Introduction

The Tsodilo Hills are located in the Kalahari Desert of northwestern Botswana, 48 km to the west of the Okavango River. The highest hill is nearly 400 m above the surrounding plain giving some idea of the dominance of the Hills in the region. Tsodilo is a new World Heritage site, known for its rock paintings and a wide variety of other archaeological findings including information on the advent of food production and metallurgy, intensive specularite mining, and deep rock shelters containing Later and Middle Stone Age deposits (Campbell et al. 1994; Denbow and Wilmsen, 1986; Robbins et al. 1998, 2000). The rock shelter excavations, coupled with work on lake deposits south of Tsodilo and on nearby sand dunes, have also provided a wealth of new paleoenvironmental evidence for the Kalahari. In this paper we provide an analysis of the sediments of Depression Rock shelter and place the information in the local and regional paleoenvironmental context. In addition, some comparisons will be made between the sedimentary and archaeological evidence.

Archaeology

While the archaeology has been discussed elsewhere, the extrapolated dates based on the sediment analysis discussed below provides for a better assessment of the probable age of the deeper deposits that underlie the radiocarbon dated levels (Robbins and Campbell 1989; Robbins 1990; Donahue and Robbins 1989). A brief summary of the archaeological findings follows.

Artifacts were found throughout most of the 510 cm of deposits, however as can be seen in the last column of Figure 2 there were substantial changes in artifact frequency, and the deposits between 245 and 270 cm in square 5 were sterile. The highest frequencies of artifacts were clustered between approximately 20-60 cm and 420-510 cm while comparatively few artifacts were found between 100-370 cm. Fauna was generally rare, most likely due to conditions of preservation. The fauna consisted mainly of unidentifiable small fragments of burned bone found dispersed in the upper meter of deposits, dating to the Holocene. Animals identified by R. G. Klein included hare, springhare, warthog, steenbok and gray duiker; all of which are found in the area at present (Table 2 in Robbins 1990). Reptiles identified...
Figure 1: Map of Depression rock shelter showing 1 x 1 m squares excavated in 1987.

Table 1. Depression Rock Shelter Uncalibrated and Calibrated Radiocarbon Ages

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Laboratory Number</th>
<th>Radiocarbon Age (years B.P.)</th>
<th>Calibrated**Age (2 sigma)</th>
<th>Years BP** (2 sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-60</td>
<td>Beta 22878</td>
<td>1860±90</td>
<td>BC 40-AD 390</td>
<td>1775±215</td>
</tr>
<tr>
<td>90-100</td>
<td>Beta 22879</td>
<td>3540±120</td>
<td>BC 2200-1540</td>
<td>3820±330</td>
</tr>
<tr>
<td>140-150</td>
<td>Beta 22880</td>
<td>7100±90</td>
<td>BC 6100-5780</td>
<td>7885±165</td>
</tr>
<tr>
<td>160-170</td>
<td>Beta 22881</td>
<td>10900± 420 BC</td>
<td>BC 11890-9620</td>
<td>12705± 1135</td>
</tr>
<tr>
<td>200-210</td>
<td>Beta 22882</td>
<td>13060±280</td>
<td>BC 14680-12360</td>
<td>15470± 1160</td>
</tr>
<tr>
<td>270-280</td>
<td>Beta 22883-ETH3531</td>
<td>18910± 180*</td>
<td>BC 21280-19740</td>
<td>22465± 765</td>
</tr>
</tbody>
</table>

* AMS date
** Calibration by Beta following Stuiver and van der Plicht (1998), Stuiver et al. (1998), and Talma and Vogel (1993)
Figure 2: Variations in sediment texture, shape, and color with depth at Depression rock shelter in relation to artifact frequency. The time scale at right reflects calibrated charcoal ages to 275 cm (~22.5 ka) and then ages based on a constant rate of sedimentation between 510-275 from 39-22.5 ka. The scale is therefore not linear above 275 cm, but is from 275-510 cm.
**Figure 3**: Calendar year age-depth relationship at Depression. Symbols show charcoal ages and errors in both depth and age estimates for the samples. The linear regression is forced through depth = 0, age = 0 and with depth as the dependent variable predicts an age of 37400 cal BP at 510 cm.

Regression Equation:

\[ \text{Calendar Age} = 73 \times \text{Depth} \]

Typical LSA tools include segments, small scrapers and backed drills. These types of artifacts were especially common in the upper 50 cm of deposits. The small scrapers were not found below a depth of 120 cm. Raw materials include locally abundant quartz and lesser amounts of non-local cherts, jasper, chalcedony and silcrete. There was generally a preference for using the non-local material for making microlithic tools, while the debitage was predominantly quartz.

Early Iron Age potsherds similar to those occurring at the Tsodilo village sites of Nqoma and Divuyti, along with iron artifacts were occasional finds, mainly in the upper 40 cm. The most significant iron artifacts were several wrist guard clips identical to those found at the nearby village sites. The sherds and iron artifacts were found along with numerous LSA tools and debitage.
Pre-Holocene LSA materials typically do not contain many formal tools. The deepest backed segment was recovered at a depth of between 320-330 cm and is estimated on the basis of evidence discussed below to be approximately 25,000 years old (Figures 2 and 3). However evidence of a microlithic reduction technique clearly extends to the base of the site. For example, the debitage found between 480-500 cm in square 5 contained 23 bladelets, 7 bladelet cores and 174 flakes as well as a number of other artifact classes. Significantly, a small piece of ground chromite, most likely used to produce pigment, was also found at this depth. As will be discussed, these deposits (480-500 cm), with evidence of microlithic technology and likely production of pigment are now estimated to be approximately 37/39,000 years old (Figure 2). When the early microliths were first found at the base of the Depression site, the discovery was surprising, given the possible age and the location. However, early evidence for microliths at Tsodilo is now also confirmed at White Paintings shelter where microliths, as well as larger tools, occur in association with extinct Equus capensis in the Lower Fish deposits (Robbins et al. 2000).

The Sediments: Field and Laboratory Methods

In order to provide a context for understanding the sediments some general comments about the setting follow. The Hills are composed of Upper Proterozoic Damara sequence metamorphosed sediments principally schist, quartzite, dolomitic limestone and mafic volcanic rocks. West of the Okavango River and delta are extensive longitudinal dunes which support open savanna vegetation communities dominated by Burkea africana and Pterocarpus angolensis. By contrast the calcritised sandy soils of the linear, inter-dune hollows are covered with grass and scrub (Grove 1969). The longitudinal dunes are massive, relict features with a spacing of 1.75 ± 0.3 km. Grove (1969) notes that the dunes are likely the degraded remnants of large sand ridges comparable to those presently found in the Namib Desert and were possibly 90 m high when active. Near the Tsodilo Hills the pattern of the dunes is disrupted presumably because of the effect of the hills on wind and sand movement at the time of dune formation. Sand has piled up on the eastern side of the hills but longitudinal dunes are lacking to the west in a streamlined area about 40 km in length (Grove 1969:198).

The Depression site is located on the northeastern-facing slope of the Female Hill. The bedrock of the shelter is quartzite. Significantly, the excavated area is open to the movement of windblown sand from the east and southeast (i.e. it is on the windward side of the hill). It must also receive inputs of wind-blown and water transported sediment derived locally from the hill complex.

The deposits in the excavation consisted of about 1 m of gray-black sandy soil overlying ~4 m of red-orange sand. There was no visible stratification. Samples were collected for sediment studies after excavations were completed. Samples of ~200 g were taken every 10 cm through the sediment column (i.e., at 8-10, 18-20, 28-30 cm and so on). An additional sample was collected from the surface (0-2 cm depth). Samples from 0-100 cm were collected from the walls of square 1, those from 100-280 cm from square 2, and those from 280-510 from the walls of square 5, the excavation unit providing the deep sounding (Figure 1). In addition, representative samples of sediment were collected from the quartzite hill slope above the shelter and from nearby dunes for comparative purposes.

Sediment color was determined on dry, untreated samples using a Munsell color chart. Each sample was split to obtain a representative 25 g sub-sample for chemical analysis. Macro-organic matter and human artifacts were first removed and then the sample was sieved to obtain particles coarser than 1Φ. The samples were then treated with 0.5 N HCl to remove carbonates (Jackson 1969). Any remaining organic matter was removed by oxidation with hydrogen peroxide (Singer and Janitzky 1986). What remained of each sample was then dispersed in a solution of sodium hexametaphosphate and wet-sieved through a 4Φ sieve to remove silt and clay. Particles coarser that 40 were dry-sieved at 10 intervals in the range from ~2 to 1Φ and at half Φ intervals from 1 to 4Φ. The 4Φ silt and clay fraction was then subjected to pipette analysis. Withdrawals were taken to divide the sediment at the 5,6, and 9Φ size intervals. Mean grain size, sorting, skewness and kurtosis were determined by the graphical method of Folk and Ward (1957).
Sub-samples were also subjected to double acid extraction (HCl-HNO₃ at a ratio of 2:1) and concentrations of 20 elements determined by inductively coupled argon plasma (ICAP) spectrometry. Three samples from 2.8, 3.5 and 5.0 m were examined for clay mineral characteristics. A portion of these samples was suspended in DDH₂O and wet-sieved through a -325 screen; the resulting clay suspension was air dried. The dried material was lightly crushed and passed through a -200 mesh prior to XRD mount preparation. Square discs were prepared which give good preferred orientation as well as minimize sample surface related errors. The samples were X-rayed with Cu Ka radiation and scanned at a rate of 4 degrees 2 theta per minute. All three samples showed the same general mineralogy, namely kaolinite and quartz. The kaolinite appears to be soil derived in that three samples showed the same general mineralogy, namely kaolinite and quartz. The kaolinite appears to be soil derived in that the XRD reflections are rather broad and diffuse indicating fine particle size, small coherent domains, and poor structural order, all of which are characteristic of kaolinites from oxidized soils.

Particle shape was determined microscopically using the visual comparison chart of Powers (1953). The 1.0-1.5, 1.5-2.0 and 2.0-2.5φ fractions were analyzed. One hundred grains in each size fraction were classified and sample roundness was quantified using the method of Folk (1955). These size fractions were chosen for analysis because the grains spanned a range from predominantly angular (1.0-1.5φ) to predominantly rounded (2.0-2.5φ) and so were considered to be the most sensitive to any changes that might have occurred in the input of angular versus rounded grains to the site.

**Site Chronology**

A chronology was established for the site by dating charcoal found in the excavated levels (Table 1, Figure 3). This charcoal could not be ascribed to an exact depth but was assumed to have originated from the mid point of the 10 cm layer from which it was taken so the depths have an error of ± 5 cm. Six ages were obtained in stratigraphic sequence the oldest being 18,910 ± 180 ¹⁴C years BP. Calibrated ages ranged up to ~22,500 calendar years (~22.5 ka). All of the charcoal dated was recovered from square 5 while the sediment samples for these depths were obtained from squares 1 and 2 after the excavations were completed. As a result, it is likely that the ages ascribed to particular sediment samples will be slightly in error, particularly at depths where sediment sampling moved from one square to another. In addition, sand is easily bioturbated and use of the shelter by humans and animals may have led to fragments of charcoal being trampled into the sediments of the floor. So, it is likely that actual sediment ages are slightly older than the charcoal ages assigned to them. Separate linear regressions of depth versus age and age versus depth, each forced through depth = 0, age = 0, suggest that the basal sediments at 510 cm are 38.5 and 37.4 ka, respectively (Fig. 3). Assuming a constant sedimentation rate throughout deposition (275 cm in -22.5 ka) gives an age of 41.7 ka for sediment at 510 cm. As we cannot be sure which of these estimates is correct we averaged them giving an age for the basal sediments of 39 ka. Ages for sediments below 275 cm were estimated by assuming a constant sedimentation rate over the period 39-22.5 ka.

**The Sediment Record**

We believe that finer-grained, better-sorted sediments at the rock shelter should equate with drier conditions when more material was transported into the shelter by wind. In addition, with increased aeolian transport we might expect more sub-rounded to rounded grains in the sediments. Under slightly wetter, semiarid conditions, there should be an increase in coarse and very coarse sand and gravel, and in sub-angular to angular sand derived from the quartzite walls of the shelter and from hill slopes that channel water through the shelter. We might also expect a reduction in the input of aeolian sand, silt and clay from the dunes that envelop the valley in which the Depression rock shelter is located. Under conditions of even greater wetness, the input of aeolian sand, silt and clay should be reduced still further due to a denser vegetation cover in areas surrounding the shelter. Also, there should be a greater accumulation of coarse material produced by increased breakdown within the shelter and increased runoff into the shelter carrying particles not easily transported by wind. Also, the Kalahari is fairly cool, especially in winter, and sharp frosts are quite common in the early morning at the height of the dry season. This suggests that during the Last Glacial Maximum, when conditions were 6°C cooler than now (Stute and Talma 1997), frost action might have caused breakdown of the rock shelter with the production of angular gravel.
Variations in sediment characteristics are shown in Figure 2. Mean grain size varies from 2.33Φ at 70 cm to 1.08Φ at 500 cm, or from an average of fine sand to an average of medium sand. The sediments range from moderately sorted to very poorly sorted (0.9Φ at 70 cm to 2.09Φ at 500 cm). The median grain size varies from 2.38Φ at 460 cm to 1.70Φ at 310 cm, which is from fine to medium sand being the dominant size fraction. Skewness varies from very negatively skewed at 500 cm to negatively skewed at 50 cm indicating that all of the samples have a mean less than the median and therefore a tail towards coarser particles. Kurtosis varies from 0.68 at 500 cm to 1.65 at 460 cm indicating a range from platykurtic to very leptokurtic.

Sediments above 250 cm depth that are younger than ~20 ka are noticeably finer than deeper deposits. The ratio of medium, fine and very fine sand to coarse and very coarse sand above 250 cm is ~4 compared to ~2 for deeper sediments. Also, below 250 cm (20-39 ka), and above 115 cm (5-0 ka), grain size fluctuates sharply with depth as illustrated by grains coarser than 2Φ which vary from 50-30% of the sediment in as little as 10 cm. Gravel (<1Φ) is most common at 500-300 and 125-40 cm with a minor peak at 210 cm (39-26, 7.5-1.75, and 16 ka). Grain shape also varies markedly through the sediment column, with angular grains more abundant at 5 10 and 410 cm (39 and 32 ka), from 315-200 cm (25-15 ka) and at 55 cm (2 ka), and peaks in the number of subrounded, rounded and well rounded grains occurring at 465, 355, 75, and 5 cm depth (36, 27, 2, and 0 ka). Coarser and more angular sediments with greater variability in grain size with depth, suggest frequent heavy sununer rains in a wetter climate, with a reduced input of aeolian, finer-grained, more rounded sands. Finer, less variable, and more rounded sediments imply greater input by wind under drier conditions, and a reduced input of locally derived angular debris.

Peaks in Al, Fe, Si, K, and P in the present B horizon at 10 cm, and also at 60, 100, and 200 cm, and buried A and B horizons at ~60 cm, indicate enhanced soil development probably under wetter conditions at 2, 4, and 15 ka. Variations in particle shape and texture indicate increased wetness ~39, 34-29, and 26-15 ka (with a possible short, dry interval ~22 ka). In addition, the calibrated radiocarbon ages for charcoal in the upper 100 cm of sediment indicate Holocene wet phases at 4 and 2 ka. There are noticeable peaks in artifact frequency during the two earliest and during the two Holocene wet intervals, and a minor peak at ~24 ka. However, during most of the wet interval from 26-15 ka (325-200 cm) very few artifacts were encountered in excavations and some layers were sterile. We cannot rule out that people camped elsewhere at the site during this time or at other more favorable sites. It is also interesting to mention that during the earliest wet interval at ~39 ka, the use of local quartz as a raw material reached its highest level: 480-500 cm (96% quartz, 4% chert/jasper, N=314). We cannot say whether groups did not travel far from Tsodilo during this wetter time or, perhaps, this reflects expedient use of local raw materials at this site. Other factors such as more restricted exchange networks, or even sampling error could also be responsible for this high percentage of quartz usage. Whatever the case may have been, there seems to be a different pattern in the upper 1 m of deposits (beginning at ~4 ka) where there is increased use of non-local raw materials in all of the levels in these deposits, varying from 19 to 50%.

**Discussion**

Grove (1969) suggests that the longitudinal dunes of northwest Botswana, including those at Tsodilo, represent a period of aridity when the annual rainfall was less, probably much less, than 250 mm/yr, as compared with more than 500 mm/yr at present. In fact, OSL ages on dune sands south of Tsodilo Hills indicate accumulation at 98.1 ± 9.2 ka and in the intervals 35.4 ± to 33.8 ± 2.8 and 28.1 ± 4.6 to 29.8 ± 4.4 ka (Thomas et al. 2003). The ages agree well with the sediment evidence from Depression of dry intervals at ~36 and ~28 ka.

Diatoms and freshwater mollusk shells south of Tsodilo Hills indicate the former existence of an extensive, sometimes permanent lake at 40-32, 27-22, and 19-12 ka, while fish bones and the bones of wetland animals in sediments at White Paintings rock shelter in the Male Hill indicate wet conditions at ~43-32 and 8-4 ka (Robbins et al. 2000; Thomas et al. 2003). This record closely parallels the paleoenvironmental record from the Depression rock shelter discussed above.

Research in the summer rainfall zone of Namibia also supports the climate record from Depression rock shelter and data from other sites at or near Tsodilo Hills. The sedimentology of relict terrace...
sediments in the Khumib and Hoarusib river valleys of NW Namibia, dated by OSL, indicates that the climate of the Namib Desert was wetter at ~40 ka, from 28-25 ka, and from 21-15 ka (Srivastava et al. 2003a, 2003b). Lacustrine sediments in the Namib Sand Sea dating to 34-32, 27-23, and 18-13 ka present a similar history of wet intervals (Teller et al. 1990). Finally, variations in the frequency of speleothem and tufa ages in the summer rainfall zone of southern Africa indicate wet intervals with enhanced deposition at 38-36, ~31, 27-24, ~16, and in the Holocene at 9, 5, and 2 ka (Brook et al. 1997; see also Figure 12 in Robbins et al. 2000). Findings at Depression rock shelter thus support evidence from other areas of southern Africa of major wet intervals centered at 39, 32, 23, and 15 ka. The Depression data indicate at least two wet intervals during the Holocene at 4 and 2 ka while tufa and speleothem ages indicate three wet intervals at 9, 5 and 2 ka. Artifact counts show that the Depression site was used more during periods of wetter climate except from 23-15 ka when some sediments are even sterile.

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