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Landscapes of human evolution: models and methods of tectonic geomorphology and the reconstruction of hominin landscapes

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Abstract

This paper examines the relationship between complex and tectonically active landscapes and patterns of human evolution. We show how active tectonics can produce dynamic landscapes with geomorphological and topographic features that may be critical to long-term patterns of hominin land use but that are not typically addressed in landscape reconstructions based on existing geological and paleoenvironmental principles. We describe methods of representing topography at a range of scales using measures of roughness based on digital elevation data, and combine the resulting maps with satellite imagery and ground observations to reconstruct features of the wider landscape as they existed at the time of hominin occupation and activity. We apply these methods to sites in South Africa, where relatively stable topography facilitates reconstruction, and demonstrate the presence of previously unrecognized tectonic effects and their implications for the interpretation of hominin habitats and land use. In parts of the East African Rift, reconstruction is more difficult because of dramatic changes since the time of hominin occupation, while fossils are often found in places where activity has now almost ceased. However, we show that original, dynamic landscape features can be assessed by analogy with parts of the Rift that are currently active and indicate how this approach can complement other sources of information to add new insights and pose new questions for future investigation of hominin land use and habitats.

Keywords: East African Rift, Hominin landscapes, Roughness, Satellite imagery, South Africa, Tectonics, Topographic complexity *T*

Introduction

In this paper we examine the role of active tectonics in shaping complex landscapes as potential selective agents in hominin evolution and dispersal. We approach the problem of reconstructing tectonically active landscapes in two ways. First we look at methods of characterizing and mapping landscapes using “roughness”, techniques that make it possible to visualize complexity at a variety of geographical scales. Second, we examine active tectonic landscapes in relation to case studies of archeological and fossil sites, using satellite images and ground observation. This allows us to identify specific features associated with ongoing active faulting and to show how these aid in reconstructing and interpreting paleolandscapes.

The methods we use are adapted from the discipline of tectonic geomorphology, which has evolved from earthquake studies and has limited roots in conventional geomorphology. We provide a brief review of recent developments, since many specialists working within the field of human evolution, including geomorphologists, structural geologists and sedimentologists, are not familiar with them. We show that tectonic activity creates and sustains characteristic features of surface morphology at spatial and temporal scales that overlap with biological processes of ecological interaction and evolutionary change and which are therefore potentially important to hominins and other species. In particular, we show how ongoing activity can maintain hydrological regimes, topography and environmental conditions substantially different from adjacent landscapes that are tectonically inactive.

We describe in detail the techniques we adopt to identify topographic heterogeneity, and apply these techniques in different ways starting at the scale of the African continent and then focusing down to regions around inland sites in South Africa and Afar (Ethiopia). We choose South Africa because it is an important region of early hominin fossils and archeological assemblages, but one where ongoing tectonic activity and localized tectonic features have not been identified in previous geological studies or recognized as significant in the interpretation of hominin landscapes. We choose the Afar as another important concentration of early hominin discoveries, but one where the rate of tectonic activity has resulted in much more rapid and dramatic geomorphological change, so that local scale reconstructions of Plio-Pleistocene landscapes are only possible through an analogical approach. Finally, we consider the implications of such studies in the interpretation of hominin paleolandscapes and discuss the directions in which future research might be developed, building on the methods presented here.

Models and Methods

Earthquake studies and the development of tectonic geomorphology

A key event in the development of earthquake studies was the 1980 El Asnam earthquake ($M_s \sim 7.2$) in Algeria, which changed our views on the mechanism of fold formation and initiated a new approach to seismology and the understanding of structural geology (King and Yielding, 1984). Subsequent papers (Stein and King, 1984; King et al., 1988; Stein et al., 1988; Tapponnier and Armijo, 1989) extended to other regions the view that deformation due to repeating earthquakes dominates the form of landscape features in active areas. Of particular relevance to this paper, the uplift and damming of the Chelif River by the El Asnam earthquake and previous events provided the first clear example of how tectonic activity can locally modify the effect of climate change (Vita-Finzi 1969; King and Vita-Finzi, 1981; King and Bailey, 2006). Although this was noted, the subsequent development of tectonic geomorphology concentrated on primary objectives of studying earthquake hazard and the growth of mountains and rifts (e.g. Armijo et al., 1996; Tapponnier et al., 2001).

Tectonic geomorphology depends on identifying features of surface morphology that are characteristic of an active landscape. These include fault scarps, modified river terraces, wetlands or lakes, plus

other features that can only persist if ongoing tectonic activity continually renews them. These features are usually studied by tectonic geomorphologists as a means to establishing seismic hazard, but here we consider them in their own right for their potential role in creating and maintaining environments favorable to hominins (for additional examples of this approach see also King and Bailey, 1985; Bailey et al., 1993; King et al., 1994; King et al., 1997; Bilham, 1988; Bailey et al. 2000; Jackson, 2006; Force, 2008).

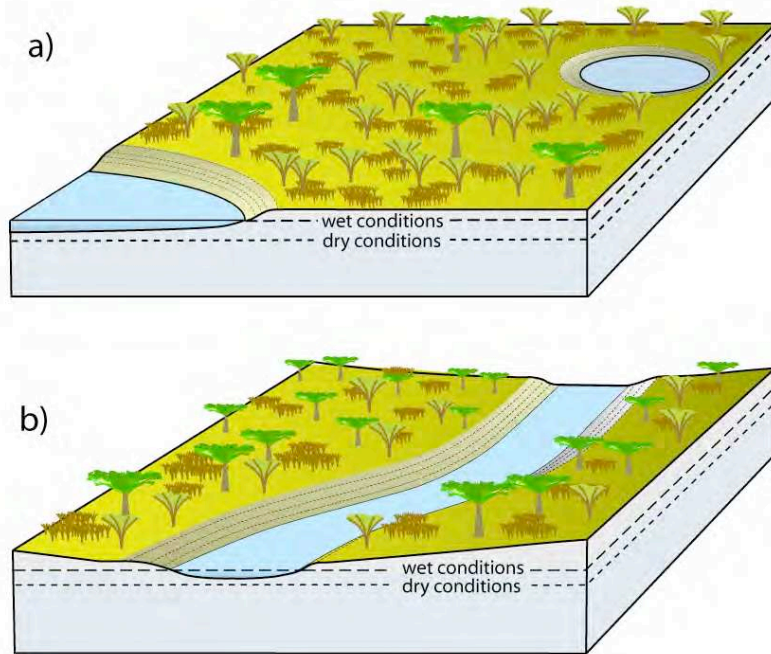


Figure 1 Schematic illustration of effects of changing water table in flat landscapes

- a) In regions of low relief, pans, water-holes and lakes are sensitive to changes of climate and can become dry if the water table drops.
- b) Rivers in regions of low relief are also sensitive to changes of water table resulting from climate change and can be perennial or completely dry. If there is a reliable source of water from a high rainfall headwater region such rivers can be more reliable.

intersects the surface (Figure 1a). These features and associated vegetation such as riverine forest are often seen as likely hominin habitats. However, the availability of surface water in such conditions is vulnerable to fluctuations in water supply. A climatically induced drop in the water table will change water levels, leading in extreme cases to complete desiccation. Similarly, rivers in inactive terrain are vulnerable to climatically induced fluctuations in water flow unless their headwaters lie in upland regions of persistently high rainfall (Figure 1b). In areas of low relief, even the most reliable rivers or lakes may dry up, creating localized conditions of extreme aridity. Such sensitivity is documented in North Africa (Vita-Finzi, 1969).

In tectonically active areas, the pattern of faulting can be dominated by three types of activity. Reverse faulting (Figure 2a) is typical of environments where the Earth's crust is contracting. Normal faulting (Figure 2b) occurs where the crust is being extended. In both cases, tectonic activity results in uplifted and down-dropped blocks of land at a range of scales. At the escarpments of normal faults themselves, steep slopes and almost vertical escarpments are often created and the fronts of reverse fault folds are commonly associated with rugged terrain that is difficult to traverse. A third pattern of faulting is strike-slip, which occurs where crustal blocks are moving horizontally with respect to each other. This

faulting is also associated with some vertical motion as a secondary consequence of geometric complexity (e.g. Bilham and King, 1989; Bowman et al., 2005), and can produce topographic features similar to those created by normal and reverse faulting (King and Bailey, 2006), but is not relevant to the examples discussed in this paper.

As a result of the disrupted land surface, rivers are disturbed, with terraces and gorges forming in the uplifted blocks. Water and sediments are ponded in the down-dropped regions, resulting in the

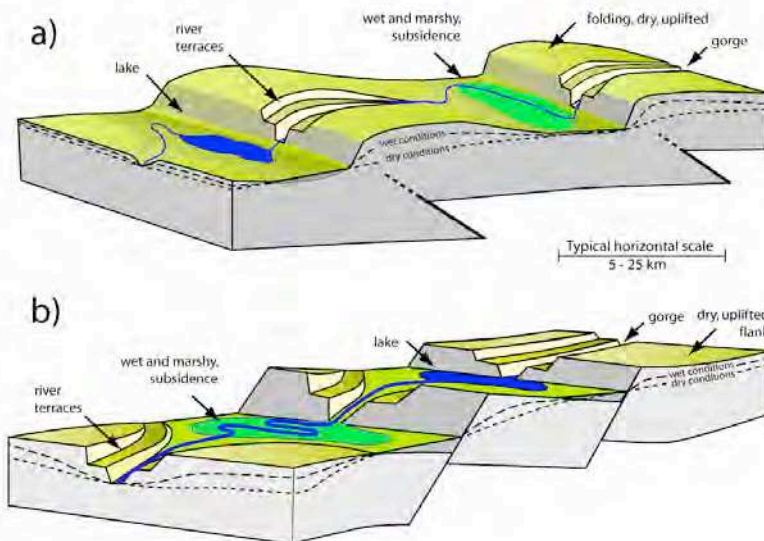


Figure 2
Schematic illustration of the effects of tectonic activity creating landscape features illustrated by examples in this paper. The scale bar shown in the figure is approximate. In each figure two faults are shown that could host repeated earthquakes with Richter magnitudes between 6 and 7. Smaller events in the same region with magnitudes between 3 and 4 will occur 10,000 times more frequently. In commonly visited 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 ~1 Ma. The Sea of Marmara did not exist at 4 Ma. Greek history records towns and villages that have sunk below the sea because of faulting. An easily accessible tourist site is the now submerged Byzantine church at Kekria (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 still generates spectacular features within human life times. In 2003 a small volcanic eruption was associated with dyking and faulting extending for 60 km with faults moving by 5 metres or more (Ayele et al., 2007; Rowland et al., 2007). Fault features such as those shown in Figure 18 only 30 km south of the 2003 volcanic faulting could have been created in less than a hundred years and may be active again in the near future.

a) Features typical of contractional (reverse-faulting) environments where the surface expression of faulting appears in the form of folds as well as faults that cut the surface.

b) Features typical of extensional (normal-faulting) environments. These produce similar features as in (a) but the faults usually fully cut the surface.

development of marshes or lakes (Fig 2a and 2b). In reality, the resulting topography is a more complex pattern of landscape features at a greater range of scales than is indicated in these simplified figures, comprising sedimentary basins and lakes of varying extent that trap the run-off from adjacent areas of uplift, and which are surrounded by barriers and enclosures of varying size. Many of the barriers could obstruct the movement of cursorial mammals while being negotiable by primates, hominins or modern humans, resulting in relatively secure enclosures with impeded drainage and localized areas of fertility.

The fault-bounded basins are rejuvenated by periodic earthquakes, and maintain a water table at or close to the surface that can persist almost indefinitely, except under very extreme conditions of reduced water supply. These conditions prevail only as long as the tectonic activity continues. Once it ceases, uplifted areas are liable to erode, subsided regions fill with sediment, the water-

table drops beneath the flattened surface topography, and surface water supplies subsequently become scarcer in the affected regions. It is only as a result of continuing tectonic motion that favorable conditions of sediment and water supply in the down-dropped regions are continuously rejuvenated.

In the African Rift, volcanic activity adds to these effects. At any given time activity is concentrated in the active rift, a zone a few kilometers wide, and includes episodic dyke injection associated with the creation of steep normal faults at the surface (e.g. Manighetti et al., 1998; 2001). Vertical motions are also associated with caldera collapse, resulting in crater lakes, and many forms of lava flow present barriers to certain animal species and enclosures that afford similar features of topographic complexity to those associated with faulting (King and Bailey, 2006, figure 2).

The common model of structural geologists (e.g. Woldegabriel et al., 2000), which averages long term rift evolution, is not, in fact, how such rifts evolve over shorter time spans of <1ka to >1Ma (e.g. Yirgu et al., 2006). This is well illustrated by the recent volcano-seismic crisis in Afar, which resulted in an average extension of 6 m over a distance of 60 km in the course of a few days in association with a small ash eruption (Ayele et al., 2007; Rowland et al., 2007; Wright, 2007). The common association of basalt flows and ash flows found at hominin sites is *prima facie* evidence that the majority of hominin sites occur in areas close to a locus of volcanic activity, and hence to the zone of active rift formation at the time when the hominins were present.

Characterizing landscape roughness

Maps that describe and date all the relevant active tectonic and volcanic features do not currently exist. Traditional geological maps often do not show even major active structures. For example, the active fault that bounds the southern side of the Gulf of Corinth has had more than 5km of dip-slip displacement in the last 1 Ma (Armijo et al., 1996) but is not marked as a fault on published maps. Maps or cross-sections of the East African Rift rarely distinguish between those parts that are currently active and parts that have long since become almost inactive (Manighetti et al., 1998). The features identified as geologically significant offset hard rock and are now inactive. On the other hand morphological features resulting from more recent and localized tectonic activity are not identified since they show no stratigraphic offset. Or else they are dismissed as the result of differential erosion

or compaction. Some maps of ‘active tectonics’ exist, but are of limited reliability (e.g. USGS tectonic maps). It will be many years before maps correctly identifying active features become readily available and the rates of motion are established. Volcanic features are more easily mapped and dated and detailed work has been done in areas such as Hawaii (Wolfe and Morris, 1996).

In developing such maps, tectonic geomorphologists have experimented with proxy measurements, some of which can be very complicated (e.g. Ouillon et al., 1997). One of the more useful is topographic ‘roughness’, which is a measure of irregularities in surface morphology commonly (but not uniquely) resulting from tectonic activity, and one which we

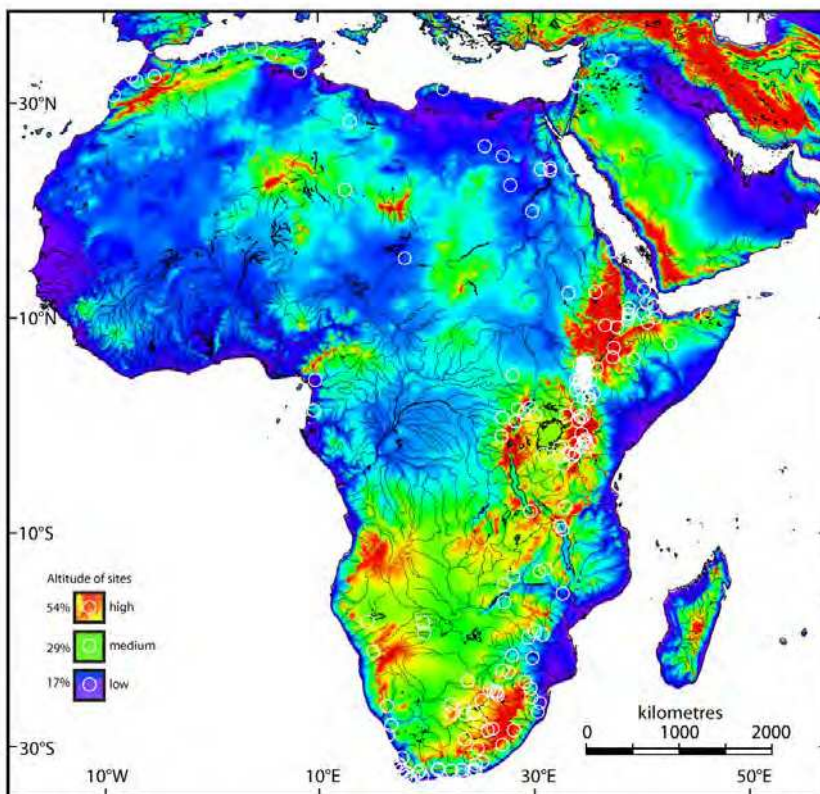


Figure 3
a) Topographic relief based on SRTM 30 data, colored according to altitude. Hominin sites (white circles) are listed in Appendix 2, and the percentage association with different altitude bands is also shown. Sites are shown to provide a general indication of the relationship between concentrations of early hominin and archaeological sites and topographic features. 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.

suggest is well adapted to paleoanthropological investigations.

Roughness maps, in conjunction with the identification of faults and other features from satellite imagery such as Landsat, SPOT, and Ikonos, can help to identify and characterize active landscapes, but they cannot replace further ground observations and field interpretation. In this paper we make use of satellite techniques to illustrate general correlations between roughness, seismic activity and volcanism, and show with some specific examples how the proxy representations relate to specific examples studied in the field and how they can help to identify the nature of environments that existed when hominin fossils and archeological materials were being deposited.

A rough surface can be described as an 'uneven or irregular surface; not smooth or level' (Soanes and Stevenson, 2005, p. 1535).

Broadly speaking rough terrain refers to small scale features rather than large scale ones. Roughness was probably first introduced into scientific discussion by Bowden and Tabor (1958) to characterize surfaces brought into frictional contact. Studies of this sort have continued to this day including attempts to characterize the (frictional) processes that occur on earthquake faults, to define landforms, to identify slope hazards in mining engineering and avalanche prediction, and to produce maps suitable for air navigation, road-building and military maneuvers (Bobrowsky, 2002; Scholz, 2002; Barnett et al., 2004; Haneberg, 2004). They were scarcely practical to apply to geomorphology prior to the advent of freely available Digital Elevation Models

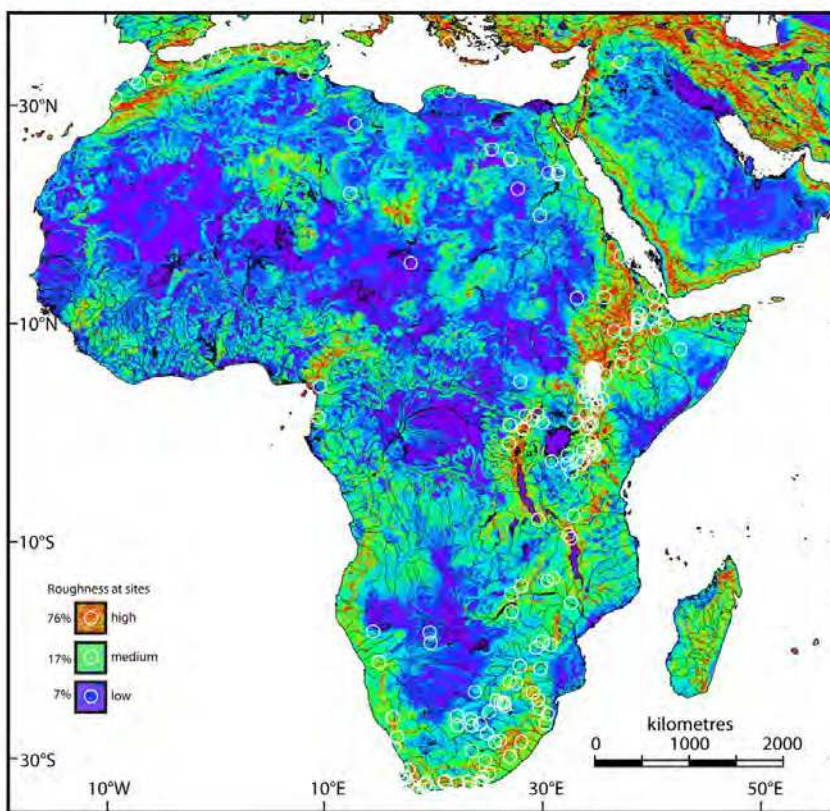


Figure 3
b) Roughness, with hominin sites as in Figure 3a. The raw digital elevation data has been filtered using an ~18db/octave hi-pass filter to de-emphasize the amplitude of wave length components inversely as the cube of the wavelength. This has the effect of emphasizing roughness at scales of approximately 5 km and less. Site information as in Figure 3a, but note the higher proportion of sites associated with rough topography, compared to the distribution of sites by altitude as shown in Figure 3a.

(DEM) and early tectonic studies were limited to the very few researchers who had access to classified American Defense Mapping Agency data (Scholz, 2002; Turcotte, 1997).

In this paper we use SRTM 30 (Shuttle Radar Topography Mission) and SRTM 3 Digital Elevation Model (DEM) data with a horizontal resolution of about 30 arc sec (~900m) and 3 arc sec (~90m), respectively, and a vertical resolution of <20m. In specific cases, we also use a ~10m resolution DEM derived from Stereo SPOT images. The two-dimensional elevation data are converted into measures of

roughness using a variety of filter functions. The simplest filter function is the measurement of slope angle, but more advanced filters are required to ensure that important small scale features (high-frequency, short wavelength) are not swamped by large scale features (low-frequency, long wavelength) such as large mountain ranges. The two critical steps in the construction of these maps are the choice of filter function and the choice of color table to highlight features of significance in the resulting maps. Appendix 1 provides an explanation of the basic principles in terms of Fourier transforms.

In principle the minimum pixel size available sets a limit on the information that can be obtained about roughness, however a number of authors have noted that landscapes often have a fractal distribution (Turcotte, 1997). Under these conditions roughness apparent at larger scales of observation is likely to be present at sub-pixel scales. This renders roughness maps more useful to characterize landscapes than might be supposed bearing in mind the limits on the resolution of available DEMs.

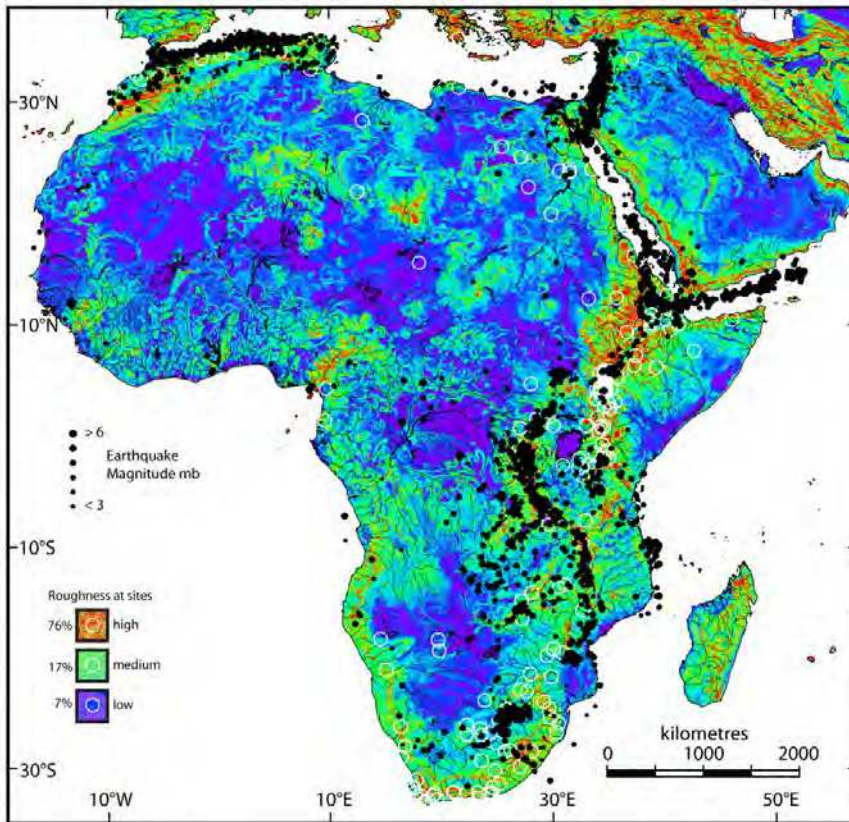


Figure 4 a
a) Roughness as in Figure 3b with seismic activity added (all events $\leq 3.5mb$). Site information as in Figure 3b.

Finally, it is important to fully appreciate that a roughness map is not the same as a relief map, and that a slope map is only one sort of roughness map. Rough terrain in the sense in which we define it can occur at high elevations and at low ones, and on steeper slopes as well as in flatter areas. It may occur at large scales (such as major fault scarps tens to hundreds of meters high and erosional features like deeply incised gorges) and at smaller scales (minor fault scarps meters high or eroded boulder fields of lava). Small features can pose equally formidable constraints 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 verify without extensive ground-truthing. Our objective is to find methods of analyzing and representing in map form topographic roughness at a scale relevant to the land use and environments of hominins and other fauna taking account of the models discussed above.

Roughness and Tectonics at an African scale

We first consider the relationship between roughness and tectonic activity for Africa as a whole. The purpose of this exercise is to provide an illustration of the mapping technique and to explore at a

general scale of observation the relationship between roughness and tectonic activity, using simplified maps of elevation or relief (Figure 3a), roughness (Figure 3b), modern seismicity (Figure 4a) and volcanism (Figure 4b). As can be seen from a comparison of Figure 3a and Figure 3b, elevation and roughness produce rather different patterns. At a very coarse scale, regions of high relief tend to be associated with high measures of roughness, reflecting the fact that both tend to be associated with high levels of tectonic activity, especially areas subject to contraction and mountain building at plate boundaries as in Northwest Africa, or in major rift areas such as the African and Red Sea Rifts, where widening of the rift and subsidence of the rift floor is accompanied by progressive elevation of the rift flanks. But the reverse does not apply. Not all areas of high relief are rough, notably the highland regions of Southwest Africa. Within areas of high relief roughness can occur both at higher and lower altitude, and

high levels of roughness are also present in areas of more subdued relief such as the Sinai Peninsula and the Syrio-Jordanian Rift (strictly a region of strike slip). Commonly, roughness shows a correlation with areas of known and 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. In the context of this paper, it is of particular relevance to note significant areas with high levels of roughness in South Africa. South Africa is generally considered to have relatively modest levels of tectonic activity (Wagner, 1927; McCarthy and Hancox, 2000) and, in contrast to the African Rift, no volcanic activity. Some further insight into these patterns comes from a consideration of seismic and volcanic activity (Figures 4a and 4b). We use all records of earthquakes of Magnitude 3 (Mb) or greater recorded since 1933, but note that the catalogue is not complete since the distribution of seismic stations in Africa is poor. It also reflects only the most recent history of tectonic activity, just 80 years, a very short geological time span indeed. Only when catalogues are long compared to the return times of large earthquakes can they be considered fully representative, since the interval between large events may show little or no seismic activity. For example, much of the stretch of the San Andreas Fault (western coast of USA) that moved in 1906 shows no recorded seismic activity at present. Earthquakes can also

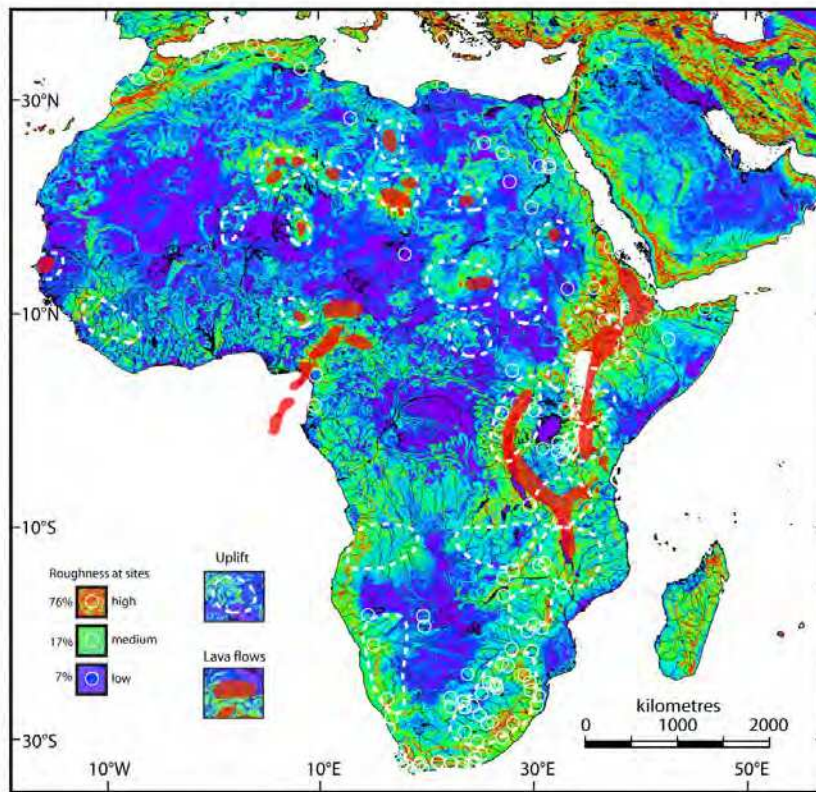


Figure 4
b) Regions of uplift and volcanic activity over the last 30Ma modified from Burke (1996). Many of these regions have been active in the last 4Ma and are still active today. The white dashed lines enclose regions of uplift thought to be due to heating from the mantle and most are associated with volcanism. The Cameroun volcanic region is a rift formed as a failed arm associated with the opening of the Atlantic. Mount Cameroun is an active volcano today. Although there is substantial uplift in Southern Africa, volcanic activity is absent (see text for further discussion and Burke 1996). Site information as in Figure 3b.

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appear in bursts of activity, well illustrated from a long historical knowledge of the North Anatolian Fault in Turkey (Ambraseys & Melville, 1995; Hubert-Ferrari et al., 2002). Nevertheless our maps show clear links between roughness and seismicity along the African Rift, the Aden and Red Sea Rifts and in Northwest Africa. Cosmogenic dating is now available to measure rates of fault movement (e.g.

Tapponnier et al. 2001) but little dating work of this type has yet been applied to studies of African tectonics.

It is easier to determine long term volcanic activity since lava flows are easier to identify and date than active faults (Figure 4b). Many volcanic regions in Africa have been active over the past 4 Ma and are still active today. Major volcanism is concentrated along the East African Rift. Such activity is consistent with an extensional area of rifting and crustal thinning, but nonetheless by global standards it is unusually active. A second belt of volcanic activity extends inland from off-shore Cameroun and was originally associated with the opening of the Atlantic (Figure 4b) but has continued activity throughout the last 30 Ma (Burke, 1996). Other concentrations of volcanic activity are associated with uplift thought to be due to heating from the mantle, notably in the Hoggar, Air and Tibesti Mountains

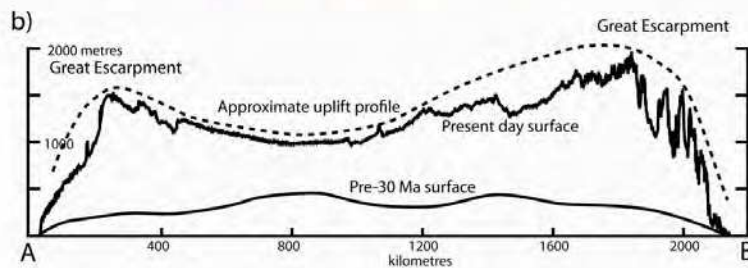
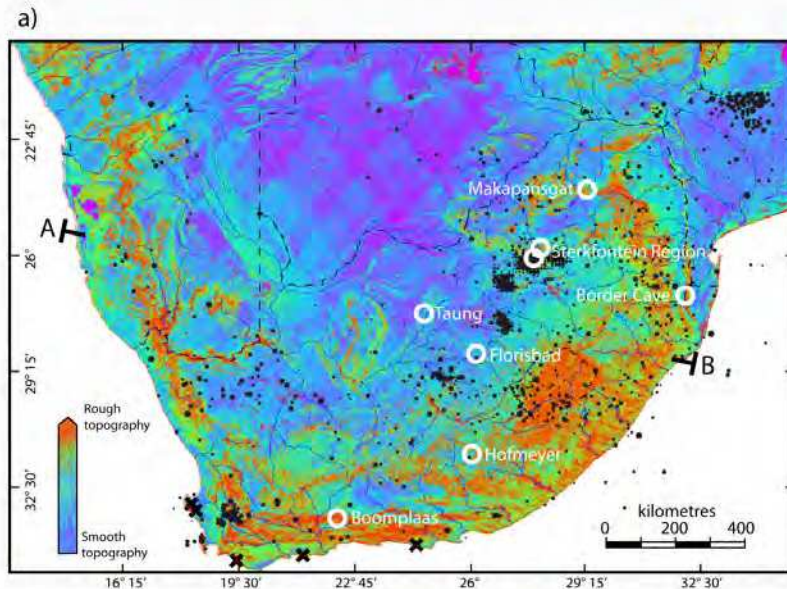


Figure 5 South African topography
a) Map of roughness and seismicity as reported by Saunders et al (2008). Roughness is based on SRTM 3 digital elevation data, using an ~18db/octave high-pass filter. In this case the filter emphasizes roughness at horizontal scales less than about 500m. Inland hominin sites are indicated by white circles and coastal sites by black crosses.
b) Topographic cross-section along A-B in Figure 5(a). Prior to 30Ma the land surface was smooth and at low altitude similar to much of Australia today. Uplift has been more than 1000m in places.

of North Africa. These areas of major volcanic activity are also associated with high levels of roughness (Figure 3b).

South Africa appears different from the rest of Africa in that substantial uplift has occurred in this region without volcanism, and there are extensive areas of roughness, but these are not closely related to instrumentally-determined seismic activity (Figure 5a). Some small regions of activity are related to mining, either directly, or indirectly because of the premature triggering of events that would otherwise occur at a later time (Saunders et al., 2008).

Two other factors are at work here. First, South Africa has undergone a general dome-like uplift of more than 1 km in the last 30 Ma, believed to be the result of expansion due to heat from the mantle acting on a stationary overlying plate (Figure 5b). Second, the great escarpments that bound southern Africa to the east and west are the result of erosion around the edges of this uplifted dome, with

spectacular effect (Burke, 1996). This has produced extensive areas of roughness but the topography differs from the roughness associated with faulting, lacking the fault-bounded sedimentary basins typical of the latter (Figure 2). Nonetheless, seismic activity does occur in South Africa and faults that have hosted very large earthquakes in the past can be identified close to major sites and control the morphology, as we demonstrate below.

Many of the rock formations of South Africa are very hard with the exception of minor sedimentary infill, are resistant to erosion (McCarthy, 2008) and tend to maintain vertical cliffs and fissures rather than degrading to the rounded and flattened features that result from erosion of softer rock formations. Thus although the rate of tectonic activity associated with faulting in southern Africa is relatively modest (i.e. with a longer return time for events of all magnitudes), the landscape and hydrological features that result from such activity (Figure 2) are better preserved in the intervening periods than in regions where the rocks are more easily eroded.

These features of the geology in South Africa have two consequences for the reconstruction of hominin landscapes. First, despite the relatively limited amount of faulting, we would expect landscape features like those illustrated in Figure 2 to have been created and to have persisted in some parts of the wider landscape. Second, because the specific landforms associated with particular archeological or fossil sites have been maintained in a relatively unchanged state over much longer periods of time than in the African Rift, it should be that much easier to reconstruct landscapes at the local scale as they would have existed two or three million years ago. In the African Rift, the higher levels of tectonic activity have often destroyed or transformed beyond recognition the original details of the local landscape, especially in very active areas such as the Awash region of Ethiopia. Thus, while we can say that in general terms Plio-Pleistocene localities in these very active regions were associated with high levels of tectonic and volcanic activity and consequent topographic roughness, we are unable to undertake the detailed reconstructions of local

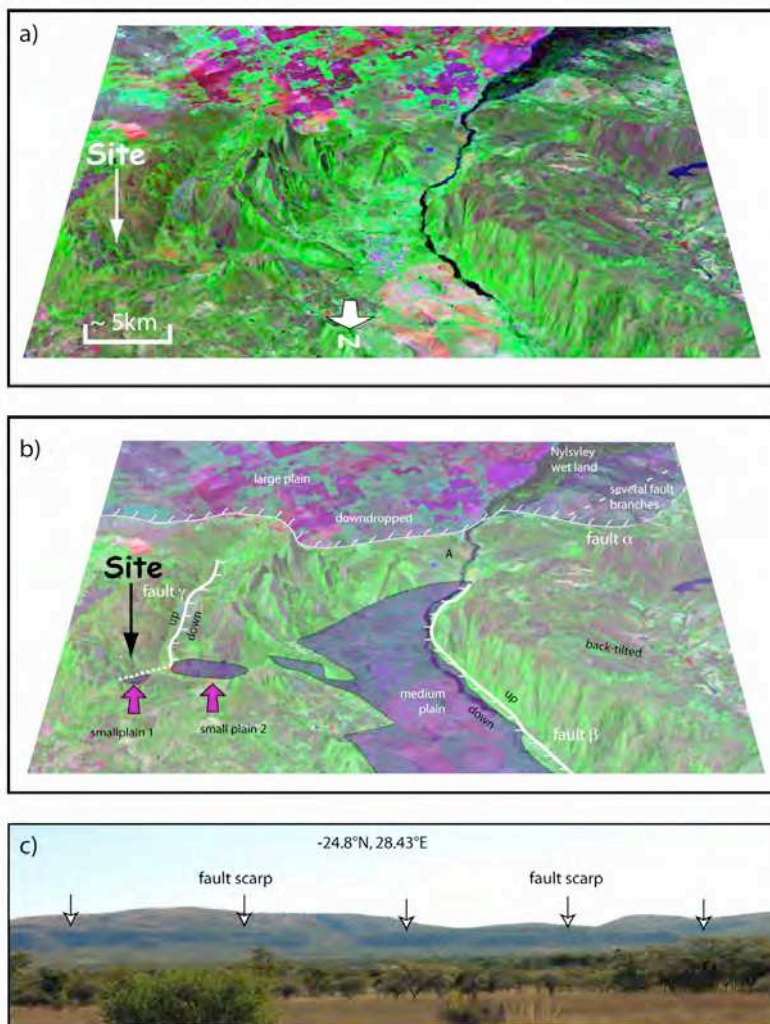


Figure 6 Region around the Makapan Valley, Northern Province, South Africa
a) A Landsat thematic mapper image (bands 2, 4, and 7 are red, green, and blue respectively) draped over exaggerated digital elevation data to give a 3D effect. A vertical exaggeration of between 5 and 10 times the standard elevation is used for oblique images, which enhances the visual interpretation of high-lying versus low-lying regions. The effect of this exaggeration gives an impression similar to that of a land-based observer viewing the topography.
b) Faults α , β and γ are identified. Recent activity of α is partly demonstrated by the presence of the Nylsvley wetland, which results from a perturbed river (plotted by McCarthy et al., 2004).
c) A fault scarp typical of repeated earthquakes is associated with fault α . Fault β may be active, since the river is displaced to the west side of the valley, but river displacement could also be due to sediment sources coming from the east. Fault γ close to the site is clearly active (see caption to Figure 7).

landscape features that would allow a closer analysis of that relationship or a test of its significance. This is a difficulty we examine in more detail later. For the moment we turn to a closer examination of the South African evidence, where the landscape has undergone less dramatic transformation over the past 3 Ma than in the East African Rift.

South African Landscapes

Figure 5a shows the distribution of roughness, seismic activity and key archeological sites in South Africa. This highlights the limited correlation between roughness and instrumentally located seismicity noted above. Large areas of roughness around the rim of the escarpment are clearly apparent. No early hominin material has been found in these areas although later sites such as Border Cave and Boomplaas, both associated with active faulting, are present there. Seismic activity is distributed in a broad band from southeast to northwest, with concentrations in the Western Cape, the Orange Free State southwest of Florisbad, and particularly intense activity triggered by mining south of the Sterkfontein region (Figure 5a). In examining sites in more detail we pay particular attention to sites with early dates, and compare local-scale roughness and tectonic features at Makapansgat, Sterkfontein and Taung. At the resolution provided in Figure 5a, these three sites are all associated with tectonic activity. The clearest are Makapansgat and Taung, which are both associated with morphology-controlling active earthquake faults. In both cases the important features of the roughness

are associated with tectonic activity that continues to the present-day. Ongoing tectonic activity is less clear for Sterkfontein although important indicators are present. We exclude from further consideration coastal sites because of the complications associated with sea-level variation and coastal change, but we include two later sites, Boomplaas Cave and Florisbad by way of contrast and comparison.

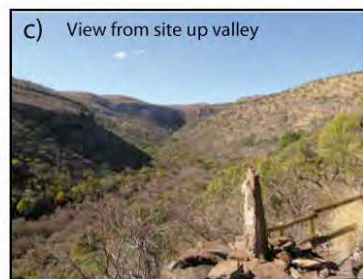
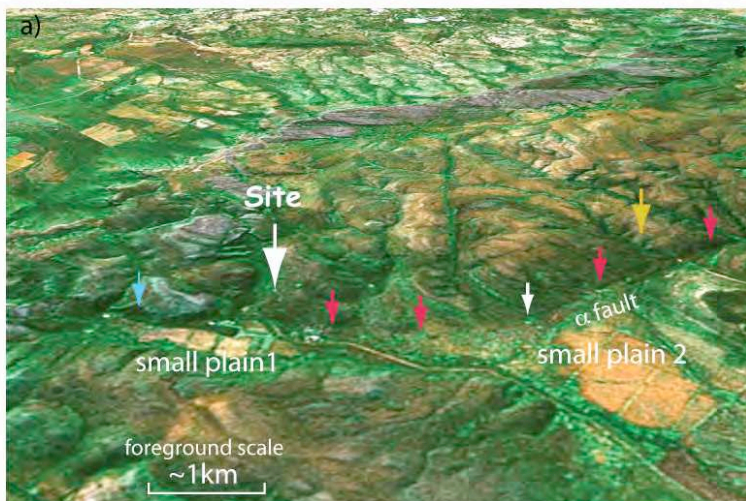


Figure 7 Close-up of Makapan Valley
a) Closer view of the topography modified from Google Earth image. Fault γ is indicated by arrows. Red arrows indicate steepening of the base of the slope. A yellow arrow indicates a "wine glass", a valley which narrows towards the fault. A blue arrow indicates a spur that has been truncated by the fault. Together these features are unambiguous evidence of active faulting. Small fertile plains result from sediment back-filling of earlier features as a result of the tectonically modified drainage.
b) Sediment-filled valley resulting from down dropping on fault γ .
c) Steep topography in the Makapan Valley

The Makapan Valley

The Makapan Valley contains a series of caves dating to various periods within the Plio-Pleistocene and into historic times, such as the Buffalo Cave, Cave of Hearths and the famous Makapansgat Limeworks (Figure 6). From the Limeworks Cave Member 3 and 4 breccias (dated at 3.2–2.7 Ma), a total of 27 fossil specimens of *Australopithecus africanus* have been recovered, equivalent to a minimum number of 10 individuals of varying ages (Tobias, 2000). Hominins and cercopithecine monkeys were accumulated by various predators, including hyenas, birds of

prey and other carnivores (e.g. Reed, 1997). The later deposit, Member 5, contains a small assemblage of mammalian fossils but no hominin specimens.

Varied habitat reconstructions have been proposed for the Member 3/Member 4 period, ranging from woodland (Vrba, 1982), to densely forested conditions (Cadman and Rayner, 1989), to more open, savannah woodland (Wells and Cooke, 1956). Reed (1997: 305) proposes a ‘habitat mosaic that

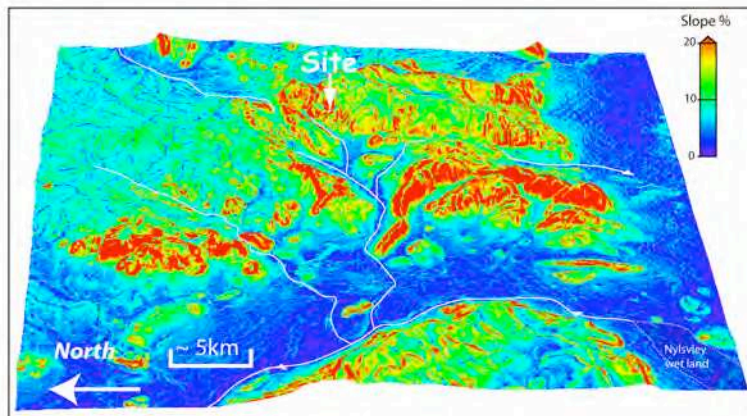


Figure 8
3D representation of topography in the Makapansgat region. This is a slope map based on SRTM 3 digital elevation data, with steeper slopes shaded in red (see scale), with rivers in white and the location of the Makapan Valley caves marked. This is equivalent to a roughness map in which the raw digital elevation data have been filtered using a -6 db/octave high-pass filter. This reduces amplitude inversely with wave length, in order to highlight all slopes regardless of spatial scale. The roughness has two sources; the faulting of the present tectonic regime, which is likely to have been active throughout the past 3Ma, and an earlier topography, now purely erosional, inherited from an earlier tectonic regime.

contained riparian woodland, bushland, and edaphic grassland’, and the biodiversity of the fossil species, which is one of the highest from the southern African fossil sites (McKee, 1999), might be taken as a strong indication that the full range of proposed habitats could have been present simultaneously. Recent stable isotope studies of the diets of *A. africanus* from the Limeworks Cave reveal a significant C₄ (grass and sedge) signal (Sponheimer and Lee-Thorp, 1999), possibly deriving from wetland plant foods (Peters and Vogel, 2005). High numbers of extinct reedbuck (*Redunca darti*), believed to

have lived in riparian habitats, also suggest the close proximity of water and wetlands (Reed, 1996, 1997; Sponheimer et al., 1999).

Environmental reconstructions based on fossil mammal communities appear to conflict with paleoclimatic reconstructions from speleothem data (e.g. Hopley, 2004; Hopley et al., 2006), with fossil fauna suggesting the sustained presence of water in close proximity to the site, while high resolution speleothem studies from Buffalo Cave indicate cooling and drying with gradual spread of grassland vegetation, which corresponds to Milankovitch orbital forcing.

A key factor in helping to resolve the types of habitat and vegetation present is the reconstruction of the landscape. A three-dimensional view highlights the topographic complexity of the Makapan Valley region (Figure 6a), and faults and other geomorphological features are interpreted in Figure 6b, with close up detail in Figure 7. In the south (upper part of Figures 6a and 6b) there is a large plain now exploited for agriculture which is down-dropped with respect to the mountains in the foreground by an active fault system identified here as fault Alpha (α). A contemporary feature of this plain is the Nylsvlei wetland, which has long been considered to be possibly related to continued tectonic activity (Wagner, 1927; McCarthy and Hancox, 2000; Tooth and McCarthy, 2007). The active fault scarp probably associated with the creation and maintenance of the wetland forms a geomorphic feature shown in Figure 6c. A second fault, Beta (β), can be identified with the river Nyl running close to its base. The asymmetry of the valley could indicate continued tectonic activity or simply a shift of the river course to the west by sediment that reaches the valley from the east (left). A third fault, Gamma (γ), passes close to the site. It shows unequivocal evidence for ongoing activity (Figure 7) and is responsible for uplift and consequent down-cutting and sedimentation close to the site, conditions

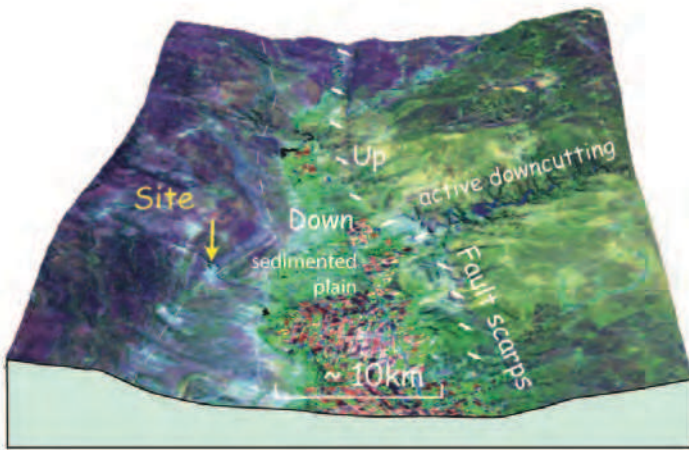


Figure 9
 Region around the Taung Valley. A Landsat thematic mapper image (bands 2, 4, and 7 are red, green, and blue respectively) draped over exaggerated digital elevation data to give a 3D effect. An earthquake fault scarp on the east side of the valley is indicated by white arrows. The fault cross-cuts geological features and varies in altitude and thus cannot be a river terrace or other erosional or depositional feature. Uplifting of the eastern flank has caused rivers to incise and the down-dropped valley has been filled with sediment. Faulting may also be associated with the western side of the valley, causing the incised valley that hosted the breccia with the hominin fossil. The down-dropped sedimented basin is today used for agriculture.

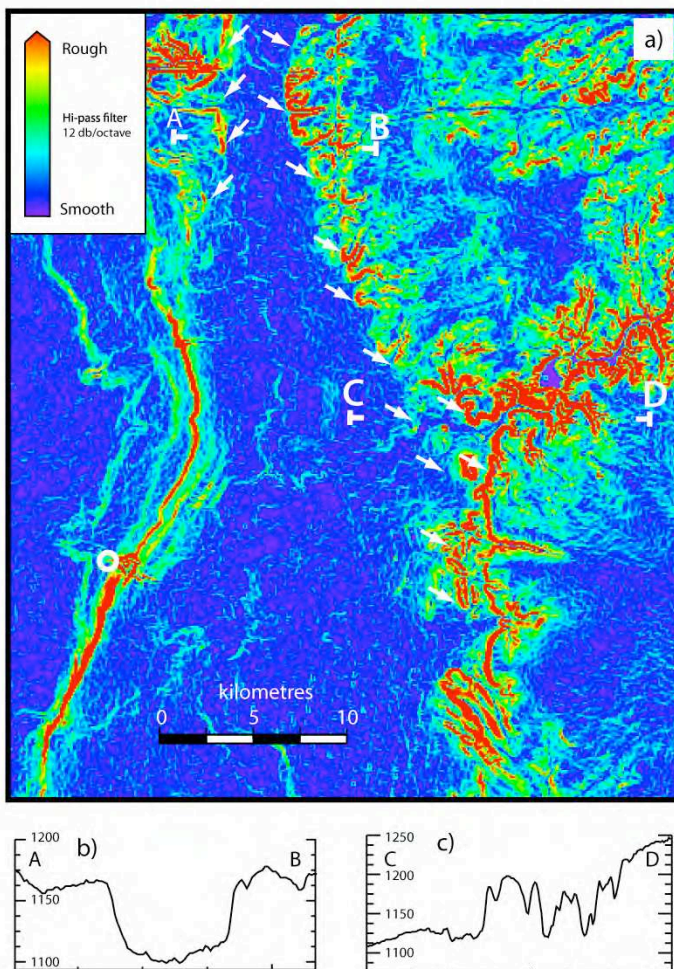


Figure 10. Roughness map of the Taung valley. The quarry site where the Taung fossil was found is shown by a white circle. Surface fault scarps are indicated by white arrows. Evidence for active faulting extends both to the north and south of that indicated but surface scarps are less clear. Roughness is based on SRTM 3 digital elevation data, using a ~ 12 db/octave hi-pass filter, which reduces the amplitude of wave length components inversely as the square of the wavelength. This emphasizes roughness at horizontal scales less than ~ 900 m.

corresponding to the model outlined in Figure 2b. The roughness map for the region (Figure 8) demonstrates the wider pattern of topographic complexity and its relationship to the tectonic history of the region.

According to Anton et al. (2002), the foraging range of an individual australopithecine might be as small as 38 hectares (essentially the area within ~ 500 m of a given point in the landscape), so that topographic and environmental features within that range of a site are likely to have been of particular significance. In this respect the rough terrain of the gorges and the characteristic cliffs of the Makapan Valley would have afforded important opportunities for safety and security. The river and the fertile, well-watered, sedimentary plains would have afforded good foraging areas close to the caves. The wider area around the Makapan Valley reveals a combination of smaller plains, large open plains and wetlands within ranging distance of the valley itself. In addition, a variety of valley conditions ranging from dry to marshy would have offered a range of habitats. These features strongly support the interpretation of the on-site indicators as representative of diverse habitat conditions within close range of the site, and also provide specific confirmation of the nearby presence of wetlands.

Taung

The lime-mining quarry at Taung is the site of the discovery of the type specimen of *Australopithecus africanus* in 1924 (Dart, 1925), though dating based on faunal correlations suggests that it is younger than other australopithecine sites, with an age of ca. 2.6–2.4 Ma (McKee, 1993; Partridge, 2000; Tobias, 2000). Much of the original hominin-bearing tufa deposit was destroyed by mining processes before systematic excavation could be undertaken, and many more hominin specimens and other remains may have been destroyed during these mining activities. In this case, we rely for paleoenvironmental

interpretation solely on the reconstruction of the surrounding landscape. Fortunately, despite the obvious destruction of the fossil-bearing sediments, the landscape features of the Taung valley have changed little (Figures 9 and 10).

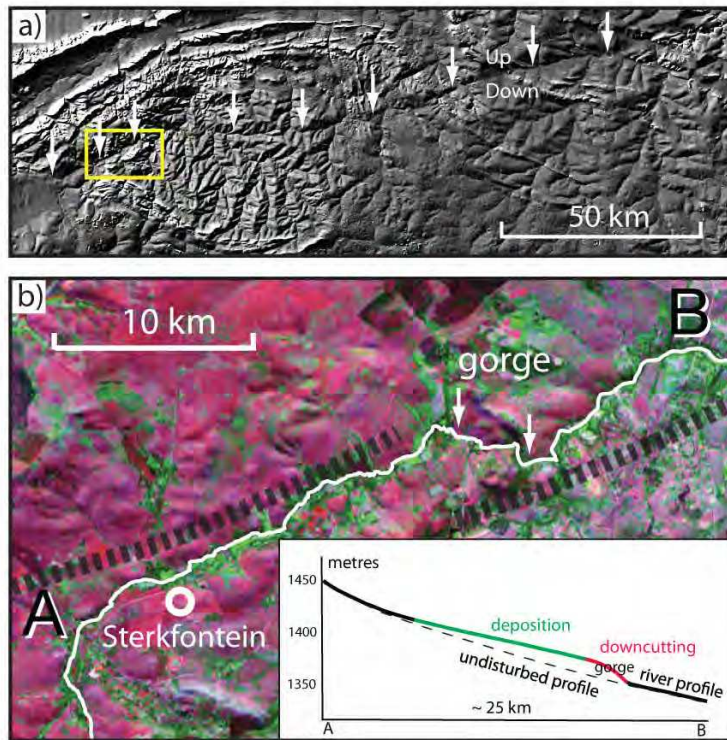


Figure 11 Evidence of tectonic activity in the Sterkfontein region
 (a) Shaded relief map of the Sterkfontein “Cradle of Humankind” area (yellow rectangle) and the region to the east. White arrows indicate an east–west fault. This substantial feature extends for >150km, offsets the morphology (up to the north, down to the south) and cross-cuts earlier geological structures. The shaded map uses SRTM 3 data with the light source located at N45°W at an elevation of 5°.
 (b) A Landsat thematic mapper image (bands 2, 4, and 7 are red, green, and blue respectively) with relief shading based on digital elevation data (~10m resolution) derived from Stereo SPOT images. The fault identified in (a) passes to the north of the Sterkfontein site (dashed grey line) and apparently controls the position of the Blaaubank River, which follows the northern side of the valley. As it flows to the east the river passes through a gorge (several meters deep). The inset shows a profile of the river (from SPOT DEM), which is down-cutting in the gorge and aggrading above it. Such a profile is commonly associated with active faulting.

roughness. All these features indicate essentially similar conditions to those in the Makapan Valley, corresponding to the model outlined in Figure 2b, with varied habitats near the site and a complex topography affording opportunities to hominins for protection in the immediate vicinity and for monitoring of the wider landscape.

Sterkfontein

The “Cradle of Humankind” World Heritage site containing the famous Sterkfontein hominin fossils and archeological material is shown in Figure 11. Other cave sites shown in the figure also contain early hominin fossils while others contain only non-hominin fauna. The deposits at Sterkfontein comprise seven members, of which two are well-studied: Member 4 (ca. 2.8–2.4 Ma) with *Australopithecus africanus* fossils and Member 5 (ca. 2.5–1.4 Ma) with a succession of Oldowan and Acheulean stone tool industries as well as two later species of hominins, namely early *Homo* and *Paranthropus* (Kuman and Clarke, 2000; Pickering et al., 2004). Faunal remains indicate a mixture of

Two faults on either side of the Taung region create a rift valley (graben) with uplifted, drier flanks on each side and a down-dropped, sedimenting plain in the centre (Figure 9). As can be seen in the foreground, this fertile plain is today being used for agriculture. The faulting has down-dropped the valley causing rivers to cut into the uplifted valley sides. These faults crosscut earlier geological structures and are not controlled by them. Two rivers are shown on either flank, and the river on the right flank is actively cutting down into the uplifted sediments. The Thabaseek River can be seen running next to the Taung site on the uplifted Ghaap escarpment (Partridge, 2000). On each side of the uplifted rift flanks, the rivers experience drainage disturbances when they intersect with the faults (Figure 9). Roughness results from fault scarps and steep sided gorges where the rivers cut into the uplifted sides of the faults (Figure 10). The Taung gorge is one small example of this effect. Topography that may be unrelated to on-going activity is subdued and contributes little to the

grassland and woodland species in Member 4, and fossilized wood fragments indicate the presence of gallery forest and tropical understorey shrubs in the near vicinity of the site (Bamford, 1999). In Member 5 times, faunal indicators suggest generally more open conditions but with some persisting woodland.

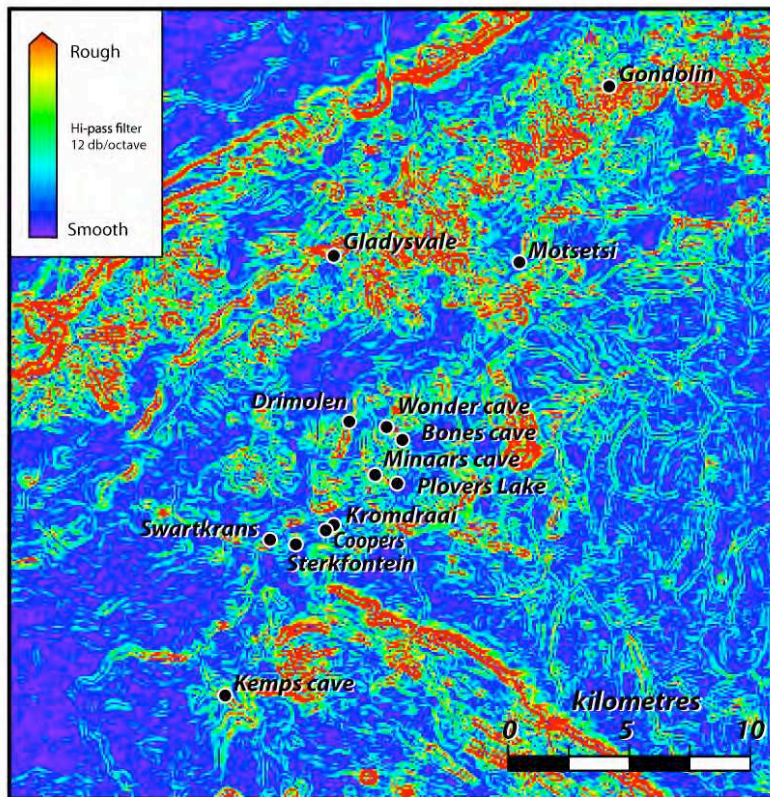


Figure 12
Roughness map of the Sterkfontein "Cradle of Humankind" region using SRTM 3 data and a ~12db/octave hi-pass filter. This emphasizes roughness at horizontal scales less than ~900m. Although there is some evidence of tectonic activity, the complex topography of the region is related in part to erosion of now-inactive features. Sites shown include those with hominin fauna and those with non-hominin fauna.

The topographic setting of the site (Figures 11 and 12) shows evidence for faulting, which crosscuts the mapped geological structures and has disturbed the profile of the adjacent river to create areas of sedimentation and down-cutting of several meters, most probably due to continued movement (as in Figure 2b). However there are no clear earthquake fault scarps as at Makapansgat and Taung so that continuing activity cannot be unequivocally established as yet. In the region of Gladysvale and Gondolin to the north, the rivers are deeply incised, again suggesting activity. The region exhibits a similar set of features to the other sites and is consistent with the presence of environmental signals in the onsite evidence

indicating a combination of open grassland and more wooded habitats. A project is currently underway to determine rates of erosion, to improve the seismic network coverage in the area and to measure down-cutting rates using cosmogenic dating.

Florisbad

Florisbad is the site of a hominin skull now dated to c. 259 ka and variously attributed to an early form of *H. sapiens* or *H. helmei*. There are also stone tool assemblages including an early phase of the MSA, contemporaneous with the hominin skull, later MSA assemblages extending to 121 ka, and some poorly preserved traces of later, LSA, activity (Kuman et al., 1999). The sites occur around the edge of a lake created by warm water springs emerging from an underground aquifer as a result of dyke intrusion into the shale bedrock. The region at large is seismically active and rejuvenation of spring activity has been attributed in part to tectonic activity (Vissner and Joubert, 1990, 1991; Douglas, 2006). However there is limited surface evidence of faulting and the topography is relatively smooth (Figure 13). Sedimentological analysis (Vissner and Joubert, 1991) has demonstrated fluctuations between wetter and drier episodes that appear to have been primarily controlled by climatic variation, suggesting circumstances closer to the situation modeled in Figure 1a rather than

Figure 2b. The sites represent hominin visits to the locality for the hunting and butchering of medium-sized bovids and scavenging of hippo carcasses.

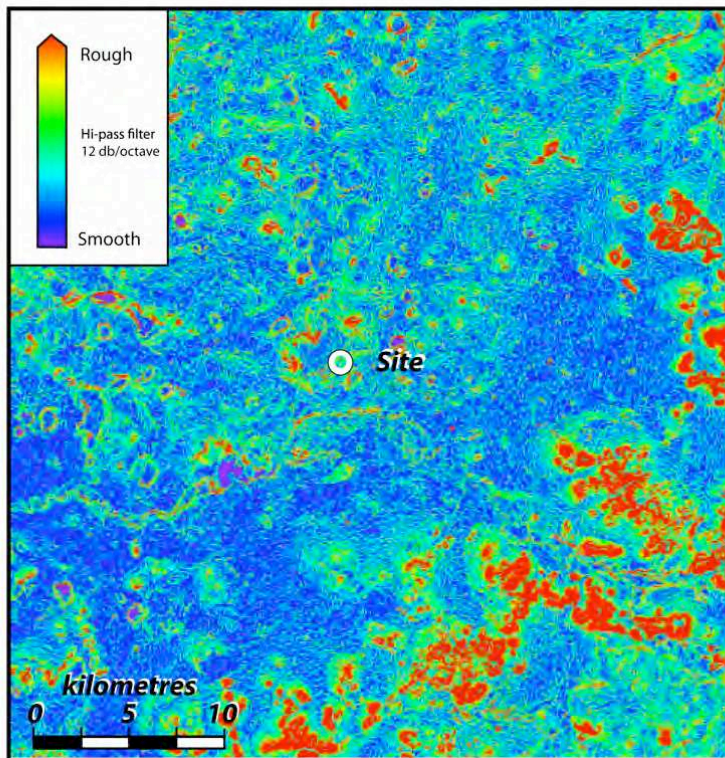


Figure 13 Roughness map of the Florisbad area, using a ~12db/octave hi-pass filter, emphasizing roughness at horizontal scales less than ~900m. Sites indicated include those with hominin remains and those lacking hominins but containing other faunal remains.

The expedient nature of the tools in the later MSA levels at 121 ka suggests short-lived visits by people who lived elsewhere (Kuman et al., 1999: 1423). Whether this applies to the earlier occupations, and where people lived at other times of the year, is unclear. The roughness map suggests areas of rougher topography to the southeast that might offer promising environmental conditions for alternative activities and perhaps for the search for complementary archeological sites.

Boomplaas Cave

Boomplaas Cave has an important sequence of deposits dating from about 70 ka onwards and includes stone tools from the MSA industries of Still Bay and the succeeding Howiesons Poort, Later Stone Age material, and evidence of sheep pastoralism (Deacon et al., 1978; Deacon, 1995; Henshilwood,

in press). The cave itself has an open aspect overlooking a valley filled with sediment, and Deacon (1979) suggests that the site was well placed to intercept animal migrations. From a topographic perspective, the site is located on the boundary between a down-dropped valley and an uplifted scarp (Figures 14 and 15). The valley area has been down-dropped by the fault to the north, and this has caused valleys in the earlier topography to become partly buried, resulting locally in highly fertile sediment-filled valleys. A second fault crosses the region to the south causing similar effects. Slopes in the region are partly inherited from an earlier topography and partly the result of later fault action and rejuvenated erosion. The cave site itself was formed in the earlier topography and is not a consequence of the system that is now active. Fault scarps like those shown in Figure 14 can be found elsewhere in the Cape region and may well partly control coastal sites.

Middle Awash Valley, Afar region (Ethiopia)

The Awash River Valley in the Afar has yielded the oldest stone tools, dated at 2.6–2.5 Ma, and cut-marked bones suggesting scavenging and butchery around 2.58–2.1 Ma (de Heinzelin, et al., 1999; Semaw, et al., 1997; Dominguez-Rodrigo, et al., 2005), and a succession of hominin finds (White et al., 1993, 1994, 2003, 2006). The region clearly played an important part in hominin evolution, with a number of localities that have produced fossil material (Figure 16). This concentration and time depth

of finds invites investigation of environmental, topographic and tectonic conditions. As the numerous habitat reconstructions for the Middle Awash Valley indicate, a range of vegetation types was probably present during the time of hominin occupation including swamps, seasonal 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, 2000, 2001; Semaw et al., 2005). These reconstructions, in their turn, as in the Makapan Valley, suggest a combination of different habitats affording a variety of foraging opportunities within a relatively restricted area.

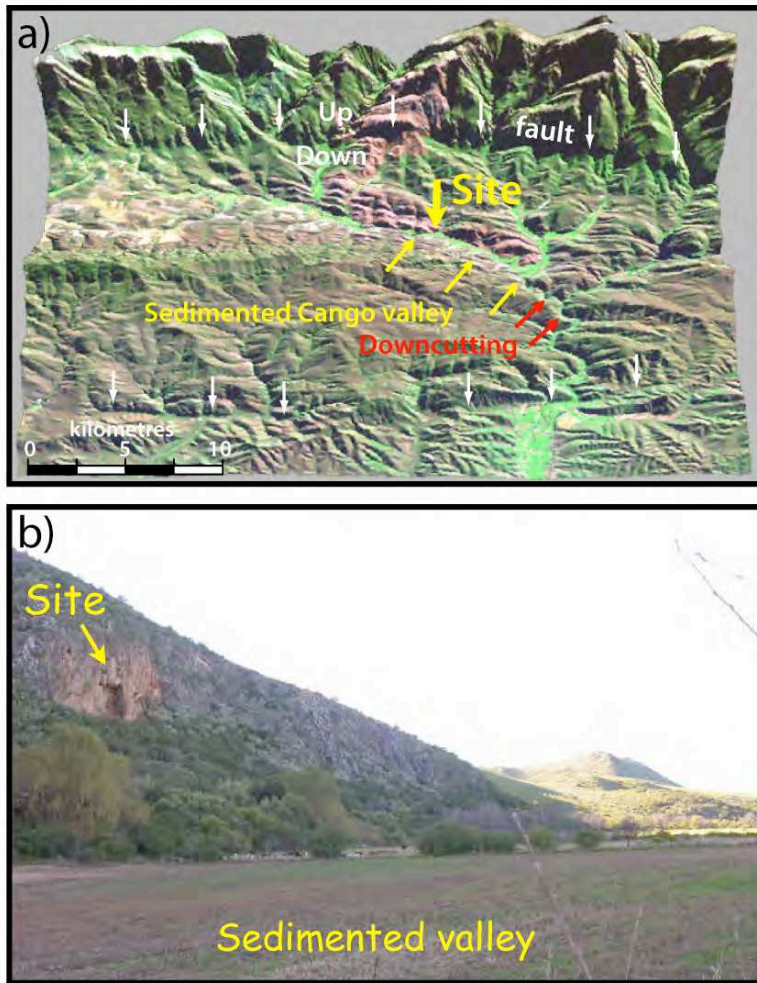


Figure 14
Evidence for tectonic activity in the Boomplaas region
(a) A Landsat thematic mapper image (bands 2, 4, and 7 are red, green, and blue respectively). White arrows indicate two faults. Yellow arrows indicate the sediment-filled Congo valley. Red arrows indicate down-cutting.
(b) View of cave site showing the Congo valley in foreground. The valley is subject to intermittent flooding and provides rich farmland. Earthquakes are commonly felt in this region.

active rift (Figures 17 and 18) and which did not exist when the fossil sites were active (Inset Figure 16). This is chosen because it is where the Awash River now enters the currently active rift floor and is therefore a close equivalent to the fossil regions when inhabited. This analog region is now very arid (although inhabited). Morphology similar to that shown can be found in parts of the rift that are less arid, but such regions are not photogenic – thicker vegetation masks critical small-scale features on land-based and satellite photographs, hence our deliberate choice of these specific examples.

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 shepherds (Figure 17). The Afar region has in the past been more humid (Gasse, 2001) with the light colored region probably occupied by a fresh water or slightly

However, there are much greater difficulties of detailed landscape reconstruction in this region. The landscape of the area today has been so transformed that, as Taieb (pers. comm., 2001) has pointed out, if we are to find present-day conditions analogous to those that pertained in Plio-Pleistocene times, we need to go to an area where the Awash River emerges onto the currently active rift floor (Figure 16). We therefore provide a reconstruction of just such an analogue region in the area of the Karub volcano, which lies in the

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, enclosed fertile valleys, and blocky lava flows. Such features may have provided some measure of protection against cursorial carnivores, and offered secure areas for vulnerable hominin young (Figure 18). In the locations where Plio-Pleistocene fossils are found (Region A of Figure 16), important details of landscape features have now been eroded and smoothed over time, but these details are still clear and uneroded in the modern analog region. 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.

Discussion

In the previous sections we have outlined techniques adapted from tectonic geomorphology for identifying the role of active tectonics and volcanism in creating and maintaining landscapes of potential importance in hominin evolution, and shown how maps can be reconstructed that relate these features to the location of fossil and archeological discoveries.

The idea of studying African hominin sites in their local landscape setting is not new and extends from early attempts by Isaac and others to characterize landscapes over geographically intermediate scales (Isaac (1972, 1981; Cachel and Harris 1998) to a focus on the paleoenvironmental and geochronological analysis of valley-floor sediments and paleosols in the immediate vicinity of individual sites (e.g. Bunn et al., 1980; Johanson et al. 1982; Feibel and Brown, 1993; Rogers et al., 1994; Peters and Blumenshine, 1995; Blumenshine and Peters, 1998; Potts et al., 1999; Blumenshine et al., 2003). More recently, computer simulation and satellite imagery have facilitated modeling of environmental features at a continental scale using low resolution environmental proxies (e.g. Field et al., 2007, Hughes et al., 2007). Similarly, tectonic factors have long been recognized as potentially significant factors in the African context, though largely at a macro-geographical scale – in mediating global and regional climatic effects, in fragmenting biogeographical distributions, in creating fertile soils, or as a ‘discovery factor’ in

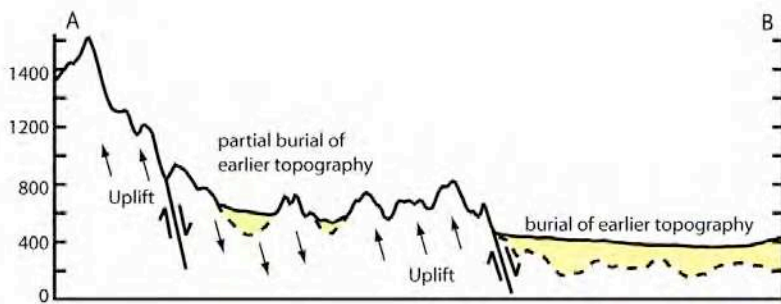
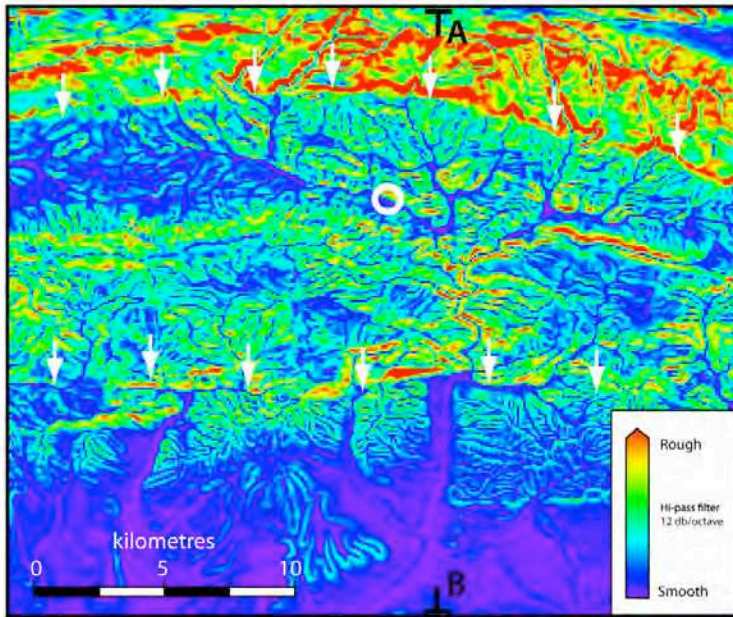


Figure 15
Roughness map of the Boomplaas area, using a ~12db/octave hi-pass filter, which emphasizes roughness at horizontal scales less than ~900m. The Boomplaas cave site (white circle) is in a region that has been down-dropped by a fault to the north that has caused valleys in earlier topography to become partly buried, resulting locally in highly fertile sediment-filled valleys. A second fault crosses the region to the south causing similar effects. Slopes in the region are partly inherited from an earlier tectonic regime and partly the result of on-going fault action and rejuvenated erosion and deposition associated with the current tectonic regime. The cross section shows the two faults and the sediment infilling that has buried earlier topography. The formation of the cave itself predates the present tectonic regime.

preserving and exposing early fossil and archeological material (Coppens, 1994; Ambrose, 1998; Partridge and Maud, 2000; Woldegabriel et al., 2000; Maslin and Christensen, 2007).

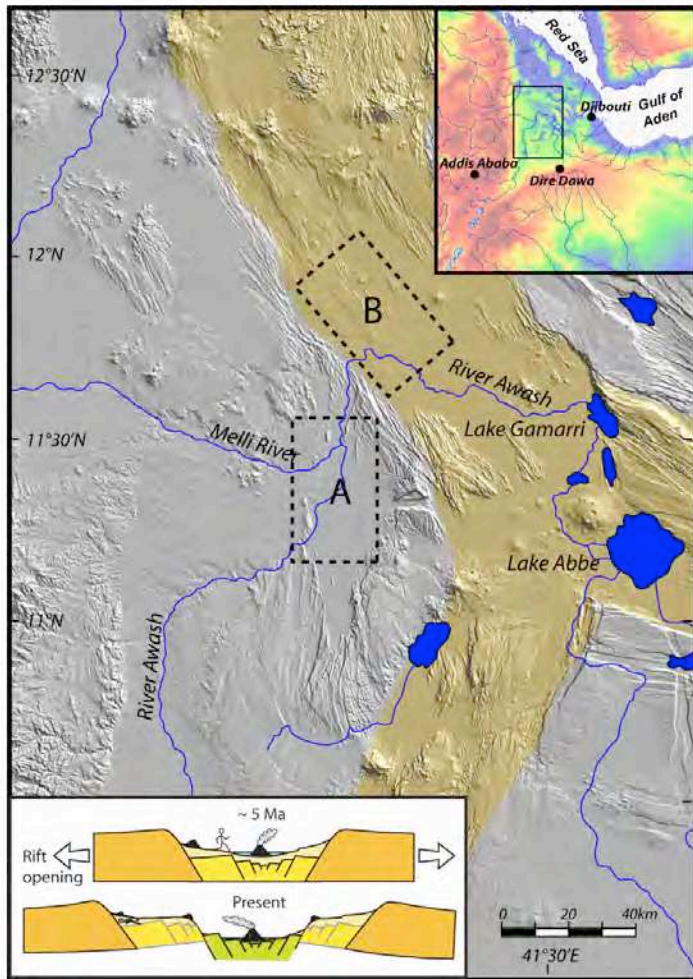


Figure 16
The Afar region of Ethiopia. The area shaded in light brown is the currently active Rift. Rectangle A shows the region of the fossil sites of the Middle Awash River. It is located on the now-uplifted flank of the active Rift, but at the time when the sites were being formed it was located in 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., 2005; Ayele et al., 2007)

Where our approach differs is in its emphasis on more localized tectonic processes and topographic features and their reconstruction at a range of geographical scales, made possible by new developments in tectonic geomorphology. In this respect our approach provides a complement to other methods of paleoenvironmental reconstruction, and an alternative source of information. It also brings into sharper focus the following issues and the need for topographically informed investigations to pursue them.

Discovery factor

A major impediment to the application of tectonic methods and interpretations is the widespread assumption that the differential occurrence of hominin fossils and archeological materials is largely or solely the product of the 'discovery factor', the idea that sites are best preserved and then re-exposed to investigation by high levels of tectonic activity, and that any supposed correlation between tectonically active and topographically complex landscapes

and concentrations of archeological sites is simply a fortuitous byproduct of differential preservation and visibility, compounded by intensive prospecting in certain regions. This issue of 'landscape taphonomy' in interpreting patterning in the geographical distribution of archeological or fossil material is all pervasive, regardless of time period, and regardless of whether the sites in question are caves, rockshelters, or open-air locations. Other studies that have sought patterning in large-scale distributions relating to early hominins have identified similar confounding problems (e.g. Wood and Strait, 2004; Holmes et al., 2006). The problem is further complicated by the effects of variable time averaging and palimpsest effects (Stern, 1994, Holdaway and Wandsnider, 2008). The patterning is in every case at least in part a function of the geological and geomorphological processes that have created and further modified the locations of discovery and their associated deposits. Differential effects of this sort are unquestionably an important factor, particularly for African Rift sites. They should not be ignored; nor should they be assumed to be insoluble, or prevent a closer examination of the apparent correlation between active tectonics and site distributions and its potential ecological and

evolutionary significance.

One strategy for dealing with this problem is the search for patterning that is independent of taphonomic effects. For example, in the European context, not all caves or rockshelters available for human occupation contain evidence of use; of those that do, some demonstrably show greater intensity

of activity or more persistent and repeated use over longer periods of time than others; and open-air sites provide a further control (Bailey, 1983; Bailey et al., 1997). Similar strategies can be applied to other types of geological exposures, but in every case a key prerequisite is an understanding of the geological processes that have created and modified the land surfaces on which finds have been discovered, which brings us back to our starting point about the need for an understanding of tectonic processes and investigation of their effects at an archeological scale of enquiry.

The South African examples that we address are important in this respect since the presence of fossils and their discovery at Makapansgat and Boomplaas Cave cannot be explained as the result of exposure by earlier motion on the active structures we identify here. The caves date from much earlier times and the burial of fossils in the cave deposits is related to local in-wash of sediment and roof collapse. For some later hominin and modern human examples the

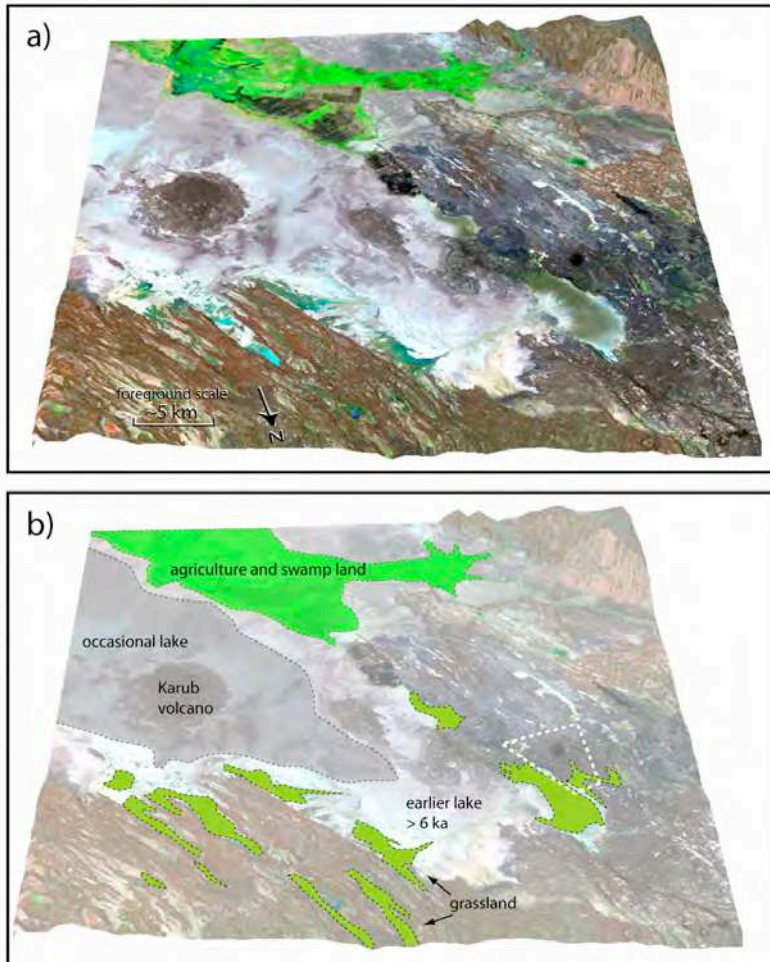


Figure 17 The analogue region situated in the active Rift margin (B in Figure 16). The features found in this region are characteristic of the active Rift and could be illustrated in other places.
 (a) A Landsat thematic mapper image (bands 2, 4, and 7 are red, green, and blue respectively) draped over exaggerated SRTM 3 digital elevation data to give a 3D effect of the area in the vicinity of the Karub volcano.
 (b) Interpretation of (a) showing salient landscape features: 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 18.

concentration and location of sites is demonstrably not due to the ‘discovery factor’ and has to be because tectonic activity confers specific advantages (Bailey et al., 1993; King et al., 1994; King et al., 1997; Bilham, 1988; Jackson, 2006; Force, 2008). The relative influence of taphonomic and behavioral factors in earlier hominin site distributions will emerge from new field investigations that draw on the predictive insights of tectonic modeling and from analysis of more examples using the techniques described here, rather than from preconceptions about the effects of geomorphological processes on differential preservation.

Comparative landscape reconstruction

Reconstruction of topography and hydrological regimes cannot be achieved to the same level of detail in every region. Detailed reconstructions over a deeper time depth are more easily achieved in South

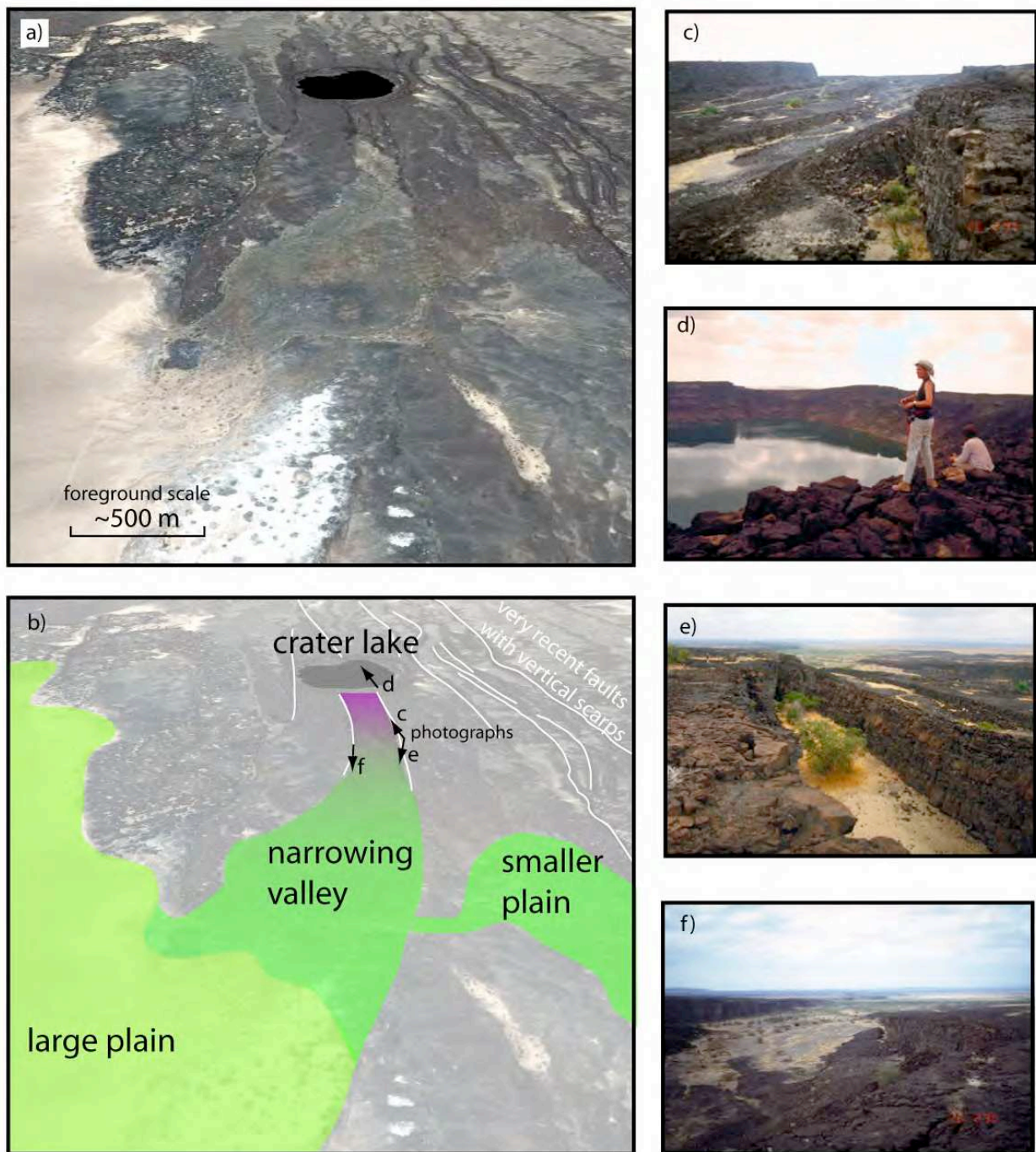


Figure 18 Close up of the region indicated in Figure 17
 (a) Modified Google image showing a crater lake, volcanic lavas and fault scarps in the vicinity of the Gablaytu volcano.
 (b) Interpretation of features shown in (a), highlighting the Gablaytu crater lake, a narrow valley confined by lava flows and faults, and associated plains of varying size.
 (c)–(f) photographs of features indicated in (b), showing, respectively, major fault scarps (c), crater lake (d), and valleys bounded by relatively impassable lava flows and fault scarps (e) and (f).

Africa than in the most active parts of the East African Rift, where too much has changed to allow the same degree of reconstruction, and where it is only possible to identify the types of topographic features that might have existed at a local scale by analogy with more recently formed rift landscapes,

as we have shown with the Afar example. Even so, comparisons between different regions at a more general level of reconstruction using the mapping techniques described here may throw significant new light on similarities and contrasts, which can then be mapped on to the differential occurrence and concentration of archeological sites and hominin fossils, taking account of the taphonomic factors highlighted above. For example, Reynolds (2007) has suggested that the higher turnover of mammalian species in East Africa compared to South Africa may be related to general differences in tectonics, the greater activity of the Rift contributing to a greater rate of speciation and heightened risk of extinction, an idea that could be further developed by more detailed mapping and comparison, and extended to inter-regional variations of hominin behavior and evolutionary trajectories.

Local climatic effects

Another question brought into sharper focus by reconstructions of tectonic geomorphology is the mediation of global and regional climatic effects by local features. Hypotheses about the interaction of climate and evolutionary change have attracted substantial recent interest (Vrba et al., 1995; Bobe and Behrensmeyer, 2004; deMenocal, 1995, 2004; Potts, 1996, 1998; Sepulchre et al., 2006; Kingston, 2007; Maslin and Christensen, 2007). However, these climate models are generally applied to static landscapes, without taking account of long-term topographic change or local variability, apart from large scale changes in regional altitude. As we have pointed out (see also Figure 2), the response of the hydrological system of an active landscape is very different from a static landscape even if the topography is superficially similar. This ability of active tectonics to locally buffer some of the effects of climate change offers obvious advantage to species that occupy such regions, and needs to be taken into account when applying climatic models to evolutionary trajectories.

Mosaic environments

Reconstructions of tectonic geomorphology also provide a new perspective on the concept of mosaic environments, long regarded as a distinctive feature of hominin landscapes, and believed to be associated with relatively high levels of biodiversity (e.g. O'Brien and Peters, 1999; see also Kolasa and Pickett, 1991; Hutchings et al., 2000; du Toit et al., 2003). Although loosely defined, a mosaic environment could be seen as resulting from complex topography, with a diversity of resources in close proximity including plants and animals from both arid (C₄) and humid environments (C₃) (Sponheimer and Lee-Thorpe, 1999, 2003; Sponheimer et al., 1999, 2005, 2006; Wood and Strait, 2004). The insights of tectonic geomorphology suggest that there may be a tectonic basis for such diversity, which requires further investigation.

Strategic use of topographic barriers

The distinctive topography of barriers and enclosures resulting from localized faulting and associated tectonic effects raises the question of how far such features may have provided selective advantage during the course of human evolution, providing protection from predators and competitors and facilitating access to otherwise elusive mobile prey (King and Bailey, 2006). The need for secure locations where food could be transported and vulnerable group members defended against carnivore attack must have been a high priority throughout the different stages of human evolution (Brain, 1981, 2005; Blumenshine et al., 1994; Rose and Marshall, 1996; Hart, 2007; Lockwood, et al., 2007). Trees are usually invoked as safe places or sleeping sites for early hominins, a notion reinforced by the retention of climbing abilities in the upper limbs alongside a general trend towards specialized bipedalism in the lower limbs (Latimer and Lovejoy, 1989; Senut, 1980; see Stern, 2000 for extensive review).

However, areas of rough topography offer alternative strategies for protection. Cliffs and lava flows have been used to protective and tactical advantage by a variety of mammals, including baboons, klipspringer, leopards, and modern humans (Kummer, 1968; Estes, 1992; McGregor, 2007). Well-developed climbing (hill and rock climbing) and walking abilities, as well as a certain degree of manual dexterity, would have allowed effective negotiation of barriers (such as steep, rocky cliffs or blocky lava flows) and might equally well account for some of the trends in hominin anatomical evolution. Covering large distances on smooth terrain and diurnal activity (e.g. Wheeler, 1991, 1992) may not have been the only evolutionary forces in the evolution of hominin body forms, but equally an ability to occupy and defend regions of complex topography with reliable food and water. These hypotheses

remain to be investigated, but suggest the sort of questions that can be posed if the nature of topography associated with earlier hominins can be defined more clearly.

Conclusions

In this paper we have set out a new approach to the examination of the African landscapes in which hominins lived and evolved, based on recent developments in the analysis and understanding of tectonic geomorphology. We have shown how active tectonics create and sustain dynamic landscapes of topographic heterogeneity with localized features that can provide important resources for hominins, including reliable surface water, greater

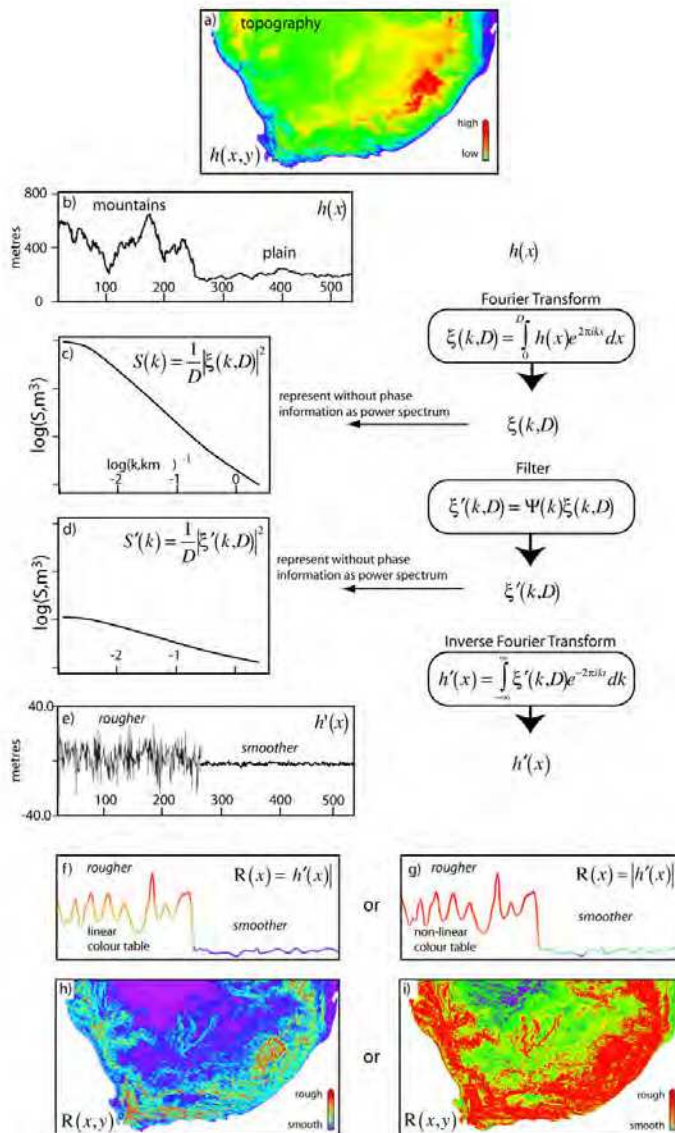


Figure 19 Preparation of Roughness Maps. Graphical representations of spatial filtering using Fourier Transforms (see Appendix 1 text for explanation).

biodiversity, protection from predators and competitive advantage. We show that these tectonic features are more widespread than has been appreciated in previous studies, particularly in South Africa, and can be reconstructed at a variety of geographical scales through a combination of satellite imagery using measures of roughness and ground observations. We have also shown how an analog approach can be used for early dated sites in very active areas of the Rift, where rapid and ongoing tectonic activity has dramatically modified earlier topographic features or erased them beyond recognition. We have emphasized active tectonics as being of most relevance to the understanding of hominin landscapes in Africa, but note that conditions of topographic complexity can also be created by other sorts of crustal movements and geomorphological processes notably in coastal regions of sea-level change and regions of glaciation.

The resulting maps are not a substitute for other methods of paleoenvironmental analysis or for ground observations but rather provide a complementary source of information. In this respect the approach developed here fills a gap in the currently preferred approaches to interpretations of site environments, which tend to focus either on the immediate surroundings of particular sites (e.g. lake edge, gallery forest, streambed, cave), thereby missing a wider perspective, or on reconstruction of climatic and vegetational zones at a sub-continental scale that are too broad to be sensitive to more localized detail.

We recognize that the sample of sites that we have so far examined is still quite small and that it is not yet possible to demonstrate rigorously consistent patterns of preferential selection for particular landscape features using large samples of sites and landscape areas, or to eliminate sources of potential bias such as differential preservation and visibility of sites or differential intensity of investigation. Also, rates of tectonic activity remain to be more accurately determined in most cases. This situation will change, however, as the methods we have presented in this paper are applied more widely and in more detail, and combined with other sources of paleoenvironmental, geomorphological and archeological information.

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Appendix 1. The mathematical basis of roughness calculations

The purpose of maps is to provide an accessible visual representation. For topographic maps a major advance was the introduction of contours and contour shading. The advent of digital data has permitted a range of new techniques such as easily modified coloring with altitude or shading mimicking illumination from an oblique angle. These can be combined in various ways. There is no right way to represent topography. The best is the one that allows visualization of relevant features. This applies equally to roughness maps. If they help they are useful. It has become familiar to manipulate photographs and other images using programs such as Adobe Photoshop. The end result is the justification of the methods and most users do not understand the underlying mathematics and do not need to. The same applies to roughness. The following description of the method is intended to be sufficient for someone with a basic understanding of image processing to be clear about what we have done. The test of usefulness of the method, however, is whether it helps understanding in the eye of the beholder.

Reducing the visibility of large features relative to small features is the objective of creating roughness maps. This involves the manipulation of two dimensional fields of height data points. The processes involved fall into the general topic of field theory and specifically depend on concepts such as the Fourier transform and filtering originally developed for the manipulation of time series (Blackman and Tukey, 1958). The purpose of this appendix is not to describe the mathematics in detail, which can be found in the references quoted and in many text books, but to give a graphical representation of the stages involved in processing a Digital Elevation Model to provide a Roughness Map (Figure 19 a-i).

A surface can be defined as $h(x,y)$ where h is the height of a point at horizontal positions x and y (e.g. Figure 19a). Manipulations of topography are carried out in two dimensions, but the principles can be illustrated in one. Figure 19b shows a topographic section $h(x)$. Over some region (0 to D) this can be characterized in the wavenumber k domain by the Fourier transform where k is the reciprocal of wavelength λ . $\xi(k,D)$ in general has real and imaginary parts. The full Fourier transform $\xi(k,D)$ contains identical information to the original function, but is not straightforward to represent, although the complex function can be represented as amplitude and phase spectra. It is more straightforward to show the power spectrum $S(k)$, which gives the square of the amplitude as a function of wavenumber irrespective of phase (Figure 19c). It can be seen that amplitudes are greatest at small wavenumbers (long wavelengths). It can be shown that spectra of this form indicate that the original surface had a fractal character (Turcotte, 1997). The full complex spectrum $\xi(k,D)$ can be modified by some function $\Psi(k)$ (also complex) to provide a new complex function $\xi'(k,D)$ with a power spectrum of $S'(k)$. The function $\Psi(k)$ is described as a filter. Examining the power spectrum $S'(k)$, it can be seen in Figure 19d that the amplitude of small wavenumbers (long wavelengths) has been reduced relative to large wavenumbers (short wavelengths). The function $\xi'(k,D)$ can now be re-transformed to the spatial (x) domain to provide $h'(x)$. As a consequence of the filter, the amplitudes of long wavelength features in $h'(x)$ are reduced relative to short wavelength features (compare

Figure 19e with Figure 19b). The overall amplitude of the features in $h'(x)$ rather than their form is commonly of interest. Thus a function $R(x)$ can be created that is the amplitude of the signal irrespective of sign. This can be the modulus or the Root Mean Square (RMS). This is represented in Figures 19f and g.

A final step is to determine how a 2-dimension function is to be represented. A whole range of mapping techniques are possible which include contouring, oblique lighting or color mapping. These offer a wide range of choices which depend on creating the most visually accessible result. The final map can depend critically on the choice of colour table. Figures 19f and g show respectively the results of using a linear table and a non-linear table. The former only shows very rough topography in red while the latter also picks out less dramatic roughness. Figures 19h and 19i show equivalent 2-dimensional representations to Figures 19f and 19g respectively.

The foregoing description allows the two most critical steps in creating a roughness map to be identified. The first is the choice of the filter function. There are an infinite number of possibilities that reduce the amplitude of small wave numbers with respect to large wave numbers. These are known as high pass filters. Some simple high pass filters can be applied without passing through the wave number domain. An $h'(x)$ can be formed using the spatial derivative (slope) $h'(x) = \frac{dh(x)}{dx}$. This

operation is equivalent to applying a k-domain filter $\Psi(k) = 1/k$. Differentiating twice is equivalent to $\Psi(k) = 1/k^2$, a stronger high pass filter. In either case sign information is removed to provide an $R(x) = |h'(x)|$. Another approach is to smooth the data $h(x)$ using some function. The result is then subtracted either wholly or partly from the original $h(x)$ to form a new $h'(x)$ and corresponding $R(x)$. Some of the simple operations can be carried out with 2-dimensional programs to manipulate photographs (e.g Adobe Photoshop[®]), Image Analysis and Geographic Information System programs (e.g., MaPublisher, ITT ENVI[®], used in this paper). The full range of operations can be carried out using higher level programming languages (e.g ITT IDL[®], Matlab[®]).

The second critical step in forming a roughness map representing $R(x,y)$ is the choice of color table. This can have a major influence on the visibility of features and is chosen to enhance the required features.

In this paper we use SRTM 30 and SRTM 3 (Shuttle Radar Topography Mission) data with a spatial resolution of about 30 and 3 arc sec, respectively. The vertical resolution is < 20m. Roughness can be determined from scalar slopes determined at a pixel level to provide:-

$$R(x,y) = \sqrt{\left(\frac{\partial h(x,y)}{\partial x}\right)^2 + \left(\frac{\partial h(x,y)}{\partial y}\right)^2} \quad 1)$$

The maximum resolution is determined by the pixel size. No wavelength can be resolved unless it is defined by a sufficient number of pixels. This limit is known, traditionally, as the Nyquist frequency

(although in our application Nyquist wavenumber would be more correct). As noted in the text, landscapes tend to have a fractal distribution. An important consequence is that roughness below the Nyquist frequency (i.e. at a scale resolved given the pixel size) can be considered to indicate that roughness is also present at sub-pixel scales. Such a filter provides reductions of amplitude approximately in proportional to wavelength (6 db/octave). More aggressive filtering can be simulated by re-applying a slope filter to give filters of approximately (12db/octave, 18db/octave ...).

Appendix 2: Lists of African sites by country

Morocco (n = 12): Aïn Maarouf; Dar-es-Soltan; Grotte d'el Mnasra; Jebel Irhoud; Kébitat (Rabat); Le Chaperon Rouge; Mugharet el-Aliya; Salé (Casablanca); Sidi Abderrahman; Témara; Thomas I Quarry; Zourah;

Tunisia (n = 1): El-Guettar

Algeria (n = 4): Bérard; Oued Djebanna; Tighénif (Ternifine); Ain Hanech

Libya (n = 3): Haua Fteah; Uan Afuda; Uan Tabu

Egypt (n = 7): Bir Sahara East; Bir Tarfawi; Dakleh Oasis; Nazlet Safaha; Sodmein Cave; Soleb; Taramsa; Kom Ombo (Gebel Silsila)

Niger (n = 1): Seggédim

Chad (n = 3): Bahr el Ghazal; Koro Toro; Toros-Menalla

Sudan (n = 1): Singa

Equatorial Guinea (n = 1): Mosumu

Cameroons (n = 1): Njuinye

Ethiopia (n = 17): Aduma; Bodo; Gademotto; Gadeb; Gorgora; Kukuleti; Lake Ziway; Melka Konturé; Omo; Porc épice (Dire Dawa); Hadar; Middle Awash (Adu-Asa; Aramis); Gawis; Gona; Dikika; Konso-Gardula; White Sands (Usno); Maka and Belohdelie

Eritrea (n = 2): Buias; Massawa

Djibouti (n = 1): Wadi Dagladlé

Somalia (n = 1): Midhishi

Uganda (n = 1): Magosi

Kenya (n = 25): Cartwright's Site; Eliye Springs; Enkapune ya Muto; Guomde; Kabua; Kapthurin; Lainyamok; Loyangalani; Lukenya Hill; Malewa Gorge; Muguruk; Olorgesailie; Prolonged Drift; Prospect Farm; Simbi; Songhor; Wetherall's Site, Koobi Fora; Allia Bay, Kanapoi; Tugen Hills; Chemeron; Chesowanja; Tabarin; South Turkwel; Kanjera

Tanzania (n = 8): Olduvai Gorge; Isimila; Eyasi; Mumba Shelter; Nasera Rock Shelter; Nduu; Ngaloba; Peninj (Lake Natron)

Democratic Republic of Congo (n = 3): Ishango; Matupi Cave; Katanda

Zambia (n = 5): Twin Rivers; Kabwe (Broken Hill); Kalambo Falls; Kalembe; Mumbwa

Malawi (n = 2): Uraha; Chiwondo Beds

Namibia (n = 3): Apollo 11 Rock Shelter; Berg Aukas; Windhoek

Swaziland (n = 1): Lion Cavern

Lesotho (n = 1): Sehonghong

Botswana (n = 3): White Paintings Shelter; #Gi; Rhino Cave

Zimbabwe (n = 3): Bambata; Pomogwe; Nswatugi

South Africa (n = 79): Cradle of Humankind and environs: Sterkfontein; Swartkrans; Kromdraai; Drimolen; Gondolin; Gladysvale; Maropeng; Goldsmith's Farm; Makapansgat Limeworks, Historic Cave, Cave of Hearths, Buffalo Cave, Equus Cave; Taung;

Other South African Sites: Border Cave; Still Bay; Strathalan; Rose Cottage Cave; Sibudu Cave; Florisbad; Paternoster; Peer's Cave; Sea Harvest; Nelson Bay Cave; Montagu Cave; Boomplaas Cave; Hofmeyr; Klasies River Mouth; Boegoeberg; Boskop; Bushman Rock Shelter; Diepkloof; Die Kelders; Dunefield Midden; Elands Bay Cave; Herold's Bay; Hoetjiespunt; Howisons Poort; Kasteelberg; Orangia; Rooidam; Sibebe Rock Shelter; Tuinplaas, Kudu Koppie; Hackthorne, Keratic Koppie; Northern Kruger Park; Olieboomport Shelter; Three Rivers; Klipplaatdrif; Kathu Pan; Wonderwerk Cave; Cornelia; Munro; Pniel; Canteen Koppie; Muirton; Doornlagte; Orange River Scheme; Port Edward (Pondoland); Seacow Valley Survey; Amazi Springs; Elandsfontein; Duinefontein; Cape Hangklip; Swartlintjies; Black Earth Cave; Heuningneskrans Shelter

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