Stratigraphy, palaeoenvironments and model for the deposition of the Abdur Reef Limestone: context for an important archaeological site from the last interglacial on the Red Sea coast of Eritrea

J. Henrich Bruggemann¹,²,*, Richard T. Buffler³, Mireille M.M. Guillaume⁴, Robert C. Walter⁵, Rudo von Cosel⁶, Berhane N. Ghebretensae⁷, Seife M. Berhe⁸

¹ Department of Marine Biology, University of Groningen, P.O. Box 14, 9750 AA Haren, The Netherlands
² Département des Milieux et Peuplements Aquatiques, BOME UMR 5178 CNRS/UPMC/ Muséum National d'Histoire Naturelle, 61 Rue Buffon, 75005 Paris, France
³ Institute for Geophysics, University of Texas, Austin, TX 78712, USA
⁴ Department of Geosciences, Franklin and Marshall College, Lancaster, PA 17604-3003, USA
⁵ Département de Systématique et Evolution, USM 0602, Muséum National d'Histoire Naturelle, 55 Rue Buffon, 75005 Paris, France
⁶ Department of Mines, Ministry of Energy and Mines, P.O. Box 272, Asmara, Eritrea
⁷ African Minerals Inc., P.O. Box 5284, Asmara, Eritrea

Received 23 September 2002; received in revised form 7 May 2003; accepted 18 September 2003

Abstract

Stone tools discovered within uplifted marine terraces along the Red Sea coast of Eritrea at the Abdur Archaeological Site, dated to 125 ± 7 ka (the last interglacial, marine isotope stage 5e), show that early humans occupied coastal areas by this time [Walter et al. (2000) Nature 405, 65-69]. In the present paper the stratigraphy, facies types and faunal composition from 25 measured sections of the tool-bearing Abdur Reef Limestone (ARL) are documented in detail and interpreted to provide a palaeoenvironmental context for the stone artefacts and a model for the deposition of the ARL. The ARL represents a complex marine terrace sequence. Erosional surfaces indicative of interrupted sedimentation are locally observed at two levels within the ARL. They subdivide the complex into three subunits, named 5e₁, 5e₂, and 5e₃, representing different stages of the marine isotope stage 5e sea level highstand, comprising six depositional phases (I–VI) of the ARL. Subunit 5e₁ begins with the initial transgression of the 5e sea level highstand leading to the deposition of widespread lag gravels on which rich oyster beds developed in shallow water (phase I). It further records rapid deepening accompanied by the deposition of low-energy carbonates with scarce corals (phase II), and later shoaling characterised by local development of a fringing reef tract in a sedimented environment (phase III). Subunit 5e₁ is capped locally by a burrowed hardground that is laterally equivalent to depositional discontinuities, interpreted as caused by a globally recognised mid-5e sea level low stand (phase IV).
Extensive reef build-up in response to sea level rise and improved conditions for coral growth characterises subunit 5e2 (phase V). A possible second sea level drop during the 5e highstand is inferred from the oyster-encrusted upper surface of subunit 5e2. Subunit 5e3 encompasses restricted coral patches that developed on the upper surface of the underlying subunit during the last stage of the 5e marine high stand (phase VI). Two different toolkits are found in the ARL. One consists of bifacial hand axes and cores of the Acheulian industry, typically associated with the oyster beds encrusted on the transgressive lag deposits. The other consists of Middle Stone Age (MSA)-type obsidian flakes and blades, mainly found in the nearshore and beach environments alongside debris from marine invertebrates and large land mammals. The distribution of these tools suggests that foraging activities of early humans varied with environmental setting. The Abdur Archaeological Site represents a late example of the Acheulian/MSA transition, seen as a benchmark for early modern human behaviour, and is, to date, the earliest well-dated example of early human adaptation to marine food resources.

© 2003 Elsevier B.V. All rights reserved.

Keywords: Pleistocene; coral reefs; sea level change; human evolution; stone tools; palaeoecology

1. Introduction

Stone tools within emerged reef terraces on the western shoreline of the Buri Peninsula, Red Sea coast of Eritrea, dated to the last interglacial, 125 ± 7 ka, are the earliest well-dated evidence for human occupation of coastal marine environments (Walter et al., 2000). This archaeological site, termed the Abdur Archaeological Site, is located ca. 60 km southeast of the port town of Massawa near the village of Abdur on the eastern edge of the Gulf of Zula (Fig. 1).

Numerous bifacial hand axes of the Acheulian tradition were found in situ along with obsidian flakes and blades of the early Middle Stone Age (MSA) tradition in various facies of a complex of Pleistocene marine terraces, which we previously named the Abdur Reef Limestone (ARL) (Walter et al., 2000). The discovery of MSA artefacts within last interglacial reef terraces is unique and sheds important new light on human adaptive strategies and migration paths out of Africa (Stringer, 2000; Weyhenmeyer, 2000; Faure et al., 2002). Climatically driven human adaptations to coastal marine environments may have led to continental shores becoming routes for dispersal out of Africa and migration along the shorelines of Arabia into southeast Asia during sea level low stands (Stringer, 2000; Walter et al., 2000).

Available fossil hominid evidence from East Africa (Clark, 1988) and recent mitochondrial DNA studies (Ingman et al., 2000) predict an origin for anatomically modern humans in sub-Saharan Africa at 170 ± 50 ka ago. Hence, the Middle to Late Pleistocene is a crucial period for ultimately resolving debates about the origin and evolution of our species. This period is not well represented in the terrestrial sedimentary record of East Africa (Clark, 1988). Uplifted Pleistocene marine terraces, like those around Abdur, are a novel and untapped geological resource for the
study of human evolution and behaviour. Last interglacial (marine isotope stage, MIS, 5e) reef terraces are among the commonest landforms of the Red Sea coastline (Taviani, 1998, and references therein), while older interglacial terraces (MIS 7, 9, and 11) are exposed less frequently.

The purpose of this paper is to provide a palaeoenvironmental context for the artefacts that were discovered in the last interglacial reef terraces at Abdur. Detailed information about the stratigraphy, facies types, and faunal composition of the ARL is presented and interpreted to provide a model for the deposition of the reef terraces near Abdur during the MIS 5e sea level highstand. Furthermore, the geologic setting and distribution of different types of stone tools discovered in these terraces are discussed in the context of landscape evolution along this portion of the Red Sea coast. Such details are critical for evaluating the palaeoecological history of this important archaeological site, as well as for guiding future explorations – at Abdur and elsewhere along the coast of the Red Sea – in search of artefacts and fossils relating to the origin, evolution, and migration paths of modern humans. The geologic and structural setting of the ARL and the background of this research project are discussed in more detail by Walter et al. (2000) and Ghebretensae (2002).

2. Geology and physiography of the Abdur area

The Abdur study area lies along the northern extension of the Danakil Depression (Fig. 1). The most prominent feature is a rift graben system, the Zula-Alid-Bada graben that extends from Bada northwest to the Gulf of Zula, itself a down-dropped sediment-filled depression that is flooded by the Red Sea (Fig. 1). The Abdur Archaeological Site is located on the Buri Peninsula along the eastern shoreline of the Gulf of Zula.

The Abdur study area encompasses several uplifted marine terraces in an area of 6.5 km by 1 km (Fig. 2). On the basis of differences of stratigraphic and tectonic setting, the area is subdivided into three geographic districts: Abdur South (AS), Abdur Central (AC), and Abdur North (AN). The AN district has been studied in most detail. Here, three main stratigraphic units have been defined:

(1) the Buri Sequence, which consists of a series of marginal marine, estuarine, and fluvial sediments consisting of limestones, mudstones, sandstones, and conglomerates with ash and pumice beds. Ar–Ar dating of pumice and tephras put the time of deposition of this unit between 0.90 ± 0.04 and 0.72 ± 0.01 Ma (Ghebretensae, 2002). These layers were faulted, folded, and eroded prior to the deposition of the overlying ARL;

(2) the Abdur Volcanic Complex, a series of basalt flows that form the highlands just east of the area. Basalt samples collected from the AN area were dated at 1.27 ± 0.01 Ma, while basalts
Fig. 2. (a) Generalised geologic map of the Abdur study site showing the location of the three geographic districts (AN, AC and AS) and the three major stratigraphic units (Buri Sequence, Abdur Volcanic Complex, and ARL). Location of described sections and transects at AC and AS are indicated. (b) Enlarged map of the AN district, showing location of described sections and transects. Reef form lines represent ramps and scarps of fore reefs seen on aerial photographs of AN. The cross section is shown in Fig. 3. See Fig. 4 for section elevations.

taken from AS area were dated at 0.44 ± 0.02 Ma (Ghebretensae, 2002), indicating that the Abdur Volcanic Complex has been tectonically and magmatically active prior to, during, and after the deposition of the Buri Sequence. The Abdur volcanics overly the Buri Sequence along the eastern edge of the area and are overlain by and lapped onto by the ARL;

(3) the ARL itself, which consists of a basal transgressive lag deposit overlain by an extensive build-up of molluscs, echinoderms, bioclastic sands, and corals (Fig. 3). At AN, the ARL un-
conformably overlies the Buri Sequence and the Abdur Volcanic Complex. It is uplifted and tilted 1–2° in a seaward direction and faulted in places. The top of the terrace is now about +10 m above high tide level along the coast, and rises up to +19 m further inland (Fig. 3). At AC and AS, the top of the terrace rises from near sea level at the coast to an average of +15 m near the contact with the Abdur volcanics. The differences in elevation of the terrace between the three areas is probably due, in part, to regional NNW–SSE trending normal faults that step up, en echelon, to the northeast (Walter et al., 2000; Ghebretensae, 2002). At AC and AS, the underlying Buri Sequence is either not present or not exposed, and here the ARL overlies an older reef sequence of unknown age, but likely to represent one of the preceding sea level highstands (MIS 7, 9, or 11). The older reef sequence laps onto the Abdur volcanics, is tilted 5° in a westward direction, and is truncated by an erosional surface forming a hardground.

The ARL is the remnant of a shallow marine reef system deposited approximately 125,000 years ago (Walter et al., 2000) along the margins of volcanic highlands as well as covering large parts of the Buri Peninsula to the north of the study area during the last interglacial (personal observations by authors). Similar terraces and deposits also are observed on numerous islands of the Dahlak Archipelago (Conforto et al., 1976; Carbone et al., 1998) and are common landforms on the Red Sea coasts of Africa, from Egypt to Djibouti (e.g. Faure et al., 1980; Hoang and Taviani, 1991; Hoang et al., 1996; El-Asmar, 1997).

3. Methods and terminology

After archaeological and palaeontological discoveries were made in uplifted reef terraces near Abdur in January 1997, reconnaissance geological fieldwork was carried out then and in May 1997. More extensive geological work and collection of fossil reef fauna were conducted in January–February 1999, and in March 2001.

General descriptions of existing surface outcrops were made throughout the study area, documenting facies characteristics, the lateral and vertical distribution of facies and the dominant fossil types. Stratigraphic details of the ARL were collected from 25 sections. Thickness of sections was measured with a ruler, while elevation was determined by Brunton compass levelling relative to high tide level (measured from high-tide mark of dry algae washed on the beach; tidal range is ca. 0.8 m). Facies descriptions are based on field observations of grain size distribution, visual estimates of surface area of bioclastic elements in outcrop and faunal composition. When
present, type, material and stratigraphic context of stone tools were recorded. Sections are located along transects which have a general orientation from west to east, i.e. from the seaward margin of the terrace toward (and sometimes onto) the mainland where the ARL onlaps the volcanics (Fig. 2). In the AN district, 20 sections are described along five transects (named A to E, Fig. 2b). At AC, three sections are described (transect F) and at AS two sections are described (transect G, Fig. 2a).

For textural classification of carbonate sediments the Embry and Klovan (1971) system was used with some minor modifications. All fine-grained bioclastic sediments are named grainstones, even when they include small fragments >2 mm, such as fine gravel size. Floatstones are defined as matrix supported bioclastic sediments with >10% of outcrop surface area made of elements larger than 1 cm. Rudstones are defined as sediments dominated by such larger bioclastic elements, even if they contain minor amounts of supporting and cementing sediments. Facies dominated (>60% of outcrop surface area) by a growth fabric of in situ and in growth position skeletons of scleractinian corals are called coralstone. Coralstone growth fabrics are detailed following Insalaco (1998): the term pillarstone refers to growth fabrics dominated by upright, branching coral colonies, while mixstone includes growth fabrics constructed by a variety of coral growth forms.

Faunal inventories of the ARL are used to reconstruct palaeoenvironments, based on the present-day habitats of the species collected as fossils. Fossil corals, bivalves, gastropods, echinoderms and crustaceans were sampled from a variety of measured stratigraphic sections, selected to represent different environments during the 5e sea level highstand. In the AN district, samples were collected from section AN-13a to c (transect A), section AN-14a to c (transect B), section AN-4 (transect C), section AN-7a (transect D), and section AN-10a to c (transect E). From AC samples were collected from section AC-1a and b (transect F), and at AS from section AS-2a (transect G) (Fig. 2). The lower parts of the ARL, being easily accessible, were more intensively sampled than the upper levels. Molluscs and corals were identified with the aid of reference collections of the Muséum National d’Histoire Naturelle (MNHN) in Paris, France, and using the following references: Kilburn and Rippey (1982), Oliver (1992), and Bosch et al. (1995) for molluscs, plus Scheer and Pillai (1983), Sheppard and Sheppard (1991), and Veron (2000) for corals. Habitat preferences of identified species were taken from the references mentioned above, Harry (1985), Carriker and Gaffney (1996), Sheppard et al. (1992), and supplemented with personal observations of J.H.B., M.G., and R.v.C. in the Red Sea and other localities.

4. General stratigraphy of the ARL

The general stratigraphy and composition of the ARL can be summarised as follows. The contact between the ARL and the older sedimentary rocks is an irregular erosional surface, an angular unconformity that truncates the underlying tilted Buri Sequence in the AN district (Fig. 3) and the tilted older reef sequence at AC and AS. Throughout the study area, overlying these surfaces and at the base of the ARL, there is a distinctive 0.1–0.5 thickness deposit consisting of volcanic clasts, locally derived limestone, and here and there distally derived quartz, metamorphic rock fragments, and chert (basal cobble zone of Walter et al., 2000). These gravels are embedded in a carbonate sand matrix. The lower part of the ARL is composed of bioclastic grainstones, floatstones, and rudstones, with bivalves, gastropods, echinoderms and crustacean parts in varying proportions. Corals are scarce here (Fig. 3). Facies in this part of the ARL characteristically coarsen upward from grainstones and/or floatstones below to rudstones above. Corals are found mainly in the upper levels of the ARL. In most places they increase in abundance gradually upwards, but in the AN district abrupt upward facies changes are observed at several locations.

Erosional surfaces indicative of interrupted sedimentation are observed at two levels within the ARL at AN along transect B (Figs. 2b and 3). The lower of these discontinuity surfaces presents
itself as a burrowed marine hardground. This surface is overlain by an extensive reef build-up (Fig. 3). A second discontinuity, characterised by an oyster-encrusted surface, may exist near the upper part of the ARL where the reef terrace shows maximum vertical development. Here, this surface is overlain by restricted oval-shaped patches of in situ corals. These discontinuity surfaces are used to subdivide the ARL into three subunits, named 5e₁, 5e₂, and 5e₃, representing different stages of the MIS 5e sea level highstand (Fig. 3).

5. Transect descriptions and interpretations

Stratigraphy, lithofacies, and main faunal components of all measured sections are described along each of the seven transects. Palaeoenvironmental interpretations are also presented here. The ultimate goal is to develop a model for the depositional history and palaeoenvironmental changes of the ARL, and to provide a context for coastal occupation by early humans, their tools, and the exploitation of the nearshore marine food sources.

5.1. AN – Transect A (sections AN-13a to c)

5.1.1. Description

The northernmost transect comprises three sections (AN-13a to c) located along the southern tip of the extensive uplifted terraces north of the Misri River (Figs. 2b and 4a). The basal gravel zone has an average thickness of 0.3 m and is composed of bioclastic sand, locally derived limestone, and abundant rounded volcanic clasts and chert nodules, except at section AN-13c where the basal gravels are entirely angular volcanic clasts. Large oysters, a species attributed to the genus *Saccostrea* and presently extinct in the Red Sea, are found in growth position on the lag gravel. Giant clams (*Tridacna maxima*) occur in situ on these gravels at section AN-13c. At AN-13a and b the lag deposits are overlain by 0.7-0.8 m floatstone containing bivalves and gastropods approximately 50% by outcrop surface area in a sand matrix (lower part of subunit 5e₁). This grades upward into 1.6-2.1 m of rudstone with 80-90% molluscs, echinoderms, and crustacean parts (upper part of subunit 5e₁). At section AN-13b, a distinct 0.7 m subunit of coralstone (subunit 5e₂) overlies the rudstone, with a sharp boundary (but no hardground) separating the facies. The coralstone is a mixstone, composed of pillar-like branching corals (*Goniopora*) and massive corals (*Favia, Favites, Platygyra*) in growth position. Section AN-13c is located immediately adjacent to the volcanic flow edge. The lithofacies above the lag deposit is entirely floatstone containing broken shells and crustaceans, fining upward into bioclastic sands with some coral fragments near the top. Rounded basalt pebbles and numerous fossil vertebrate bones (hippopotamus, elephant, bovid and rhinoceros) occur throughout this section.

5.1.2. Interpretation

The basal gravel zone is interpreted as a lag deposit that formed during marine transgression when wave activity winnowed away finer particles, leaving the coarse gravels behind. Living oysters of the genus *Saccostrea* prefer intertidal and shallow subtidal hard substrates, suggesting that the oysters on the lag gravel colonised these substrates quickly after submergence and prior to further deepening and deposition of the overlying floatstones. The passing upward from floatstone to rudstone indicates shoaling. The ecology of the mollusc and echinoid species found in the floatstones and rudstones suggest soft, sandy substrate in a medium to shallow subtidal environment. The boundary seen at section AN-13b between shelly rudstone below and coralstone above is interpreted as an unlithified discontinuity surface, probably caused by a short-lived sea level drop during the transgression cycle (see Transect B for more detailed evidence). The coralstone above the boundary is part of a fringing reef system that developed in shallow water during a transgressive phase following this sea level drop. Section AN-13c represents a nearshore environment with lithofacies reminiscent of beach deposits that incorporate bioclastic components from the seaward fringing reef as well as land-derived debris, such as volcanic boulders and the bone fragments of terrestrial vertebrates.
5.2. AN – Transect B (sections AN-11, AN-14a to c, AN-12)

5.2.1. Description

This transect tracks the northern edge of the AN platform in a NW–SE direction (Figs. 2b and 4b) and comprises five sections. The best coral reef development in the study area is seen along this transect. Furthermore, two discontinuity surfaces separate three superimposed subunits. The observed stratigraphy and its correlation along this transect are key elements to unravelling the depositional history of the ARL.

The basal lag deposit is well developed everywhere (0.3–0.4 m thickness), with subrounded to rounded basaltic clasts predominating in all sections. Abundant reworked limestone derived from adjacent palaeotopographic highs in the Buri Sequence are found at section AN-11, whereas quartz and metamorphic cobbles and pebbles, presumably carried from distal sources by the adjacent Missi River, are found in the lag deposits at AN-11 and AN-12. Large oysters (Saccostrea sp.) still attached to the gravels of the lag deposit occur in several places along the transect and form rich oyster beds at sections AN-11 and AN-12 (Fig. 5a).

Limestones overlying the basal lag are grainstone and floatstone facies (subunit 5e1). At section AN-11, these thin from 3 m to 0.9 m over the upthrown side of a NW–SE trending normal fault in the Buri Sequence, accommodating pre-existing topography (see Fig. 2b of Walter et al., 2000). The top of subunit 5e1 has a widespread flat upper surface with oysters (Saccostrea sp.) and giant clams (Tridacna sp.) in growth position (e.g., AN-11, Fig. 4b). At section AN-14a the basal lags are overlain by 1.4 m coarse grainstone composed of broken shells, echinoderms, and claws of calianassid crabs. Extensive burrowing, presumably by these crustaceans, plus the presence of several mollusc species not found elsewhere in the ARL (e.g., Fulvia australis, Circe rugifera, Dentalium sp., Cerithium rueppelli, Conus textile and Bulla ampulla) suggest a sea-grass habitat. The grainstone is overlain by 1.2 m of floatstone with dominant whole shells, which ends with a sharp transition at the contact with the overlying coralstone.

Further to the SE, at section AN-14b, subunit 5e1 consists of 3.5 m of fine grainstone overlying the lag deposit, containing infrequent massive coral colonies of Favites bennettia. Upward, the grainstone grades into 0.8 m dense pillarstone formed by an extensive stand of branching Goniopora sp. (Fig. 5b). The upper parts of these corals pass vertically into 0.5 m fine grainstone with numerous large burrows (Fig. 5b). The latter were probably made by the bivalve Lutraria australis, a species that was found only in the coralstone directly above the burrows. The upper surface of the grainstone forms a smooth to slightly undulating resistant surface, which we interpret to be a marine hardground (Fig. 5b) that dips seaward of the Goniopora stand and gradually fades out (Fig. 4b). In the opposite direction, this hardground remains horizontal and distinct for over 100 m. The hardground is no longer present at section AN-14c, but here the boundary between the upper coral unit (5e2) and the mollusc-dominated floatstone (5e1) is abrupt (Fig. 4b). At section AN-12 the lag cobbles with oysters are overlain by 2.0 m of floatstone with scattered whole bivalves (5e1). The transition to the overlying subunit 5e2 is more gradual, and corals are scarce here.

At sections AN-14a through AN-14c the discontinuity surface is overlain by extensive coral rudstones and coralstones of 5e2, presenting a striking facies change from the grainstones and floatstones present below the surface (Figs. 4b and 5c). On the platform, the western edge of this subunit forms a minor scarp with diverse corals (e.g., Goniastrea retiformis, Echinopora gemmacea, Galaxea fascicularis, Plategyra lamellina) in growth position and a gently seaward-sloping ramp consisting mainly of coral debris. This geomorphologic feature runs approximately N–S across the AN terrace, and can be recognised easily in the field and on aerial photographs (see form lines on Fig. 2b). At section AN-14a the lower part of the ramp is represented by 1.6 m of coral rudstone (Fig. 4b). Subunit 5e2 reaches maximum thickness at section AN-14b. Here the hardground is overlain by 3.1 m of coralstone (>90% of surface area is coral skeletons) with varying growth fabric styles. Mixstone predomi-
nates (Fig. 4b), but is locally replaced by Gonio-
pora pillarstone near the seaward edge of this
unit. In the landward direction, dense Stylophora
pistillata pillarstone becomes the dominant
growth fabric (e.g., at section AN-14c, Fig. 5c).
Tridacna sp. occurs in growth position just under
the upper surface of this unit. Further to the SE
along the outcrop toward section AN-12, the cor-
alstone of subunit 5e2 passes into bioclastic rud-
stone with dominant bivalves and minor gastro-
pods, echinoderms and broken corals in a sandy
matrix (Fig. 4b). Abundant Saccostrea oysters are
found in growth position on the generally flat
upper surface of subunit 5e2 in several locations
(e.g., at sections AN-14b and c).

Oval-shaped patches of in situ corals of ca. 30 m
by 15 m in size and attaining 0.6 m thickness
overlie the highest levels of the subunit 5e2 at
two sites (see form lines on Fig. 2b), and are des-
ignated as subunit 5e3 (section AN-14b, Fig. 4b).
Massive corals (Goniastrea retiformis, Platygyra
lamellina) in growth position dominate its sea-
ward perimeter, which locally becomes indistin-
guishable from the scarp of the underlying reef
terrace (Fig. 5d). Corals with mixed growth forms
(Porites compressa, Goniopora sp., Galaxea fasci-
cularis) prevail along the eastern perimeter of
these patches. In contrast to the characteristically
flat upper surface of the underlying subunits, the
upper surface of subunit 5e3 is rugged (Fig. 5d).

5.2.2. Interpretation

Discontinuity surfaces observed along this tran-
sect imply that the build-up of the AN platform
occurred in stages; the facies changes across the
lower of these surfaces indicate a change in palaeo-
environment from the first to the second stage.
The setting during the first stage of the 5e trans-
gression is interpreted as follows. Oysters (Saccos-
trea sp.) developed on the gravels of the lag de-
posits upon submersion. A tabular body of soft
sediments composed of the remains of molluscs,
echinoderms, and crustaceans, developed over the
lag deposits in deeper water after sea level rise.
Mollusc species suggest that sea-grass beds oc-
curred on fine-grained sediments in slightly deeper
areas formed by depressions in the Buri Sequence
or along the sides of the Missi River valley. Cor-
als were scarce in this turbid environment, and
were restricted to species that can withstand
high sedimentation (e.g., Stylophora pistillata and
Favites bennettiae). Shoaling is indicated by the
upward coarsening of lithofacies, passing
from grainstones and floatstones gradually into
rudstones by the increasing abundance of large
clasts of contemporaneous organisms. Sedimenta-
tion catching up with sea level created shallower,
well-illuminated environments in which corals be-
came more prolific. At this stage a reef tract of
branching Goniopora sp. developed locally above
the level of the sediment bed. The various Goniopora
species recovered from the ARL are found
today in sheltered, sedimented habitats between 2
and 5 m depth, often with turbid waters.

The geomorphology and the facies of the over-
lying subunit 5e2 are clearly reefal. Initiation of
reef growth seems to have been almost instantan-
eous on the hardground, which provided a suit-
able substrate for the settlement of corals. A
fringing reef system developed of which different
reef zones are recognised. The N–S trending scarp
and coralstone in section AN-14b represent the
reef front, while the seaward sloping ramp and
coral rudstone of section AN-14a represent the
fore reef slope. The reef flat zone is represented
by extensive stands of Stylophora pistillata pillar-
stone (section AN-14c), while the mollusc-domi-
nated rudstones (section AN-12) characterise the
back reef zone.

Saccostrea oysters growing on top of subunit
5e2 suggest the presence of a second discontinuity
surface and another temporary interruption of
reef growth. Reef development resumed (5e3),
but now on a very modest scale, as suggested by
the formation of small oval-shaped coral patches
above this surface on the highest levels of the
underlying subunit 5e2.

5.3. AN – Transect C (sections AN-2, AN-1,
AN-3 to AN-6, AN-8)

5.3.1. Description

The transect includes seven sections located at
the seaward margin, SW corner, and southern
edge of the AN terrace (Figs. 2b and 4c), and
has an overall NW–SE orientation. The lag deposi-
it along transect C is 0.3–0.5 m thick, containing principally rounded cobble-sized volcanic clasts. However, the lag gravels may be absent over truncated topographic highs caused by resistant, tilted limestone beds of the Buri Sequence (e.g., section AN-3, Fig. 5e), or enriched with numerous limestone pebbles in sections adjacent to such high grounds (section AN-8). Oysters (*Saccostrea* sp.) growing on lag gravels are found in section AN-4.

At sections AN-1 through AN-6, the limestones overlying the lag deposits form a single unit (sub-unit 5e1). They consist of bioclastic floatstones and rudstones varying in thickness from 2.4 m to 1.3 m, accommodating palaeorelief of the
eroded underlying Buri sequence. Lithofacies generally coarsen upward; only in section AN-2 is this trend reversed with fine-grained floatstone occurring above rudstone. Faunal composition and grain size of the bioclastic limestones varies greatly over short distances laterally and vertically, e.g., shifting rapidly from mainly sand dollars to predominantly bivalves, and from nearly all whole shells without matrix (e.g., section AN-3, Fig. 5e) to being entirely composed of small fragments of broken shells. Corals become a significant part of the faunal assemblage only in the upper parts of this subunit, mostly as coarse debris from various species, but locally along the seaward edge of the platform as stands of *Turbinaria peltata* in growth position (e.g., at section AN-4). Fungiid corals are abundant and diverse, e.g., seven of the 12 species of Fungiidae that occur in the ARL were found in section AN-4.

At section AN-8, the bivalve dominated rudstone of 5e1 is overlain by a distinct 0.5-m-thick subunit of coral rudstone containing huge overturned massive coral colonies, designated as subunit 5e2. The facies boundary between the subunits is sharp but not lithified.

5.3.2. Interpretation

Gravels of the lag deposits are generally overlain by fine-grained limestones that coarsen upward, reflecting first deepening and later shoaling of depositional environments during 5e1. The pronounced lateral variations in faunal composition

---

![Fig. 4 (Continued).](image-url)
in the limestones of sections AN-1 through AN-4 probably reflect differences in wave energy and microhabitat related to bathymetric differences along the seaward margin of the carbonate shelf that developed over the lag gravels. However, as most of the mollusc and coral species recovered from section AN-4 characterise sandy, turbid and sheltered environments at shallow to mid depths, the general depositional setting during the deposition of 5e1 was probably of low energy. The coral rudstone overlying shelly floatstone at section AN-8 (5e2) is similar to that of section AN-14a (transect B, Fig. 4b), as projected south by the form lines across the AN platform (Fig. 2b). Hence, this facies is interpreted as representing part of the reef slope seaward of the fringing reef tract.

5.4. AN – Transect D (sections AN-7a and b)

5.4.1. Description

Transect D consist of two sections flanking a river valley that cuts across the ARL at the southern part of the AN district (Figs. 2b and 4d). The lag gravels are rounded and vary in size and composition from pebble-sized volcanic and limestone clasts at section AN-7a to cobble- and boulder-sized volcanic clasts with minor limestone and quartz at section AN-7b. At section AN-7a the limestones above the basal lag comprise two subunits. The lower subunit 5e1 is composed of 1.6 m of dark, fine-grained floatstone with scattered broken shells, predominantly bivalves. Upsection this facies passes abruptly into 1.3 m of light-coloured rudstone (5e2) dominated by molluscs (bivalves and gastropods) but also containing scattered branches of Acropora corals. The upper 1.1 m of the 5e2 subunit is coralstone characterised by extensive stands of Galaxea fascicularis and Stylophora pistillata. At section AN-7b the ARL overlies the Buri Sequence close to where the ARL onlaps the Abdur volcanics (Fig. 2a). Three sections were described along a transect bearing from the NW tip of this terrace to where the ARL onlaps the Abdur volcanics (Figs. 2a and 4e). The transgressive lag deposits are well-developed (0.4–0.5 m thickness) and consist of subrounded to rounded volcanic cobbles and boulders. In section AN-9, fragments of limestone from an elevated part of the underlying Buri Sequence are reworked among the volcanic clasts. Oyster beds are found in growth position on the volcanic clasts in sections AN-10a and AN-9.

5.5. AN – Transect E (sections AN-10a and b, AN-9)

5.5.1. Description

The southernmost extension of the AN district is a small reef terrace adjoining the volcanic highlands (Fig. 2a). Three sections were described along a transect bearing from the NW tip of this terrace to where the ARL onlaps the Abdur volcanics (Figs. 2a and 4e). The transgressive lag deposits are well-developed (0.4–0.5 m thickness) and consist of subrounded to rounded volcanic cobbles and boulders. In section AN-9, fragments of limestone from an elevated part of the underlying Buri Sequence are reworked among the volcanic clasts. Oyster beds are found in growth position on the volcanic clasts in sections AN-10a and AN-9.
bivalves, gastropods, echinoderms, and crab parts. At section AN-10a, floatstone grades upward into 1.5 m of coral rudstone and coralstone, in which stands of branching *Goniopora savignyi* form conspicuous elements (Fig. 4e). No depositional breaks are detected in this section, and the different facies are attributed to a single subunit that is correlated with 5e1. At section AN-10b a sharp but un lithified depositional break separates the floatstone of subunit 5e1 from overlying limestones that comprise a 1.5-m-thick mollusc-rich rudstone that grades upward into a 0.5-m-thick coralstone dominated by massive corals. We correlate this with subunit 5e2. At section AN-9, bioclastic floatstone contains abundant coral fragments, giant clams (*Tridacna maxima*), crab parts, and broken shells. In a southward direction, where the ARL thins over the Abdur Volcanics, small shell fragments with only minor coral rubble replace the larger bioclastic elements.

### 5.5.2. Interpretation

Floatstones of subunit 5e1 correspond to the soft-sediment environment that developed over the lag deposits. Reef development in this setting occurred later and only locally (section AN-10a) involving various species of zooxanthellate corals, but dominated by the branching *Goniopora* sp. corals. The rudstones and coralstones above the depositional break (subunit 5e2, section AN-10b) are interpreted as part of the larger reef complex that developed during the later phase of ARL deposition. Facies at AN-9 correspond to nearshore and beach environments.

### 5.6. AC – Transect F (sections AC-1a to c)

#### 5.6.1. Description

Three sections were described at AC along a W–E transect across the terrace from its seaward edge to where it onlaps the Abdur Volcanics (Figs. 2a and 4f). Here, as in AS, the ARL overlies an older reef sequence that is more than 4 m thick. The older reef portrays a typical coarsening upward sequence with burrowed calcareous mudstones and grainstones near the base (which itself is not exposed), grading upward into a more resistant bioclastic limestone that includes shells and some massive coral colonies near the top. The older reef sequence is over lain by a hard ground dipping 5°W (Fig. 5f). The Buri Sequence is either not present or not exposed.

The basal gravel zone above the older reef limestone consists of a variety of rounded volcanic clasts, probably carried by a watercourse coming from the Abdur volcanic highlands. Giant clams (*Tridacna maxima*) and oysters (*Saccostrea* sp.) occur in situ either on the gravels of the lag deposit (section AC-1a) or directly on the underlying hardground (section AC-1b).

Limestones overlying the lag deposits comprise a single unit (subunit 5e1) of varying thickness, thinning in an eastward direction over the tilted hardground. At section AC-1a, subunit 5e1 reaches 4.3 m thickness and shows vertical facies changes that correspond to a coarsening upward sequence (Fig. 4f). The lower parts consist of burrowed grainstone and floatstone with sparse scattered shells. Upsection the floatstone grades via coral rudstone into a mixstone facies with abundant *Goniopora savignyi*, *Platyrhiza crosslandi*, and *Lobophyllia corymbosa* in growth position. The coralstone facies continues horizontally in an eastward direction until a break in depositional slope causes the ARL to dip gently in seaward direction (Fig. 5f). Here, the coralstone is replaced by coral rudstone. In an eastward direction along the transect, coralstones directly overly the lag gravels (e.g., section AC-1b, Fig. 4f). The growth fabric is mainly dense pillarstone composed of monospecific growths of *Goniopora* sp. and *Stylophora pistillata*, interspersed locally with mixstone facies. The upper 0.3 m of this section is sandy and burrowed, bestowing an impression of reworking. At section AC-1c the reef terrace onlaps basaltic flows of the Abdur Volcanic Complex, and here the limestone is composed of broken shells, echinoderms and coral fragments with volcanic debris. Bone fragments of crocodile and hippopotamus occur near the top of the section. The upper surface of the ARL is characterised by cross-bedded low-relief ridges made of fine-grained bioclastic sediments departing at oblique angles from the palaeoshoreline. This section is where the first MSA flake tools were discovered in the ARL in 1997.
5.6.2. Interpretation

The single limestone unit that overlies the lag deposits is interpreted as contemporaneous to the shelly sediments of subunit 5e1 seen throughout AN and which formed during the first stage of the 5e sea level highstand. Facies changes in the bioclastic sediments show a characteristic pattern of fining over the lag gravels and subsequent coarsening (section AC-1a), similar to that observed in the AN district, and indicative of deepening followed by shoaling of the depositional setting. It is plausible that the tilted hardground that caps the underlying older reef sequence provided a naturally sloping shore. Fine-grained sediments from molluscs and echinoderms accumulated downslope in deeper water (section AC-1a), while corals settled in shallower water directly on the hardground and on the lag deposits (section AC-1b). Here, dense stands of branching corals form a reef flat. The sequence of facies observed in section AC-1a, from grainstone via floatstone and coral rudstone to coralstone, suggests seaward progradation of a fringing reef that initiated closer to the shore. Section AC-1c represents a nearshore or beach environment, with beach rock incorporating sand-sized fragments from marine organisms, small volcanic pebbles and sand from the shore, and bones of large terrestrial vertebrates. The cross-bedded ridges probably represent beach ridges (sensu Angelucci et al., 1975) formed by currents. Scattered bone fragments of crocodile and hippopotamus may have been carried to the shore from inland sources, or alternatively, may attest to the proximity of fresh-water bodies near the coast.

5.7. AS – Transect G (sections AS-2a and b)

5.7.1. Description

Stratigraphic details of the ARL in the AS district are represented by two sections located along a W–E transect from the seaward edge of the terrace toward the palaeoshoreline (Figs. 2a and 4g). Underlying the ARL is an older reef sequence of which only the upper few metres are exposed. Coralstone (1.8 m thickness) composed of massive *Favia*, *Platygyra*, *Goniastrea*, and *Porites* colonies is overlain by 0.6 m of bioclastic limestone with shell fragments and branching corals near the top. The upper zone is burrowed and altered by dissolution to the extent that corals cannot be identified. The older reef sequence is tilted 5° in westward direction and an erosional surface separates it from the overlying 5e1, a setting similar to AC.

The basal lag deposit is entirely composed of rounded volcanic cobbles and boulders. Oysters (*Saccostrea* sp. and *Hyotissa hyotis*), giant clams (*Tridacna maxima*), and small coral colonies (*Coscinarea monile* and *Leptastrea transversa*) occur in situ on these boulders in section AS-2a (Fig. 4g). A layer of 0.9-m resistant floatstone with abundant whole shells overlies the lag deposits in section AS-2a. Upsection this passes into less resistant burrowed grainstone, containing numerous claws of callianassid crabs. At the same level just west of this section, fine-grained siliciclastic sands form a wedge that thins and pinches out in eastward direction over the resistant floatstone (not shown in section AS-2a). The grainstone coarsens upward into floatstone with scattered corals, molluscs and echinoderms. Further upsection, another resistant layer is created by bioclastic rudstone containing corals and whole shells mixed with abundant volcanic clasts. The upper 2 m of the section is a floatstone facies with an increasing proportion of coral colonies toward the top. The bioclastic limestones overlying the lag deposits at section AS-2a total 6.8 m in thickness. No discontinuity surface is present, and the section is attributed to be a single depositional sequence, tentatively correlated with subunit 5e1 at AN. This is considerably thicker than any other single depositional sequence observed in sections at AN or AC.

Section AS-2b is located near the contact between the ARL and the Abdur Volcanic Complex. The basal cobbles are overlain by floatstone with scattered whole shells. The upper surface of the terrace is characterised by cross-bedded, seaward dipping prograding bar forms of bioclastic grainstone that run approximately parallel to the shoreline.

5.7.2. Interpretation

The now familiar cycle of fining and coarsening
of lithofacies, corresponding to deepening and shallowing of depositional environments, is well represented in section AS-2a. The abundant cal­lianassid claws and burrows in the grainstone facies suggest a seagrass habitat in slightly deeper water on the sloping flanks of the adjacent Dan­kano River valley, a setting similar to that seen along the Missi River of the AN district (Figs. 2b and 4b). A wedge of siliciclastic sediments within the bioclastic grainstone suggests that the discharge of Dankano River has, at times, been an important source of siliciclastic sediments from the volcanic hinterland. Although corals become more abundant during later stages of the build-up of the nearshore carbonate sediments, they do not form interlocking frameworks. The absence of framework facies at AS may reflect marginal conditions for reef development. Fossil marine terraces disappear entirely to the south of Abdur, suggesting that conditions for reef growth were not optimal further south in the Gulf of Zula during the last interglacial. The cross-bedded bar forms on the upper surface of section AS-2b suggest a nearshore or beach environment where currents produce the beach ridges.

6. Invertebrate fauna of the ARL and palaeoecological implications

6.1. Invertebrates other than corals

From the sampled sections, 37 taxa of bivalves, 24 of gastropods, five of echinoderms, and four of crustaceans have been identified, mostly to species level, and their habitat preferences documented. The majority of these invertebrates were retrieved from the lower and middle parts of subunit 5e1, reflecting the dominance of these invertebrates in these levels of the ARL (e.g., Fig. 5e). Corals become locally dominant only in the upper parts of 5e1 (Fig. 5b), and predominate in the overlying 5e2 and 5e3 subunits (e.g., Fig. 5c).

All known species of the oyster genus Saccos­tre a grow on intertidal and shallow subtidal rocks and other hard substrates (Kilburn and Rippey, 1982; Harry, 1985; Carrière and Gaffney, 1996). Large numbers of Saccostrea sp. were found in growth position on the lag gravels (e.g. Figs. 5a and 6a), but also on the upper surface of subunits 5e1 and 5e2. Presumably the oysters colonised these substrates in shallow water, before the environment became too deep. Such conditions existed at the onset of the 5e transgression cycle, but possibly also during or after episodes of sea level drop during 5e. Sea level lowering interrupts sedimentation and causes quick lithification of the sea floor (Schlager et al., 1994; Soreghan and Dickinson, 1994). These processes may have provided a surface for colonisation by Saccostrea sp. during or after periods of lowered sea levels. The implication is that the oysters on upper surfaces of subunits 5e1 and 5e2 probably mark episodes of sea level fall. Oysters in general are considered part of the omission suite (terminology of Brom­ley, 1975) associated with discontinuity surfaces (Immenhauser et al., 2000).

Of the 53 mollusc taxa that were collected from subunit 5e1, 38 inhabit shallow, soft-sediment habitats. Some abundant representatives of these molluscs are: Codakia tigerina, Tellina remies, Circe rufigera, Callista florida, Strombus fasciatus, Tibia insulaechorab, and Volema paradisiaca. Soft-bottom dwelling echinoderms, like Clypeaster humilis and C. reticulatis, are locally the dominant clasts of floatstone and rudstone facies of subunit 5e1, while spines and tests of Maretia planulata are common in the burrowed grainstone facies that overly the basal gravels. This indicates that the depositional setting of the lower parts of the ARL was probably a sandy environment in shallow to moderately deep water.

The remainder of mollusc taxa (15 of the 53) from subunit 5e1 characterise hard substrates associated with coral reef habitats. Some examples are: Spondylus spinosus, Plicatula plicata, Tridac­na maxima, Tectus dentatus, and Cypreea pantherina. Spines of Echinometra mathaei and Diadema cf. setosum are found scattered in the limestones of subunit 5e1. These invertebrates indicate that coral reef habitats existed during at least part of the time during which subunit 5e1 was deposited. Non-coral invertebrates are too sparse in subunits 5e2 and 5e3 to provide such a detailed palaeoen­vironmental interpretation as for 5e1.
Fig. 5. Photographs showing facies, stratigraphy, and discontinuity surfaces. (a) Basal lag deposit with volcanic gravels and associated Saccostrea oysters at section AN-12. (b) Goniopora pillarstone and burrowed hardground of subunit 5e₁ at section AN-14b. Part of the mixstone of subunit 5e₂ is seen overlying the hardground. (c) Mixstone facies of subunit 5e₂ at section AN-14c. (d) View from AN-14b to the south across the westward-tilted AN terrace. In the foreground, a coral patch of subunit 5e₃ overlying the highest level of 5e₂ at section AN-14b. (e) Rudstone composed of sand dollars and bivalves over resistant limestone beds that form a topographic high in Buri Sequence at section AN-3. (f) Last interglacial reef overlying the older reef sequence capped by tilted hardground at section AC-1a. Upper surface of last interglacial reef shows break in depositional slope marking the transition from the reef flat to fore reef slope.
6.2. Corals

We recovered 49 coral taxa, all zooxanthellate scleractinians, of which 42 could be identified to species level. Based on the stratigraphic context of the sampled corals, a comparison of the coral assemblages was made between the observed subunits of the ARL. Subunit 5e1 yielded a total of 32 identified coral species, collected primarily from the upper parts of this subunit. Here, the coral assemblage is characterised by a high diversity and abundance of species that are generally found in turbid, sedimented environments, such as several species of Cycloseris, Fungia and Goniopora, plus Lobophyllia corymbosa and Turbinaria peltata. This assemblage includes 11 species that are found only in subunit 5e1 and not found in the overlying subunits 5e2 and 5e3. The coral species unique to the lower subunit are predominantly species characteristic of soft sediment habitats, comprising Cycloseris cyclolites, C. costulata, Fungia fralinae, F. repanda, and Goniopora columna, and other species that may occur in such habitats, e.g., Fungia concinna and F. granulosa. The palaeoenvironmental interpretation of the subunit 5e1 coral assemblage is a reef that formed at shallow to mid-depths in a sedimented, sheltered environment. This inference is in line with the interpretation of environments during the deposition of subunit 5e1.

From subunit 5e2 a total of 30 identified coral species were collected, nine of which are species that were not found in underlying subunit 5e1. The coral assemblage is characterised by a high abundance and diversity of Faviidae: 15 out of 17 identified species of Faviidae from the ARL were found in subunit 5e2, and four of these were unique to this subunit. High diversity of faviid corals is usually correlated with good reef development (Sheppard and Sheppard, 1991). Moreover, the coral assemblage of subunit 5e2 includes a large proportion of species representative for reefs with relatively well-developed zonation, comprising species characteristic of shallow reef flats (Favites chinensis, Favites pentagona, Leptastrea botiae, Hydnophora microconos), and of fore reef slopes (Goniastrea pectinata). Sediment tolerant corals of the genera Cycloseris, Fungia, and Goniopora are less abundant and diversified than in the lower subunit 5e1. A fungiid coral only found in subunit 5e2, Herpolitha limax, is a species with habitat preferences different from most other Fungiidae, preferring consolidated rubble and hard bottoms rather than soft sediments. In summary, the composition of the coral assemblage of subunit 5e2 differs significantly from that of the underlying subunit 5e1. The faunal changes involve species that prefer low sedimentation and low turbidity in the water column, and improved water circulation (less sheltered conditions). Such environmental changes may have positively affected reef growth, eventually leading to a well-developed reef tract.

Subunit 5e3 is very limited, both laterally and vertically. Only a handful of coral species were found here (e.g., Porites compressa, Goniastrea retiformis, and Platygyra lamellina), and none was unique to this level. It seems likely that the environmental conditions during the deposition of this subunit were quite similar to those prevailing during the deposition of the underlying subunit 5e2, but the paucity of fossils makes any palaeoenvironmental interpretation based on faunal composition tenuous.

7. A model for the deposition of the ARL

The ARL platform at AN is the most laterally extensive and best studied of the three geographic districts. The age of the ARL is well constrained to 125 ± 7 ka by U–Th (TIMS) analyses on corals collected from the upper levels of subunit 5e1 (mainly from section AN-4, see Walter et al., 2000). The facies changes and stratigraphic breaks observed along transect B (Figs. 3 and 4b) offer the best clues to resolving the sequence of depositional phases of the ARL during the 5e sea level highstand. A generalised cross section, constructed across the northern part of the AN platform (Fig. 3), is based in part on this transect and on the geographic positions and measured elevations of the geomorphological features on top of the platform (Fig. 2b). The relatively uniform thickness of the terraces implies that their seaward
inclination is largely due to later tectonic tilting. Inferred erosional surfaces or hardgrounds, indicative of interrupted sedimentation, are observed at two levels and are used to subdivide the ARL into three subunits, designated \( 5e_1 \), \( 5e_2 \), and \( 5e_3 \) (Fig. 3). This cross section is used to develop a model for the developmental of the ARL and to discuss six phases in the depositional history of the ARL, reflecting the \( 5e \) sea level highstand punctuated by one or more sea level drops.

### 7.1. Phase I – initial transgression (basal lag)

During the initial transgression of the \( 5e \) sea level highstand, lag gravels were deposited throughout the study area at the base of the ARL (Fig. 3). They formed when wave energy winnowed away finer particles and left the coarser gravels behind. Size and composition of the transgressive lag deposit varies according to depositional setting. Gravels are composed mainly of volcanic clasts, but may contain varying proportions of limestone eroded from pre-existing topographic highs in the Buri Sequence underlying the ARL in the AN district. Minor lithologies are distally derived metamorphic rocks and quartz, and these occur primarily along the river valleys (e.g., transects A and B bordering the Missi River, Fig. 4a,b). The virtual absence of corals on the lag gravels in the AN district suggests that the environment must have been unsuitable for coral settlement and growth during this transgression phase, possibly due to high turbidity and/or scour. Oysters in growth position on the lag deposits are predominantly *Saccostrea* sp. The ecology of these bivalves suggests that they colonised the gravels quickly upon submergence. Their accessibility in shallow water, their large size, and their high abundance, forming dense oyster beds locally, must have made these oysters an attractive and easily accessible food source for early humans.

### 7.2. Phase II – rapid deepening (lower subunit \( 5e_1 \))

The basal lag deposits generally are overlain by grainstone or floatstone facies (Fig. 3). Such fining upward indicates that the depositional setting rapidly shifted to deeper conditions. Most exposures of the lower subunit \( 5e_1 \) in the study area show this general pattern (Fig. 4). Only at sections AN-I through AN-4 along transect C in the AN district (Fig. 4c), do rudstones rather than floatstones directly overlie the basal gravels, probably reflecting more exposed conditions at the seaward margin of the ARL. Limestones of the lower parts of subunit \( 5e_1 \) are composed primarily of the remains of molluscs, echinoderms and crustaceans. The remains of these organisms created a level sediment body that infilled the pre-existing relief (Fig. 3). Corals were scarce in this environment, but not altogether lacking (e.g., the large in situ colony of *Favites bennettae* in grainstone facies of section AN-14b, Figs. 3 and 4b). The presence of such zooxanthellate corals is significant because it implies that deposition occurred at relatively shallow depth, within the photic zone. Still, the paucity of corals indicates sub-optimal conditions for coral growth, probably due to a lack of firm substrates for settlement of coral larvae and to low light levels resulting from high turbidity.

### 7.3. Phase III – shoaling and local reef development (upper subunit \( 5e_1 \))

A clear shoaling cycle is apparent in the upper parts of subunit \( 5e_1 \): grainstones and floatstones coarsen upward into rudstones and coralstones (Fig. 3). The presence of the shoaling cycle itself indicates that the relative sea level change was slow (Immenhauser et al., 2000), and most likely the result of 'catch-up' growth of the carbonate platform (Kendall and Schlager, 1981). An outcome of this shallowing upward trend is the proliferation of corals. Fringing reef tracts nucleated at several places, such as at section AN-14b of transect B (Figs. 4b and 5b), and at section AN-10a of transect E (Fig. 4e). Dominant and primary engineers of these reef tracts are species of branching *Goniopora* (*G. savignyi* at section AN-10a of transect E, and at sections AC-1a and b along transect F, Fig. 4c,f). A suite of other, subordinate coral species is found in association with these habitats. Separate stands of *Turbinaria pel-
tata occur scattered on the coquina sands and coral debris (Fig. 4c) seaward of the fringing reef tracts at mid-depths, possibly between 5 and 10 m depth. The ecology of the species in the coral assemblage indicates sedimented, sheltered conditions during this phase of the deposition of the ARL.

Together, phases II and III may represent a common response of carbonate platforms to marine transgression, involving an initial ‘start-up’ phase during which sedimentation temporary lags behind the rise of the sea (Phase II), followed by a shoaling-upward sequence that characterises a catch-up growth phase of the platform (Phase III) (Kendall and Schlager, 1981).

7.4. Phase IV - sea level drop with local hardground development (discontinuity)

The presence of a level, burrowed hardground at the top subunit 5e₁ indicates interrupted sedimentation and submarine lithification of the sea floor. This surface is laterally equivalent to abrupt vertical facies changes and to the presence of encrusted oysters on this surface (Fig. 3). This hardground is interpreted as caused by a temporary sea level lowering during the 5e highstand.

The hardground extends more than 100 m along transect B (Fig. 4b – section AN-14b, Fig. 3). It truncates 0.5 m of grainstone that overlies an extensive stand of branching Goniopora corals (Figs. 4b and 5b). The hardground surface is perforated by borings, and the underlying grainstone shows extensive reworking with prominent oval-shaped burrows up to 5 cm in cross section. These burrows are tentatively attributed to Lutraria australis, large bivalves that were retrieved from the overlying subunit. Reworking of the hardground by biological agents must have occurred when the surface was at subtidal depths, during or shortly after the temporary sea level lowering.

The excellent preservation of the coral branches below the hardground (Fig. 5b) suggests that sediments buried the reef tract quickly, precluding later modification of the lower parts of the branching corals by mechanical or biological agents. While the hardground remains distinct and horizontal over a long distance landward of the Goniopora stand, it dips and fades immediately seaward of it (Fig. 3). These features suggest that the branching corals formed a resistant rim rising above the floor of the carbonate shelf, acting as a sediment trap (the ‘bucket principle’, Kendall and Schlager, 1981). This rim became entombed and preserved during offshelf migration of lagoonal and beach sediments during marine regression.

Diagenetic lithification of carbonate sea floor may occur during periods of rapid sea level fall, and is not necessarily related to emergence. While sedimentation is interrupted by lowering of the effective wave base onto the sea floor, wave action and currents rapidly pump large quantities of seawater through the pore space (Schlager et al., 1994), leading to early submarine lithification (‘catch-down’, Soreghan and Dickinson, 1994). We are presently unable to determine whether or not the hardground of transect B ever emerged. Although deep-cutting karstification of this surface was not observed, this in itself is not proof of the absence of a subaerial exposure stage (Immenhauser et al., 2000). Petrographic and geochemical data, as well as a more detailed palaeontological study, are needed to ascertain emergence and exposure to meteoric diagenesis of the hardground horizon of the ARL.

Laterally, the hardground is correlated with abrupt vertical facies changes in other sections along the same transect (Figs. 3 and 4b). In fact, such abrupt vertical facies changes, generally from mollusc-dominated floatstones and rudstones into overlying coral-dominated rudstones and coralstones, are observed along all transects of the AN district (Fig. 4a–e). These abrupt facies changes are interpreted as un lithified (or partly lithified) depositional discontinuities, probably caused by the same sea level event.

Carbonate sedimentation on coral reefs essentially occurs in shallow water, and is rapidly arrested during sea level lowering. Encrusting oysters, as part of a larger suite of omission-related organisms (Bromley, 1975), are indicative of such regressions because they readily settle and grow on firm substrates in shallow water. Saccostrea sp. oysters were found in growth position on the upper surface of 5e₁ sections along the seaward
edge of the AN district (e.g., section AN-11, Figs. 3 and 4b), providing additional evidence that this horizon represents a discontinuity in the development of the ARL, correlated with the hardground and abrupt facies changes observed in other sections.

At the AC and AS districts, no discontinuity surfaces are discerned between the basal lag deposits and the top of the platform. The top of the 5e1 unit at AC (section AC-1, Fig. 4f) shows reworking above local coral development, similar to the reworked grainstone above the Goniopora pillarstone at the top of 5e1 at section AN-14b (Fig. 4b). The implication is that the deposition of the ARL at AC and AS was coeval with the deposition of subunit 5e1 of the AN district.

7.5. Phase V – sea level rise accompanied by extensive reef growth (subunit 5e2)

When sea level began to rise again after the regression event, reef development followed suit (Fig. 3). An initial lag period prior to the onset of reef development is not represented in the facies of the subunit 5e2. Instead, initiation of reef growth appears to have been almost instantaneous, at least on the hardground, as is evidenced by the coralstones that overlie this surface (Figs. 3, 4b and 5b). The hardground itself probably facilitated rapid start-up of reef development by providing a favourable substrate for the recruitment and attachment of coral larvae. Previous studies show that early start-up of reef systems during the Holocene transgression are correlated with karstified limestone foundations or similar surfaces (Hopley et al., 1983; Cabioch et al., 1995).

Differences in the timing of starting-up reef growth may provide an explanation for the differences in the thickness of subunit 5e2 that are observed across the AN district. Where underlying carbonate sands and gravels (subunit 5e1) were not or insufficiently cemented and stabilised during the preceding sea level event, delayed initiation of reef growth may have resulted in lower vertical accretion during the second of the 5e sea level highstands. This situation may have occurred where superstratal reef tracts, capable of retaining sediments that would become lithified during the sea level lowering, were lacking or less well developed, such as along transects A and E (Fig. 4a,e). Thus, the nature of the foundation may control the timing of reef initiation.

Conditions for reef development were favourable during the deposition of subunit 5e2. Rates of vertical reef growth matched or exceeded rates of sea level rise. This 'keep-up' type of reef growth (Kendall and Schlager, 1981) is illustrated in the first place by the lack of distinct deepening or shoaling cycles, such as seen in the underlying subunit 5e1. A single facies type, coral mixstone, overlies the hardground where reef growth was initiated and maximum vertical reef accretion was realised (section AN-14b, Figs. 3 and 4b). Secondly, the geomorphology of subunit 5e2, a flat-topped prograding platform, suggests a keep-up type of reef growth (Kendall and Schlager, 1981). The presence of corals typical of exposed reef flats (e.g., Favites chinensis and Goniatrea retiformis, Sheppard and Sheppard, 1991) in growth position on the seaward scarp, indicate that the platform rim was near sea level. Overall, the dominance of symbiotic scleractinians above the discontinuity surface suggests an environmental change from soft sediments and high turbidity during the first stage of the 5e marine transgression (phases I, II, and III), to hard substrates in clear, shallow water during its second stage (phases IV and V). While the arrested sedimentation and submarine lithification caused by the sea level drop probably had stabilised the soft substrates of the carbonate shelf to some extent, climatic factors may also have contributed to the environmental changes observed.

7.6. Phase VI – a possible second sea level cycle and development of patch reefs (subunit 5e3)

A possible second sea level event during the 5e highstand is inferred from the palaeontology and the topography on top of the upper surface of 5e2 (subunit 5e3, Fig. 3). The abundance of encrusting oysters (Saccostrea sp.) on this surface (Figs. 3 and 4b) may indicate temporary sea level lowering or still stand, assuming that oyster-encrusted surfaces reliably indicate interrupted sedimentation
resulting from such sea level events. Subsequent rise of sea level is indicated by the topography of subunit 5e3 on the upper surface of 5e2, revealing two restricted oval-shaped patches of in situ corals of approximately 0.6 m thickness (see form lines on Fig. 2b and 5d). These are interpreted as representing the last phase of the 5e marine high stand before final sea level drop caused by abrupt cooling associated with the onset of MIS 5d glacial period.

8. Climate variability and sea level changes during the last interglacial

The model for the development of the ARL presented above indicates three major environmental changes that may be related to global and regional climatic events. These changes are: (1) a mid-5e sea level lowering, (2) a pronounced mid-5e change in environmental setting, and (3) a possible second sea level drop near the end of the 5e interglacial.

8.1. Mid-5e sea level drop

Sea level reached its maximum elevation during substage 5e (ca. 130–117 ka, but see Gallup et al., 2002), when it was 5–10 m higher than today (Aharon and Chappell, 1986; Edwards et al., 1997). This is the only stage to correlate with the last interglacial – Eemian – in the terrestrial record. Studies from many parts of the world have shown that substage 5e itself is marked by climate instability and sea level variability. Evidence for sea level variability during the last interglacial is provided by stratigraphic records from New Guinea (Bloom et al., 1974; Chappell and Veeh, 1978; Aharon et al., 1980; Aharon, 1983), the Caribbean (Neumann and Moore, 1975), the Mediterranean basin (Hearty, 1986), the southeast US Coastal Plain (Hollin and Hearty, 1990), Jamaica (Precht, 1993), and Oahu, Hawaii (Sherman et al., 1993). An equivalent mid-5e depositional discontinuity indicating a lowstand of the sea is described from the Bahamas (Hearty and Kindler, 1993, 1995, 1997, Neumann and Hearty, 1996; White et al., 1998; Wilson et al., 1998). Stratigraphic evidence for the occurrence of a mid-5e lowstand in the Red Sea is documented by Plaziat et al. (1998). U-series dating of corals in fossil reefs of the Bahamas (Chen et al., 1991) and Jamaica (Precht, 1993) suggest the timing of this last interglacial sea level drop at about 125 ka.

Sea level variability is primarily caused by changes in terrestrial ice volume that are driven by atmospheric cooling (Lambeck and Chappell, 2001). Climatic instability during the last interglacial, involving several abrupt cooling events, has been documented in ice core records from Greenland (Taylor et al., 1993; GRIP members, 1993; Johnsen et al., 1995), and in pollen, insect, and magnetic susceptibility sequences from peat bogs and annually laminated lake sediments in Europe (Guiot et al., 1993; Field et al., 1994; Tzedakis et al., 1997; Thouveny et al., 1994). Also marine records have provided ample evidence for one or more cooling events during the last interglacial, such as those of planktonic foraminifers from the North Atlantic (Cortijo et al., 1994; Sejrup et al., 1995; Fronval and Jansen, 1996), of benthic foraminifers from the European continental shelf (Seidenkrantz et al., 1995; Seidenkrantz and Knudsen, 1997), and of planktonic foraminifers off Cap Blanc, West Africa (deMenocal et al., 2000). Thus, the first of the environmental changes during the last interglacial at Abdur, the mid-5e sea level lowering, documented in the stratigraphy of the ARL as the discontinuity between 5e1 to 5e2, is compatible with climatic and sea level changes recorded at many locations around the world.

8.2. Mid-5e environmental change

The facies and faunal changes that occur with the passing from subunit 5e1 to 5e2 characterise a shift in environmental setting from a sedimented, turbid and sheltered milieu during the first stage of the 5e sea level highstand (e.g., Fig. 5b), to clear, open-water conditions after the mid-5e sea level drop (e.g., Fig. 5c). Part of this environmental change may be related to alterations of the carbonate shelf itself, resulting from the tempo-
rary sea level lowering, leading to interrupted sedimentation and hardground formation, favouring the start-up of a new reef during resumed sea level rise (see phases IV and V). Changes in seawater conditions may also have been controlled by important climatic changes in the southern and central Red Sea during the last interglacial. The climate in this region is under influence of the Indian Ocean monsoon. During the southwest monsoon, nutrient-rich water from the Gulf of Aden enters the Red Sea, causing pronounced seasonal increase in planktonic production, while moisture-laden winds bring rainfall on the arid coastal lowlands and the lower parts of the escarpment of the Eritrean plateau. A 380-ka-long core from the central Red Sea, analysed by Hemleben et al. (1996) and Almogi-Labin et al. (1998), revealed pronounced glacial-interglacial variations in foraminifer and pteropod assemblages, indicating orbitally driven variations in southwest monsoon activity. Notably, during the MIS 6/5 transition and the first part of substage 5e (at ca. 130 ka) monsoon activity was high, implying a more humid climate in the southern Red Sea. In the course of the substage 5e, monsoon activity weakened, leading to increased aridity in this region. The marine environments at Abdur are likely to be strongly affected by changes in monsoon strength. A large alluvial fan complex, deposited by the present-day Haddis River and other major ephemeral streams emanating from the Eritrean escarpment, is present near the town of Foro on the western shore of the Gulf of Zula (Fig. 1), 20 km across from the Abdur Archaeological Site. Strong monsoon activity would increase the sediment load and turbidity in the Gulf of Zula due to high terrestrial run-off and through high planktonic production. High sedimentation and turbidity generally impairs coral reef development (Hatcher et al., 1989). Later in substage 5e, weakened monsoon influence probably improved conditions for coral reef formation, as is reflected in the reef facies of subunits 5e2 and 5e3.

8.3. Late-5e sea level drop

A possible second sea level drop near the end of the 5e sea level highstand, recorded as the discontinuity between 5e2 and 5e3 in the ARL, is not supported by stratigraphic evidence from fossil reefs elsewhere. One explanation may be that the second half of substage 5e is not well-represented in the sedimentary record of fossil reefs (e.g., Stirling et al., 1998), preventing the recognition of a small sea level event globally. Regional effects of hydro-glacio-isostatic loading of the continental shelf during the maximum 5e sea level highstand (Lambeck and Nakada, 1990) may provide an alternative explanation for the third apparent sea level highstand observed in the ARL. Isostatic loading of the wide continental shelf offshore may have caused local subsidence along the active fault margin of the Zula–Alid–Bada graben, creating some additional space for vertical reef accretion (subunit 5e3). In any case, the possible second sea level lowering at Abdur was probably minor, and may have been merely a last wavering of the 5e sea level highstand before the final drop related to the onset of the 5d cooling and an increase in high latitude ice volume.

9. Context, distribution, and significance of stone tools in the ARL

9.1. Context

Several hundred stone tools were found in situ within several facies and stratigraphic levels of the ARL over a 6.5-km² area. These artefacts include bifaces (large, flat, teardrop shaped tools flaked over at least part of both surfaces) and cores (stones from which flakes or blades have been removed, and which may be used as tools themselves) of the Acheulian tradition, as well as flakes and blades of the MSA tradition (Walter et al., 2000). The bifaces and cores range from 6 to 25 cm in length and are made primarily from fine-grained volcanic rocks (aphyric rhyolites, ignimbrites and basalts; Fig. 6c), but also from obsidian (Fig. 6b), chert and quartz (see Walter et al., 2000; Fig. 2c). Flake and blade tools range from 5 to 15 cm in length, and are primarily made from obsidian (Fig. 6d), although chert and quartz flake tools are also found.

Some of the raw materials for these tools are
found within the study area. The lag deposit at the base of the ARL and the adjacent Abdur Volcanic Complex are potential sources for fine-grained basalts. Chert occurs within a hydrothermally altered fault block just south of AN-13. However, most of the raw materials must be from sources outside the Abdur area. At least four major rhyolitic volcanoes occur within a 60 km radius of Abdur that could be sources of tools made from fine grained lavas, ignimbrites and obsidians. The basement rocks of the Buri Peninsula and in the neighbouring region contain quartzites and quartz veins that could be the source for tools occasionally made from these materials. This implies that the hominids travelled various distances to acquire raw materials.

The in situ tools are embedded in densely packed bioclastic limestones that were deposited in low-energy environments. There is no evidence that the tools could have filtered down into the reef at some later time. Nearly all of the tools have sharp cutting edges, show no signs of damage due to wave action, aqueous transport or long exposures to weathering, and they are distributed throughout a wide area in several facies of the ARL. Even the tools associated with the basal lag deposits have clean, sharp edges, and are rarely encrusted by marine organisms, while the gravels that comprise the lag are rounded and are often encrusted with oysters and barnacles (Walter et al., 2000). We interpret these observations to mean that the tools are in primary context, and that they were brought into the nearshore environments by hominid activity.

9.2. Distribution

The distribution of artefacts in the ARL is
briefly summarised here, first following the described transects and sections, and supplemented with general observations about other outcrop locations.

Along transect A, chert flake tools are found in the basal cobble layer in AN-13a and obsidian flake tools occur in large numbers throughout the nearshore section AN-13c (Fig. 4a). At transect B, various tools, including an obsidian discoid at section AN-11, and an obsidian biface at section AN-12 (Fig. 6a,b), are found in situ at less than 10 cm above an oyster bed on the basal lag gravels (Fig. 4b). Following transect C, a bifacial hand axe of fine-grained volcanic rock occurs associated with the lag deposit at section AN-1 (Fig. 6c). At section AN-4, two obsidian flakes occur in situ among the lag gravels, while a quartz hand axe is found embedded in the overlying shelly rudstone (Fig. 4c). Along transect D, an obsidian flake occurs about 0.5 m above the lag deposit of section AN-7a. Hundreds of obsidian flake tools occur throughout the ARL at the erosional embayment on the eastern edge of the platform halfway between AN-8 and AN-12 (Fig. 2b).

In summary, there appear to be two different toolkits in the ARL. One consists of hand axes and cores, typically associated with the oyster beds (*Saccostrea* sp.) encrusted on the basal lag deposits or occurring within the lower half metre of the overlying limestone. So far, hand axes and cores have only been found in AN. The other toolkit consists of MSA-type obsidian flakes and blades. These tools occur in abundance in all three districts (AN, AC, AS), mainly in the nearshore and beach environments alongside debris from marine invertebrates and large land mammals.

### 9.3. Significance

The occurrence of distinct toolkits in different palaeoenvironments suggests that foraging activities of early humans varied with environmental setting. *Saccostrea* oysters are cemented to intertidal and shallow subtidal firm substrates, and require strong and heavy tools to harvest. All the extant species of this genus are quite large, and form important food items today (Carriker and Gaffney, 1996). The species found at Abdur is also large (15–25 cm), abundant, and could have been a profitable source of nutrition to early humans. During the initial transgression of the sea, early humans may have collected oysters in shallow water, using a special tool shape (bifaces and cores) to harvest them, then used other, smaller kinds of tools (flakes and blades) to extract the edible parts from oysters and other marine foods along the beach.

During later phases of the deposition of the ARL, potential food types changed. Large oysters were no longer abundant, but other molluscs and crustaceans were to be found in intertidal and shallow subtidal sediments and later in different habitats of the fringing reef system. The edible invertebrates in these facies include bivalves (*Anadara ehrenbergi, Spondylus spinosus, Codakia tigera*, *Fulvia fragilus, Tridacna maxima, Tellina remies, Gafarium pectinatum*), gastropods (*Strombus tricornis, Tibia insulaechoarab, Chicoreus virgineus, Volema paradisiaca, Pleuroloca tra-
pezium), and crustaceans (Carpilus sp., Charybdis japonica). These diverse food types are not as conspicuous as oysters, but are often rather cryptic and require intimate knowledge of habitat in order to exploit them profitably. Such foraging activity can be done only in shallow and calm water, but without the need for heavy tools. The small tools would be required to clean the collected seafoods on the shore. Thus, environmental changes in coastal habitats during the last interglacial may have led to new behavioural repertoires in early humans (Bruggemann et al., 2000).

The best evidence for transformations in early hominin behaviour is found in the archaeological record of Africa (Clark, 1980, 1981, 1988). In this context, perhaps the most significant event of the Pleistocene is the disappearance of the highly successful, more than one-million-year-long Acheulian biface industry (representing late African Homo erectus and Homo heidelbergensis technologies) and its replacement by MSA flake and blade tools (representing early Homo sapiens technologies). The transition from Acheulian to MSA technologies is viewed as a benchmark for early modern human behaviour and is thought to have occurred before 200 ka (Wendorf et al., 1993; McBrearty and Brooks, 2000; Tryon and McBrearty, 2002). The discoveries at Abdur show that the Acheulian and MSA technologies continued to co-exist for much longer, at least until the last interglacial. Recent palaeontological and archaeological discoveries at Herto, Ethiopia (Clark et al., 2003), dated to between 160 and 154 ka ago, also support the long association of Acheulian and MSA elements. Such technological diversity may reflect diverse palaeoenvironments requiring complex hominin adaptations. On the Red Sea coast, the Acheulian biface persisted, possibly because it acquired a new, profitable use for the exploitation of aquatic resources. Acheulian occurrences from this late period may in fact be widespread on the Red Sea littoral, from Egypt to Djibouti (Balout and Roubet, 1978; Montenat, 1986), and if the Acheulian/MSA transition is regarded as the inception of modern human behaviour, then this milestone may have ranged from >285 ka (the first appearance of MSA, Tryon and McBrearty, 2002) to 125 ka (the last appearance of Acheulian, this publication), a broad period of transition rather than a sudden behavioural modification.

The Abdur Archaeological Site represents a late example of the Acheulian/MSA transition, and the earliest best-dated evidence for early human adaptation to marine food resources. Not far from Abdur, on the Buri Peninsula and in the Northern Danakil Depression, older archaeological sites extend back to ca. 1 Ma (Abbate et al., 1998). These sites represent various Pleistocene habitats ranging from fluvio-lacustrine, estuarine and marginal marine, to nearshore (Faure and Roubet, 1968; Walter et al., 1997; Abbate et al., 1998; Ghebretensae, 2002, Lisa Park, pers. comm.). Together, these sites offer a rare opportunity to document the chronology of the transitions from African Homo erectus to early modern humans in the framework of Pleistocene climate change, and may provide a key to understanding the evolution of early humans and their dispersal out of Africa, possibly along littoral routes.

Acknowledgements

We commemorate the late Gail Smithwalter, who with the keen eye of a professional artist discovered many artefacts and fossils during the 1999 field season. She also videotaped our toils in the field, which she later edited and produced for the Canadian Discovery Channel (http://www.exn.ca, search under 'Eritrea'). Permission for fieldwork was granted by the Ministry of Energy and Mines and by the University of Asmara. We are grateful to Alem Kibreab, Michael Abraha and Tesfamichael Keleta of the Department of Mines, and to Yoseph Libsekal and staff of the National Museum of Eritrea for their support. We further thank Mike Tesfaye for logistical arrangements and Nasser Mohammed for helping with collecting fossils. The assistance from Louis Le Vert and the French Ministry of Foreign Affairs is much appreciated. Financial support was provided by grants from Anadarko Petroleum Company and the National Science Foundation (EAR-9725405). We acknowledge the following specialists for their collaboration in the identifica-
tion of invertebrate fossils: Didier Néraudeau (echinoderms), Danièle Guinot, Ho Nguyen, Michèle de Saint Laurent (crustaceans), Henk Dekker and Jean Tröndle (molluscs). Michel Pichon confirmed the names of some coral species. Collette Roubet provided independent comments on the stone tools. We thank Mohammed Abdelsalam for providing a satellite image of the study area and Dick Visser for preparing the figures. The reviewers, Brian Rosen and Paul Sanlaville, are thanked for their comments that improved the manuscript. J.H.B. is grateful to Dominique Doumenc for his invitations to work at the MNHN in Paris.

References


ization mass spectrometry: Implications for Quaternary climate change. Science 276, 782–786.


Fleisch, H., Sanlaville, P., 1974. La plage de +52 m et son Acheuléen à Ras Beyrouth et à l’Ouadi Aabet (Liban). Paléorient 2, 45–85.


Neumann, A.C., Hearty, P.J., 1996. Rapid sea-level changes at the close of the last interglacial (substage 5e) recorded in Bahamian island geology. Geology 24, 775–778.


