sites at the head of the Wabi Shebele River Canyon. The thick (300–400 m) Butajira Ignimbrite (3.5 Ma), exposed along the eastern and western rift margin (Fig. 3E), was not found in the Wabi Shebele Canyon adjacent to the Gadeb archeological locality (Williams et al., 1979; WoldeGabriel et al., 1990). About 10–15 km downstream from the Gadeb plain archeological site, the Wabi Shebele Canyon is more than 350 m deep. About half of the section consists of agglomerates and bedded volcaniclastic sediments that are overlain by mafic lava, 50 m of silicic tephra, and a trachytic lava with an age range of 16.9–16.1 Ma (WoldeGabriel et al., 1990). A localized unconformity separates the middle Miocene volcanic rocks and the overlying late Pliocene mafic lavas (2.86–2.82 Ma) along the north wall of the Wabi Shebele Canyon. The localized nature of this erosional surface is indicated by the occurrence of diverse volcanic rocks of basalt, trachyte, phonolite, and silicic flows, ranging in age from 12.1 Ma to 2.54 Ma, that occur along the margins of the adjacent rift floor. However, the absence of the thick tephra deposits of the rift margins from the Wabi Shebele Canyon stratigraphic sequence is probably due to erosion and topographic barriers created by the central volcanoes located along the eastern rift shoulder between Gadeb and the rift floor.

The Pliocene–Pleistocene lake in the Gadeb area on the eastern rift shoulder was created by faulting, topographic control, or isostatic depression similar to that observed in the Nyanza Rift of Kenya (Pickford, 1986). However, a topographically controlled basin appears to have been the cause for the formation of the lake. The Gadeb archeological site is bounded to the south by the northern flanks of the Neogene Bale Mountains of the Southeast Plateau, by a middle Miocene phonolite (e.g., Mt. Chike), and by Pliocene trachytic volcanoes (e.g., Mt. Kaka) just to the north of the archeological site. Late Pliocene basalt flows from centers southeast of Gadeb and the central volcanoes to the north flowed into and blocked the valley, creating a Pliocene–Pleistocene lake on the plateau adjacent to the rift floor. By early Quaternary time, the area was occupied by hominids (Clark and Kurashina, 1979). Major rift-bound silicic centers such as Aluto, Bora, Corbetti, Gademsa, Gademotta, and Shalla, located along the rift floor of the central sector between Lake Awasa and the Awash River due south from Melka Kunturé (Fig. 1) , were active during the Pleistocene, in addition to basaltic fissural eruptions of the Wonji Group (Di Paola, 1972; Mohr et al., 1980; WoldeGabriel et al., 1990). Based on the sizes of the calderas associated with these centers, it appears that voluminous tephra erupted and covered the rift floor and surrounding areas. Such an environment probably made the rift floor inhospitable. This suggests that volcanism might have encouraged dispersal and migration of hominids outside the rift basins during major eruptive interludes.

The rift floor between the Gademotta caldera Middle Stone Age locality and the Kesem-Kebena Acheulean sites in the northern sector of the Main Ethiopian Rift also contains Quaternary silicic centers that are broadly spaced compared with the central sector (Fig. 1). However, basaltic centers and widespread fissure eruptions along the rift axis were more intense in the northern sector of the rift floor, when compared with the central part (Brotzu et al., 1980, Kazmin et al., 1980). Except for the Melka Kunturé Paleolithic site at the headwaters of the Awash River along the western rift margin southwest of Addis Ababa, no other paleoanthropological site has been reported from this part of the rift floor. The early Pleistocene (=1.5 Ma) Melka Kunturé Paleolithic site is in an erosional valley cut by the present Awash River. It contains evidence for hominid occupation and vertebrate remains in fluvial sediments of conglomerate, sandstone, and clays interbedded with marker tuffs (Chavaillon et al., 1979). Like the Gadeb site, Melka Kunturé occurs outside the rift floor in an ancestral river system that drained into the basin. Fluvial and lacustrine sediments of unknown age also occur below basaltic and silicic tuffs along stream cuts and fault scarps east of Melka Kunturé (e.g., Mojo, Nazret, and Wolenchiti areas) along the Awash River and its tributaries.

Northern Sector of the Main Ethiopian Rift

The Main Ethiopian Rift broadens northward into the Afar Rift. Late Miocene and Pliocene–Pleistocene sediments occur along ancestral marginal grabens on both sides of the northern sector of the Main Ethiopian Rift between the Kesem-Kebena and the Middle Awash region of the southern Afar Rift (Fig. 1). Several new localities with vertebrate fossils and Acheulean and Late Stone Age artifacts were discovered in the Kesem-Kebena area along the foothills of the western rift margin by the Paleoanthropological Inventory Project of Ethiopia in 1989 (WoldeGabriel et al., 1992a). Unlike survey results in the central sector, which is characterized by the absence of fossiliferous sediments, survey results in the northern sector indicated that the fossiliferous sedimentary units and interbedded tephras were deposited along a marginal graben between >3.7 Ma and 1.0 Ma. The sedimentary succession in the area contains Pleistocene Acheulean lithic assemblages and fauna dated to ca. 1.0 Ma. Coarse conglomeratic units within alluvial fans occur along the slopes of the rift margin, whereas fossiliferous volcaniclastic fluvial sediments with minor lacustrine deposits are confined to the axis of the ancestral graben. The parent sources for these volcaniclastic sediments are the thick Oligocene to Miocene basaltic flows and subordinate silicic lavas and tephra exposed along the rift shoulder. There are also diatomaceous sediments, bentonites, or paleosols within the sedimentary sequence. The conglomeratic alluvial fan deposits at the foothills of the western margin are devoid of fossils. Temporally correlative sediments were not found in the Awash River Gorge south of the Kesem-Kebena area (Fig. 1) where late Miocene to Pleistocene (5.6–1.5 Ma) basalt flows and silicic tephra beds are exposed (Kazmin et al., 1980; WoldeGabriel et al., 1992a). This is consistent with the confinement of the Pliocene–Pleistocene Kesem-Kebena sedimentary rocks to a marginal graben parallel to the rift escarpment.

On the eastern side of the rift margin, late Miocene fossiliferous fluvial and lacustrine diatomaceous sediments (Chorora Formation) occur along the foothills of the southeastern escarpment of the Afar Rift (Sickenberg and Schönfeld, 1975) (Fig. 1). The diatomaceous deposits are interbedded with welded tuffs and other volcanic rocks probably erupted from centers that were precursors to the silicic volcanoes located to the west of the graben. The western border fault of this ancestral graben appears to have controlled the eruption of late Miocene and early Pliocene rift-oriented silicic centers (e.g., Woldoy, Gara Gumbi, Assabot, Afdem, and Boraat) (Chernet et al., 1996). The late Miocene to Pliocene (9.0–3.0 Ma) Nazret Group ignimbrites were also confined to this graben, consistent with their absence in the Awash River Gorge (Kazmin et al., 1980). Diverse vertebrate faunal, floral, and archeological remains were collected from these late Miocene and Pliocene–Pleistocene volcaniclastic sediments (Sickenberg and Schönfeld, 1975; Asfaw et al., 1990).

Southern Afar Rift Basin

Recent paleoanthropological research in the Middle Awash–Hadar region of the southern Afar Rift has yielded an unparalleled record of early hominid biology and technology (Johanson, et al., 1978; Kalb et al., 1982, Kalb, 1993; Clark et al.,1984; White et al., 1993; Clark et al., 1994). The Hadar area is one of the richest vertebrate fossil sites in the East African Rift System. The remains of dozens of individuals of *Australopithecus afarensis,* including the partial skeleton of 'Lucy," were collected from this area beginning in the early 1970s (Johanson et al., 1978). The major discovery of new hominid genera and species, *Ardipithecus ramidus* and *Ardipithecus garhi* (White et al., 1994, 1995, Asfaw et al., 1999), that were dated at 4.4 Ma and 2.5 Ma, respetively (WoldeGabriel et al., 1994, 1995; de Heinzelin et al., 1999) have established the Middle Awash upriver from Hadar as one of the world's most important paleoanthropological sites (Table 1).

Late Miocene and Pliocene–Pleistocene fossiliferous fluvial and lacustrine sediments interbedded with mafic and silicic lavas and tephra are exposed along rift margins, rift-bound fault blocks, and stream cuts along the rift escarpments and within the rift floor of the Middle Awash region of the southern Afar Rift (Kalb, 1993; White et al., 1993; WoldeGabriel et al., 1994, 1995 de Heinzelin et al., 1999; Renne et al., 1999). Kalb (1993) grouped the Neogene volcaniclastic rocks of the Middle Awash region and the Chorora Formation at the eastern margin of the northern sector of the Main Ethiopian Rift into the Awash Group with little or no temporal and spatial controls of the defined type sections and marker beds. Moreover, the late Miocene diatomaceous Chorora Formation is not part of the Middle Awash sedimentary basin and was deposited in a separate basin along the rift-oriented marginal graben close to the southeastern rift margin (Sickenberg and Schönfeld, 1975; Kazmin et al., 1980). Pliocene–Pleistocene volcaniclastic sediments ranging in age from 4.26 Ma to 0.6 Ma were mapped on the east side of the Middle Awash (Hall et al., 1984; White et al., 1993). Uplift and erosion on the west side directly across from the outcrops on the eastern side expose late Miocene (>5.0 Ma) to Pleistocene (≤1.0 Ma) volcaniclastic sediments (de Heinzelin et al., 1999; Renne et al., 1999). The fossiliferous volcaniclastic sediments of the east side of the Middle Awash yielded *A. afarensis* remains dated at 3.4 Ma and between 3.89 Ma and 3.86 Ma (White et al., 1993). Older sediments from the west side of the Middle Awash yielded the remains of *Ardipithecus ramidus* (White et al., 1994, 1995). Correspondingly, typical Acheulean tools were discovered on the east side, whereas the west side has provided early Acheulean and Middle Stone Age artifacts (Clark et al., 1994; de Heinzelin et al., 1999).

More detailed geological studies at paleoanthropological localities within the east and west sides of the Middle Awash, Gona, and Hadar areas provide well-constrained temporal controls for stratigraphic classification of the volcanic and sedimentary rocks of the basin (Figs. 3F–3I). The stratigraphic studies were aided by fieldwork, geochronological, and geochemical data from mafic and silicic lavas and tephra interbedded with the sedimentary units (Hall et al., 1984; Renne et al., 1993; Walter, 1994; WoldeGabriel et al., 1994, 1995; Semaw et al., 1996; de Heinzelin et al., 1999; Renne et al., 1999). According to biochronological and geochronological constraints of volcanic rocks, late Miocene and Pliocene (>4.4 Ma) fluvial and lacustrine sediments occur along the western rift margin and the west side of the rift floor of the Middle Awash region (Kalb, 1993; WoldeGabriel et al., 1994, 1995; Renne et al., 1999). On the east side of the Awash River, a sedimentary sequence of lacustrine and fluvial origin is interbedded with volcanic rocks that range in age from 4.26 Ma to 0.6 Ma (Hall et al., 1984; White et al., 1993). Downstream from the Middle Awash, the Gona and Hadar areas are dominated by late Pliocene (3.22–ca. 2.0 Ma) fluvial and lacustrine sedimentary rocks and volcanic flows (Tiercelin, 1986; Walter, 1994; Semaw et al., 1996). A cyclic sedimentary sequence of alternating fluvial and lacustrine volcaniclastic sediments with interbedded vitric, bentonitic, and zeolitized silicic and basaltic tuffs and carbonate layers, decreasing in age from

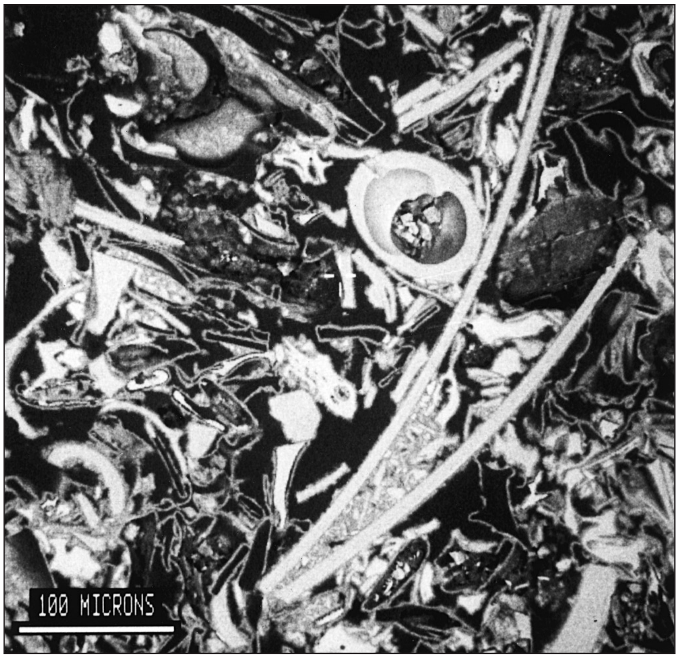

Figure 4A. Gàala Silicic Tuff—typical ash fallout tuff from the Middle Awash. The 1.6-m-thick Gàala Tuff, as exposed along the Kada Sagantole, appears to have been deposited as ash fallout during a single eruption. Individual beds within the tuff show considerable evidence of reworking by sheetwash, perhaps reflecting short breaks between periods of ash fall and heavy rain. The Gàala Tuff may be fairly near (tens of kilometers) the source; although it is generally fine grained, it contains subunits with pumice clasts up to 1.8 mm long. The ash is compositionally bimodal, consisting of rhyolitic, Y-shaped, curved, thick-walled shards and bubbles; ~40% of the rock consists of finely vesicular pumice clasts of 100–800 µm diameter; some shards are as much as 400 µm long, but most are 20–80 µm wide. There are also aphyric sideromelane scoria.

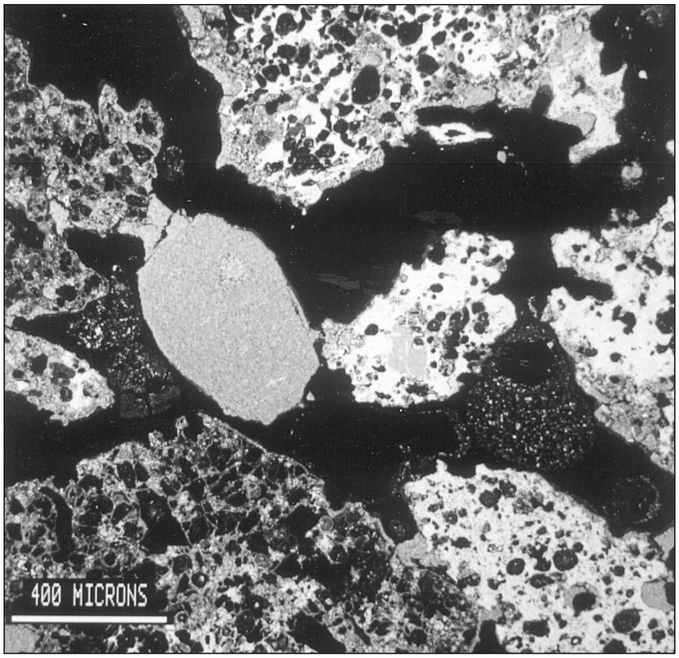

Figure 4B. Daam Aatu Basaltic Tuff from the Middle Awash. This well-bedded, 5–10 cm thick, coarse-grained, gray basaltic tuff consists of 0.6–1.5-mm-long pyroclasts, including: (1) rounded, equant, finely vesicular sideromelane, (2) angular, poorly vesicular sideromelane, (3) rounded, finely vesicular tachylite, and (4) sideromelane droplets (poorly vesicular). All of the pyroclasts contain 1–5% small plagioclase and clinopyroxene phenocrysts. The surfaces of many of the sideromelane grains are altered. The ash is most likely local fallout from Strombolian activity at one of the scoria cones. In many cases, the basaltic tephras are altered to yellowish-green clay.

the late Miocene Middle Awash sequence to the late Pliocene Hadar deposits, is exposed along the southern Afar Rift floor (Figs. 3F–3I). Most of the secondary minerals in the basin formed from the alteration of primary and reworked silicic and mafic tephra (Figs. 4A and B). According to Fisher and Schmincke (1984), volcanic glass is unstable and reacts with pore fluids readily before the other components of the volcaniclastic deposits and/or volcanic flows are affected. The preferential dissolution of glass is indicated by the preservation of shard pseudomorphs (Fig. 5). Increased alkalinity from the hydrolysis of silicic and basaltic glass enhances the formation of authigenic minerals during burial and leads to compaction and reduction of porosity. Precipitation of cement following the dissolution of the tuffaceous rocks reduces porosity and permeability in fluvial and lacustrine sediments. The alteration products replace and cement organic remains in the depositional environment, thus leading to their preservation.

The stratigraphic sequence within the Middle Awash–Gona–Hadar region indicates a complex interplay of rifting, volcanism, and sedimentation processes during the late Miocene and Pliocene–Pleistocene periods. The older sedimentary units are exposed by uplift, faulting, and stream erosion. Sediment sources for the southern Afar Rift include rift-bound, topographically elevated, Pliocene–Pleistocene volcanic terrane and uplifted fault blocks and the adjacent rift escarpments and shoulders (Fig. 2). Most of the sediment sources on the rift escarpments are Oligocene to Miocene basaltic and silicic rocks. Crystalline basement and Mesozoic sandstone, limestone, and mudstone, exposed along the southern Afar margin, also contributed detritus to the rift floor sedimentary succession. Preservation of terrestrial and aquatic organisms within the Middle Awash–Gona–Hadar region is good and allows easy comparison with other paleontological localities within the East African Rift System. Diagenetic processes in the form of calcification, pedogenesis, silicification, zeolitization, and clay formation were widespread within the sedimentary deposits of the region. Widespread carbonate horizons within paleosol zones are sometimes associated with the hominid fossils on the west side of the Middle Awash. Moreover, extensive alteration of early Pliocene basaltic tephra is evident in the area, and aquatic organisms like fish are perfectly preserved in these lacustrine sediments.

A number of widespread Pliocene tephra deposits interbedded with fossiliferous fluvial and lacustrine sedimentary rocks were mapped within the paleoanthropological localities of the

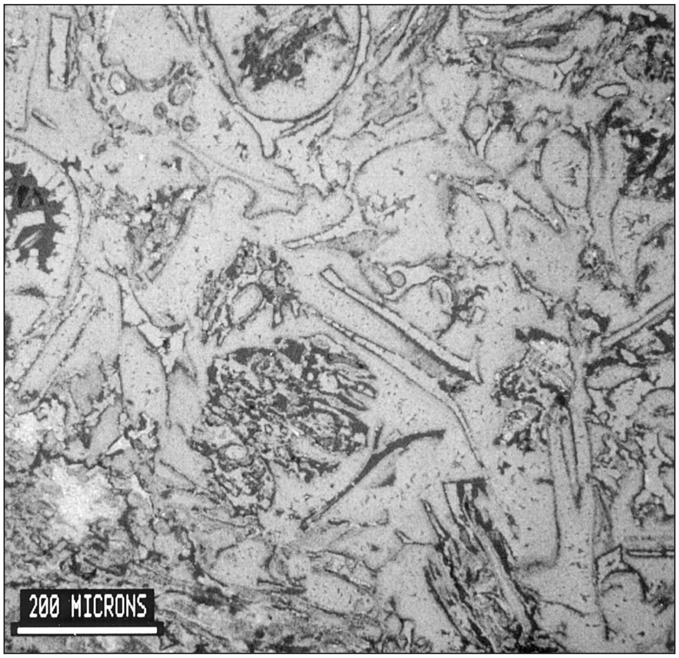

Figure 5. Typical bentonitic ash from the Middle Awash. This 30-cm-thick altered tuff is interbedded with bentonitic clastic sediments. The tuff is completely bentonitic, but relict textures are excellent. It was an ash fall bed that was altered *in situ.* Leaching during hydrolysis of the glass was responsible for the reduction of porosity. The relict textures indicate that the ash fallout consisted of large, thin-walled (10–30 µm long), elongate, straight, slightly curved platy shards. These are also some hollow spheres. The ash also contained ~25% equant, 100–200- µm-wide, angular pumice clasts (up to 2 mm long). The tuff is nearly aphyric, with only traces of very small, angular sanidine phenocrysts. Compare with the unaltered ash in Figure 4A.

Ethiopian Rift System (Fig. 3). The Middle Awash–Gona–Hadar region of the southern Afar Rift contains tuffs that range in thickness from a few centimeters to ~1.5 m and range in age between 4.4 Ma and 2.5 Ma (Hall et al., 1984; White et al., 1993; Walter, 1994; WoldeGabriel et al., 1994, 1995; Semaw et al., 1996). Some of these tuffs also occur within the Omo-Turkana Basin, the Omo River Canyon, and the central sector of the Main Ethiopian Rift (Fig. 3).

DISCUSSION

Abundant faunal remains in rift settings, including hominids, suggest that the Ethiopian Rift System created productive ecosystems during Pliocene–Pleistocene time. The volcanic rocks within the fossiliferous sediments provide temporal information for calibrating and sequencing hominid and other faunal evolution. Detailed geochemical and geochronological studies on volcanic rocks from the different localities form the basis for establishing accurate biostratigraphic and lithostratigraphic information, sedimentation rates, and paleoenvironmental and tectonic histories of these areas. Interbedded volcanic rocks allow determination of the time of rifting, the beginning of sedimentation, sedimentation rates, and the oscillation from lacustrine to fluvial environments. The cyclic environmental transitions recorded in the sedimentary sequences of the rift basins are caused by tectonic activities (uplift and subsidence), changes in relief, and climatic variations. Changes in topographic features, coupled with volcanic damming, created basins for the accumulations of thick lacustrine and fluvial volcaniclastic sequences with terrestrial and aquatic fossils. Changes from finely bedded lacustrine deposits to fluvial sediments are commonly noted in the sedimentary sequences and reflect environmental and tectonic changes that can be temporally determined. Moreover, regional correlation based on the chemistry and geochronology of interbedded tephra has made it possible to establish accurate stratigraphic relations that are useful for paleoenvironment reconstruction and evolutionary studies of fossil remains in the rift valleys across East Africa.

Regional tephra correlation is being used increasingly to link sites together, and has already established that similar tephra layers are known from Lake Albert, Uganda (Pickford et al., 1991), Baringo, Kenya (Namwamba, 1992), the Omo-Turkana Basin (Brown, 1994), the Omo River Canyon (WoldeGabriel and Aronson, 1987; Hart et al., 1992; WoldeGabriel et al., 1992b), the Main Ethiopian Rift (Hart et al., 1992; WoldeGabriel et al., 1990, 1992b), the Middle Awash (Hall et al., 1984; White et al., 1993), the Gona-Hadar areas (Walter, 1994; Semaw et al., 1996), and the Gulf of Aden (Sarna-Wojcicki et al., 1985). There is a great potential for further correlation of tephra in the Ethiopian Rift System and marine sediments in the Arabian Sea. The Arabian Sea has a continuous record of deposition that extends to at least 7 million years. Terrestrial volcaniclastic sediments with interbedded tephra that are within the age range of the ODP Ocean Drilling Program 721/722 stratigraphic sections of the Arabian Sea are also present within the rift floor and the western rift margin of the Middle Awash region. Chemical and chronological correlations of ash beds within the rift sequences of East Africa have been made with ashes described in marine (Deep Sea Drilling Project) sections in the Gulf of Aden (Sarna-Wojcicki et al., 1985; Brown et al., 1992). Detailed correlations based on orbitally calibrated time scales of paleomagnetic stratigraphy within tuffaceous siltstones of rift deposits in the Middle Awash (Renne et al., 1999) will provide ties to establish global climate changes based on the terrestrial and marine sediments of the Middle Awash and ODP 721/722 sections.

Sediments eroded from volcanic, sedimentary, and crystalline basement rocks were responsible for quick burial of fossils in the Omo Basin. The composition of the source rocks and sediments aided fossil preservation during diagenesis. For example, carbonatite ashes in Kenya and Tanzania were credited for the excellent preservation of fossils and footprints by providing fine-grained ashes and carbonate compounds that quickly lithified (Hay, 1986; Pickford, 1986). According to Pickford (1986), fossil preservation in sediments derived from silicic rocks (>6 wt% silica) is generally poor when compared with sediments from Carich source rocks (>10 wt% CaO). However, most of the fossil-rich fluvial, deltaic, and lacustrine volcaniclastic sediments of the Omo Basin were the products of mafic and silicic lavas and tephra from west-central and southwestern Ethiopia. Silicic and mafic tephra are least stable in a fluvial and lacustrine depositional environment because of hydrolysis during burial, compaction, and diagenesis (Fisher and Schmincke, 1984). In this kind of depositional environment, fossiliferous sediments with terrestrial and aquatic fauna and plant remains are generally exposed to mineralized aqueous solutions that are released during diagenetic processes. These processes include silicification, calcification, pedogenesis, clay formation, zeolitization, and feldspathization that begin from the time of deposition to moderate burial. In the Fejej area, abundant Oligocene and Pliocene–Pleistocene silicified woods are present (Davidson 1983; Asfaw et al., 1992). Moreover, paleosols, clay deposits, and limestone beds underlying early Pliocene basalts (4.2–4.4 Ma) are commonly noted in the area and may have aided in fossil preservation through calcification and silicification processes in a water-saturated environment. Thus, volcanic rocks greatly contributed to the preservation of the fossil record in the rift basins by providing sediment for quick burial and secondary minerals from water-rock interaction for cementation and replacement of organic remains. However, historical records and recent events indicate the destructive nature of volcanic eruptions. Although no fossil record has been discovered that indicates the disruptive effects of the Pliocene–Pleistocene volcanic eruptions on the fauna and flora of the Ethiopian Rift System, modern and historical analogs can be used to assess the impact of these processes on life in the geologic past.

Volcanic Hazards to Fauna and Flora

The Pliocene–Pleistocene stratigraphic sequence of the Central Awash Complex (CAC) in the Middle Awash region is comproised of tuffaceous clastic sediments (mostly siltstones) and fresh and altered tuffs (Figs. 4 and 5). Even interbedded carbonates contain glass shard relicts. Within the CAC, ash fallout consist of mostly fine grained, platy shards, which make up thick distal(?) beds. *A. ramidus* was found interbedded between the underlying Gaàla Tuff and overlying Daam Aatu basaltic tuff (Fig. 3F). The Gaàla Tuff here is 1.7 m thick and is made up of eight fallout units, which appear to have fallen during a single eruption. Higher up in the section of the CAC, a thick (6.05 m), aphyric, unnamed tuff is comproised of seven subunits, with a mean bed thickness of 0.76 m. These beds appear to be from a single eruption and consist of fine-grained (40–50 µm) platy shards. Only the lowest bed contains some small pumice clasts. All beds are similar chemically. The surface of each of the six lowest subunits is slightly reworked by sheetwash, and the uppermost 25 cm of the top unit is reworked. The fallout that formed this tuff would have devastated the area totally and loaded streams with fine ash for decades afterward.

Effects of Volcanic Ash on Life Forms

The effects of a much less catastrophic eruption than that responsible for burial of the CAC 4.4 m.y. ago was the well-documented eruption of Parícutin, Mexico, which erupted in the early 1940's (Rees, 1979). After heavy ash fallout began covering the countryside in 1943, livestock began to sicken and die. Wild fruit, bees, and deer began to disappear from the countryside. Corn seeds were planted while the eruption was continuing in early 1943, but most of the plants were buried faster than they could grow. Plants that survived burial were killed by fungi that entered plant tissues damaged by the ash. In areas without lava flows, the thickness of the ash layer dictated survival of plants within Parícutin's area of influence. Where the ash was more than 1.5 m thick, all living plants died. Rees (1979) also noted that where the ash was between 0.5 m and 1 m thick, trees and shrubs were heavily damaged. The ash stripped leaves directly from the trees, or else formed a thin coating on broad leaves that restricted access of CO_2 to the plant necessary for growth. Fruit trees were affected as far as 48 km from Parícutin. Fine ash prevented pollination, but it didn't matter for there were no bees to pollinate the flowers. The ash was lethal to bees because it stuck to their fuzzy bodies. Most preexisting shrubs and trees survived where the ash layer was less than 0.5 m thick; chances of survival were significantly improved on steep slopes where ash was washed away by water runoff after rain. Thick ash beds in flat areas remain sterile to this day (50 yr after the eruption), but the rugged lava flows are generally reforested because they retain moisture on their surfaces. By 1960, 33 species of plants including pine trees, ferns, and mosses were sparsely growing on lavas. Allison and Briggs (1991) note that the best-preserved plant fossil records are those where forests are buried in volcanic ash. Even delicate plants can be preserved. Conversion of glass shards to smectites supplies silica to the environment and aids silicification of fossils (Murata, 1940; Hay, 1968, 1986).

The lessons of Parícutin can be applied to interpretations of the effects of massive ash falls on life forms within the Ethiopian Rift of 4.4 Ma. Ash would have stripped trees and bushes and buried grasses, eliminating the food supply for many species. Sheetwash derived from ash bed surfaces would have clogged streams and lakes, affecting many aquatic lifeforms. Windblown ash may not have killed animals, but it would have weakened them by causing pulmonary damage and/or tooth abrasion. Starvation may have been the main effect of the ash fallout. Recovery from burial by ash is dependent upon the climate. In tropical areas like Indonesia, where the Krakatau eruption of 1883 devastated parts of Sumatra and Java, and after the 1939-1940 eruption of Rabaul volcano, New Guinea, recovery was rapid, with abundant plant life starting anew after only a few years, and with animals quickly following (Docters van Leeuwen, 1936; Johnson and Threlfall, 1985). There are fewer examples of post-eruption rapid recoveries in arid regions. We have no idea of the size of the area covered by the thick ash beds studied in the CAC. At the top of the CAC section, there are pre–Moiti Tuff (3.9 Ma) distal ash beds, which are more than 1.0 m thick. Although the source area and the lateral extent of these distal ashes are unknown, the area of destruction by ash fallout would have been enormous. For example, short- and long-term population reductions and morphological changes (e.g., dental dimensions) were noted in fossil remains of mammals affected by the deposition of a 1.65–1.8-m-thick Miocene tuff in Argentina (Anderson et al., 1995).

A number of well-characterized tuffs of the Ethiopian Rift (e.g., 3.9 Ma Moiti Tuff/VT-1, 3.75 Ma Wargolo/VT-3, 3.5 Ma Lokochot/BT-75, and 3.4 Ma Tulu Bor/Sidi Hakoma Tuff) have been correlated from Lake Turkana, the Main Ethiopian Rift, and the Middle Awash to the Gulf of Aden, a distance of 1,400 km (Brown et al., 1992, Hart et al., 1992; WoldeGabriel et al., 1992b). There are not yet enough thickness measurements of undisturbed Moiti ash or the other tephra to determine volumes, but the magnitudes may be estimated. They would lie somewhere between those of the Lava Creek B Tuff and the Bandelier Tuff. The Lava Creek B Tuff (one of the three Yellowstone National Park calderas, Wyoming; Smith and Braile, 1984) has a volume of 1,000 km^3 and covered 4 million km^2 with ash centimeters to meters thick. At the smaller end of the range would be the Upper Member of the Bandelier Tuff (Valles caldera, New Mexico), which has a volume of ~150 km^3 (dense rock equivalent; the actual ash fallout volume is larger; Heiken, unpub. data, 1990). In any case, the Moiti ash fall and the other tuffs would have devastated much of the land within the Ethiopian rift and beyond at the respective eruption periods, which were separated by ca. 0.1–0.2 Ma. Most of these tuffs appear to have erupted from the central sector of the Main Ethiopian Rift (Hart et al., 1992; WoleGabriel et al., 1990, 1992b). The effects of such successive voluminous eruptions would have been to fragment species ranges of plants and animals repeatedly and isolate peripheral populations. Ultimately, this could have triggered speciation although there is not much evidence to support this hypothesis.

Excess Sedimentation After an Eruption

Ash fallout blankets the countryside, drastically changing patterns of erosion and deposition. As was discussed in the preceding section, vegetation is destroyed in areas with thickest ash fallout. However, even relatively thin (centimeters to decimeters) ash beds can change the relative rates of infiltration of rain, causing up to 80% of rainfall to run off (Waldron, 1967). A thin "crust" is formed at the ash bed surface, sustaining this excess runoff. The runoff cuts through into the ash bed, causing accelerated sheet and rill erosion, as was the case for the ash fallout from Irazú volcano during the eruption of 1963–1965 (Waldron, 1967). Downstream, excessive runoff and high-concentration stream flow cause accelerated erosion. It appears that the Central Awash Complex is too far from the sources of silicic volcanic ashes to see the immediate effects of lahars (volcanic mud flows) and large hyperconcentrated stream flows (hyperconcentrated stream flows are described by Smith, 1991). However, any streams draining the ash-covered countryside will have high sediment concentrations (fine ash) and could flood alluvial plains as was the case for streams draining Mount Pinatubo, Philippines, after the large 1991 eruption (Pierson et al., 1992). Pinatubo also affected closed basins, river mouths, and coastal wetlands. A plume of ash was visible in the ocean for several kilometers offshore at the coast; this ash must have been dispersed across a considerable area of sea floor. Clastic facies within the Sagantole Formation (CAC) indicate that much of the ash washed from the countryside was deposited in lakes or as silty overbank deposits. This excess sediment could have also smothered vegetation on flood plains and affected aquatic life in streams and lakes.

Windblown Ash

The environment in a rift basin after a major ash fallout would have been bleak. After drying out, it is possible that windblown dust (fine ash) could have caused considerable discomfort to animals remaining in the rift valley. Fine-grained ash, disturbed by animals or the wind, would have remained as a dense dust cloud for many minutes. However, it is unlikely that the windblown ash would have been much more than a severe nuisance. Martin et al. (1986) found that volcanic ash from the 1981 eruption of Mount St. Helens was not harmful to the lungs of healthy humans. There is also the possibility that teeth of grazers and browsers would have been abraded by ash, but that is not verified in this work.

CONCLUSION

The Ethiopian Rift System consists of symmetrical and half-graben basins that are in different stages of evolution. The Afar and the Main Ethiopian Rifts started to form in the late Oligocene to early Miocene periods. The 200–300-km-wide rift zone in southern and southwestern Ethiopia occurs along the northern extension of the Kenya Rift and appears to have started later. Most of the rift basins are filled with Pliocene–Pleistocene sediments, whereas some of them contain Miocene sedimentary deposits. Most of the sedimentary sequences contain faunal and floral remains including a number of hominid species. Most of the basin-fill sediments were derived from topographically elevated volcanic rocks that are present within and outside the rift basins. Lava flows and tephra are interbedded with the fossiliferous sediments.

Clastic sediments derived from volcanic rocks aided in the cementation and preservation of organic remains by providing secondary minerals released during alteration in a burial environment. Quick burial minimized the effect of preburial taphonomic processes. Moreover, chemical constituents released by the alteration of volcanic rocks were responsible for replacement and preservation of organic remains. For example, low-silica volcaniclastic sediments enriched in lime provided the best environment for the preservation of fossils (e.g., carbonatite volcanic ashes in Kenya and Tanzania.

Primary tephra deposits interbedded with sedimentary rocks have provided critical temporal and spatial information without which the study of hominid evolution and paleoenvironmental reconstruction in the East African Rift System would have been impossible. Moreover, because of tephra layers in sedimentary basins of different geologic periods, processes such as faulting, rifting, sedimentation and diagenesis, impact of climatic changes, age of fossils, nature and acquisition of archeological implements, and the origin, distribution, and functional significance of early hominid artifact assemblages can be deciphered. However, evidence on the effects of such volcanic eruptions on fauna, flora, and the ecosystem in the rift system during the Pliocene–Pleistocene periods is not clear. Historical or modern analogs illustrate the potential of the regional and sometimes global effects of such major silicic eruptions in the geologic past.

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