Geologic setting of the Abdur Archaeological Site on the Red Sea coast of Eritrea, Africa

Richard T. Buffler a,⁎, J. Henrich Bruggemann b, Berhane N. Ghebretenasae c, Robert C. Walter d, Mireille M.M. Guillaumeb,e, Seife M. Berhe f, William McIntosh g, Lisa E. Park h

a Institute for Geophysics, The University of Texas, Austin, TX, 78712, USA
b Laboratoire d' Ecologie Marine, Université de la Réunion, B.P. 7151, 97715 St. Denis, LA Réunion, France
c Department of Mines, P.O. Box 272, Asmara, Eritrea
d Department of Geosciences, Franklin and Marshall College, Lancaster, PA, 17604, USA
e Département Milieux et Peuplement Aquatiques,UMR CNRS-MNHU-UPMC-IRD BOREA, Muséum National d'Histoire Naturelle, Paris, 75005, France
f African Minerals Inc., P.O. Box 5284, Asmara, Eritrea
g New Mexico Bureau of Geology and Mineral Resources, Socorro, NM, 87801, USA
h Department of Geology, University of Akron, Akron, OH, 44325, USA

A B S T R A C T

The Abdur Archaeological Site was defined initially by the discovery and dating (125 +/- ka by Ur/Th) of in situ stone tools within uplifted marine terrace deposits located along the southern Red Sea coast of Eritrea, near the small village of Abdur. These tools represent some of the earliest well-dated evidence for human occupation of coastal marine environments. The site is located on the Buri Peninsula along the eastern shoreline of the Gulf of Zula and covers an area of approximately 7 km by 1 km. Three main stratigraphic units are defined and discussed from oldest to youngest:

(1) The Buri Formation is defined herein as a sequence of brackish–freshwater (estuarine) and fluvi-al-deltaic sediments consisting of mudstones, siltstones, sandstones, conglomerates and limestones with ash and pumice beds. Ar–Ar dating of pumice and tephras puts the time of deposition of this unit from about 0.91 to 0.72 Ma (Early–Middle Pleistocene). Several stone tools were discovered in the Buri Formation, indicating early human occupation of a coastal environment during the Early to Middle Pleistocene.

(2) The Abdur Volcanic Complex (AVC) is a small basaltic shield complex that forms the highlands along the eastern part of the Abdur Site and extends to the north and south of the area. Basalts from this center were dated from 2.12 to 0.17 Ma, indicating that the volcanic complex has been tectonically and magmatically active prior to, during and after deposition of the Buri Formation.

(3) The Abdur Reef Limestone (ARL) is the remnant of a shallow marine reef system deposited approximately 125 ka (last glacial highstand, isotope stage 5e) along the margins of the Abdur volcanic highlands. The ARL consists of a basal transgressive lag deposit overlain by extensive buildups of mollusks, echinoderms, bioclastic sands and corals up to 11 m thick. Numerous stone tools in the ARL fall into two tool kits, bifacial hand axes of the Acheulian industry and Middle Stone Age-type (MSA) obsidian flakes and blades. Their distribution suggests that foraging activities of early humans varied with environmental setting.

The Buri Formation has been folded and faulted prior to deposition of the ARL, with dips as high as 36° and vertical locally along fault zones. The ARL has been uplifted up to 8–15 m and tilted 1°–5° in a seaward direction. The area is cut by numerous faults, part of a regional NNW-trending fault system. Occurrences of Buri Formation equivalents to the north along the Buri Peninsula as well as in the area southwest of the Alid volcano suggest the area west of the escarpment was a broad lowland characterized by rivers, coastal lakes, and estuaries along the Red Sea coast during the Early to Middle Pleistocene. Reefs equivalent to the ARL covered large parts of the adjacent Buri Peninsula, the north end of Mt. Ghedem across the Gulf of Zula, and the Dahlak Archipelago to the north.

© 2010 Elsevier B.V. All rights reserved.
1. Introduction

The Abdur Archaeological Site is located 60 km southeast of the port city of Massawa, Eritrea on the eastern edge of the Gulf of Zula, a small arm of the Red Sea (centered around Lat. N 15° 10.5′, Long. E 39° 51.9′) (Fig. 1). Here, stone tools are found primarily within emerged Pleistocene reef terrace deposits, located along the western shoreline of the Buri Peninsula near the small village of Abdur (Walter et al., 2000; Bruggemann et al., 2004; Fig. 1). This Pleistocene terrace deposit is named the Abdur Reef Limestone (ARL) (Walter et al., 2000). Using samples of corals from the ARL, these deposits at Abdur are dated to the last interglacial, 125 ± 7 ka, by U–Th mass spectrometry methods (Walter et al., 2000). The numerous in situ Acheulian/Middle Stone Age (MSA) stone tools that occur within the ARL represent some of the earliest evidence to date for human occupation of coastal marine environments, particularly in northeast Africa (Walter et al., 2000; Bruggemann et al., 2004).

The discovery of stone tools (bifacial hand axes together with obsidian flakes and blades) within these last interglacial reef terrace deposits is unusual and sheds important new light on human adaptive strategies and migration paths out of Africa (Walter et al., 2000; Stringer, 2000; Bruggemann et al., 2004). From the abundance of edible resources found in proximity to these tools (based on present day use), the implication is that early humans were using them to harvest shallow marine food resources on the ancient shoreline (Walter et al., 2000; Bruggemann et al., 2004). The abundance of stone tools in the ARL, and their wide distribution in different paleo-reef environments, suggests that Abdur is unlikely to be the only location on the African coast that documents human coastal occupation by this time (Walter et al., 2000; Bruggemann et al., 2004). It is predicted that more paleolithic sites similar to Abdur will be found within other emerged marine terraces throughout the Red Sea basin of Africa, and perhaps in terraces along the Arabian, Mediterranean and Asian coasts, documenting the spread from Africa of early humans (Walter et al., 2000; Stringer, 2000).

In addition to the abundant stone tools found in the ARL, the occurrence of scattered tools (primarily obsidian flakes and blades) in an underlying Pleistocene fluvial to estuarine deposit (Buri Formation, formerly Buri Sequence of Walter et al., 2000) makes the Abdur Archaeological Site even more significant. These Buri Formation rocks...
are time equivalent to extensive Pleistocene fluvial, lacustrine and fluvial–deltaic sedimentary rocks that occur southwest of the Alid Volcano (Fig. 1) near Buia in the Danderdo and Mahable River drainages. Here abundant Pleistocene vertebrate fossils have been discovered along with a hominin skull dated to about 1 Ma (Abbate et al., 1998, 2004.)

The purpose of this paper is to provide details about the stratigraphy, depositional setting, age and structure of the Pleistocene sediments at the Abdur Archaeological Site. The emphasis here is on the older Buri Formation, since details of the ARL were presented by Bruggemann et al. (2004). There also is a brief discussion of the volcanic complex that underlies and flanks the Abdur Archaeology Site (Abdur Volcanic Complex; Walter et al. 2000, Bruggemann et al., 2004). These geological data are used to reconstruct the Pleistocene paleoenvironmental history of this archaeological site. Finally, there is an attempt to place these rocks at Abdur into a more regional context, based on the limited published literature and field observations about the regional geology. It is hoped that these observations can be used as a guide for future explorations along the Red Sea coast in the search for artifacts and fossils relating to the origins and evolution of modern humans.

2. Project background

The research presented here is part of a long-term cooperative field program being conducted in Eritrea by an international team of investigators from Eritrea, the United States, The Netherlands and France. The principal goal of the project is to study rift processes (origin, evolution and timing of sedimentation, tectonics and volcanism) in an accessible and active divergent plate boundary situated in the southern Red Sea — northern Danakil (Afar) region of Africa. A separate but related goal is to establish a geological framework for hominin evolution from fossils and artifacts within these rift basins based on integrated geological, paleontological and archaeological studies (e.g., WoldeGabriel et al., 2004).

The overall project study area, as shown on the Landsat satellite photo (Fig. 1), occurs along the coastal lowlands and extends N–S for over 100 km from the villages of Foro and Abdur on either side of the Gulf of Zula south through the Alid Volcano to the northern Danakil Depression near the small village of Bada (Fig. 1). The area extends east from the mountain front or Eritrean Escarpment to the Red Sea coast (Fig. 1).

This region of the Afar has long been recognized as a natural laboratory to study active geological processes. During the 1960s, for example, the northern Danakil area was the subject of extensive reconnaissance surveys by French, Italian, and German teams, which resulted in regional geologic maps and numerous publications (e.g., Barberi et al., 1971a,b, and references therein). Most of this work concentrated on the volcanic petrology, structure, geochemistry, geophysics and mineral resources of the area, with little systematic work done on the evolution of sedimentary basins. For the past quarter century no significant geological work has been done in this area mainly due to a 30-year internal struggle for Eritrean independence from Ethiopia, which ended with the establishment of the state of Eritrea in 1992.

We were drawn to this region in part by the pioneering work of Hugues Faure, who in the mid-1960s discovered stone tools resting on a marine terrace in a Pleistocene embayment of the Danakil Rift Valley (Faure and Roubet, 1968). After several visits to Eritrea in 1993 and 1994, the first reconnaissance field expedition to the study area was initiated by one of the team members (RCW) in August, 1995, based on the hypothesis that this area would be a natural extension of the hominin and paleontological discoveries that had been made in similar geological settings in the Afar region of Ethiopia and the rift valleys of Kenya and Tanzania. This larger field area was targeted based on satellite image interpretations (Fig. 1) and field surveys, which suggested that the area should have excellent potential for yielding terrestrial Plio-Pleistocene fossils and artifacts.

Following the 1995 reconnaissance, geological fieldwork was carried out in January–February, 1997, and concentrated in four main areas (Fig. 1): (1) Foro, on the western shore of the Gulf of Zula, where Pleistocene alluvial fans and fluvial terraces are exposed; (2) the Abdur area across the Gulf of Zula along the western side of the Buri Peninsula, where artifacts in uplifted Pleistocene reef terraces were observed; (3) the Alid Volcano area, a large, fault-bounded rhyolite volcanic complex, which is underlain by extensive outcrops of Pleistocene fluvi–lacustrine to nearshore marine rocks, and (4) the Bada region, containing a complex array of older (Miocene–Pliocene?) fluvial beds overlain by younger (Pleistocene?) terrestrial and shallow marine sediments, including evaporites deposited in a former arm of the Red Sea. Each of these regions provides evidence of contemporaneous tectonism, volcanism and sedimentation in rifted continental and/or marine environments.

The team returned to Eritrea for more concentrated fieldwork during January–March, 1999. The first part of the season concentrated on the Abdur Site, while the remaining time was spent near Bada and then the Mahable River–Danderdo River drainages south of Alid, where extensive outcrops of Pleistocene fluvial and lacustrine sediments revealed rich occurrences of stone tools and vertebrate fossils. A final short field season during March, 2001 was then conducted at the Abdur Archaeological Site to make additional detailed observations.
about the area and collect samples of the ARL. Some regional reconnaissance work on the Buri Peninsula also was conducted at this time.

Initial results of the work at Abdur were presented by Walter et al. (2000), who first reported artifacts in the Abdur Reef Limestone, provided age dates for the Abdur Reef Limestone, and discussed early human exploitation of nearshore marine resources. Walter et al. (2000) did not present much detail on the geologic setting of the area. Bruggemann et al. (2004) presented a detailed analysis of the stratigraphy and paleoenvironments of the Abdur Reef Limestone and proposed a model for its deposition. Their paper also includes a more detailed discussion of the context, distribution and significance of the stone tools found within the ARL. Little about the stratigraphy, depositional setting, or age of the underlying Buri Formation (previously called the Buri Sequence by Walter et al. 2000 and Bruggemann et al., 2004) and the associated Abdur Volcanic Complex or the structural setting at Abdur was discussed by Bruggemann et al. (2004).

Ghebretensae (2002) reported for the first time details about the stratigraphy, depositional setting, and age of the underlying Buri Formation. Data from Ghebretensae (2002) is used extensively in this paper, the primary purpose of which is to discuss the details of the Buri Formation at the Abdur Archaeological Site. The structural setting and the regional geologic setting of the site is also described herein in more detail.

3. Regional geological setting

The study area lies in an overlap region between the southern Red Sea, an active rift zone and oceanic spreading center, and the northern Danakil Depression, another active rift zone and incipient spreading center at the northern apex of the Afar Triangle or Afar Depression (Figs. 1 and 2) (Barberi and Varet, 1977; Hayward and Ebinger, 1996). The Afar Depression (Fig. 2) represents a major active triple rift junction, probably underlain in part by an upwelling mantle plume (Courtillot et al., 1984; Montelli et al., 2004). The area has long been recognized as an excellent area to study geologic processes associated with continental rifting, volcanism, sedimentation and hominin evolution. Three rift trends converge in central Afar: the oceanic Red Sea and Gulf of Aden Rifts and the continental East African Rift (Fig. 2). Since Miocene times, rifting and oceanic spreading along the Red Sea and Gulf of Aden rifts have moved the Arabian Plate away from Africa (Nubian and Somali Plates) in a northeasterly direction (e.g., Cochran, 1983; Coleman, 1993; Ghebreab, 1998; Redfield et al., 2003; Beyene and Abdelsalam, 2005; Woffenden et al., 2005; Reilinger et al., 2006) (Fig. 2). The East African Rift, an arm of this active triple junction, penetrates into the southwestern apex of the Afar as the Main Ethiopian Rift Valley. Flanking the northeastern margin of the Afar region, lying between the Danakil Depression and the Red Sea, is the large continental Danakil Block (Fig. 2), thought by some to be forming by counterclockwise rotation (e.g., Souriot and Brun, 1992). Alternatively, the block could represent a continental block isolated between overlapping spreading centers, and moving away from Africa by both rifting and strike slip motions (Makris and Rhim, 1991; Redfield et al., 2003).

The Afar, in general, is a mixture of oceanic and continental tectonic and volcanic affinities (Woffenden et al., 2005). The Gulf of Zula and northern Danakil rift valleys (e.g., Figs. 1 and 2) mark the transition from oceanic to continental rifting regimes. Incipient oceanic crust may be forming in parts of north central Afar itself, characterized by active basaltic volcanism and rifting (e.g., the active Erta Ale and associated volcanic fields) (Yirgu et al., 2006). Here the Danakil continental block is moving with respect to the African plate (Souriot and Brun, 1992) (Fig. 2). Rifting in the Afar is thought to have begun in the early Miocene (ca. 20–25 Ma) during and following the widespread eruption of voluminous Oligocene–Miocene trap basalts (Drury et al., 1994; Hofmann et al., 1997; Rochette et al., 1996; Ukstins et al., 2002; Beyene and Abdelsalam, 2005). Today, the entire area is still an active plate boundary, as indicated by recent and current volcanic activities, neotectonism and sedimentation (Redfield et al., 2003).

The most prominent structural feature in the overall study area is an active graben system (the Zula–Alid–Bada graben) extending from the northern Danakil Rift Valley (northern Danakil Depression) near Bada north through the Alid Volcano to the Gulf of Zula near the Abdur Archaeological Site (Bruggemann et al., 2004) (ZAB, Fig. 1). The graben forms a depression that is over 100 m below sea level near Bada. Fresh basaltic lavas emanate from fault zones (Fig. 1), and recent earthquakes and ground movements have been reported (Ghebreab and Solomon, 1993; Ogubazghi et al., 2004). Further north the Alid Volcano sits within the graben (Fig. 1). Alid is a large young rhyolitic geothermally-active volcanic complex flanked by many young basaltic flows and cinder cones (dark areas north and south of Alid, Fig. 1) (Duffield et al., 1997). Here the graben system is controlled on the northeast by a large normal fault, which appears on the Landsat image to be the northern extension of the graben system at Bada (Fig. 1). This northeast fault system continues further north and splays out along the east coast of the Gulf of Zula at the Abdur Archaeological Site (Fig. 3), forming a series of blocks down-dropped to the west. These faults control the linear orientation of the coastline at Abdur and further north (Figs. 1 and 3). The Gulf of Zula itself is a down-dropped,

![Fig. 3](image-url)

**Fig. 3.** A blowup of a portion of the satellite image from Fig. 1, showing details of the area around the Abdur Archaeological Site, including the three districts at Abdur, the distribution of the Abdur Volcanic Complex (AVC), the Buri Formation north of Abdur, and the extension of the Abdur Reef Limestone north of Abdur along the coast. Prominent faults offset the AVC, generally dropping blocks down to the southwest. Latitude and longitude are approximate. See Fig. 4 and Table 1 for distribution and description of stratigraphic units at Abdur.
sediment-filled depression that has been periodically flooded by the Red Sea. The graben system transfers progressively to the west, first to Foro along the west side of the Gulf of Zula (Fig. 1) and then north forming a graben along the west side of Mt. Ghedem (MG, Fig. 1). Here the graben system transforms further west, offsetting the main Eritrean Escarpment to the west (Ghebreab, 1998; Ghebreab and Talbot, 2000; Drury et al., 1994; Drury et al., 2005).

Most of the highlands region flanking the study area to the west and forming the Eritrean Escarpment (Fig. 1) consist of mainly Precambrian basement rocks with a few scattered outcrops of Mesozoic sedimentary rocks (Ghebreab, 1998; Talbot and Ghebreab, 1997; Drury et al., 1994; Barberi et al., 1971a,b). Basement rocks also occur in scattered outcrops throughout the lowlands, such as on the Buri Peninsula. Most of the hills within the lowlands are made up of young volcanic centers. Some are rhyolitic centers and others are basaltic flows, dikes and sills. For example, Alid Volcano and the lighter area at the south end of the Gulf of Zula (Fig. 1) are large rhyolitic centers, while the darker areas north and south of Alid and at Abdur are basaltic volcanic centers (Figs. 1 and 3). These paired centers form an excellent example of the differentiation process from silicic to basaltic volcanism that occurs during rift propagation in the Afar (Lahitte et al., 2003). The rest of the lowlands are underlain by young Miocene?, Plio-Pleistocene and Recent rift-basin fills, consisting mostly of siliciclastic sandstones, conglomerates, mudstones and some limestones, deposited in fluvial–lacustrine and marginal marine environments (Barberi et al., 1971a,b). In the northern Danakil Depression there are extensive deposits of marine evaporites (halite, gypsum) and limestones (white areas in Fig. 1), deposited in a former

---

**Fig. 4.** Geologic map of the Abdur Archaeological Site showing the location of the three geographic districts (Abdur North, AN; Abdur Central, AC; and Abdur South, AS) and the distribution of the three major stratigraphic units (see legend). a) Map of entire area shows location of described sections and transects at AC and AS; b) enlarged map of AN district shows the location of described sections and transects (see Fig. 10). Map is from Bruggemann et al. (2004) and is based on field work and interpretation of aerial photographs.
arm of the Red Sea. These areas evidently were only recently isolated from the sea by tectonic uplift, volcanic eruptions or a combination of the two (Barberi et al., 1971a,b).

Underlying the coastal plain and the broad offshore shelf areas to the north, there is a thick complex section of mainly siliciclastic sedimentary rocks ranging in age from Oligocene to Recent. The section contains a thick interval of Miocene evaporites (Amber Formation). The loading and the subsequent flow of the evaporites have deformed the overlying sedimentary section (Desset Formation) (Ross and Schlee, 1973; Angelucci et al., 1981; Ministry of Energy and Mines, 2000). This northern area is where exploration for oil and gas has been conducted, and several test wells have been drilled (Savoyat et al., 1989; Mitchell et al., 1992; Bunter et al., 1998; TGSNOPEC, 2005).

4. Geology of the Abdur Archaeological Site

4.1. Setting and stratigraphy

The Abdur study area encompasses an area about 7 km long and 1 km wide along the eastern shoreline of the Gulf of Zula. The general setting is shown on a satellite photo (Fig. 3) and on a geologic map (Fig. 4). The mapped area is subdivided into three geographic districts: Abdur South (AS), Abdur Central (AC), and Abdur North (AN) (Figs. 3 and 4a).

Abdur North, the most extensive of the three districts, has been studied in more detail (Fig. 4b). Here three major stratigraphic formations are defined as shown by the map (Fig. 4b) and a generalized stratigraphic column (Table 1). From oldest to youngest these are: (1) the Buri Formation (previously called the Buri Sequence by Walter et al., 2000 and Bruggemann et al., 2004), defined here as a sequence of fluvial to estuarine mudstone, siltstone, sandstone, conglomerate, limestone, ash, and pumice; (2) the Abdur Volcanic Complex (AVC), basaltic flows that form the highlands along the eastern edge of the area and to the north and south (Figs. 3 and 4). The flows interfinger with and overlie the Buri Formation. They are onlapped and overlain by the ARL; and (3) the Abdur Reef Limestone (ARL), an extensive marine terrace deposit up to 11 m thick composed of the whole and partial remains of marine organisms (largely mollusks, corals, and echinoderms) and bioclastic sandstone (Fig. 4). The ARL unconformably overlies the deformed Buri Formation (Fig. 4b).

In the Abdur Central and Abdur South districts, the ARL laps directly onto the Abdur Volcanic Complex (AVC) (Fig. 4a). Here the underlying Buri Formation is not exposed and may not be present. The ARL overlies older coral reef sequences of unknown age (Fig. 4b).

Table 1

<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Depositional environments</th>
<th>Artifacts</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdur Reef Limestone</td>
<td>Basal transgressive lag with volcanics, oysters; over lain by carbonate buildups – mollusks, echinoderms, bioclastic sands, corals; 3–11 m thick</td>
<td>Widespread shallow marine shelf, reefs and nearshore – beach equivalents</td>
<td>Abundant stone biface s and cores; obsidian flakes and blades</td>
</tr>
<tr>
<td>Abdur Volcanic Complex Buri Formation</td>
<td>Basaltic shield complex; basalt flows</td>
<td>Terrestrial and shallow marine Estuarine, brackish– freshwater, fluvi al–deltaic</td>
<td>None observed</td>
</tr>
</tbody>
</table>

Table 1

Summary of stratigraphy, Abdur Archaeological Site.

4.2. Buri Formation

4.2.1. Distribution, lithology and thickness

An enlarged version of the northern part of the geologic map (Fig. 4b) shows in more detail the spatial distribution of the Buri Formation, where it lies beneath the ARL and the AVC. Detailed measured sections of the Buri Formation were made at eight locations (AN 1, 3, 4, 5, 6, 7, 11, and 12) (Fig. 4) (Ghebretensae, 2002). These sections and other observations from the outcrop area were used to describe the lithologies and stratigraphy of the formation and interpret its depositional environments (Table 1). A defining characteristic of the Buri rocks is the considerable variation in the lithology, which ranges from mudstones, siltstones, sandstones, conglomerates, and limestones, and includes ash and pumice beds. A generalized lithostratigraphic column for one of the more lithologically complex and stratigraphically thickest sections exposed at AN 11 is presented here to illustrate this variability and the interpreted depositional environments (Fig. 5). Two photographs of the outcrops at AN 11 show the lower (Fig. 6) and upper (Fig. 7) parts of the section.

The dominant lithologies throughout the Buri outcrop area are alternating mudstones, siltstones and very fine-grained sandstones (e.g., AN 11, Figs. 5–7). These rocks are generally massively bedded. Field observations of the finer-grained rocks (mudstones and siltstones) indicate that they alternate in color from yellowish gray, yellowish brown, reddish brown, greenish brown, pale olive, to light gray, reflecting various stages of oxidation. They contain varying amounts of calcareous cements and varying amounts of volcanic ash.

The sandstones are generally very fine- to fine-grained, moderately- to poorly-sorted, and range from yellowish gray to yellowish brown. Grains were visible and consist mostly of quartz with common feldspars, mica, and volcanic rock fragments. Some sandstones contain local lenses and channels of coarse sand and gravel consisting of quartz, feldspar, mica, and reddish volcanic rock fragments, metamorphic rock fragments and pumice (e.g., Fig. 5, AN 11, 3.0–3.8 m, 4.5–5.9 m).

Many of the sandstones and siltstones contain abundant volcanic ash consisting of pumice and volcanic glass shards, which give them a greyer color. For example, at AN 11 the sandstone from 1 to 1.5 m is bluish grey in color and contains abundant ash, as does the grey
siltstone/conglomerate at about 8.3 m (Fig. 5). Samples of the volcanic materials from this section (2.6–6.0 m, 8.3 m) were used for age dating the Buri Formation (see Section 4.2.3). Prominent ash and pumice beds also occur in other sections and some were used for age dating (sections AN 1, AN 7, Figs. 4b and 8) (see Section 4.2.3). The dated white ash bed in the upper part of section AN 7 is shown in Fig. 8.

In two sections (AN 7 and AN 11, Figs. 4b–8) there are unique coarse-grained intervals with abundant reworked volcanic material (rock fragments and pumice up to 20–25 cm in diameter). At AN 7 there is a thick (over 2 m) fining-upward conglomerate and sandstone unit that has a channel-forming base and trough cross-bedding (Fig. 8). It contains abundant red and black volcanic rock fragments (basalt, scoria, and pumice), quartz, and some limestone and metamorphic rock fragments. The trough orientations suggest flow to the NNW.

A similar coarse-grained volcaniclastic unit, almost 3 m thick, occurs several km to the NNW at section AN 11 (Fig. 5, 3 to 6 m; Fig. 6) and may be the more distal equivalent to the unit at AN 7. It also contains sandstone and conglomerates, but here the conglomerates fill a series of large and small channels (Fig. 6), which also trend in a NNW direction. For example, the channel at 3.3 m is up to 40 cm thick and over 5 m wide (Figs. 5 and 6). It contains quartz, volcanic rock fragments, limestone sand and fine gravel, and pumice fragments up to 10 cm. The upper part of the unit contains numerous small gravel channels with pumice and red and black volcanic rock fragments (Figs. 5 and 6). The unit is capped by a prominent fining-upward, graded conglomeratic bed with pumice fragments up to 20 cm at the base (5.9 m, Fig. 5).

Limestones commonly form prominent resistant beds in the outcrop belt of the Buri Formation at Abdur North (e.g., AN 11, Figs. 6 and 7; AN 3, Fig. 9). They form either single beds or groups of beds up to 1 m in thickness. For example, there are 5 limestone units identified at AN 11 and numbered 1–5 from bottom to top for correlation between the measured section and the photographs (Figs. 5–7). They range in thickness from a single thin bed at 11.8 m (#4) to a series of stacked beds over 1 m thick at 13–14 m (#5) (Fig. 5). At AN 3 they form a set of three beds (Fig. 9). Some limestones are fine-grained in texture (mudstone-wackestone) (e.g., # 2 at 8.6–9 m, and #4 at 11.8 m, Fig. 5), and consist of silt-size carbonate particles and some microfossil shells (ostracodes). Others are coarsely-grained packstones and grainstones consisting of ostracodes and reworked bioclastic sand (e.g., #3 at 9.9–10.3 m, and #5 at 13–14.1 m, Fig. 5). The limestones locally often contain abundant visible detrital material (quartz, volcanic and metamorphic rock fragments) mixed with the carbonates (e.g., at section AN 1).

Where the resistant limestone beds are dipping, they often form resistant topographic highs, forming relief on the angular unconformity that separates the Buri Formation from the overlying Abdur Reef Limestone (ARL). At AN 11 the ARL onlaps the NW-dipping upper limestones (#3 and #5) and thins from over 3 m (just behind the upper right end of the ARL outcrop in Fig. 7) to 0.9 m along the upper left side of the photo (Fig. 7). At AN 8 (Fig. 4) the ARL thins from 2.0 to 2.5 m to only 1 m. At AN 3 three limestone beds about 0.65 m thick (Fig. 4) forms a resistant hill with over 1 m of relief. Here the ARL thins from over 2 m to only 1.2 m (Fig. 9).

The base of the Buri Formation is not observed, and thus the overall thickness is not known. The upper surface of the Buri Formation is a prominent erosional unconformity with several meters of relief in places. As discussed above the most relief is found where underlying resistant limestone beds form local knobs or hills on the surface (e.g., AN 11 and AN 3, Figs. 7 and 9). None of the measured sections have a stratigraphic thickness greater than the 14 m shown at AN11 (Fig. 5), but in places the beds are tilted and thus a thicker section is inferred. For example, from a continuously dipping section along a road cut in the southeast corner of the area (near section AN 7b, Fig. 4b) at least 50 m of composite section can be inferred at Abdur North (see Section 4.5, Structure).

Based on the above description, the Buri Formation is hereby defined formally as a Formation based on the criteria outlined in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005). This location at Abdur North is designated the type section. The base of the formation is not exposed and the upper surface is an angular unconformity. The maximum thickness exposed here is estimated to be approximately 50 m as outlined above.

4.2.2. Depositional environments

The dominant lithologies of the Buri Formation (mudstones, siltstones and fine-grained sandstones) (Fig. 5) suggest deposition by streams into a standing body of water. This overall fine-grained nature of the siliciclastics plus the presence of micritic limestones suggest that most of the rocks were deposited in a changing but low-energy, relatively quiet water setting. The general massive appearance and lack of obvious bedding or stratification (except locally) suggest deposition by plumes of sediment. The lack of stratification also could be due to reworking by infauna, although no obvious trace fossils (burrows, tracks or trails) were observed.

Ostracodes were identified in sections AN 1, 3, 11 and 12 (Table 2). The ostracode species recovered from these sections are brackish to freshwater species (Table 2). These include Darwinula stevensoni,
Cyprideis torosa, and several species of Candona sp. (Table 2). The presence of Darwinula stevensoni definitely indicates brackish to freshwater, as this species, while broadly tolerant of varying salinities, is not known to occur in marine environments (Carbonel and Peypouquet, 1983; Sohn, 1987; Van Doninck et al., 2003).

The lithologies and the brackish to freshwater fossils suggest that the depositional environment probably was a restricted embayment or estuary along the early Red Sea shoreline. The presence of the foraminifera species Ammonia beccarii (Table 2) suggests that there were marine influences, which is consistent with an estuarine setting (Dix et al., 1999; Ruiz et al., 2005). This species is common in shallow embayments of restricted circulation and along shore regions where the seasonal influx of freshwater results in highly variable salinities (Bandy, 1964; Dix et al., 1999; Poag, 1978; Rose and Lidz, 1977; Sen Gupta and Schafer, 1973). Hydrobid gastropods (Table 2) occur in similar settings and are definitely nonmarine, which further supports the estuary interpretation. They probably occurred in the fresher portion of the estuary, perhaps in pools of water within the overall ecosystem complex. Environmental interpretations are based on known modern as well as fossil occurrences (see Table 2 and references therein).

The general deposition of the fine-grained siliciclastics into the estuary was periodically interrupted by the input of locally-derived coarser-grained sediments. For example, the conglomerate and sandstone intervals at AN 7 and AN 11 discussed above (Figs. 5, 6 and 8) suggest a local fluvial input along a southern shoreline. The trough cross-bedded section at AN 7 (Fig. 8) suggests a larger more proximal fluvial channel, while the section at AN 11 (Figs. 5 and 6) suggests smaller more distal fluvial–deltaic distributary channels. Channels at both sections trend NNW indicating current flow in that direction. Deposition of these coarse-grained intervals could be due to
a lowering of base level, followed by a rise of base level and deepening, as suggested by the graded bed (turbidite?) lying above the conglomerate at 5.9 m (AN 11, Fig. 5).

This coarse-grained input also could be due to increased periods of flooding during times of higher precipitation. As both these units contain abundant locally-derived volcanic materials (volcanic rock fragments, pumice and ash), these intervals could reflect pulses of nearby volcanic activity as well. In addition, pulses of tectonic activity and uplift in nearby highlands would provide increased gradients in streams, allowing them to carry coarser materials. The presence of scattered metamorphic rock fragments suggests the presence of exposed basement rocks in the source area as well.

The limestones represent a changed environment caused by periodic rises of base level (sea level). These rises inundated the estuary, providing clearer water settings for the production of carbonates and the deposition and preservation of the limestones. The estuary remained restricted however, as many of the ostracodes identified were from limestones. This change was accompanied by a retreat of the shorelines, which prevented significant input of siliciclastics to this part of the estuary. In many cases this change upward from siliciclastics to limestones was gradational, as many of the beds just below the limestones are quite calcareous (e.g., just below limestones #3 and #5, Fig. 5). Occasional riverine floods from the hinterlands reached the estuaries during this time as indicated by the occurrence locally of scattered grains of fine-grained volcanic and metamorphic rock fragments in the limestones.

The alternating cycles of siliciclastics and limestones suggest the ongoing interaction of varying climatic influences on the control of base level (sea level), and thus the sediment input into the basin. Although the estuary was restricted, it probably had some connection with the nearby ancient Red Sea. These cycles or parasequences are shown in section AN 11, where five limestones define five cycles of limestone/siliciclastic couplets (Figs. 5, 6 and 7). This cyclic pattern is what might be expected during the Pleistocene (e.g., McDougall et al., 2005).

Superimposed on this climatic control of sedimentation are pulses of volcanic and tectonic activities, which apparently played a significant role in shaping the estuary and providing sediment to the rivers that drained into the estuary. Pulses of nearby volcanic activity provided the abundant volcanic rich sediment, and tectonic uplift probably controlled stream orientation, gradients and sediment load. This nearshore estuarine setting along the Red Sea coast, therefore, was probably a combination of a broad drowned river valley and a tectonically formed and structurally controlled valley. Inlets to the restricted estuary could have been controlled by sediment bars and/or tectonics.

4.2.3. Age of the Buri Formation

Six samples of volcanic ash and pumice were collected from three measured sections for radiometric dating (AN 1, AN 7, and AN 11). All dating was done using the $^{40}\text{Ar}/^{39}\text{Ar}$ laser-fusion method at the New Mexico Geochronology Research Laboratory, Socorro, NM. From each sample individual sanidine feldspar grains were picked and then irradiated in machined aluminum trays together with Fish Canyon Tuff sanidine flux monitors (28.02 Ma, Renne et al., 1998). Individual sanidine grains were fused by CO$_2$ laser and analyzed using a MAP 215-50 mass spectrometer. The single-crystal laser-fusion results from Buri Formation samples are summarized in Table 3 and discussed below. More complete analytical parameters and results are detailed in Appendix A.

Sanidine crystals from two of the six dated samples (E97-50 and AN 11 250-570) have tightly grouped, unimodal age distributions consistent with uncontaminated phenocryst populations. Feldspars from three other samples have unimodal age distributions accompanied by significantly older xenocrystic grains. Two of these three samples (AN 7, E97-40a) have sufficient primary crystals for the calculation of a precise eruption age. The third sample (AN 11, 578-598, Appendix A) has sparse (n = 4) primary feldspars which are too small to provide a precise eruption age. The sixth sample (E97-41) contains feldspars with a broad polynomial age distribution (MSWD > 10), probably representing contamination by sanidine from somewhat older Pleistocene tephra deposits. The younger crystals from this sample provide what is interpreted as a precise eruption age. Results from all samples were plotted on both isochron and probability distribution diagrams (Appendix A). Although in most cases isochron and weighted-mean ages overlap or nearly overlap at $2\sigma$, isochron ages are preferred over weighted-mean ages, because small but significant amounts of excess $^{40}\text{Ar}$ are indicated by elevated isochron intercepts ($^{40}\text{Ar}/^{36}\text{Ar} > 295.5$) and by MSWD values for isochron ages, which tend to be lower than those for corresponding weighted-mean ages.

The ages from the five well-dated tephra samples from the Buri Formation at Abdur North range from 0.72 ± 0.1 to 0.91 ± 0.04 Ma.
(Table 3, Appendix A), straddling the boundary between Early Pleistocene and Middle Pleistocene (0.78 Ma, Gradstein, et al., 2004). These dates provide precise eruptive ages for the volcanic material extracted from the Buri Formation at the three measured sections. The individual age determinations are consistent with the stratigraphic position of the samples within the Buri Formation. The oldest dated beds from the lower part of AN 11 (2.6–5.7 m), located within the fluvial–deltaic conglomerate unit (Fig. 5), is 0.91 ± 0.04 Ma, while a higher ash bed at AN 11 (8.3 m, Fig. 5) gives a younger but statistically indistinguishable age of 0.86 ± 0.01 Ma. The ash bed dated at AN 7 (Fig. 6) has a similar age at 0.90 ± 0.05 Ma, indicating that the ages of all three beds are statistically indistinguishable at 2σ. This supports the idea that the fluvial–deltaic conglomerate units in both sections are at least roughly correlative and were deposited by streams flowing in the same general direction to the NNW. Both the ages from AN 1 (0.72 ± 0.01, 0.73 ± 0.02) (Table 3, Appendix A) are internally consistent and significantly younger than the dated beds at AN 7 and AN 11, indicating that the tephras bearing beds at AN 1 are stratigraphically higher within the Buri Formation.

The eruptive ages determined from the volcanic material in the Buri Formation are probably close to the depositional ages of the formation (i.e., any delays between the eruptions and deposition were brief). Three of the samples (AN 1, E97-41 from AN 1, and AN7) are from white ash beds or tephra layers that appear to be ash fall deposits (brief). Three of the samples (AN 1, E97-41 from AN 1, and AN7) are from white ash beds or tephra layers that appear to be ash fall deposits.

Table 2
Micro invertebrate fossils from the Buri Formation.

<table>
<thead>
<tr>
<th>Locality Sample interval (cm)</th>
<th>Ostracoda</th>
<th>Gastropoda</th>
<th>Foraminifera</th>
<th>Environmental interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AN 1 340</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Estuarine</td>
</tr>
<tr>
<td>AN 1 395</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 1 695</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 1 715</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 1 930</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 3 499</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 3 860</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 3 916</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 11 100–150</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Estuarine</td>
</tr>
<tr>
<td>AN 11 220–260</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 11 628–638</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Estuarine</td>
</tr>
<tr>
<td>AN 12 1437</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
<tr>
<td>AN 12 709–717</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td>Brackish to freshwater</td>
</tr>
</tbody>
</table>

NOTE: Summary of ostracodes, gastropods and foraminifers recovered from sections AN 1, AN 3, AN 11, and AN 12. Environmental interpretations are based on known modern as well as fossil occurrences (Benson and Kaesler, 1963; Bhatia, 1968; Carbonel, 1988; Henderson, 1990; Keen, 1975; Moore, 1961; Neale, 1988; Puri et al., 1969; Rosenfeld and Vesper, 1977; Schnitker, 1974; Staplin, 1963a; Staplin, 1963b; Swain and Kraft, 1975; Wagner, 1964; Whately, 1983). Table summarizes number of individuals recovered and not percentage.
Table 3
Summary of single-crystal laser-fusion \(^{40}\text{Ar}/^{39}\text{Ar}\) results from Buri tephra sanidines.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Collector</th>
<th>Location</th>
<th>Isochron age (\text{MSWD} \pm 2\sigma)</th>
<th>(^{40}\text{Ar}/^{39}\text{Ar} \pm 2\sigma)</th>
<th>Age (Ma) (\pm 2\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E97-41</td>
<td>RCW</td>
<td>AN 1(^a)</td>
<td>9(^a) 1.8</td>
<td>308 ± 3</td>
<td>0.73 ± 0.02</td>
</tr>
<tr>
<td>E97-40a</td>
<td>RCW</td>
<td>AN 1(^b)</td>
<td>18(^b) 0.8</td>
<td>309 ± 2</td>
<td>0.72 ± 0.01</td>
</tr>
<tr>
<td>AN 7</td>
<td>RTH/BNG</td>
<td>AN 7, 10.65–11.15 m(^c)</td>
<td>13(^c) 0.6</td>
<td>290 ± 20</td>
<td>0.90 ± 0.05</td>
</tr>
<tr>
<td>AN 11 260–570</td>
<td>RTH/BNG</td>
<td>AN 11, 2.6–5.7 m(^d)</td>
<td>16(^d) 0.4</td>
<td>298 ± 14</td>
<td>0.91 ± 0.04</td>
</tr>
<tr>
<td>E97-50</td>
<td>RCW</td>
<td>AN 11, 8.3 m(^e)</td>
<td>30(^e) 1.8</td>
<td>318 ± 3</td>
<td>0.86 ± 0.01</td>
</tr>
</tbody>
</table>

Analytical and age calculation parameters are detailed in Appendix A. Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 28.02 Ma (Renne et al., 1998).

Notes:
- Location details:
  - \(^a\) Ash bed (tephra layer) just east of AN 1, top of section just below ARL.
  - \(^b\) Ash bed (tephra layer) 15 cm below E97-41.
  - \(^c\) Ash bed (tephra layer) (Fig. 8).
  - \(^d\) Ash, pillow, composite section (Fig. 5).
  - \(^e\) Ash and pumice bed (Fig. 5).

4.4. Abdur Reef Limestone

4.4.1. Age and distribution

The Abdur Reef Limestone (ARL) defined and dated by Walter et al. (2000) is the remnant of a shallow marine reef deposited during the last glacial sea level high stand (Oxygen isotope stage 5e) (Table 1). An average date of 125 ± 7 ka from coral samples was determined using U–Th mass spectrometry methods (Walter et al., 2000). The ARL forms the relatively flat-lying reef terrace deposit extending the full length of the study area from Abdur South to Abdur North (Fig. 4). It overlies unconformably the Buri Formation and it onlaps the margins of the Abdur Volcanic Complex to the east. The area has been uplifted and tilted slightly to the west. The ARL consists of a basal transgressive lag deposit overlain by as much as 11 m of limestone with mollusks, echinoderms, bioclastic sands and corals. It contains abundant artifacts consisting of both Acheulian-type bifacial hand axes and cores and Middle Stone Age (MSA)-type obsidian flakes and blades. Details of the stratigraphy and palaeoenvironment and a depositional model for the ARL were presented recently by Bruggemann et al. (2004) and only a summary of these observations are repeated here.

4.4.2. Stratigraphy and depositional model

Stratigraphic details of the ARL were recorded at 25 sections throughout the area at AN 1–11, AC 1, and AS 2 (Figs. 4 and 10) (Bruggemann et al., 2004). For convenience of presentation and discussion the sections were combined into seven transects, A–G, five at Abdur North and one each at Abdur Central and Abdur South.
(Figs. 4 and 10). Facies characteristics, the lateral and vertical distributions of facies, the dominant fossil types, thicknesses, elevations above sea level, and the presence of stone tools are summarized on the sections shown in Fig. 10 (Bruggemann et al., 2004).

The ARL represents a complex marine reef terrace sequence. Erosional surfaces indicative of interrupted sedimentation are locally observed at two levels at Abdur North (e.g., transect B, AN 14, Fig. 10). These surfaces allow the subdivision of the complex at Abdur North into three subunits, named 5e1, 5e2 and 5e3, representing different stages of the marine isotope stage 5e sea level highstand (transects B, D, and E, Fig. 10, Bruggemann et al., 2004).

A conglomerate and coarse sandstone deposit up to 0.5 m thick is present everywhere at the base of subunit 5e1 (Figs. 7, 10 and 11a, b), except locally over topographic highs on the underlying erosional surface (Fig. 9). The conglomerate consists mainly of reworked limestone and volcanic clasts (Fig. 11a) locally derived from the underlying Buri Formation and adjacent Abdur Volcanics, plus minor

---

**Fig. 10.** Facies and stratigraphy of the ARL from measured sections organized along transects A–F (Fig. 4 for locations). Subunits 5e1, 5e2 and 5e3 are defined on the basis of depositional discontinuities or hardgrounds (Hg), mainly at AN 14, transect B. Locations of in situ artifacts are noted. (from Bruggemann et al., 2004).
amounts of quartz and metamorphic rocks from more distal basement sources. This basal conglomerate unit is interpreted as a lag gravel, deposited during the initial transgression of the 5e sea level highstand, where wave energy winnowed away the finer particles. Large oysters, often in growth position, commonly occur in this gravel deposit (Fig. 11b; Fig. 2d in Walter et al., 2000). Bifacial stone tools also occur in situ (Fig. 11b) or eroded out next to the outcrops of the lag deposits. It is postulated that the oysters provided an easily accessible food source for the early inhabitants of this shoreline of the Gulf of Zula along the western Buri Peninsula.

The basal lag deposits are generally overlain by finer-grained deposits that indicate a shift to deeper water conditions as the 5e sea level continued to rise (Fig. 10). No ostracodes were observed in the finer-grained parts of the ARL. An exception to the deeper water deposits is found along transect C where rudstone overlies directly the lag deposits, probably reflecting higher energy conditions along the more seaward margins of the shallow coastal shelf (Fig. 10). The rudstone consists mostly of bivalves, gastropods, echinoderms and crustaceans (Fig. 9). Corals are generally absent or sparse from this area (Figs. 9 and 10). Abundant bifacial stone tools also occur within or eroded out of this part of subunit 5e1 (Figs. 10 and 11c; Fig. 2c in Walter et al., 2000).

The upper part of subunit 5e1 at AN represents a shoaling upward cycle, characterized by a transition up into rudstones and coralstones (Fig. 10). Corals proliferated in this upper part and formed a site of nucleation for fringing reefs at several places (e.g., at AN 14b, Figs. 10 and 12a). The reef deposits are dominated by branching Goniopora species (e.g., at AN 14b, Figs. 10 and 12a; and at AN 10a, AC 1a–b, and AS2a, Fig. 10). Locally a flat-lying, burrowed hardground occurs at the top of subunit 5e1 consisting of fine-grained limestone (Fig. 12a, b). This hardground indicates interrupted sedimentation, probably due to a temporary drop in sea level during the 5e highstand (transect B, AN 14, Fig. 10; Fig. 12a, b).

During the rise of sea level represented by subunit 5e2, conditions for reef growth apparently improved and more extensive coral reef tracts developed quickly along the margin forming subunit 5e2 (e.g., AN 12b, AN 14a–c, AN 8, AN 7a, AN 10b, Fig. 10; Fig. 12b). The coral reef tract is thickest in the northern part of Abdur North near AN 14.
The reef tract at Abdur North forms a topographic feature well expressed on aerial photographs, which is shown by a dashed line in Fig. 4. A second sea level event during the 5e highstand is suggested by another apparent break in sedimentation toward the top of subunit 5e2, separating it from localized patch-reef buildups near AN 14 designated as subunit 5e3 (AN 14b, Fig. 10).

The ARL also is widely exposed at both Abdur Central and Abdur South (Fig. 4). At Abdur Central the ARL lies unconformably on an extensive hardground that dips seaward 4–6° and again contains a basal lag conglomerate similar to Abdur North (transect F, Fig. 10; Fig. 13). Here a gently-dipping coral reef flat thinning landward and laps onto first a hardground and then the adjacent volcanics, changing facies from reef tract to beach grainstones (transect F, Fig. 10; Fig. 11d). In a seaward direction the ARL thickens from about 2 m to over 4 m, where the unit is characterized by a coarsening and shallowing upward sequence (transect F, Fig. 10; Fig. 13). Here there is a depositional break in slope from reef flat to fore reef slope (Fig. 13). Lying below the hardground/unconformity is an older reef deposit of uncertain age (OR, Fig. 13), which probably was deposited during the previous interglacial highstand, isotopic stage 7. Such older reef sequences are not observed below the ARL at Abdur North, where the Buri Formation is exposed and underlies the ARL. Abdur North may have remained a high-standing fault block during earlier Pleistocene highstand cycles.

At Abdur South the ARL also lies unconformably on a seaward-dipping hardground and contains a basal lag deposit (transect G, Fig. 10). As at Abdur Central it thins landward onto the hardground unconformity. It then onlaps the adjacent Abdur volcanics, where it changes facies into cross-bedded beach deposits (transect G, Fig. 10). It thickens seaward to over 6 m. As at AC the ARL overlies an older reef deposit (OR) representing an older sea level highstand. Both reef deposits onlap and are younger than the volcanic flows here, which were dated to 0.44 Ma (Section 4.3). No tools were observed in the older reef deposits here or at Abdur Central.

At all sections of the Abdur Reef Limestone at Abdur, the reef facies passes laterally into a beach facies where it onlaps the Abdur Volcanics (Fig. 10). The beach facies consists of coarse calcareous sandstone and local conglomerate consisting of reworked shell fragments and volcanic fragments. At Abdur Central and Abdur South, the beach facies is a cross-bedded sandstone, and often the morphology and relief of the beach itself is preserved (transects F and G, Fig. 10). The beach facies commonly contains the remains of large land mammals (e.g., Fig. 10 — AN 13c, AN 7b, and AC 1c).

4.4.3. Stone tools in the ARL

Several hundred stone tools were found in situ (Figs. 10 and 11b, c, d) or near in situ (weathered out next to outcrop) within several facies and stratigraphic intervals of the ARL. The tools appear to represent two tool kits. One consists of bifacial hand axes and cores of the Acheulian industry (Figs. 11b, c). These typically are associated with the oyster beds within the basal transgressive lag deposits of subunit 5e1 (Fig. 11b; Fig. 2d in Walter et al., 2000), but they are also found higher up in the lower half of 5e1 (Figs. 10 and 11c; Fig. 2c in Walter et al., 2000). So far, the hand axes have only been found at Abdur North. They consist mostly of fine-grained volcanic rocks (Fig. 11c), but some are made of obsidian (Fig. 11b; Fig. 2d in Walter et al., 2000), chert, or quartz (Fig. 2c in Walter et al., 2000).

The second tool kit consists of Middle Stone Age-type obsidian flakes and blades. These occur in abundance in all three districts of Abdur, mainly in nearshore and beach facies (Figs. 10 and 11d).
alongside debris from marine invertebrates and large land mammals (Fig. 10, AN 7b, AN 13c, and AC 1c).

The presence of two tool kits with different stratigraphic contexts provides clues to the human foraging activities about 125 ka years ago. During the initial transgression of the sea it is postulated that humans collected large, heavy-shelled oysters in the shallow water, and used the bifacial tools and cores to harvest and break the oysters open. During the later phases of deposition of the ARL, potential food types changed. Large oysters were no longer abundant, and they were replaced by other mollusks and crustaceans. It is further postulated, therefore, that the smaller tools (flakes and blades) could have been used in a shoreline/beach environment to extract the edible parts.

The Abdur Archaeological Site represents a late example of an apparently long Acheulian/MSA transition, which is seen as a benchmark for early modern human behavior (e.g., McBrearty and Brooks, 2000). In addition, this site, to date, represents one of the earliest well-dated examples of early human adaptation to marine food resources (Walter et al., 2000). This site and other nearby sites may provide a key to understanding the evolution of early humans and their dispersal out of Africa, possibly along littoral routes (Walter et al., 2000; Stringer, 2000). The presence of a few stone tools, possibly MSA in character, in the Buri Formation, however, suggests much earlier occupations of coastal environments could have taken place in this same area.

4.5. Structure

As discussed above under Regional Geologic Setting, the Abdur study area sits at the north end of the Zula-Alid-Bada (ZAB) graben (Bruggemann et al., 2004), which extends north–northwest from Bada through the Alid Volcano to the Gulf of Zula (Fig. 1). At Abdur the eastern fault zone bordering the graben splays out into a series of strands along the east coast of the Gulf of Zula (Fig. 3). The fault strands offset the AVC behind Abdur and form the rugged coastline south of Abdur (Fig. 3). Here the faults generally form a series of blocks down-dropped to the west into the Gulf of Zula. The linear coastline at Abdur and further north also appears to be controlled by faults (Figs. 1 and 3).
The satellite image of the Abdur area (Fig. 3), plus a generalized geologic map of the Abdur area (Fig. 14) shows linear features seen on aerial photographs that are interpreted to be faults offsetting the ARL. For example, several north-trending features separate Abdur South from Abdur Central and Abdur Central from Abdur North (Fig. 3). Another prominent feature, bounds Abdur North on the east (Figs. 3 and 14). In addition, several small faults were mapped directly during fieldwork in the Abdur Central and Abdur North districts based on small offsets in the Buri Formation and the overlying Abdur Reef Limestones, as well as zones of steeply dipping beds in the Buri Formation (Fig. 14). For example, at Abdur Central a zone of steeper dips in the ARL and a linear NNE trending gully defines a zone of deformation. This zone projects north to a zone of steeper dips (30°) at a small patch of ARL along the boundary with the volcanic rocks (Fig. 14). This zone projects further north into small flexures in the ARL in the Abdur North district (Fig. 14).

A prominent NW–trending fault cuts the Buri Formation at AN 11, dropping the north side down about 3 m (Figs. 7 and 14). Just southeast across the gully from this outcrop the Buri beds are vertical along the southeast projection of this fault (Fig. 14), and another deformed zone apparently occurs further southeast along this fault near AN 12 (Fig. 14). Another small flexure dropping the ARL down to the NW occurs just NW of AN2 and AN1, and it may project NE to where a fault is exposed along the north side of the Missi River (Fig. 14). Other fault zones may control the trend of the volcanic margin north of the Missi River, but they are not designated as such on Fig. 14. Along the north side of the river a small outcrop of the Buri Formation is locally highly deformed with dips up to 30–36° (Fig. 14), and the beds are hardened and mineralized with veins of calcite. The mineralization could be due to escaping fluids along the intersection of unrecognized fault zones in this area.

The Buri Formation is gently deformed over much of Abdur North, and highly deformed locally along presumed fault zones. Fig. 14 shows measured strike and dips at selected locations in Abdur North, and the dips are quite variable. North of the Missi River dips range from horizontal to 4–11° to the east–southeast, except for the highly deformed beds mentioned above. Near AN11, the beds dip 8–13° to the northwest, west and southwest, while in the AN3–AN8 area the beds dip gently to the east, northeast, and north. In the southeast part of Abdur North along the border fault zone near AN 7b, the beds dip consistently to the northeast from 7 to 15° forming a continuous section over 50 m thick outcropping along a local road (Fig. 14).

The top of the ARL, which presumably was deposited horizontally, now dips from 1 to 3° in a seaward direction throughout the Abdur area (Fig. 14). Some of the dip represents original dip along a reef front (Bruggemann et al., 2004), but some of it represents gentle tilting of the ARL in a seaward direction. At Abdur South and Central, the hardground below the ARL dips seaward about 5° (Fig. 13).

The ARL also appears to be uplifted. Along the front of the exposed reef tract at AN 1–4, the top of the ARL averages about 10.5 m above sea level (transect C, Fig. 10). Assuming 1) an average sea level high during the Stage 5e interglacial of about 5.5 m above current sea level (e.g., Bloom et al., 1974; Harmon et al., 1983; Chen et al., 1991; Ku et al., 1974), and 2) the top of the reef tract at this location was deposited in about 3.5 m water depth (Bruggemann et al., 2004), then the top of the ARL at these locations has been uplifted about 8–9 m. About 400 m inland at AN 13, 14, 8, 7, 10 and 9, the top of the reef tract characterized by coral reefs averages about 19.5 m above sea level (Fig. 10). Assuming these beds were deposited near the sea level, they now have been uplifted about 14–15 m, thus giving the seaward tilt to the ARL. Given the age of 125 ka +/− 7 for the ARL, this represents uplift rates ranging from about 0.053 to 0.12 mm/yr. The hinge line for this uplift and seaward tilting is projected to be just offshore of the present shoreline.

These rates at Abdur North are significant but not rapid. They are similar to rates in Haiti on the St. Marc’s peninsula (0.14 mm/yr), although slower and faster rates also occur on Haiti (Mann et al., 1995). They are slightly lower than average rates observed at Barbados (0.2–0.34 mm/yr) (Taylor and Mann, 1991) and significantly lower than the rapid rates observed on the Huon Peninsula of Papua New Guinea with uplift rates as high as 3.4 mm/yr (Chappell, 1974). In comparison to most coastlines of the world, the 0.12 mm/yr rate is a moderately rapid rate that would result in significant net tectonic motion and shoreline migration if it persisted on the Ma time scale.

Further south at Abdur South, the ARL also tilts seaward. At the contact with the volcanics the reef has been uplifted to about 12 m (transect G, Fig. 10). Outcrops located just above the current shoreline probably are still near the original depositional elevation, suggesting that the ARL at the shoreline here probably is just at the hinge line.

This uplift and tilting at the Abdur Archaeological Site could be related both to the local and the regional faultings observed (Figs. 1, 3 and 14). These tectonic movements are probably related to the regional ongoing transfer of continental rifting and seafloor spreading from the Red Sea Rift over to the northern Danakil Depression (Fig. 2). Local volcanic activity in the area related to the emplacement of the Abdur Volcanic Complex also could be playing a major role in the tectonics.

5. Regional distribution of rocks equivalent to Buri Formation and ARL

5.1. Northeast of Abdur

Rocks believed to be the equivalent of the Buri Formation occur in an extensive outcrop area about 1–2 km inland and NNE of the Abdur
Site on the opposite side of the N–S volcanic ridge forming the Abdur Volcanic Complex (Fig. 3). Reconnaissance during 1997 revealed rocks compositionally similar to the Buri Formation at Abdur (mudstone, siltstone, sandstone, conglomerate and limestones).

An exception is just northeast of the Abdur Site along the main road to the east across the Buri Peninsula (Fig. 3). Here there is an approximately 10–20 m section of cyclic carbonates, ranging from high-energy grainstones to fine-grained, wavy-laminated limestones indicative of tidal flat environments. Similar rocks were not observed at Abdur North. Just to the north of the limestones the lithologies change into fine-grained massive sandstones, while further north the section is composed of fine-grained siliciclastic beds lying between two limestone beds. The siliciclastics are interpreted to be fluvial-deltaic based partly on the occurrence of a prominent bed containing a mixture of vertebrate fossils, including freshwater fish and terrestrial mammals. These rocks suggest a similar estuarine environment as at Abdur. Also of significance is the discovery of a primitive hand axe at this location, which is larger than and more crudely made than the hand axes found at Abdur in the ARL.

5.2. Coastal area north of Abdur

A reconnaissance trip in a small University of Asmara research vessel was taken in 2001 along the shoreline for about 18 km north of...
the Abdur Site. Almost continuous reef terraces can be followed along the shoreline just north of Abdur (Fig. 3) and further north. They are assumed to be equivalent to the 5e terraces at Abdur, although there might also be older terraces present. The terraces occur at various elevations. Going north from Abdur they drop gently to about sea level at Melita Bay (prominent bay with spit) (Fig. 1). North of Melita Bay the reef terraces rise again toward a prominent hill known locally as Mt. Aleite, about 20 km north of Abdur (dark area along coast just west of MA, Fig. 1).

Along this coastline between Abdur and Mt. Aleite, outcrops of Buri-like sediments also occur and are overlapped by the reef terraces. At the base of Mt. Aleite there is exposed a thick uplifted section of sedimentary rocks (estimated over 50 m thick) capped by basaltic flows that form Mt. Aleite and the adjacent higher ridges. All the sedimentary rocks here and along the coast are tentatively correlated with the Buri Formation at Abdur, based on lithologic similarities and the almost continuous outcrop belt between Mt. Aleite and Abdur.

The thick sedimentary section outcropping just below Mt. Aleite consists of massive to crudely bedded mudstones, siltstones, sandstones and sandy conglomerates with metamorphic and quartz fragments. The volcanic flows forming Mt. Aleite and adjacent highlands appear to overlie stratigraphically the sedimentary section. Along the north end of the outcrop area the reef terraces onlap the sedimentary section and rise from near sea level up to 20–30 m above sea level in a series of steps, suggesting active uplift along the shoreline, similar to that observed at Abdur. A few bifacial hand tools were found here associated with the reef terraces. Dark rocks at the shoreline along the north end of the outcrop area are metamorphic rocks forming part of the basement complex underlying the Buri Peninsula. Similar rocks outcrop at the north end of the Buri Peninsula on Dissei Island (Fig. 1). Earlier reconnaissance trips along the coast north of Mt. Aleite by JHB observed continuous 5e equivalent reef terraces all the way to the northwest tip of the Buri Peninsula and on Hoda Island. Here the terraces “wobble” in elevation along the shoreline, reflecting varying amounts of uplift and subsidence.

A prominent resistant outcrop along the beach just southwest of Mt. Aleite exposes 9 m of multiple basalt flow units overlain by 5 m of sedimentary rocks and then almost 2 m of reef terrace. The basalts are vesicular and have polygonal jointing suggesting the possibility of pillow basalts deposited in water. The overlying sedimentary rocks consist of a basal conglomerate containing metamorphic rocks and quartz (up to 10–15 cm) overlain by fine- to coarse-grained sandstone. They are part of the Buri Formation exposed here. The overlying reef terrace deposit has a basalt lag gravel with metamorphic rocks, quartz and volcanic rocks overlain by a bed of calcareous sand with scattered shell fragments. This reef terrace is similar to the ARL at Abdur and is tentatively correlated with it based on the almost continuous exposures along the coast between here and Abdur.

Extensive reef terraces also occur in the Dahlak Islands north of the Buri Peninsula (Nir, 1971; Carbome et al., 1998), and raised reef terraces have been observed by JHB along the north and northeast end of Mt. Ghedem, a large uplifted basement block across the Gulf of Zula from the Buri Peninsula and south of Massawa (MC, Fig. 1).

5.3. Buri Peninsula

A one-day reconnaissance trip during 2001 was taken to the central Buri Peninsula in the area east of a large restricted evaporative lake basin or estuary named Lake Bordella (dark area in Fig. 1 in the center of the Buri Peninsula). The south end of the basin is characterized by an evaporative pan, while the north end is a flooded lake or an estuary. There appears to be an inlet to the sea at the north end of this basin, which apparently allows sea water periodically to flood the basin and evaporate. The flat high ground surrounding this basin is capped by an extensive uplifted reef terrace, possibly equivalent to the 5e ARL at Abdur. Sighting up from the evaporative shoreline using a Brunton compass puts the top of the highest terrace at about 12 m, indicating about 6–7 m or more of uplift. Lying below this upper terrace and rimming the inside of this basin are a series of lower and younger terraces, which probably were formed at successive shorelines as the area uplifted and the water level dropped. A long linear northwest-trending outcrop of basement rocks borders the terraces on the northeast (see linear feature in Fig. 1), comprised of light-colored reddish metamorphosed felsic volcanic rocks (basement rocks). This appears to be the north end of another long linear fault zone that extends from the northern Danakil northwest across the Buri Peninsula to the Red Sea coast, similar and parallel to the Zula-Alid-Bada graben to the west (Fig. 1). In gullies along the boundary between the upper terrace and the basement rocks, a few primitive stone tools were observed (bifacial hand axes).

5.4. Alid and area to southwest

Near the Alid Volcano to the south (Fig. 1), extensive outcrops of fluvial- to shallow-marine sedimentary rocks have been reported (Duffield et al., 1997). They appear to underlie the young volcanic rocks there, and possibly are equivalent to the Buri Formation. In addition, extensive fluvial, lacustrine, and fluvial–deltaic deposits occur south of the Alid Volcano in the Buia Region along the Mahable and Dandero drainages. They contain abundant stone tool artifacts. These areas were visited briefly during the 1998 field season and reported on by Ghebretenase (2002).

Abbate et al. (1998) reported the discovery of a human skull in this same area dated to ~1 Ma. An Italian team has been working in this area since 1996, and recently they have described their results in detail, summarizing the sediments, stratigraphy, magnetostratigraphy, fossils and tools from this region (Abbate et al., 2004; plus 7 additional accompanying papers). These fluvial, fluvial–deltaic and lacustrine rocks are probably equivalent to the Buri Formation at Abdur, as suggested by similar lithologies and similar Early to Middle Pleistocene age dates ranging from ~0.7 to 0.9 Ma at Abdur and ~1.0 Ma at Buia (Abbate et al., 2004).

5.5. Early–Middle Pleistocene paleogeography

The Early to Middle Pleistocene rocks (boundary at 0.78 Ma, Gradstein et al., 2004) apparently extended from the Mahable–Dandero area south of Alid north to the Buri Peninsula. This suggests that during this time moderate to low gradient rivers flowed off the emerging highlands to the west onto a lowland area characterized by coastal lakes and restricted estuaries along the Red Sea coast. Some rivers drained low-relief volcanic and basement highlands on the Buri Peninsula, as suggested by the abundant volcanic and metamorphic rocks in the Buri Formation at Abdur and the outcrops of basement observed nearby. Southeast of Alid an arm of the Red Sea probably extended into the northern Danakil Depression, as suggested by the thick evaporites and carbonates there, although these deposits could be younger.

The setting of the area in the Early to Middle Pleistocene, therefore, is believed to have been much simpler and less rugged than observed today. The Eritrean Escarpment to west may have just been emerging and may not have been such an imposing feature as it is today. The young ZAB graben probably had not been initiated by this time, and most of the volcanic highlands in the area probably were also not present, as the volcanics all seem to be quite fresh and young. The present setting (Fig. 1), therefore, apparently has been influenced, modified and controlled extensively by the young active tectonics and the rhyolitic/basaltic volcanism, as rifting and sea floor spreading is transferring from the southern Red Sea into the northern Danakil in this area of overlapping spreading centers (Fig. 2).
6. Conclusions

The Abdur Archaeological Site, located along the southern Red Sea coast of Eritrea, occurs along a potential migration route for early man out of Africa. It has become an important archaeological site for studying early human occupation of coastal marine environments and the early utilization of marine resources. This paper reports on the geologic setting of this important site, further defining three stratigraphic units in the area:

(1) The Buri Formation, with Abdur North as the type section, is defined as a sequence of mudstones to conglomerates and limestones up to 50 m thick deposited in estuarine and fluvial–deltaic environments. Ar–Ar dating of pumice and tephras put the time of deposition from about 0.91 to 0.72 Ma. These rocks were faulted, folded and eroded prior to deposition of the overlying Abdur Reef Limestone (ARL).

(2) The Abdur Volcanic Complex (AVC) is a small basaltic shield complex that forms the highlands along the eastern part of the site. Locally the lava flows overlie the Buri Formation and are onlapped by the ARL. Ar–Ar ages from samples of basalts collected in the area, however, indicate a long period of activity, ranging from 2.12 to 0.17 Ma.

(3) The Abdur Reef Complex (ARL), previously dated to 125 ka, is a shallow marine terrace deposit formed during the last glacial highstand (isotope stage 5e). It consists of a basal transgressive lag deposit containing abundant large oysters, which is overlain by shallow upward buildups of mollusks, echinoderms, bioclastic sandstones and corals up to 11 m thick. Locally it can be subdivided into three subunits related to different stages of the stage 5e sea level high stand.

Numerous stone tools in the ARL fall into two tool kits, bifacial hand axes of the Acheulian industry, found mainly in the lower part of the ARL, and Middle Stone Age-type obsidian flakes and blades, found mainly in the upper part and in beach facies. Their distribution suggests foraging activities of early humans varied with environmental setting. These tools represent some of the earliest-well-documented evidence for human occupation of coastal marine environments. Implied here is that these early humans utilized the marine resources available as a food source.

Of additional significance is the occurrence of stone tools in the Buri Formation. Although not abundant, the presence of crude stone tools (obsidian flakes and blades and one occurrence of a bifacial hand axe) suggests an even earlier occupation of coastal environments. Additional work on the Buri Formation at Abdur and surrounding areas is needed to better document this important find.

The Buri Formation has been gently folded and faulted prior to deposition of the ARL, but with dips locally up to 36° and vertical along fault zones. Dipping resistant limestone beds form topographic highs on the angular unconformity between the Buri Formation and the overlying ARL. The ARL has been uplifted and tilted 1–5° seaward, with uplift rates at Abdur North ranging from about 0.053 to 0.12 mm/yr. These rates are significant but not rapid. Numerous faults cut the area, mainly trending N–NW parallel to the regional fault system that forms the eastern part of the Zula-Ald-Bada graben system. A few minor faults offset the ARL indicating recent tectonic activity along this zone.

Rocks of similar age also occur to the south of Alid and more inland in the Buia region. These rocks were deposited mostly in lacustrine, fluvial – deltaic, and fluvial settings, suggesting more proximal environments closer to the escarpment. These rocks at Abdur and Buia suggest that the entire area west of the escarpment was characterized by rivers flowing east off the emerging highlands onto a broad lowland characterized by coastal lakes and estuaries along the Red Sea coast during the Early to Middle Pleistocene. Some streams flowed locally off low-relief basement and volcanic centers in the lowlands. This suggests a simpler and less rugged setting than is seen here today. The setting today is the result of younger tectonics and rhyolitic and basaltic volcanism occurring in an active setting representing the transfer of rifting and spreading from the Red Sea Rift to the northern Danakil Depression and the Afar.

Acknowledgments

Permission for field work was granted by the Department of Mines, Eritrean Ministry of Mines, Energy and Water Resources and the University of Asmara. We are grateful to Alem Kidrebah, Michael Abraha, and Tesfamichael Keleta of the Department of Mines for their assistance and support. We further thank Mike Tesfaye for logistical arrangements and Nasser Mohammed for helping in the field. Financial support was provided by grants from the Institute for Human Origins, the Anadarko Petroleum Company, the Royal Ontario Museum, the University of Toronto and the National Science Foundation (EAR-9725405 and several smaller travel grants). We thank Mohammed Abdelsalam for providing satellite images of the study area, and Fred Taylor for input on former sea level highstands and uplift rates. We are grateful to Dick Visser for early work on the figures. We especially thank Michelle Bowen for her great work on and compilation of all of the illustrations during the final phases of the paper. We appreciate very much the help of O. Frank Huffman, John Kappelmann, and Francis Brown for their extremely helpful and critical reviews, which vastly improved the manuscript. We are extremely grateful for the last minute help of Magee Mooney, who corrected and translated all the figures into usable formats for publication. We dedicate this paper in honor of Hugues Faure and all the early work he and his co-workers did in the region. This is UTIG Contribution # 2270.

Appendix A. Supplementary 40Ar/39Ar data to accompany this article

These supplementary data can be found in the online version, at doi:10.1016/j.gloplacha.2010.01.017.

References


Bunger, M.A.C., Debrettsen, T., Woldjeskog, L., 1998. New developments in the pre-


