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Dynamic landscapes and human dispersal patterns: tectonics, coastlines, and the reconstruction of human habitats

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Abstract
Studies of the impact of physical environment on human evolution usually focus on climate as the main external forcing agent of evolutionary and cultural change. In this paper we focus on changes in the physical character of the landscape driven by geophysical processes as an equally potent factor. Most of the landscapes where finds of early human fossils and artefacts are concentrated are ones that have been subjected to high levels of geological instability, either because of especially active tectonic processes associated with faulting and volcanic activity or because of proximity to coastlines subject to dramatic changes of geographical position and physical character by changes of relative sea level. These processes can have both beneficial effects, creating ecologically attractive conditions for human settlement, and deleterious or disruptive ones, creating barriers to movement, disruption of ecological conditions, or hazards to survival. Both positive and negative factors can have powerful selective effects on human behaviour and patterns of settlement and dispersal. We consider both these aspects of the interaction, develop a framework for the reconstruction and comparison of landscapes and landscape change at a variety of scales, and illustrate this with selected examples drawn from Africa and Arabia.

Keywords: Active tectonics, African Rift, Cradle of Humankind, Farasan Islands, Red Sea

1. Introduction

Our primary focus in this paper is on the physical landscape associated with early sites of human fossil and archaeological discoveries, and its influence on patterns of human evolution and dispersal. Our aim is to provide a framework for landscape reconstruction relevant to human activities that will facilitate comparative evaluation of case studies in different regions and time periods and at different scales of observation. We define physical landscape as the physical morphology of the land surface, comprising variations in topography and hydrology ─ mountains, hills, valleys, basins, slopes, canyons, cliffs, topographic irregularities more generally, rivers, lakes, streams, spring lines, and coastline morphology. These represent a suite of variables that can significantly moderate or amplify the influence of climate, shape patterns of erosion and sedimentation, and modify the distribution, productivity and accessibility of plant and animal resources. As such they are critical to an understanding of the local and regional context within which human populations make a living and, in the longer run, compete for evolutionary advantage.

The study of changes in landscape morphology falls within the province of geomorphology, but with an added emphasis on a human scale of reconstruction, that is a scale that is appropriate to the daily and lifetime activities of human groups, involving distances of kilometres to tens of kilometres at the shorter end of the spectrum, and on features that are likely to be of particular significance to human activity and livelihood. We refer to landscape reconstructions at this scale as reconstructions of site regions – areas within range of sites with significant finds of artefacts and fossils[1]. We distinguish this focus on site regions from reconstructions over larger areas and at coarser scales of observation. The latter may be continent-wide or global, and are important in comprehending the wider geophysical and other environmental processes that impinge at a more local scale, and in analysis of biogeographical distributions at the population or species level. However, they need to be complemented by studies at a site-regional scale. A fundamental difficulty with reconstructions at this scale,, which increases as one goes further back in time, is that they are seriously compromised by the often major changes brought about by earth processes and climate change, which have erased or modified beyond recognition many detailed physical features of the landscape as it existed at the time of human occupation. This problem is particularly acute in regions of very active geological change, especially regions subject to active tectonics, periodic glaciation, or sea-level change.

Given these difficulties, it is perhaps not surprising that previous attempts to study past landscapes in the early time ranges of hominin evolution have tended to focus on reconstructions of vegetation and climate rather than the physical landscape, often at a very coarse geographical scale of resolution ─ hundreds to thousands of kilometres (e.g. Adams and Faure, 1997; Mithen and Reed, 2002; Field et al., 2007; Hughes et al. 2007), on fluvial and lacustrine sediments at a regional or local scale, and on often highly localised physical features as they existed within the immediate vicinity of find spots at the time when material was being deposited (e.g. Bunn et al., 1980; Johanson et al. 1982; Feibel and Brown, 1993; Rogers et al., 1994; Peters and Blumenschine, 1995; Blumenschine and Peters, 1998; Potts et al., 1999; Blumenschine et al., 2003). These are all variables that offer a variety of insights into the relationship between environmental variability and evolutionary change, and they can to a large extent be measured without reference to the wider physical landscape or to longer-term changes that underlie the

[1] The scale we have in mind is close to that associated with site catchment studies, which have often used the concept of a site exploitation territory of10 km radius to define areas of interest (Vita-Finzi and Higgs, 1970, Bailey and Davidson 1983), or with concepts of foraging range, home range and lifetime range (Foley 1987), or locales (Gamble 1999). We prefer the term site region here as a neutral term, in order to avoid the behavioural implications associated with the other terms, and the distracting intellectual controversies they have engendered, especially with regard to the imposition of arbitrary or ill-defined limits on the definition of areas of relevance.

observable morphology. However, they largely leave out of consideration types of topographic features, geophysical processes, and intermediate geographical scales of reconstruction that are indispensable to a fuller understanding of the selection pressures imposed on evolutionary trajectories by the external environment.

In particular, a range of studies of late Pleistocene and Holocene archaeology has shown how human populations can use local and regional topographic complexity to their advantage to access food and water supplies, and especially to monitor, control and capture mobile prey (Bailey et al., 1993; Marean 1997, Dewar et al., 2006). These examples refer to modern humans, but nevertheless provide insight into the ways in which topographic complexity may have more general applicability to earlier humans. Many of the species of animal prey that are of interest to humans are fast moving, dangerous or elusive. Without effective weapons for killing at a distance, humans are at a significant disadvantage compared to other predators. A key issue in human evolution is how early humans from such a position of relative disadvantage were able successfully to target concentrated supplies of animal protein as an expanding part of their diet, thereby facilitating a prolonged childhood, a larger brain, and range expansion. We have hypothesized that the creation and maintenance of complex topography by active tectonics afforded opportunities to an intelligent but unspecialized predator to monitor animal resources, out compete other carnivores, and find protection from predators and safety for vulnerable young, thereby creating powerful selection pressures in favour of the human evolutionary trajectory (King and Bailey, 1985, 2006; Bailey et al., 1993, 2000; King et al., 1994, 1997). However, this and other such hypotheses of hominin land use depend on methods for reconstructing details of topography and topographic change at a variety of temporal and geographical scales.

Here, we aim to show how an understanding of the geophysical principles that drive changes in landscape morphology, and the development of appropriate methods, can be used to address the problem of landscape reconstruction in earlier time periods and in regions of active geological change, and provide methods for testing hypotheses about early hominin patterns of land use. We concentrate on tectonic processes because these are of central importance to understanding the regions where the earliest concentrations of fossils and archaeological materials are found, which are typically regions of active tectonics, most notably in the African Rift. Also, tectonic processes have attracted relatively little attention from Quaternary archaeologists and palaeoanthropologists. We also look at landscape changes in coastal regions. These are key regions on the primary pathways of dispersal out of Africa, are often on or close to plate boundaries with high levels of tectonic activity, and are typically subject to an additional set of crustal instabilities and landscape modifications associated with changes in sea level.

We discuss underlying geophysical principles of landscape change, propose models appropriate to a human scale of land use, and present methods for mapping relevant topographic variables over extensive areas using satellite imagery and remote sensing. We use African examples to illustrate these methods, and then discuss the Red Sea region, which holds the key to contact between Africa and Asia, and is a region where tectonic and coastal processes are combined.

2. Tectonic geomorphology

Tectonic geomorphology focuses on the way in which underlying processes of crustal deformation modify surface topography. These processes broadly fall into two categories. one associated with isostasy, the other with plate motions and rifting. Isostasy refers to vertical movements of the earth's crust resulting from the redistribution of loads on the Earth's surface. These effects are usually most pronounced in specific geological conditions, for example the loading and unloading of ice sheets at high latitudes, and the loading and unloading of seawater on the continental shelves during major changes of sea level (Lambeck 1996, 2004). They may also result from slower or more subtle processes of load redistribution associated, for example, with erosional isostasy (Westaway et al., 2002) or planetary rotation (Peltier and Luthcke, 2009). The other type of process is that associated with plate motions and rifting, which we refer to as 'active tectonics'. We include isostatic effects where relevant in the examples that we discuss later, particularly in the context of coastal regions, but we concentrate on active tectonics, because these are the most prominent processes for the regions and the time scales that we are concerned with here. They also form the basis for the methods we have developed to map the morphology of landscapes, though we note that these methods can be extended to capture morphologies resulting from other sorts of tectonic processes.

2.1. Active Tectonics

Processes of active tectonics are especially marked near plate boundaries, and have different surface effects depending on the nature of the plate motions and the spatial and temporal scale of observation. Where plates are diverging the dominant large-scale effect is crustal stretching, subsidence and formation of marine basins, with some uplift at the margins. Where terrestrial plates are converging, the dominant large-scale effect is crustal contraction, uplift and mountain building. Where plates are moving sideways with respect to each other (strike-slip), both effects may be observed locally (e.g. Bilham and King, 1989). Earthquakes are active in all these examples and can be accompanied by volcanic activity. In some regions of the world, notably in the Eastern Mediterranean, overall convergence of major plates is mediated by smaller platelet motions, resulting in a complex interplay of crustal processes including extension, contraction and strike-slip (e.g. Flerit et al., 2004)

These processes can be rapid in human terms. The Gulf of Corinth, now nearly 1.5 km deep has been created since 1 Ma, well within the time span of human interest, and the Sea of Marmara did not exist at 5 Ma (Figure 1 caption). Even on shorter time scales and in more recent periods, visible changes have occurred: the Gulf of Corinth has dropped 25 m since 500 BC, and the Byzantine chapel of Kenchreai is now partially submerged (Vita-Finzi and King, 1985). At the smallest scale of the spatio-temporal spectrum, individual earthquakes and volcanic eruptions can have an immediate human impact, often a destructive one. Of greater interest to the purposes of the present paper is what happens at intermediate scales.

During the past twenty years, a series of well-studied earthquakes and models of the associated deformation have led to an appreciation of the intimate relationship between earthquakes and changes in surface morphology (see King et al., 1988; Stein et al., 1988). Fault displacements and folding episodes modify topography, sometimes dramatically over relatively short time spans (10 to 10^3 years), with the creation of barriers, disruption of surface drainage and ponding back of stream flows and sediment. Furthermore, earthquakes tend to repeat on the same fault zones and over longer time spans (10^4 to 10^8 years). These repetitions result in major fault scarps and depressions, and ultimately new basins and mountain ranges and the geological structures that are the traditional focus of structural geology.

At the shorter end of these timescales, tectonic activity may overlap with and sometimes interact with other sorts of geomorphological processes, for example cycles of erosion and sedimentation driven by climate change, or intensive land use practices in recent millennia, both of which may by further amplified or moderated by tectonic uplift or subsidence. At these timescales, disentangling cause and effect may pose particular challenges and disagreements. Whatever the relative influence of these different processes, the key point is that the physical landscape is a dynamic and unstable surface not only on the longer timescales of geological time

but on shorter timescales too, with consequences for processes of biological evolution, ecological interaction and sociocultural change.

2.2 Models of tectonic change

In tectonically active areas, the typical local and regional surface expression of activity is faulting. This may take the form of reverse faulting (and surface folding) in contractional environments, where the crust is being compressed by plate collision (Figure 1a), or normal faulting, where the crust is being stretched by plate separation or by rifting (Figure 1b). In both cases the activity results in a series of uplifted and down-dropped blocks, which break the landscape up into a series of basins and barriers. The down-dropped basins act as traps for sediment and water, resulting in lakes and marshes, while the edges of the uplifted blocks create local topographic barriers that block or impede movement. Normal faults create steep escarpments that may be almost vertical in places and many tens of metres high, while the folds created by reverse faulting typically produce rugged terrain. In regions of strike-slip, similar effects are observed, often aligned in the form of long narrow valleys with uplifted flanks of rugged terrain on both sides showing evidence of compression and tilting, and a central basin that

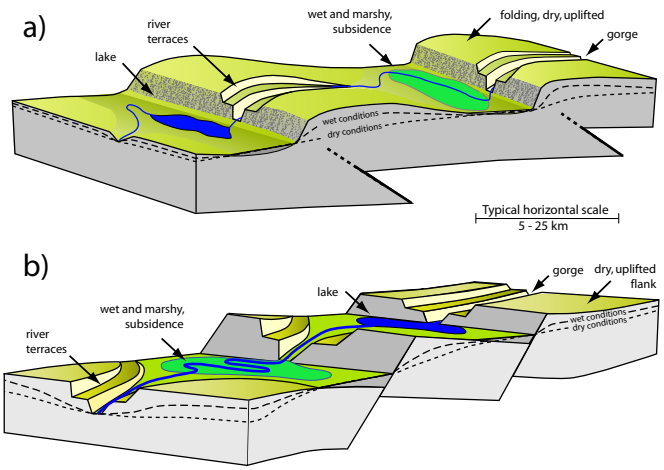
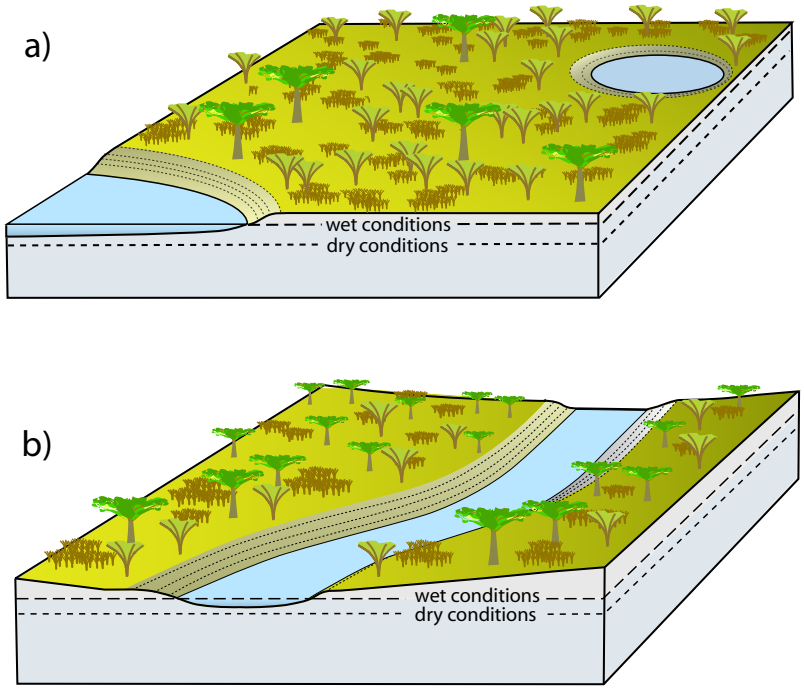


Figure 1.
Schematic illustration of the effects of changing water table in a tectonically active landscape: (a) contractional (reverse-faulting); (b) extensional (normal-faulting) environments.

In (a) the surface expression of faulting appears in the form of folds rather than faults that cut the surface. In (b) faults usually fully cut the surface. The scale bar is approximate. Both figures show how faulting and folding can trap water and sediments to sustain intermittent areas of well-watered and fertile conditions even when the water table changes because of climate change. In each figure two faults are shown that could host repeated earthquakes with Richter magnitudes between 6 and 7. Smaller events in the same region with magnitudes between 3 and 4 will occur 10,000 times more frequently. In regions of Greece or Western Turkey major events repeat every 200 years or less and create both major and minor features (e.g. Armijo et al., 1996). The Gulf of Corinth has been created in this way over the last ~1Ma, and historical records show that some areas of settlement have sunk below the sea because of faulting, as at the now submerged Byzantine church at Kenkreai (37° 52′ 56″ N, 22° 59′ 33″ E) near Corinth. Secondary effects are important, creating deep river valleys and gorges and faulting that produces small private valleys or secret bays at a range of scales hosting tiny chapels and hermit caves. Delphi is the most famous, but there are many more. Greece and Western Turkey are very active, but tiny fractions of that rate can create and maintain features. Overall rates for the East African Rift are a factor of a hundred smaller, and less is known historically, but motion can still generate spectacular features within a human life time. In 2003 a small volcanic eruption in the Ethiopian Rift was associated with dyking and faulting extending for 60km, with vertical displacement along the fault line of 5m or more (Ayele et al., 2007; Rowland et al., 2007). Fault scarps tens of metres high can be created by repeated movement on such fault lines in less than 100 years.

acts as the main drainage channel, with thick accumulations of fluvial and lacustrine sediments. Reverse faulting environments are typical of parts of southern Europe, North Africa, Anatolia and

the Zagros, representing zones of convergence between the African-Arabian and Eurasian plates. Normal faulting occurs in Greece and Western Turkey and is typical for regions of Africa,



F*igure 2.*
Schematic illustration of effects of changing water table in flat landscapes with little or no relief: (a) a region with water-holes and lakes; (b) a region with a river flowing through it.

In both cases changes in the water table are sensitive to climatic changes that affect the amount of available surface water. If climate becomes more arid, the water table drops and standing bodies of water dry out. Rivers are also liable to become dry, either seasonally or perennially, unless there is a reliable source of water from a high-rainfall headwater region.

especially the East African Rift. The Jordan valley is a typical example of a strike-slip environment. Overall vertical movements here are modest and the form of the rift has changed little over 1.5 Ma (Matmon et al., 2000, 2003), during which time horizontal motion has been nearly 1 km. At scales of a few hundred metres, deformation can be dramatic. For example at the archaeological site of Ubeidiyah, the original land surfaces on which stone tools and animal bones were deposited over 1 million years ago have been subsequently tilted locally to a steep angle (Bar-Yosef and Goren-Inbar, 1993).

The effect of such processes is to create and sustain a complex or 'rough' topography comprising local barriers and enclosures of varying size, interspersed with fertile and well-watered basins. Such a combination of conditions creates many potential advantages for an unspecialized hominin population seeking to create a viable niche in competition with other mammalian competitors: sustained supplies of surface water relative to flatter landscapes in the same climate regime and a measure of micro-environmental insulation from climatic aridity; ecological diversity and variety of food supplies over relatively short distances; and a topography that affords tactical advantage in hiding from predators or accessing and trapping large or fast-moving animal prey. In extensional, strike slip, and rift environments, volcanic activity adds to these effects, producing crater lakes in collapsed calderas, and fertile areas enclosed by lava flows that are difficult to traverse, providing additional protection or tactical advantage. Flat landscapes

in contrast lack these advantages (Figure 2). Surface water may concentrate plant and animal life and attract human settlement, but these conditions are vulnerable to changes in water table because of climate change.

The African Rift is especially active, with a distinctive combination of tectonic and topographical dynamics, and we have hypothesised that these geophysical conditions played a powerful role in creating the selection pressures that shaped the human evolutionary trajectory, with its emphasis on meat-eating, omnivory, bipedalism and an extended period of infant dependency and learning (King and Bailey, 2006).

If activity ceases or is absent, erosion will tend to wear down the topography to a smooth and flat surface, with the removal of the advantages described above. As long as the landscape remains tectonically active, the landscape will maintain its ecological and tactical advantages for hominin occupation, with continued accumulation of fertile sediments and trapping of surface water supplies in the down-dropped basins, and the maintenance or accentuation of localised barriers. Even modest levels of tectonic activity, with long intervals between earthquakes, may be sufficient to maintain the features we have described, especially where the bedrock is hard and resistant to erosion, as is the case in South Africa. In very active regions, the pace of change and the shifting focus of activity may convert earlier zones of subsidence and deposition to zones of uplift and erosion, obscuring or removing earlier features. This is particularly the case in active parts of the African Rift. These differing rates of change pose different challenges and opportunities to landscape reconstruction, and we provide illustrations of both circumstances in our examples below.

2.3. Topographic barriers

In introducing the concept of a topographic 'barrier', we distinguish between absolute physical barriers and localised barriers. Absolute physical barriers are impassable to human movement without advanced technology ─ vertical cliffs many tens of metres high, high altitude mountains, stretches of water that cannot be crossed without boats, or deserts that cannot be crossed without domestic camels. Localised barriers comprise rough terrain, which can be traversed to some degree, but which impedes ease of movement, especially for fast-moving cursorial mammals, and therefore provides opportunities for humans to track movements of animals from a distance, to escape from threats, and to protect vulnerable members of the group. Both types of barrier are important in discussing early human dispersal. Large-scale physical obstructions of sea and desert pose an obvious limit to expansion of populations into new regions, whereas rough terrain, if associated with flatter areas with extensive grasslands and abundance of animal and plant resources, can offer attractive habitat for human settlement and range extension. Both types of barriers can be created, modified or removed by geological or climate change.

2.4. Coastal regions

Coastal regions are often tectonically active, especially at plate boundaries where oceanic material is colliding with the margin of a continental plate and being subducted beneath it. Inman (1983) describes these as collision coasts, characterized by uplifted coastlines with coastal mountain ranges, a relatively narrow continental shelf, and deep ocean trenches and submarine canyons. These contrast with trailing-edge coastlines, characterized by broad coastal plains and continental shelves, which may be subject to long-term subsidence. Superimposed on these large-scale trends are sea-level variations of the glacial-interglacial cycle and vertical crustal movements resulting from isostatic loading and unloading of water masses on the continental shelf. It follows that coastlines are likely to pose many of the same sorts of characteristics of geological instability combined with topographic complexity and ecological attractiveness that we have discussed in relation to tectonically active regions.

3. Roughness maps

Detailed mapping and dating of fault scarps and other features should provide a record of the tectonic history of the landscape including the level of tectonic activity and the history of resulting morphological change. However, few such maps yet exist. Geological maps that purport

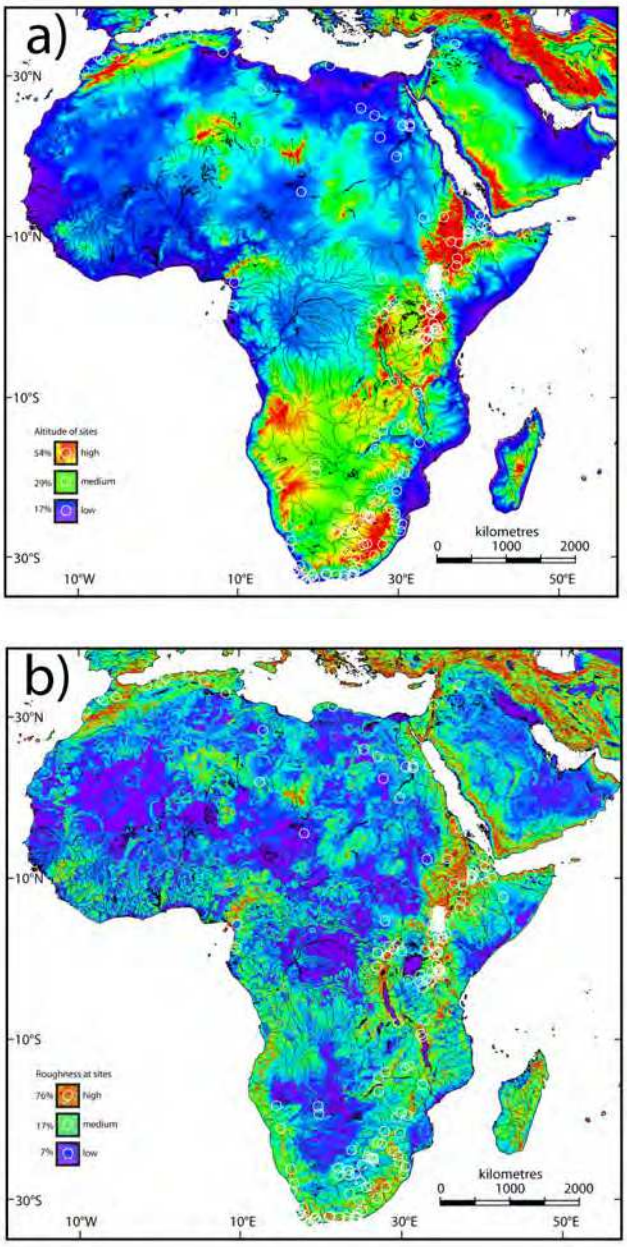


Figure 3.
African scale maps of (a) topographic relief, and (b) roughness.

Topographic relief in (a) is based on SRTM 30 data, coloured according to altitude. Early sites with hominins and/or artefacts (white circles) are shown to provide a general indication of the relationship with topographic features (site details are in Appendix 2 of Bailey et al., 2010). The percentage association with different altitude bands is also shown. While a broad correlation is apparent at this coarse scale of observation, it should be noted that other factors such as differential intensity of investigation and differential exposure or preservation of material because of geological variables are also likely to have influenced site distributions. A finer-scale analysis is required to unravel these confounding variables. For roughness in (b), raw digital elevation data has been filtered using an ~18db/octave hi-pass filter to de-emphasize the amplitude of wave length components inversely as the cube of the wavelength. This has the effect of emphasizing roughness at scales of approximately 5km and less. Note the higher proportion of sites associated with rough topography, compared to the distribution of sites by altitude as shown in (a).

to show fault zones usually map features that offset hard rock and are now inactive. They rarely show features resulting from more recent or smaller-scale tectonic activity, because these show no stratigraphic offset. Cross-sections of the East African Rift, for example, rarely distinguish

between those parts that are currently active (e.g. Manighetti et al., 1998) and parts that are almost dead.

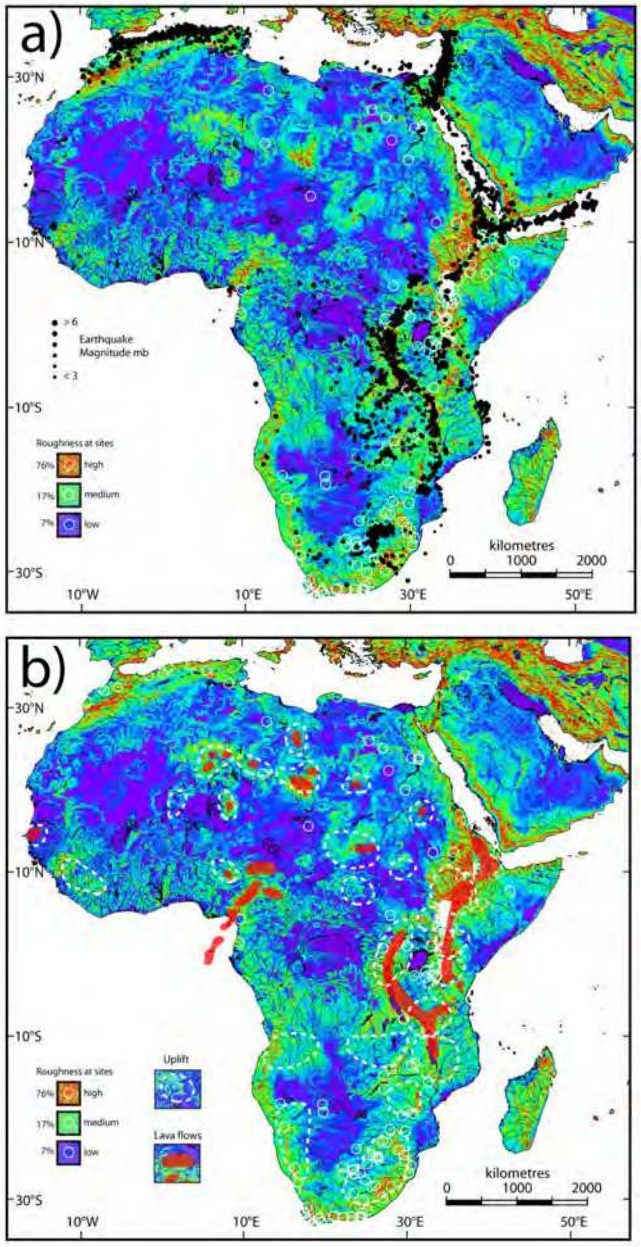


Figure 4.
African scale maps of (a) roughness as in Figure 3b with seismic activity added (all events ≤ 3.5mb); and (b) regions of uplift and volcanic activity over the last 30Ma.

Data in (b) are modified from Burke (1996). Many of these regions have been active in the last 4Ma and are still active today. The white dashed lines enclose regions of uplift thought to be due to heating from the mantle and most are associated with volcanism. The Cameroun volcanic region is a rift formed as a failed arm associated with the opening of the Atlantic, and Mt. Cameroun is an active volcano today. Although there is substantial uplift in Southern Africa, volcanic activity is absent. Site information as in Figure 3.

In developing appropriate maps, tectonic geomorphologists have experimented with proxy measurements, such as topographic 'roughness', which is a measure of irregularities in surface morphology (Scholz, 1990; Turcotte, 1997). We adopt this concept for archaeological

purposes and develop methods to create maps at a variety of scales that illustrate variations in topographic complexity. We use SRTM 30 (Shuttle Radar Topography Mission) and SRTM 3 Digital Elevation Model (DEM) data with a spatial resolution of about 30 arc sec (~900m) and 3 arc sec (~90m), respectively, and a vertical resolution of <20m. Recently, DEMs based on ASTER images have become available with a lateral resolution better than 25m and vertical resolution better than ±5 m. We convert the two-dimensional elevation data into measures of roughness using a variety of filter functions, and convert numerical measures into a colour scale for purposes of mapping and visualisation. For detailed studies of particular sites, we also use a ~10m resolution DEM derived from Stereo SPOT images, combined with field observations. Full details on the specific steps we follow to construct such maps are presented elsewhere (Bailey et al., 2010). We emphasise that a roughness map is not the same as a relief map or a slope map, although a slope map is one way to characterise roughness. Rough terrain can occur at high elevations and at low ones, and on steeper slopes as well as shallower ones. It can occur in the form of major fault scarps and deeply incised gorges hundreds of metres high, as minor fault scarps metres high, or as eroded boulder fields of lava. Minor features can pose subtle but equally formidable constraints as major ones on the relative mobility of hominins and other fauna and on local sediment and water supplies, but their presence and effects may be more difficult to identify without the application of appropriate filter functions to high resolution digital elevation data combined with ground observations.

Before considering individual site regions, we illustrate the application of these methods at an African scale, in order to demonstrate the general relationship between relief (Figure 3a), roughness (Figure 3b) and tectonic activity as mapped by records of modern seismicity (Figure 4a) and volcanism (Figure 4b). This shows that a map of relief based on differential elevation produces a different pattern from a map of roughness. There are some areas of similarity, reflecting the fact that regions of high relief tend to be the product of mountain building at plate boundaries as in Northwest Africa, or rifting, where widening of the rift is accompanied by progressive elevation of the rift flanks as in East Africa and the Red Sea. But there are also areas of high relief that are not rough, notably in the highland regions of Southwest Africa. High levels of roughness are also present in areas of more subdued relief such as the Sinai Peninsula and the Syrio-Jordanian region of strike slip.

There is a much closer correlation between roughness and known or expected high levels of tectonic activity: throughout the African Rift in both its western and eastern branches, along the Aden and Red Sea Rifts, along the Syrio-Jordanian Rift, and in Northwest Africa. There are also high levels of roughness in South Africa, a region previously considered to have relatively modest levels of tectonic activity (Wagner, 1927; McCarthy and Hancox, 2000) but now known to have evidence of recent faulting that has been overlooked in previous geological mapping (Bailey et al., 2010; Dirks et al., 2010). However, not all areas of roughness in South Africa are correlated with seismicity and this reflects the distinctive geological history of the region, where a general dome-like uplift of more than 1 km has occurred in the last 30 Ma or less, believed to be the result of expansion due to heat from the mantle acting on a stationary overlying plate or a mantle plume (e.g. Nyblade and Sleep, 2003). The great escarpments to the east and west are the result of erosion around the edges of this uplifted dome (Burke, 1996). This has produced extensive areas of roughness but without the associated evidence of faulting present in other regions of roughness.

4. Site Regions in Africa

We select two examples here to illustrate the application of the above methods at the scale of site regions in an African context. Both are associated with some of the earliest and most concentrated evidence of early hominin activity in Africa: the Awash Valley of the Afar region in Ethiopia (White et al., 1993, 1994, 2003, 2006; Semaw, et al., 1997; de Heinzelin, et al., 1999;

Dominguez-Rodrigo, et al., 2005); and the Cradle of Humankind region of South Africa (Dart, 1925; Vrba, 1982; McKee, 1993; Kuman and Clarke, 2000; Partridge, 2000; Tobias, 2000).

4.1. Awash Region

Habitat reconstructions based on the analysis of sediments demonstrate that a range of vegetation types was probably present during the time of hominin occupation, including, swamps, seasonal

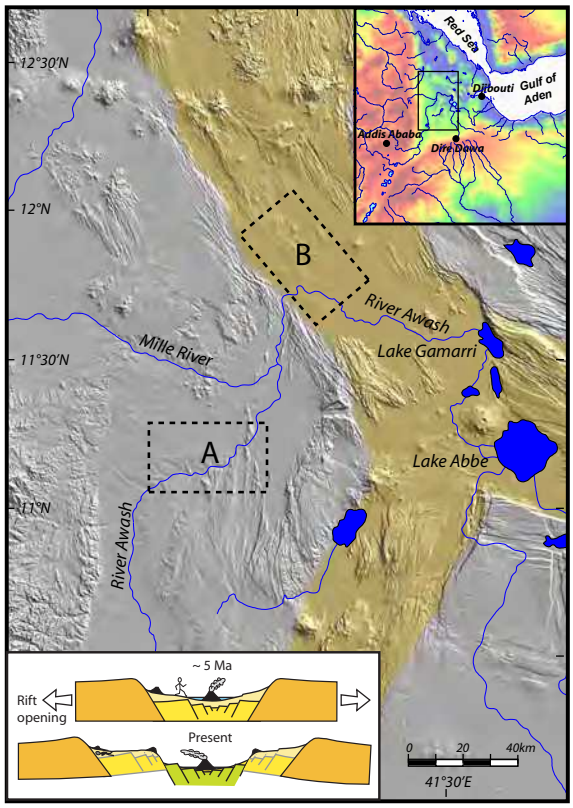


Figure 5.
The Afar region of Ethiopia, showing areas of the currently active Rift and the fossil sites of the Awash.

The area shaded in light brown is the currently active Rift. Rectangle A shows the region of the fossil sites of the Middle Awash River. It is located on the now-uplifted flank of the active Rift, but at the time when the sites were being formed it was located in the active Rift margin (see lower inset). Rectangle B is the region chosen as our analogue in the present active Rift margin (Manighetti et al., 2001; Rowland et al., 2007; Ayele et al., 2007).

pans or 'playas', and more closed, wooded regions (Johanson et al., 1982; Kalb, Oswald et al., 1982; Kalb, Jolly et al., 1982; Radosevich et al., 1992; WoldeGabriel, et al., 1994, 2001; Semaw et al., 2005). However, the relationship of these features to the original topography is difficult to establish in the present-day landscape because of the substantial changes that have been caused by active rifting over the past 2 Ma. When these sites were first created, they would have been located on the Rift floor close to the active margin of the Rift (Figure 5). The zone of active rifting is associated with high levels of local faulting and volcanic activity, and at any one time this zone is quite narrow, no more than 1–2km wide (e.g. Wright et al., 2006; Ayele et al, 2007; Rowland et al., 2007; Grandin et al., 2009). This is the local geological environment in which the sites would have been located at the time of their creation. Since then, these locations have been progressively uplifted, so that they are now far removed from the active margin of the Rift and located at a higher elevation on the uplifted flanks of the Rift. In their present location, important details of the original landscape morphology have been eroded and smoothed over time, while

river downcutting and erosion resulting from uplift have further transformed and modified the landscape with the creation of new features.

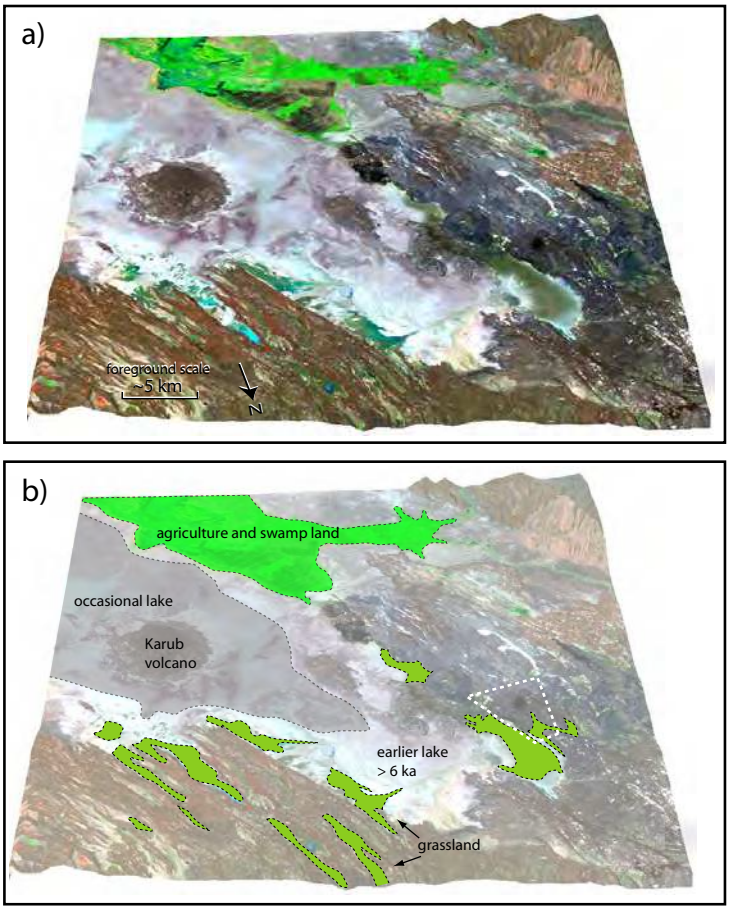


Figure 6.
The analogue region situated in the present-day active Rift margin, showing (a) a 3D image; and (b) an interpretation of the features in (a).

In (a) the image is created from a Landsat thematic mapper image (bands 2, 4, and 7 are red, green, and blue respectively) draped over exaggerated SRTM 3 digital elevation data to give a 3D effect of the area in the vicinity of the Karub volcano. In (b) the major landscape features are indicated: a wetland where the Awash River enters the plain (dark green); smaller plains (light green); and a region that hosts an occasional lake under present climatic conditions and a permanent lake prior to ~6ka (Gasse, 2001). A white quadrilateral outlines the area shown in Figure 7. The features found in this region are typical for the active Rift.

If we are to understand what the local topography and topographic dynamics were like in these locations in Plio-Pleistocene times, we need to proceed by analogy. That is, we need to go to an area where the Awash River emerges onto the currently active Rift floor. We therefore provide a reconstruction of just such an analogue region in the area of the Karub volcano, which lies in the present-day zone of the active Rift (Figures 6 and 7). The region includes a range of environments: an annual lake (shaded grey), wetland and swampland (associated with the Awash River) now flood-controlled for agriculture (light green) and many smaller zones of grassland currently exploited by modern shepherds (Figure 7). The Afar region has in the past been more humid (Gasse, 2001) with the light coloured region probably occupied by a fresh water or slightly brackish lake at >6 ka and continuous with, or linked to, the present-day lakes Adobada and Abbe. The Gablaytu volcano is dissected by active faults that create vertical cliffs and enclosed

fertile valleys. There are also blocky lava flows, which could provide tactical advantage (Figure 7). We cannot claim that the analogy replicates exactly the features that would have existed locally around the earlier sites, but features such as these are very common when a rift is active and disappear when activity ceases.

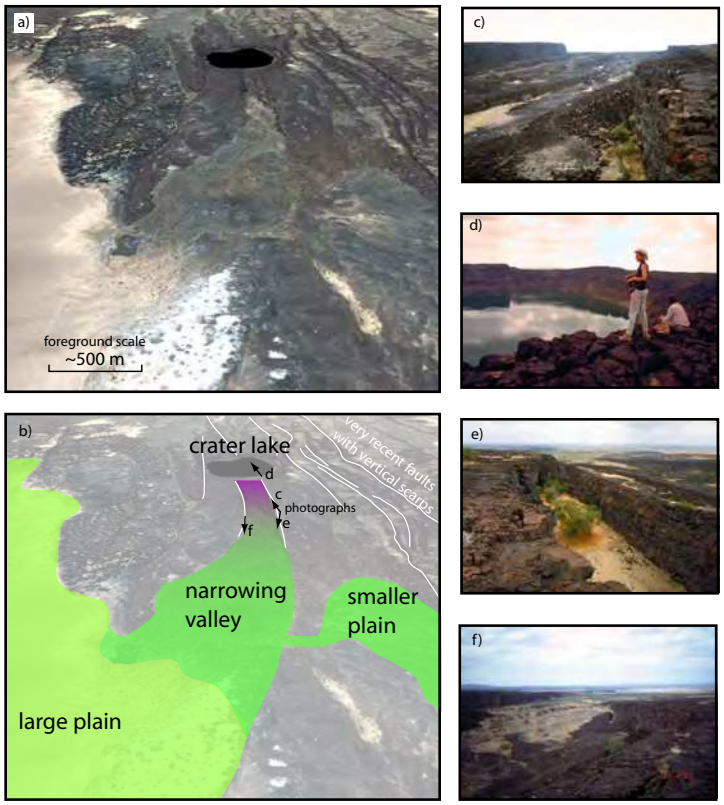


Figure 7.
Close up of the region indicated in Figure 6.

(a) is a modified Google image showing a crater lake, volcanic lavas and fault scarps in the vicinity of the Gablaytu volcano, and associated plains of varying size; and (b) is an interpretation of features shown in (a). Photographs show views of: (c) a narrow valley bounded by relatively impassable lava flows and fault scarps; (d) the Gablaytu crater lake; (e) a close-up of fault scarps with a small enclosed valley in the foreground and more open terrain in the distance; and (f) a more general view of fault scarps and lava flows with a partially enclosed plain in the middle distance and a large plains area in the distance.

4.2. The Cradle of Humankind

The "Cradle of Humankind" World Heritage site containing the famous Sterkfontein material lies within the catchment basin of the upper Crocodile River (Figure 8). This region hosts major sites with early hominin fossils and extensive non-hominin fauna, comparable in its evolutionary and archaeological significance to other regions of South Africa such as Makapansgat and Taung. Investigation of the topography and tectonic history of these latter regions has demonstrated the presence of numerous previously unrecognised tectonic features in association with fossil and archaeological finds (Bailey et al., 2010), and we extend our methods of investigation here to the Crocodile Basin. In these regions the rates of tectonic activity are much less than in the most active parts of the East African Rift, so that reconstructions of the ancient topography as it existed at the time of earliest human presence are easier to achieve, but tectonic features are certainly present.

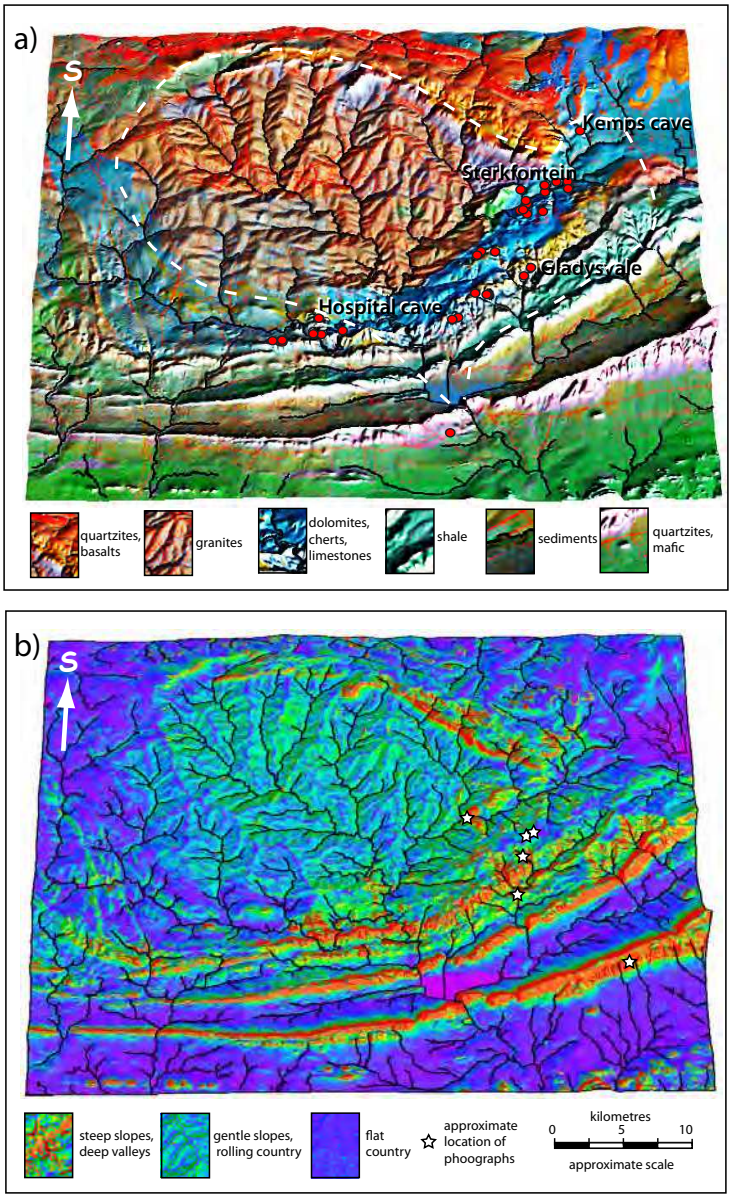


Figure 8.
The Crocodile Basin showing (a) shaded relief and geology, and (b) roughness.

In (a) the outline of the Crocodile catchment is shown by a white dashed line. Within this region the dominant geology is granite surrounded by quartzites, shales, dolomites, limestones and some other rocks. All dip away from the granite core. Fossil sites (red circles) located so far have been found in caves in limestones and dolomites around the southern margin. Four sites are identified. In (b) the granite core of the Crocodile catchment has been deeply eroded and shows a relatively smooth surface. More complex topography is created in hard rocks such as quartzites or volcanics and to some extent limestones and dolomites. The geological data in (a) is derived from the 1:250,000 geological maps. It is merged with a shaded relief map derived from the Aster DEM and draped over the DEM. The roughness map (b) results from applying a 12db/octave high-pass filter to the DEM. The result is draped over the DEM.

The strata in the region have been up-warped as a consequence of an ancient granite intrusion (~3200 Ma) to form the Johannesburg dome. The granite has eroded down to a much greater extent than the surrounding rocks and as a result the outline of the basin roughly coincides with the edges of the dome. In the past the whole region is thought to have been covered with Karoo sediments, which were then subsequently removed. Although the date of this erosion is not well established, it appears to have been relatively rapid, resulting in the present form of the Basin. The fossils are found in limestone or dolomite caves (Dirks et al., 2010), and these younger rocks lie outside the dome and are absent within it (Figure 8a).

There is considerable variation in the degree of topographic roughness across the region (Figure 8b), with the smoothest surfaces occurring on the heavily eroded granite, and the roughest terrain in the limestones, quartzites and volcanic rocks around the margins of the basin. Here there are steep escarpments and incised river valleys. Some recent cosmogenic results quantify

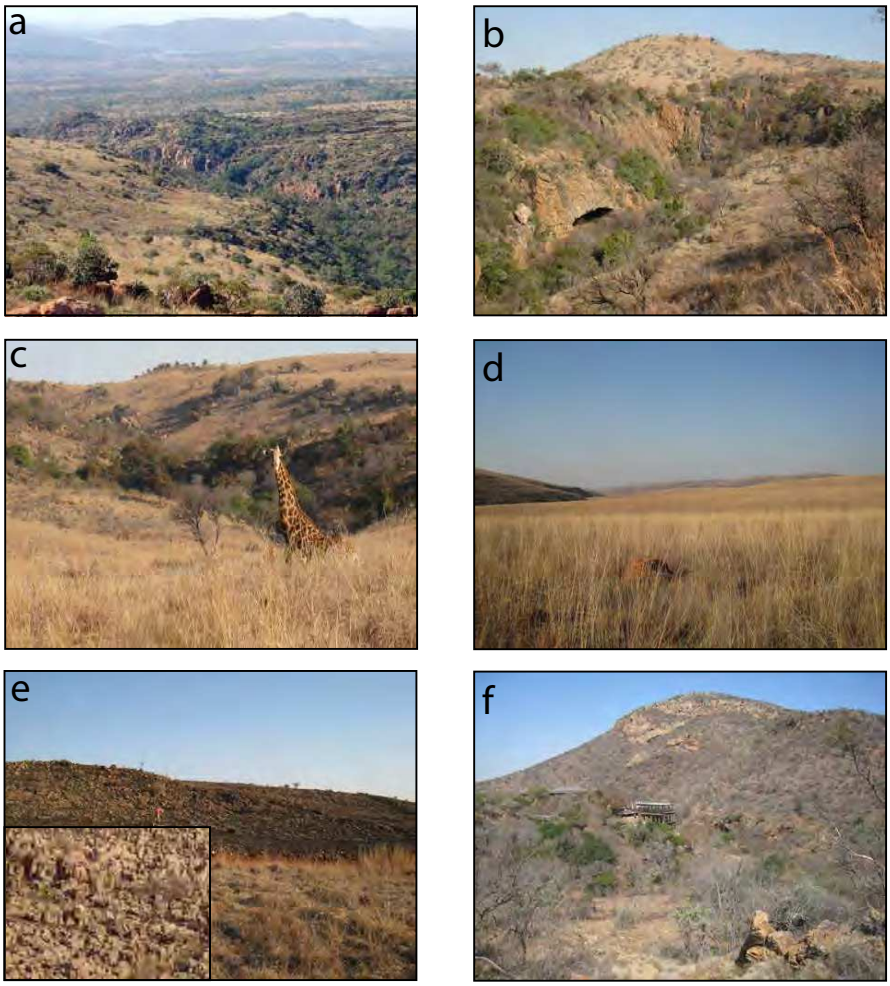


Figure 9.
Examples of landforms in and around the Crocodile Basin.

Figures 9(a) and (b) show streams incising hard quartzitic rocks, with a plain in the background (a) and smooth topography on higher ground (d), (c) and (d). The limestones and dolomites provide good grazing but the grass lands can conceal a rough (angry) karst which is difficult to cross. The extent of the karst is only revealed as in (e) following periodic fires. Figure 9(f) shows complex topography close to the site of Sterkfontein.

down cutting rates (Dirks et al., 2010). An old surface, perhaps the African Surface (Burke and Gunnel, 2008), is being eroded at ~5m/Ma. The immediate region of Sterkfontein is eroding at ~20m/Ma and a river valley in the NW part of the basin by 30m/Ma (Gladysvale and Gondolin region). At these rates most of the basin could have been created in less than 5Ma. Why this region should erode more rapidly than adjacent regions is not clear. A number of explanations are possible. At a broad scale it is the result of head-ward erosion of the Limpopo system (of which the Crocodile River is a tributary) caused by the uplift of Southern Africa discussed earlier. More local tectonic effects may have been a contributory factor, although unambiguous evidence for faulting that disturbs surface morphology can only be found near Sterkfontein and not throughout

the region (Bailey et al., 2010). Only more extensive cosmogenic dating in the future will resolve these questions.

Nonetheless, over a wide region the Crocodile basin exhibits features commonly associated with local tectonic activity (Figure 9). Figure 9 shows streams incising into hard quartzitic rocks. There are both high and low plains The limestones and dolomites make good grazing but the grass lands conceal a rough (angry) karst which is difficult to cross and of known danger to cursorial mammals such as giraffe (Warden of Nash Game Reserve, pers. comm.. 2007). The extent of the karst is only easy to see following periodic fires. This and previous papers discuss rough topography at the scales of 10s of metres to 10s of kilometres. However small scale roughness on the scale of 10s of centimetres commonly occurs for some rock types (limestones, dolomites and basalts). Although not easy for humans and their ancestors to cross, such rough ground can be a much more substantial obstacle to some cursorial mammals. In addition to the topographic features shown, reliable springs are a characteristic of the region, particularly in the limestones and dolomites. Although erosion has been substantial in the last 4 million years, similar features to those shown in the photographs would have been distributed across the Cradle of Humankind region throughout that period.

5. The Red Sea Basin

If topographic features created and sustained by active tectonics are important in the core areas of human evolution in Africa, the question naturally arises as to their impact on pathways of dispersal beyond Africa. By longstanding convention, the primary exit point for the earliest expansion of human populations out of Africa and into surrounding regions has been assumed to be the Nile Valley and the Sinai Peninsula, and this continues to be the favoured hypothesis, principally on the grounds that it does not presuppose any abilities to cross sea barriers, and that the currently available evidence is most economically explained in terms of a land route (Derricourt, 2005). One side effect of this hypothesis has been to deter consideration of the Arabian Peninsula as a region of any significance in early human settlement and dispersal, a neglect reinforced by the difficulties of working in the region, the absence of well-dated early finds, and an assumption of persistent climatic aridity during the Pleistocene. However, recent interest in the 'southern corridor' across the southern end of the Red Sea as a potential alternative pathway of human expansion, particularly in relation to anatomically modern humans (Lahr and Foley, 1994), and the demonstration of an abundant Palaeolithic archaeological record of obvious (if not well dated) time depth and episodes of Pleistocene climate wetter than at present (Petraglia and Rose, 2009), has focussed attention on the Red Sea region as a whole as a potentially suitable habitat for human settlement and dispersal, particularly with respect to its potential marine resources (Stringer, 2000; Walter et al., 2000; Bailey, 2009). Our discussion of tectonic models and methods of mapping provides a useful point of entry into the evaluation of these ideas and the potentials of the region more generally for human settlement and dispersal.

The Red Sea Basin extends for 2000km on a north-south axis with a maximum width of c. 350km and a maximum depth of c. 2850m, and originated as a terrestrial depression over 150Ma ago. Rifting, propagating from the Indian Ocean perhaps as early as 40Ma, and separation of the Arabian and African Plates by pulses of seafloor spreading, created a progressively wider and deeper marine basin and uplift of the adjacent mountain ranges, particularly after 5Ma (Girdler and Styles, 1974; Omar and Steckler, 1995; Manighetti et al., 1997). The timing of these processes and rates of change are not well constrained, but plate motions and volcanic activity are ongoing today. The resulting geological structure of the adjacent coastal regions is one of crystalline basement and sedimentary rocks of Oligocene and later age, which form mountain escarpments reaching elevations of over 3000m in the south, with extensive distribution and thickness of basalt flows, many of Pleistocene age or more recent. Sand and gravel outwash deposits of Pleistocene or Holocene age cover much of the coastal plain, with coral reefs and recently formed salt flats along the coast edge. Older shorelines are present as uplifted and cemented coral reefs in some areas (Gvirtzman, 1994; Taviani, 1998). Evaporites, formed during the Miocene when the Red Sea was cut off from the Indian Ocean, achieve considerable thicknesses and create additional tectonic warping and instability as a result of local salt doming

and dissolution (Bosence et al., 1998; Plaziat et al., 1998; Warren, 1999). The region is therefore one of considerable and ongoing geological instability, resulting from a combination of rifting and volcanism, more localized salt tectonics, and isostatic warping associated with sea-level change.

5.1. Absolute barriers

A first and obvious question to pose is the impact of these geological changes on the Red Sea as an absolute barrier to Pleistocene human dispersal, particularly at the southern end. The Bab al Mandab Straits is today 29km wide, an effective barrier to movement in the absence of seafaring technology. However, 100km north of the Straits at the Hanish Sill, the seabed is only 137m deep, and this raises the question of how the geometry of the Red Sea opening has been affected by sea level changes of the glacial-interglacial cycle and by longer-term opening by rift propagation. Modelling of palaeoshorelines taking account of isostatic adjustment suggests that the Straits would have narrowed considerably but not closed completely at maximum sea level regression (Lambeck et al. forthcoming; Bailey et al., 2007), and this is consistent with isotope data from deep sea cores, which show continuous water flow between the Indian Ocean and the Red Sea over the past 450,000 years (Siddall et al., 2003). However, at low sea levels the sea channel would have been long and narrow, and detailed consideration of the duration of these episodes and the associated channel geometry suggests that crossing by swimming or rafting could have occurred without difficulty over many thousands of years during the glacial cycle (Bailey et al., 2007; Bailey, 2009).

A more difficult issue to resolve is how the width and depth of the channel have been affected by rift propagation, particularly in the time range beyond the currently available isotope record, between 450,000 years and the putative first exit of human populations out of Africa some time after 2Ma. Simple extrapolation of recent measurements for the rate of movement of the Arabian Plate suggests that a land bridge could have been present as recently as 1.4Ma (Edgell, 2006). However, the rate of plate separation has most probably not been constant, and most of the plate motion in the south is taken up by deformation in the Danakil depression of Ethiopia, rather than in the Bab al Mandab region. Uncertainty persists on this issue, but the current assessment is that crossing of the channel would have been no easier during the late Pliocene and early Pleistocene, and perhaps less likely given the lower amplitude of sea level variation in that period (Bailey, 2009).

At the northern end of the Red Sea, absolute physical barriers blocking human and animal movement are less obvious, and dispersal into the southern part of the Arabian Peninsula could always have taken place via movements from the north, given suitable ecological conditions for range expansion, even if a sea channel at the southern end created an insurmountable barrier to a direct crossing from Africa to Arabia. However, just as the southern end is not such an impassable barrier to human movement as previously assumed, so the northern end may have been subject, at least intermittently, to geological processes liable to form obstacles to easy passage. At lowered sea levels, the relatively shallow Gulf of Suez would have dried out, offering a broader land route into the Sinai Peninsula. Conversely, the Nile periodically would have formed an extensive delta as today or a deeply incised series of gorges in its lower reaches, depending on the position of relative sea level, and both of these extremes could arguably have posed obstructions to easy movement. For much of the Lower Pleistocene there was no water flowing in the Lower Nile at all (Butzer, 1980; Said, 1993; Vermeersch. 2001). Thus, dispersal out of Eastern Africa via the Nile Valley and the Sinai Peninsula was not obviously superior to passage across the southern end of the Red Sea, or at any rate not persistently and uniformly so throughout the Pleistocene.

5.2. Roughness at Basin-wide and site-regional scale

A second question to pose, then, is how the geological history of the Red Sea Basin has affected conditions of topography and ecology in different regions. A simple, low-resolution roughness map with major lava fields added shows that there is considerable variability in the distribution of roughness, with the most obvious combinations of rough terrain and smooth plains lying on either

side of the Ethiopian Plateau, including the Afar Depression and the coastal region of Eritrea, the western and eastern flanks of the Arabian escarpment along its full length from Yemen in the south to the opening of the Jordan Valley in the north, and the Sinai Peninsula (Figure 10). These

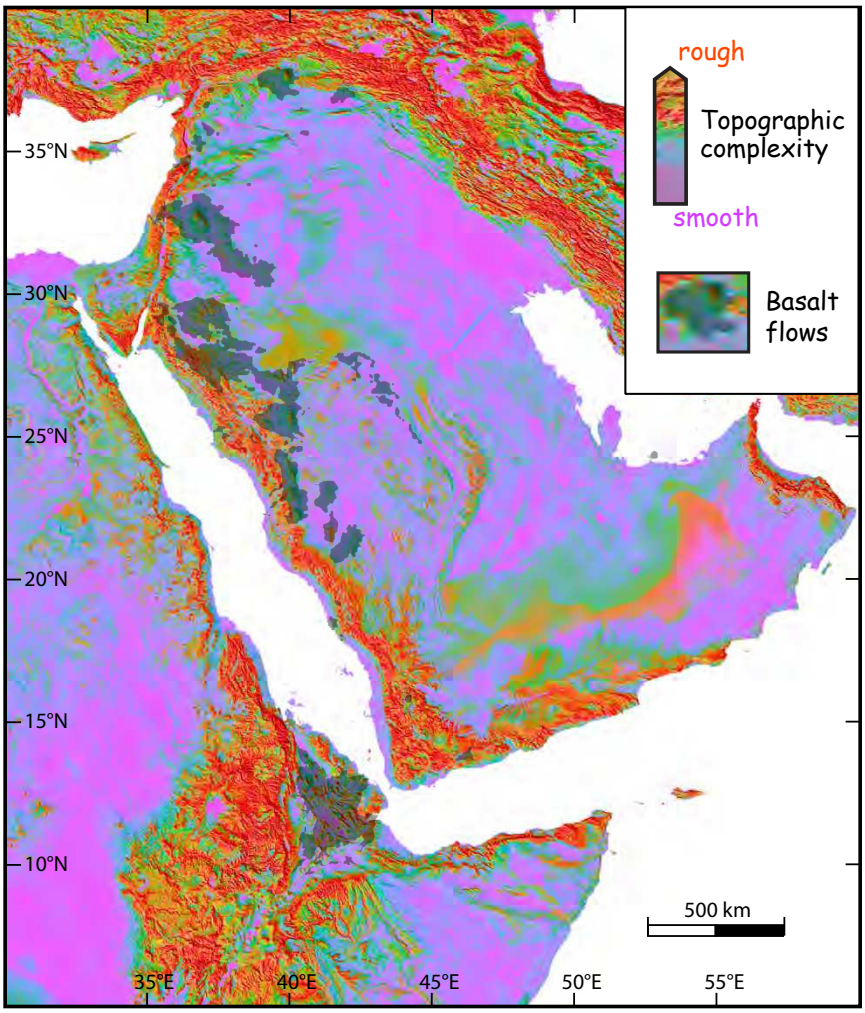


Figure 10.
Map of the Arabian Peninsula, showing relief, topography, roughness and major lava fields.

The base map is shaded relief. As indicated in the key red colours indicate rough topography and purple smooth topography. Lava flows are indicated as shown in the key. The combination of lava flows and rough topography found in Afar and the African rift is also found in the western Arabian Peninsula. SRTM 3 provides the base data for the map. Roughness is calculated using a 12db/octave high-pass filter. This is merged with grey scale shaded to produce the final map.

areas also coincide with the major basaltic lava flows, important as sources of easily accessible and workable raw material for stone tools. They are typically associated with some of the largest and most numerous Palaeolithic find spots in Arabia, though these are mostly surface sites and at present remain undated except in very broad terms (Petraglia and Rose, 2009). Moreover the western side of the Arabian escarpment including some of the most extensive lava fields are traversed by major drainage systems that today are mostly dry, but which contain substantial aggradations of river sediments indicating higher flows of water in the past. This corresponds to other palaeoclimatic indicators more widely distributed in the Arabian Peninsula demonstrating

periodically wetter conditions during the Pleistocene including shallow lakes in interior desert regions (Parker, 2009).

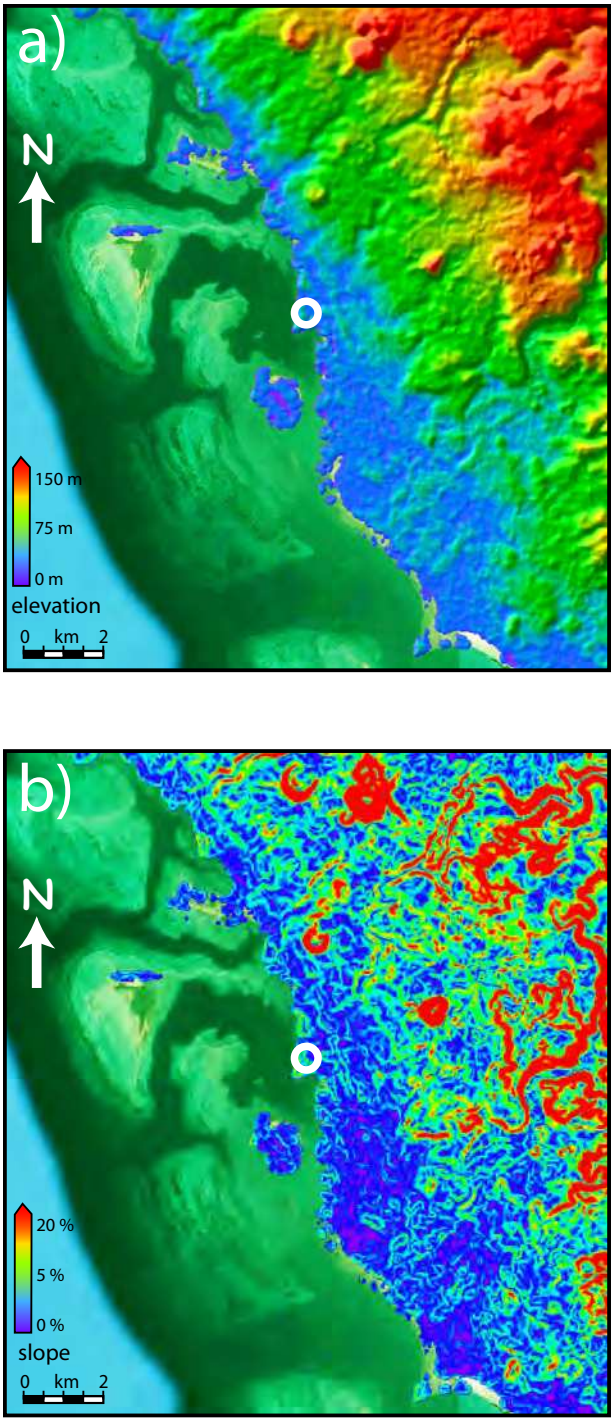


Figure 11.
The Al Birk site region, showing (a) topography and relief, and (b) roughness.

In (a), the onshore altitude is colour coded, and the Google image provides some indication of offshore bathymetry within about 2 km of the shore, although the depth is not calibrated. In (b), roughness for the on-land region is

represented by slopes indicated as percentages in the key. Slopes are one form of 6db/octave high-pass filter. The main causes of roughness are river incision and volcanics.

The most favourable and enduring conditions for human settlement on the basis of this roughness map, and the most obvious pathways of dispersal, are Eritrea and Afar in the

Figure 12.
Local area of fertility amidst a volcanic landscape in the hinterland behind Al Birk.

Southwest, and the flanks of the Arabian escarpment. This zone of favourable conditions continues northwards without interruption into the so-called Syrio-Jordanian Rift and then eastwards along the foothills of the Taurus-Zagros arc. Extensive fingers of rough terrain extend into the central Arabian Peninsula, and there are smaller-scale surface irregularities in this region not visible at this resolution but potentially of significance at the local scale. However, large-scale roughness tends to disappear as one travels eastwards across the southern part of the Arabian Peninsula. On this basis, the primary areas for earliest hominin settlement and dispersal, and the areas that would have been most persistently attractive and supported the largest populations, are likely to have been on a north-south axis between the Afar and the east coast of the Red Sea, extending northwards along the Syrio-Jordanian Rift, and around the Zagros arc to the head of the Gulf region between Arabia and Iran, rather than eastwards by the more direct route along the Indian Ocean coastline. The greater similarities of the stone tool assemblages in southwest Arabia to those in the Levant, at least those of Middle Palaeolithic type, rather than those further to the east, lend some support to this hypothesis (Marks, 2009).

An illustration of roughness at a more local scale is presented in the site region of Al Birk (Figure 11), an extensive scatter of stone tools of Lower and Middle Palaeolithic type close to the present-day coastline (Zarins et al., 1981; Bailey et al., 2007). The geology of the wider area is dominated by basaltic lava flows and cones of extinct volcanoes, and alluvial gravels. In the immediate vicinity of the site the lava cones have been dated at 1.3 Ma, which provides a

maximum date for the earliest artefacts in the area, while artefacts of Middle Palaeolithic type sit on the surface of a marine coral terrace most likely formed at about 130,000 years ago. Extensive lava fields appear at first sight arid and barren areas with few resources other than rocks for making artefacts. However, these lava fields present a locally rough surface that can trap sediment and water and create local 'oases' surrounded by rough terrain affording safety in the face of predators, competitors, or other threats (Figure 12). These are very similar conditions to those found in the lava fields of the African Rift (Bailey et al., 2000).

However, the map of the Al Birk site region highlights a significant problem. Today the site is on the coast edge, and an extensive area on the seaward side of the site simply appears as a blank area. But we have no reason to suppose that this is where the coastline was located when the site was in use. If sea level was lower than the present, then this blank area would have represented an important extension of land and resources of potential significance in the site region, and an area that needs to be investigated with the same techniques of landscape reconstruction as on dry land.

5.3. The submerged landscape

The drop in sea level throughout long periods of the Pleistocene is not only important in facilitating movement across pre-existing sea barriers. It would also have exposed an extensive new increment of land beyond the present coastline with potentially different conditions of

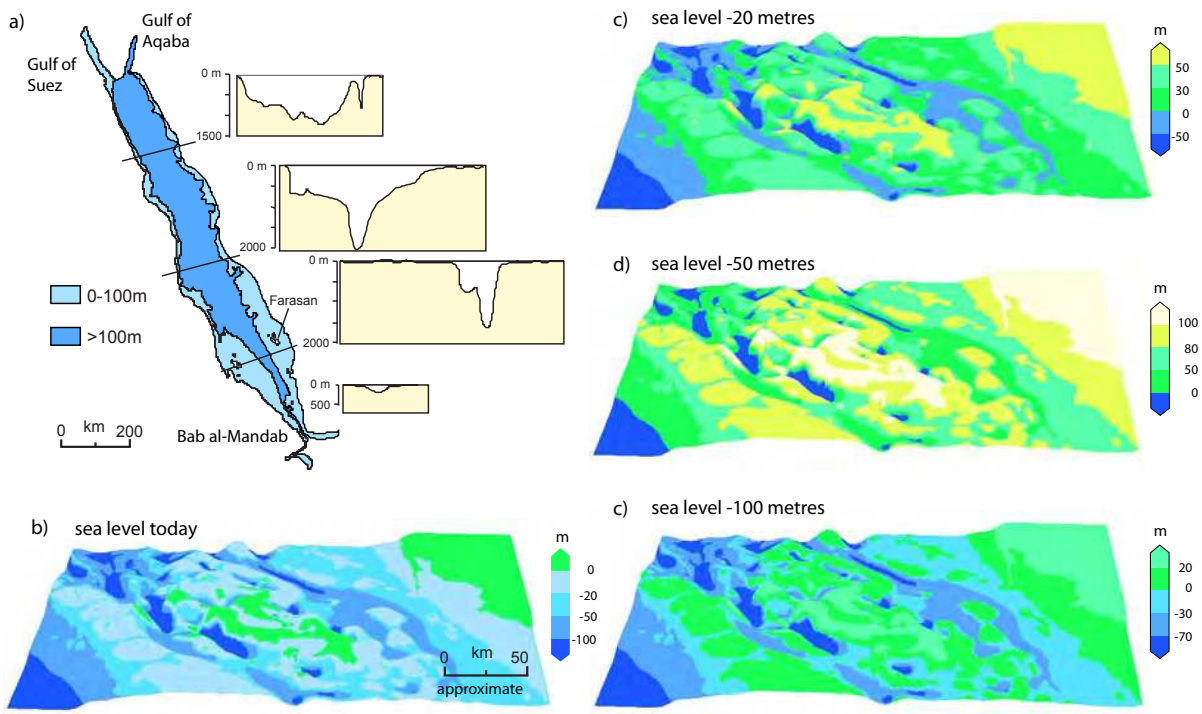


Figure 13.
Bathymetry of the Red Sea Basin and the region of the Farasan Islands.

In (a), regions of the Red Sea Basin shallower than 100m show that lower sea level exposed substantial areas of land especially in the southern part of the Basin. In (b) to (e) the topography of the exposed land in the region of the Farasan Islands is mapped at successively lower sea levels, at 0m (present-day), -20m, -50m, and -100m respectively, and presented as 3D images. These are based on bathymetry contours derived from navigation charts. The limited number and resolution of depth contours limits the methods that can be used to represent topographic complexity.

ecology and topography, and this would have been true both at the site-regional scale of Al Birk and more generally in coastal regions as a whole. Since sea levels have been substantially lower

than present for most of the Pleistocene period, this is a highly significant variable that needs to be factored into landscape reconstructions and models of dispersal. Many of the features observed on modern coastlines are the result of morphological changes in response to postglacial sea level rise (Westley & Dix, 2006). Coastlines that today look unattractive or impassable because of cliff lines and limited water supplies or extensive and impenetrable river deltas would have looked quite different at different sea level conditions. The areas that would have been most affected are those where the offshore shelf is shallow and the increment of new land most extensive. This is especially the case at the southern end of the Red Sea, where new areas of dry land exposed on both the Arabian and African sides of the Basin at maximum sea level regression would have extended offshore from the modern coastline by 100 km or more. The present-day archipelagos

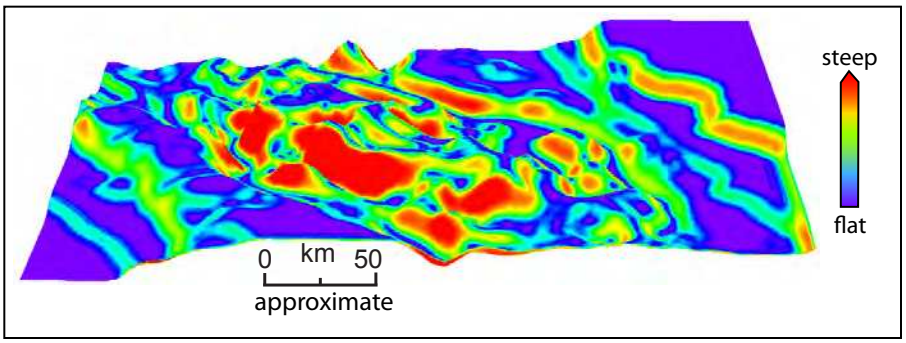


Figure 14. *Roughness map of the Farasan Islands.*

such as the Dahlak Islands and the Farasan Islands would have appeared as low hills in an extensive coastal plain (Figure 13). However, even on steeper parts of the continental shelf along the Red Sea and around the Indian Ocean coastline of southern Arabia, the increment of new land, though narrower, may have created quite different and potentially more attractive conditions.

The topography and environment of this now submerged landscape is largely unknown, although obviously important to the analysis of human dispersal routes. However, it is possible to make some initial comments on the basis of current information. Navigational charts, even though they provide only general indications of bathymetry, show that the topography of the submerged surface in the Farasan region has a surprising degree of complexity for a shallow shelf region, and this can be demonstrated by applying the same techniques of roughness mapping to the bathymetric data that we have developed for the analysis of terrestrial topography from satellite data (Figure 14). This topography is due to the effect of salt doming with uplift of evaporite deposits accompanied locally by salt withdrawal to form deep depressions, as well as to more widespread processes of rift propagation. The result is a complex topography with localised barriers and basins that would be very familiar to human populations adapted to conditions in the African Rift. The results are obviously quite crude because of the limited number of data points currently available and their low resolution, but improved detail could certainly be obtained with the application of the appropriate methods of underwater survey.

Some of this exposed region would most likely have been covered in linear sand dunes accumulated from deposits picked up by wind action from the exposed sea floor, as is the case in parts of the modern coastal plain (Munro and Wilkinson, 2007). But, as in the present topography, so on the now-submerged landscape, this was most likely only one element in a complex mosaic of surface conditions. In such topography we would expect to find localised areas of greater fertility with traps for sediment and water, and it is possible that ground water movements associated with a drop in sea level would have created better-watered conditions than is the case today (Faure et al., 2002), an outcome that would have been of great significance to human settlement in periods when climatic conditions are likely to have been at their most arid in the adjacent hinterlands. Moreover, these conditions of topographic complexity are also likely to have produced conditions favourable to the preservation and protection of local terrestrial features

and archaeological deposits from the destructive impact of inundation during periods of sea-level rise (Bailey et al., 2007).

We cannot pursue the reconstruction of the submerged landscape in more detail with the available information, but these considerations strongly point to the need for a more detailed and extensive programme of underwater survey using techniques of swath bathymetry and sub-bottom profiling, coring of sediments in the shelf region, divers, and underwater vehicles. In this way, it should be possible to produce roughness maps of the submerged continental shelf to complement those that we can produce for the present-day land surface from satellite data, together with palaeoenvironmental data from sediment cores, and possibly archaeological material. With the development of such underwater surveys, it should then be possible to complement, extend and refine the modelling techniques that have been recently applied to assess patterns of human dispersal in Arabia and adjacent regions (Field and Lahr, 2005; Field et al., 2007).

6. Discussion

With the examples presented above, we have shown how the mapping of roughness, in combination with additional data from satellite and ground observations, highlights the association of active tectonics and complex topography with the archaeological and fossil material, even in areas such as South Africa where these features have not previously been identified or recognised as significant variables in hominin land use. This in its turn suggests a preference by hominins for such conditions with their attendant advantages of local resource fertility and diversity, enduring water supplies, and improved access to prey and avoidance of predators. However, there are some important qualifications that should be recognised.

First, the sample size of site regions presented here is small. There are many other sites and site regions that we could have selected to provide a larger comparative sample. However, comparative analysis and interpretation is not simply a case of producing more roughness maps. Many other studies should ideally be carried out in relation to roughness reconstructions at the local and site-regional scale, including studies of the underlying regional tectonics and geology, and chronologically-based studies of local landscape change, if the benefits of the methods proposed in this paper are to be effectively realised. One important variable is detail on rates of tectonic movement and landscape change. These are likely to have been quite variable as between the different regions we have examined. We know that changes occurred more rapidly and with more dramatic effect in the Awash region than elsewhere, so dramatically that we have resorted to an analogical approach to landscape reconstruction. Changes on a similar scale may have occurred in other parts of the Rift, and this degree of inter-regional variability may have been highly significant in relation to ecological and evolutionary changes. Few detailed geochronological studies have yet been undertaken on the scale necessary to facilitate geographically extensive reconstructions of landscape change, although the necessary techniques such as cosmogenic dating of fault movements and radiometric dating of lava flows and sediment infills are available to develop such an approach in future research.

Secondly, there is, in theory, a risk of auto-correlation between the visibility of archaeological and fossil sites and the degree of geological instability and topographic complexity in the regions where they occur. For example, it could be hypothesised that the abundance and concentration of archaeological finds in areas of active tectonics is not due to their inherent ecological attractiveness as areas for human settlement and activity, but to higher levels of preservation and exposure of archaeological material by high rates of faulting, erosion and sedimentation. However, the relationship between tectonic activity and site preservation is not a simple one. Tectonics may destroy as much as (or perhaps more than) it preserves or exposes to view. We could equally well hypothesise that archaeological materials, especially durable items such as stone tool artefacts, are likely to be more visible in areas of stable and smooth topography, not less visible, since once deposited on a flat surface, they are likely to remain there indefinitely, being subjected neither to movement nor to burial by later sediments. The problem of 'site taphonomy' – the differential visibility of archaeological sites and materials resulting from differences of geological context, differential preservation, differential exploration, differential

recovery, and differential amenability to dating – is all pervasive, and confronts all attempts to seek significance in spatial and chronological patterning. Differential preservation and visibility are undoubtedly important factors that need to be addressed. The issue here is not whether variations in the distribution of archaeological and fossil sites are either solely the product of differential preservation and visibility, or solely the product of differences in the density of human populations and the intensity and duration of human activities. Rather, the issue is the relative influence of each of these variables on the resulting pattern. And this is only likely to become clearer through the application of the methods of landscape reconstruction described here, and the development and further testing of hypotheses suggested by the patterns that emerge from these reconstructions.

Finally we should emphasise that our perspective does not rule out use of regions with less topographic complexity or geological instability. Our point is that these regions are likely to be more vulnerable to climate fluctuations, and less favourable to persistent and enduring human occupation, or alternatively more demanding of social and technological innovations. The consequence is that archaeological data in such regions are likely to be sparser and less visible, or late in date. The evidence for intermittent expansion of human settlement into the most arid parts of the desert interior in Africa and Arabia in conditions of limited relief and topographic complexity, and their subsequent abandonment (e.g. Osborne et al., 2008; Parker, 2009; Uerpmann et al., 2009), is a powerful testament both to the importance of surface water as an attractor and limiting factor in human settlement, and to the vulnerability of such regions to changes of rainfall.

7. Conclusion

We have presented methods for reconstructing landscapes at a wide range of geographical scales, taking advantage of modern satellite imagery and concepts of roughness as a proxy measure of geological instability. We concentrate on the description and illustration of the results for a small number of selected case studies, each drawn from different geological and tectonic conditions, rather than on interpretation in relation to specific issues of evolution and dispersal or specific periods of time, in order to lay the foundation for the finer-grained reconstructions, more geographically extensive comparative studies, and more detailed integration of archaeological and fossil evidence, which will be necessary for such purposes. We have also shown how this approach can be extended offshore to the mapping of submerged land surfaces exposed when sea level was lower than present, highlighting the need to develop a seamless approach to the reconstruction of landscapes across the modern boundary between land and sea. This type of underwater investigation is still in its infancy and poses many financial and logistical challenges. But as the techniques become more widely applied and the potential of such studies more firmly established (e.g. Gaffney et al. 2007, 2009), so the submerged landscapes of the continental shelf are likely to emerge as a critical variable in hominin evolution, dispersal and social development, and one demanding the same degree of attention and investigation as the evidence on dry land. Our preliminary studies of changing conditions in the Red Sea suggest that this type of investigation will be especially critical in the analysis of different 'Out-of-Africa' scenarios of human dispersal.

The underlying theme of our investigation is that regions with high levels of geological instability are likely to be inherently attractive to humans, despite the occasional disruptions or destructive impacts that can occur in such conditions. This does, however, pose a paradox, and that is that such geologically unstable regions are also by definition the regions where it is likely to be most difficult to reconstruct in detail the original landscape morphology. Nevertheless, we have presented here methods of investigation and mapping that can circumvent or limit such difficulties.

Interest in abiotic environmental factors in human evolution is not new, but it has been dominated for the most part by an emphasis on climate. The availability of a wide range of climate proxies, more or less continuous sequences of climate change, often with fine chronological resolution, a world-wide framework provided by marine isotope stratigraphy, and a broad consensus about the global mechanisms that drive climate change and their regional

impacts, have resulted in a variety of hypotheses about the interaction of climate and evolutionary change (Vrba et al., 1995; Bobe and Behrensmeyer, 2004; deMenocal, 1995, 2004; Potts, 1996, 1998; Sepulchre et al., 2006; Kingston, 2007; Maslin and Christensen, 2007). By comparison, investigating changes of the physical landscape has been severely handicapped, with poorer quality data, greater difficulties of reconstruction, more severe problems of dating and correlation, especially at increasing geographical scales of observation, and uncertainties about the relative influence of climatic and tectonic processes on changes in surface morphology. As a consequence, the study of landscape variability and its influence on ecology and evolutionary trajectories has received relatively little attention. Here we have shown how variations in landscape morphology and variations in the underlying geophysical processes that create such morphology can affect the suitability of different regions for human habitation and dispersal. We have also presented methods that facilitate comparative analysis of landscape variability at a full range of spatial and temporal scales. With the further development and application of these methods, it should be possible to develop a framework for the comprehensive investigation of the relationship between landscape change and human evolution, and one that complements and integrates the evidence of changes in palaeoclimate.

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