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TAPHONOMIC OBSERVATIONS ON A CAMEL SKELETON IN A DESERT ENVIRONMENT IN ABU DHABI

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ABSTRACT

A camel skeleton in a desert environment in Abu Dhabi was monitored for 15 years to record stages of weathering, dispersal, carnivore action and trampling in this extreme environment. Weathering was substantially less rapid than that recorded in tropical environments, being slower both in inception and in later development. Skeleton dispersal was mixed, with a core group of ribs and vertebrae remaining close to the death site, but individual bones being traced for up to 60 m and many disappearing altogether. Scavenging took place, and the size of tooth marks indicated foxes and jackals. Trampling was the major source of breakage of bones, most of which were too robust for small carnivores like foxes and jackals to break.

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INTRODUCTION

Modifications of vertebrate carcasses and bones have been studied in many parts of the world, from tropical Africa to northern temperate regions (Behrensmeyer 1978, 1983, Haynes 1983, Blumenschine 1986, Korth 1979, Lyman 1994, Andrews and Cook 1985, Andrews and Armour-Chelu 1998), but little is known about the effects of weathering and other modifications in mid-latitude desert environments. These are inhospitable environments for both living and dead, with high solar radiation, extreme daily temperature fluctuations, high seasonality (both daily and annual), little vegetation and little or no rain sometimes for years at a time. For survival of bones exposed on the surface, these conditions pose problems not encountered elsewhere. For example, the lack of vegetation, which could shade and protect bones from the intense solar radiation, lack of rain and the dryness of the air expose bones to extreme drying

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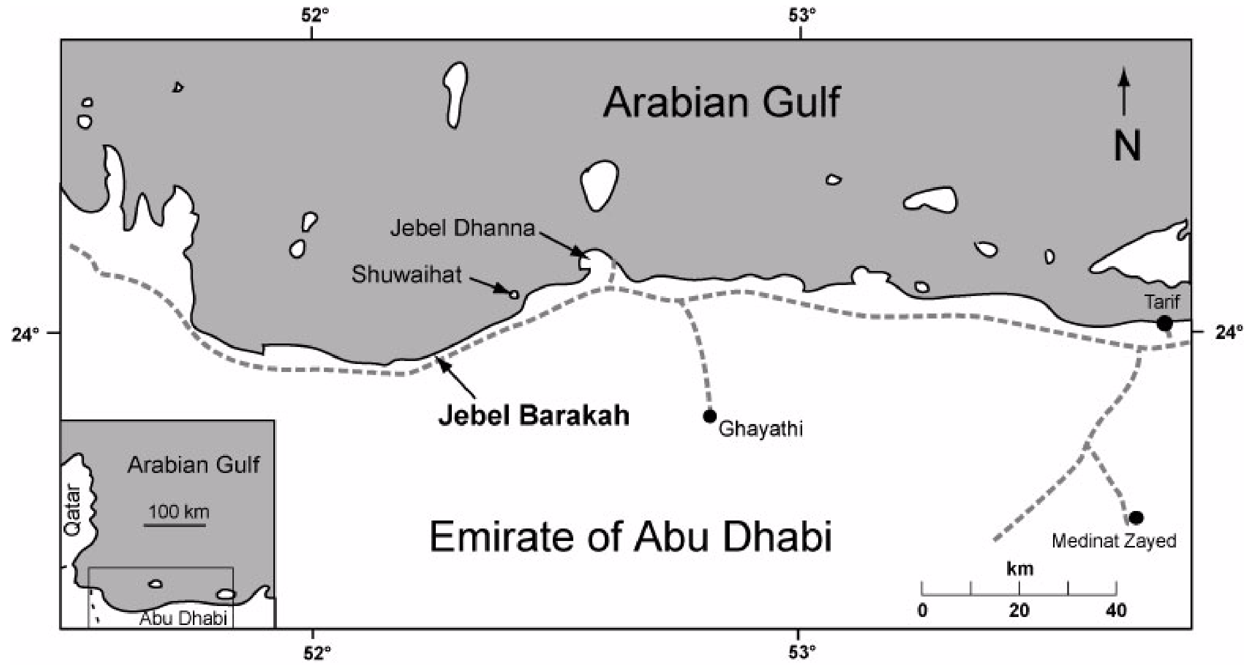


Figure 1. Locality map of the northern coast of Abu Dhabi showing the position of Jebel Barakah.

conditions; and the large daily temperature changes expose the bones to heating and cooling on a regular basis. Rainfall, when it occurs, can be extremely violent, resulting in flash floods in gully systems. It might be expected, therefore, that burial of bones would be slow, transport of bones in gullies would be rapid, and that the extremes of weathering would result in the rapid breakdown of bones exposed on the surface.

In order to test these predictions, long-term studies of bones under differing environmental conditions are needed. Only one such study has been published (Behrensmeyer 1984, Trueman et al. 2004), and the environment of exposure is a tropical African savanna with higher rainfall and greater solar radiation. A long-term monitoring experiment (20 years) in a temperate environment is in preparation (Andrews and Armour-Chelu 1998), and the results suggest that in temperate climates both the rate and the type of taphonomic modification is very different from that observed in tropical Africa. The intention of the present study was to investigate the effects of intermediate environmental conditions in the mid-latitudes.

In the 1980s, we undertook a series of fossil collections in Qatar and Abu Dhabi, organized by Peter Whybrow. Although he prematurely and unfortunately died, the present work owes much to his dedication and capacity to embrace new ideas. In 1984, we set up a series of taphonomic trials to monitor the effects of desert environments on the preservation of bones (others described in Andrews and Whybrow, in press). Most of these trials failed as a result of human interference, but the one reported here was the discovery of a recently dead camel in a broad shallow valley on Jebel Barakah, a remnant hill of Miocene deposits by the edge of the Arabian Gulf. Jebel Barakah is in the far west of Abu Dhabi (Figure 1), close to the border with Saudi Arabia. The camel was in a secluded valley well away from any likelihood of human interference so that any modifications produced during the breakdown of the skeleton are likely due to natural causes. The following analysis is based on monitoring this single individual for a period of 15 years, from 1984 to 1998, and all results must be viewed as tentative since a larger sample was not available.

Material and Methods

Five surveys were made over a period of 15 years, the periods being dictated by times of expeditions to collect Miocene fossils. The first survey was made on January 5, 1984, and the last on November 8, 1998, when we completed our programme of field work in Abu Dhabi. The specimen studied was a young adult of the Arabian camel *Camelus dromedarius* (Harrison and Bates 1990) in a broad shallow gully on the lower slopes of Jebel Barakah (Figure 2): latitude 24º 00' 25.7"N, longitude 52º 19' 43.1"E. The cause of death of the camel and the exact date when it died are unknown, but the bones formed a compact cluster that had not been dispersed down the gully. Many of the bones were still covered in skin or other soft tissue and, from observations of other recently dead camels in Arabia and the extent of rainfall over the preceding few years, we estimated death was about two years earlier, some time in 1982. It was a young adult individual with the postcranial epiphyses fused but some of the vertebral epiphyses either unfused or partly fused.

A base line was set up along the line of the gully in which the skeleton was first found, and fixed marker points were used to ensure that the same line was used throughout for measuring dispersal of the bones. All visible bones were recorded on each of the five surveys, but no attempt was made to locate any bones below the surface until the final collection in 1998. Measurements were in two dimensions, including length along the datum line and distance perpendicular from the line. Angles of orientation were measured, although numbers of specimens were too small for reliable results. Angles of dip were not measured since most bones were resting on the surface of the soil, and their dip was a function of the angle of slope of the ground. Some bones became buried during the course of the monitoring of the skeleton, but also some bones previously buried were uncovered by the shifting of the sands covering much of the site. Weathering was recorded following the scale published by Behrensmeyer (1978), and other damage was assessed qualitatively, particularly the presence of root marks and other aspects of soil corrosion. Presence of carnivore tooth marks was investigated.

Description of the Site

All the bones were in or close to the bottom of a broad shallow gully, which slopes slightly north of west (282º) down towards the Arabian Gulf. The gully is cut by a shallow water channel about half a metre deep (Figure 2). The substrate is unconsolidated sand overlying Miocene deposits consisting at this level of moderately calcified silts and sands. The sparse vegetation consists of widely separated clumps of grasses and low-growing thorny shrubs (Figure 2). Most of the camel bones were lying on the north side of the gully on a gently sloping platform, but some had fallen into the vertical-sided channel that cuts along the platform. There were no bones on the south side of the channel.

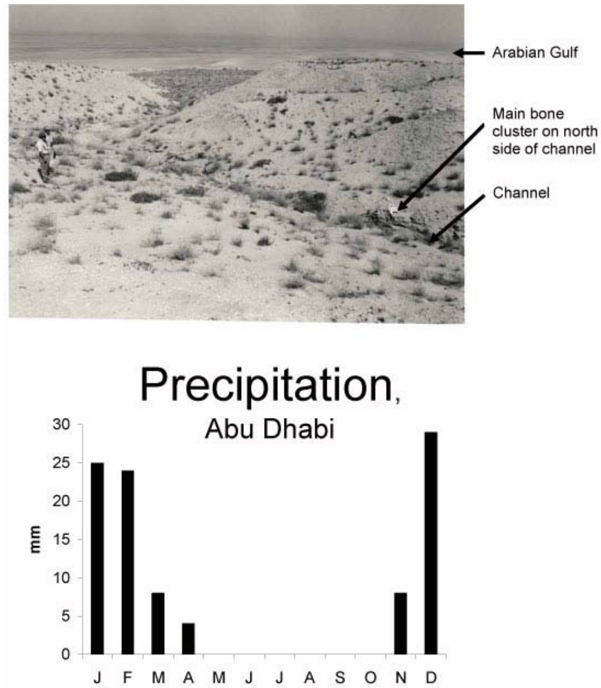


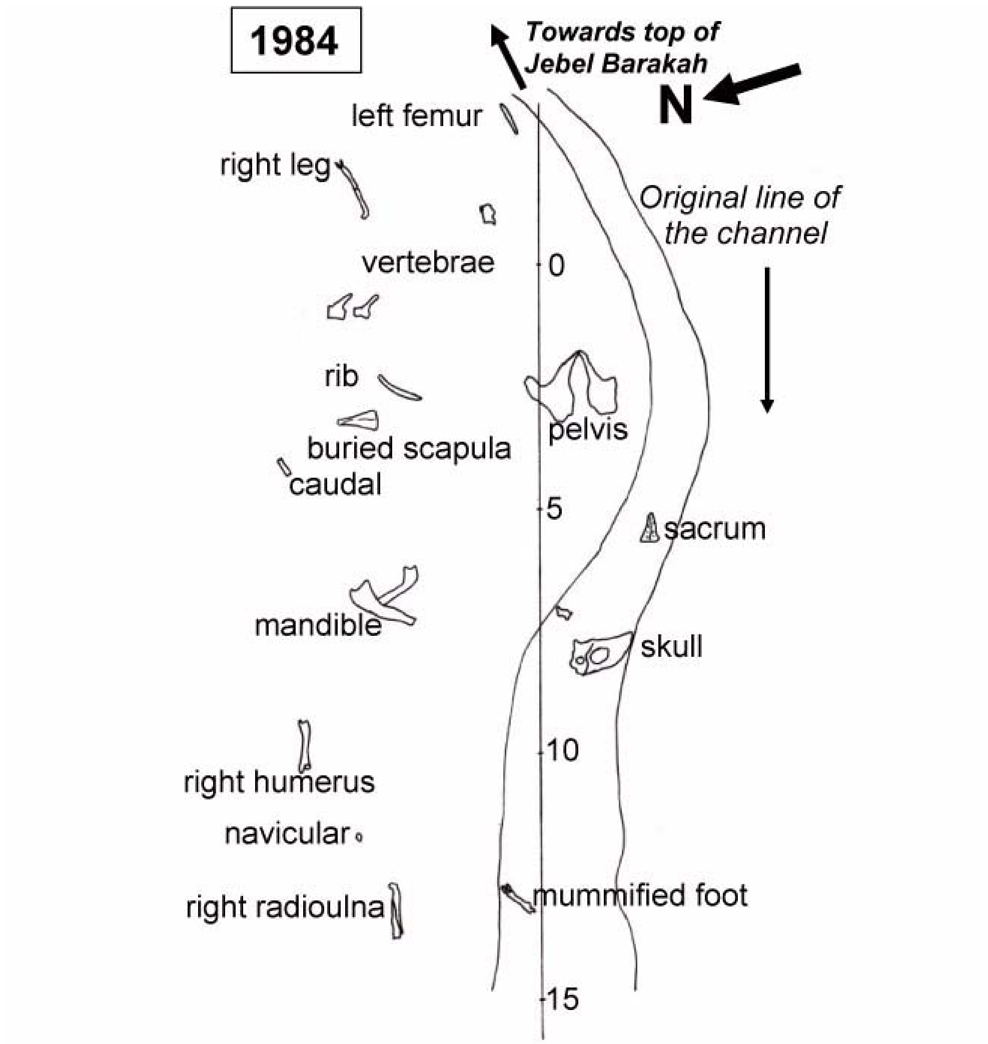
Figure 2. General view of the camel site on Jebel Barakah looking due north. Some of the camel bones can be seen lower right, with the gully trending diagonally to the left before bending almost 90° to the right towards the Arabian Gulf. Annual rainfall distribution for Abu Dhabi is shown below.

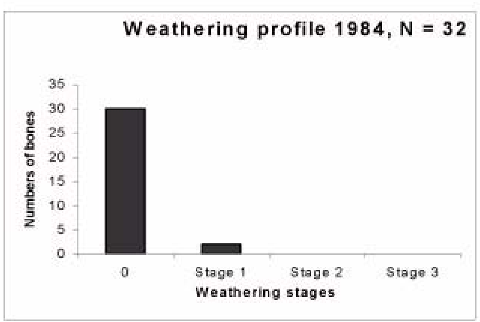
RESULTS OF MONITORING CHANGES IN THE SKELETON

1984 Survey

The distribution of the camel skeleton in January 1984 is shown in Figure 3. The maximum dispersal of the skeleton was along the line of the gully over a distance of 18 m. The main concentration of bones covered an area of about 140 m^2, extending 12 m along the gully bottom, with two outlier bones, a mummified foot and the right radioulna. There was little lateral movement of the bones away from the bottom of the gully.

Several of the bones still had dried skin attached, including the radioulna, one of the detached feet and the whole of the right hind leg. Most of the bones were on the surface, but no excavation was done at this stage and it is probable that some bones were still present but buried beneath the surface. Most of the ribs and many of the vertebrae could not be found (Table 1), and it was considered likely that many had already been carried away or destroyed by scavengers. The skull was broken, with the braincase missing, but the mandible was intact. Both right legs were preserved but lacking the right scapula, but both left legs were missing except for the left femur, which was the most extensively broken bone in the skeleton. The left scapula was present, half buried. It would seem that the dead animal had been lying on its right side, protecting the right limbs from scavengers but leaving the left side exposed. Orientations of the bones were influenced by their position on the surface (Figure 3), the bones on the north side of the gully aligned to the south and





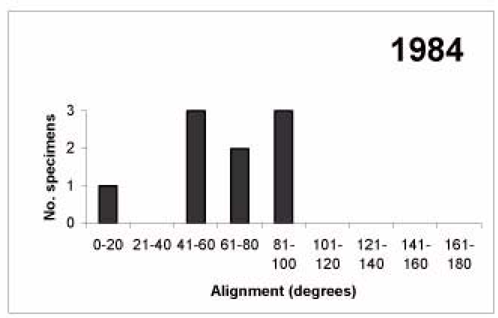


Figure 3. Plan view of the camel skeleton made on January 5, 1984. Datum line is marked in metres and is set out at 282°. Below right is a plot of the alignments of the bones (N = 9), and below left is the weathering profile (Behrensmeyer 1978) of the bones that could be located at this time.

west, at 221º to 280º, following the slope of the side of the gully towards the channel. (Bones with equal but opposite direction are combined so that the scale on Figure 3 is shown from 0 to 180º.)

There was little in the way of surface modifications on the bones. Two bones have very slight etching of the surface, mainly because they were stabilised in the ground. The scapula, for example, was half buried, and the top of the scapular spine showed a very early stage of weathering, intermediate between 0 and 1 in Behrensmeyer's (1978) scale (Figure 3). The pelvis, like the scapula, provides a wide surface area to weathering, and since the two sides were still in articulation, it could not easily be turned over, so that the exposed side showed the same early stage of weathering. No

Table 1. Percentage representation of bones exposed on the surface.

Element	Brief description	1984 %	1992 %	1994 %	1998 %
skull	frontal and zygomatic region	100	100	0	0
maxilla	became separated from skull 1984-1992	100	100	50	0**
mandible	complete	100	0	0	0
vertebrae	atlas, caudal, 2 thoracic, 1 lumbar	16	13	23	26**
humerus	right humerus buried	50	0	0	0
radioulna	complete, right, skin still attached to olecranon process	50	0	50	0*
femur	left broken, right associated with articulated leg	100	0	0	0
tibia	associated with right articulated leg	50	50	0	0
foot	complete, right, mummified	50	calcaneus	calcaneus	calc.+ astrag.
ribs	two fragments	9	21	46	8*
sacrum	lowest process broken	100	0	0	0
pelvis	complete, but epiphyses broken	100	100	50*	50
scapula	left scapula seen in 1984, right seen in 1994	50	50	50	0*
phalanges	none seen in earlier surveys	0	0	0	8

* one specimen collected in previous years

** two specimens collected in previous years

evidence of carnivore chewing was seen at this stage, which is puzzling since many of the ribs and vertebrae were missing. It will be seen later that both rib and vertebra numbers were higher in later surveys, and the most likely solution is that the bones were there but buried beneath drifting sand.

1992 Survey

Just over eight years after first discovery, the camel skeleton was mapped again and some bones collected on April 12, 1992. The extent of the main bone cluster was little changed (Figure 4), with the scatter extending about 10 m along the axis of the gully, but the position of the channel had changed. Whereas before it had curved around the position of the pelvis (Figure 3), it now passed right through this position, splitting the pelvis into two halves, one on each side of the channel. It is odd that both fragments remained on the banks above the channel, neither falling into the channel itself. This suggests that the water flow was not excessively fast.

The skull had disintegrated, leaving only two maxillary fragments, one of which was collected (Figure 5), and some skull fragments that had moved up the gully, probably carried by a scavenger. One of the maxillary fragments was in the bottom of the channel partly buried, and the other was on the platform above the channel. The pelvis had been split in two as mentioned above, and one of the scapulae was found half buried in the bottom of the channel (it is likely that this was the left scapula recorded outside the channel in 1984, but our records do not show which side it was from - see below). More ribs were seen on this occasion, five in all, and four vertebrae that were extremely broken up. Some of the bones from the previously articulated leg were still in the same place, with the tibia, metatarsal and calcaneus/astragalus still being present. No forelimb elements were seen, apart from the scapula just mentioned, and the mandible had disappeared, as had the sacrum and the mummified foot. Bone orientations were similar to those seen in 1984, with directions being determined by the slope of the land westwards along the line of the gully and (on the north side of the gully) southwards towards the channel running down the middle of the gully (Figure 4).

No soft tissue was present, and the majority of specimens still showed no evidence of weathering. The scapula had early stage 1 weathering along the scapular spine, the only part exposed. The right pelvis also showed early stage 1 weathering, with no weathering on the protected side and early stage 1 on the exposed side. The maxilla had no evidence of weathering on the internal, lingual side, but stage 1 weathering on most of the exposed buccal side, with fine cracking along planes of weakness (Figure 5). Nearly one quarter of the bones had incipient or full stage 1 weathering compared with 6% in 1984 (Figure 4).

1994 Survey

Two years later on April 8, 1994, the bone cluster was still intact, but some of the bones had been moved some distance down the gully (Figure

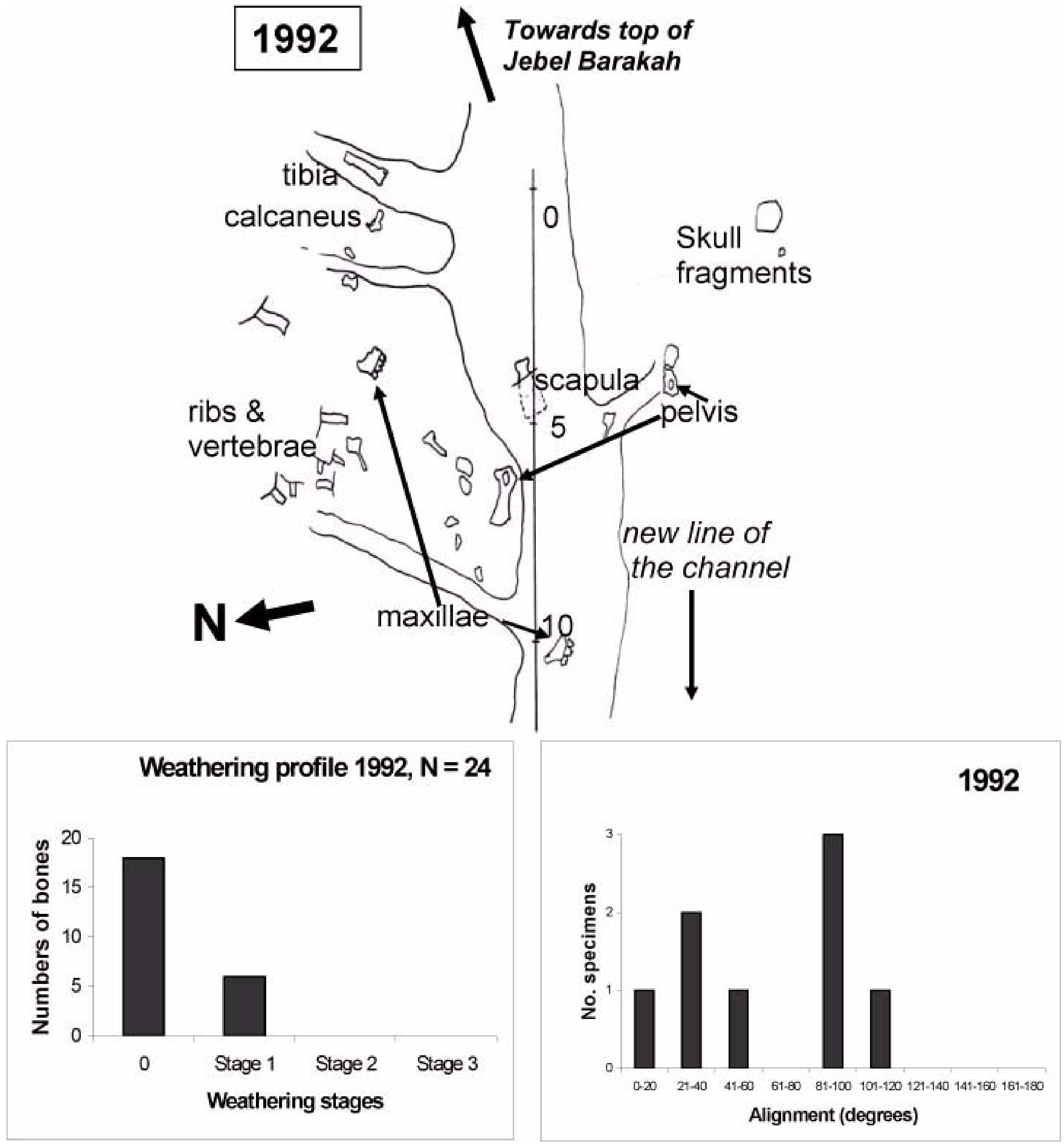


Figure 4. Plan view of the camel skeleton made on April 12, 1992. Datum line and scale as in Figure 2. Below right is a plot of the alignments of the bones (N = 8), and below right is the weathering profile (Behrensmeyer 1978) of the bones that could be located at this time.

6). The right scapula was seen for the first time, in the channel 13.5 m down the gully from the main bone cluster. By an unfortunate omission, the scapula seen in the channel in 1992 (see above) did not have its side recorded, and so it is not certain if this is the same specimen moved 9.3 m down the channel (in 1992 it was at 4.2 m - see Figure 4) or if it had been moved earlier and buried, so that it was not seen until 1994. There were also two intact ribs not seen in previous surveys, both 21 m down the channel. Neither of the ribs was broken and neither had been visible in earlier surveys. It is presumed that they were buried in the channel deposits, and this might suggest that both they and the scapula had been transported down the channel at an earlier time. The radioulna was located 24 m down the gully just off to the side of the main channel (Figure 6), and at 30 m was one of the fragments of maxilla. Bone orientations were again similar to those seen in 1984 and 1992, with

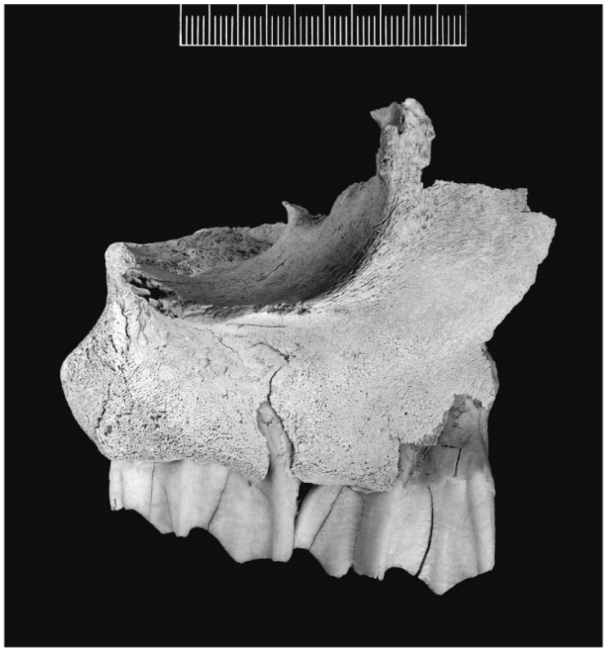


Figure 5. Right maxilla collected in 1994, 10 to 12 years of exposure, buccal view. Superficial cracking is apparent anteriorly, and slightly deeper cracking is present at the posterior end of the maxillary body. Scale is millimeters.

directions being determined by the slope of the land westwards along the line of the gully and (on the north side of the gully) southwards towards the channel running down the middle of the gully (Figure 6).

The main bone cluster consisted of ribs and vertebrae. There were nine rib fragments, two of which were exposed on the surface and the others were partly buried so that it could not be determined how complete they were. There were seven vertebrae still relatively complete (Figure 7), and one calcaneus still close to the position of the left leg but now all that remained of the leg. The remains of the pelvis were still on the south side of the channel, and part of this was collected for further examination.

Modifications of the bones were greater than was observed in the 1992 survey. More than half the bones had now reached stage 1 weathering, three were at stage 2, but a significant minority of bones still showed no evidence of weathering (Figure 6). The pelvis fragment had the top edge of the ilium extensively broken, probably as a result of trampling by camels and goats that graze in this area. No carnivore damage was seen, and weathering was at an early stage, fine splitting but no flaking, indicating stage 1 weathering. No sign of the other half of the pelvis, which previously had been present on the north side of the channel, was seen. The radioulna had evidently been mobile, given its position down the gully, and it was evenly weathered on all surfaces at early stage 1 (Figure 7). The ribs and vertebrae were assessed for weathering but only one of each was collected at this stage. In general they had low levels of weathering, stage 1 for the most part but with areas of flaking indicating early stage 2 weathering (Figure 7). The parts of the bones that were buried, even under a few millimetres of sand, had no weathering and were stained light brown in contrast to the bleached white of the exposed bone. The exposed part of the vertebra had extensive splitting and early stages of flaking, while on projecting processes the flaking goes deeper, producing roughened patches of bone greater than 10 mm^2, and so by definition it is at stage 2 even though most of the surface is minimally weathered. The maxilla had no weathering on the internal, lingual side, but stage 1 weathering on most of the exposed buccal side, with fine cracking along planes of weakness. There was localised flaking on the thin alveolar bone covering the tooth roots and on the diastema, so that this specimen could be categorised as early stage 2. The teeth also show evidence of cracking and splitting of enamel. There was limited carnivore damage along the broken upper edge where a series of small punctures ranging from 1.4 to 3.2 mm in diameter occurred along the broken edge.

1995 Collection

No survey was done this year, but two more bones were collected on March 6, 1995, for examination in the laboratory. These were the right scapula and another vertebra. The scapula had no weathering on the side in contact with the substrate, but the upper, dorsal, side had variable weathering, ranging from stage 1 over much of the scapular blade to extensive flaking along the spine and along the vertebral edge (Figure 8), indicating stage 2/3 weathering. The vertebra was complete except for one of the lateral processes (Figure 8). It had moved around on the surface so that the degree of weathering was similar on all surfaces. Extensive splitting was present with localised flaking, and the top of the vertebral spine showed deeper and more extensive flaking, so that this bone can be characterised as mainly stage 2 with beginning stage 3. Carnivore damage was seen on the broken process, and there were also chewing marks on the end of the unbroken lateral process, giving a range of pit diameters from 1.4 to 2.1 mm (see below - Surface Weathering).

1998 Survey

In 1998 we made one last survey of the camel skeleton on November 6 and collected all the

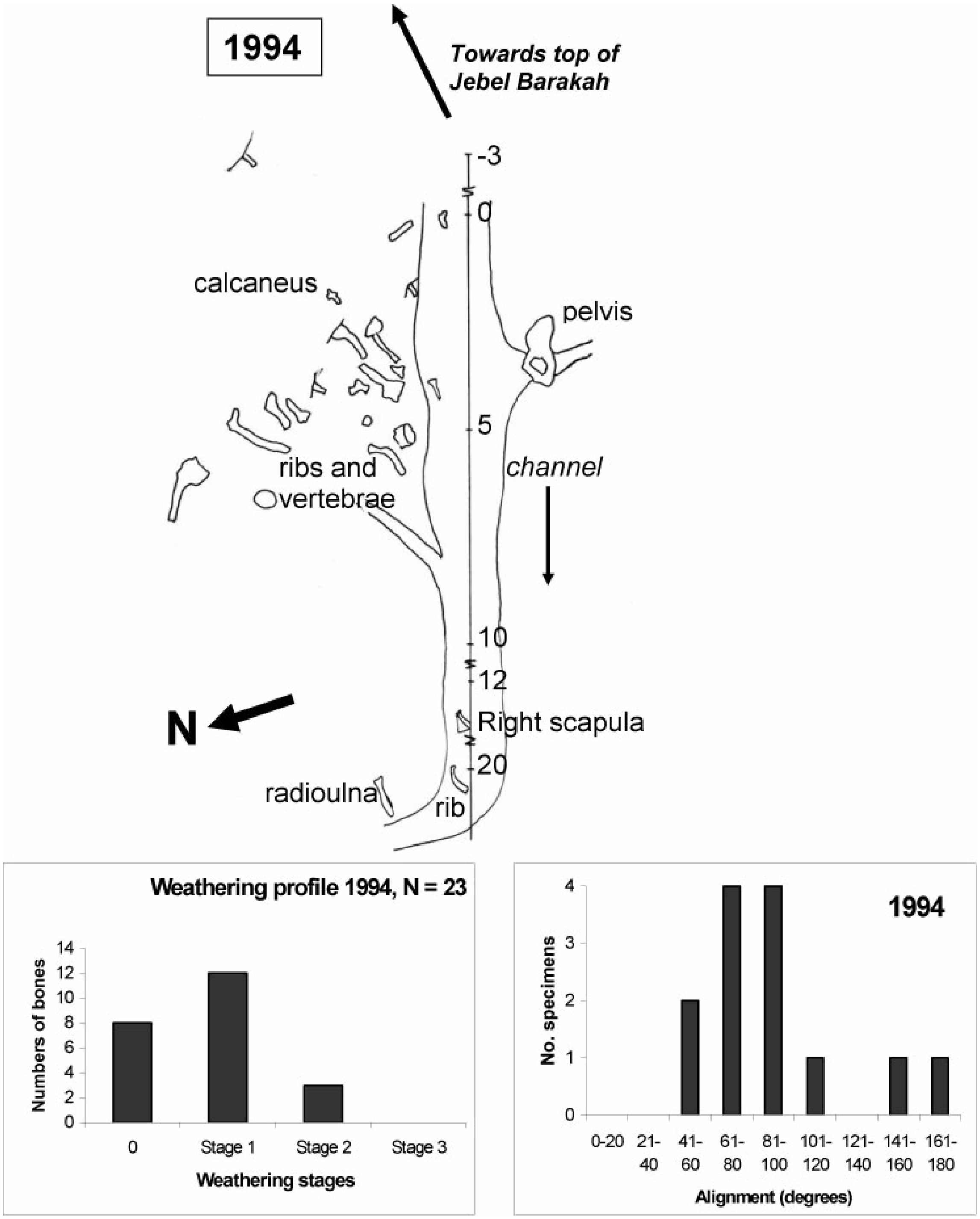


Figure 6. Plan view of the camel skeleton made on April 8, 1994. The main bone cluster was now reduced to 7 m with a rib 2.8 m up the gully from the cluster and several bones from 13 to 24 m downstream. The maxilla measured at 30 m down the gully did not have its position recorded. Nothing was found between 2 and 13 m or between 24 and 30 m, and so the plan has been truncated to cut out these regions, but otherwise the scale and datum line remain the same. Below right is a plot of the alignments of the bones (N = 13), and below right is the weathering profile (Behrensmeyer 1978) of the bones that could be located at this time.

bones we could find, both above and below ground, although we did not carry out a systematic excavation. Altogether we found eight vertebrae, part of the pelvis, two ribs, two phalanges, a calcaneus and an astragalus. None of the long bones were found and no trace of any cranial element, neither teeth nor mandibles. There had been considerable drifts of sand blown over the area, how-

Figure 7. A, rib collected in situ 8 April 1994, 21 m down gully; **B,** radioulna collected in situ 8 April 1994, 24 m down the gully. **C,** lateral view of vertebra collected on 8 April 1994 showing early stages of flaking, with some deeper flaking producing roughened patches of bone. The length of the body (i.e. from left to right on the picture) is 66 mm.

ever, and it is likely that several elements were preserved buried under considerable depths of sand.

The distribution of bones (Figure 9) indicates that there had been a general movement of bones down the channel. The bones seen previously 20 to 24 m down channel had disappeared, and now there was a single bone 45 m down the channel, the astragalus, which previously had remained with the cluster of bones at the death site. The pelvis on the north side of the channel, seen previously in 1992 but not in 1994, was found, but the other half of the pelvis on the south side of the channel had disintegrated in 1994 and the remaining parts collected that year. The calcaneus remained in the bone cluster, but 5 m down slope from the place where the left leg had last been seen. Only two bones could be measured for orientation, and these were non-conclusive.

Overall, some bones had now reached stage 3 weathering, and the majority were at stages 1 and 2 (Figure 9), but it is difficult to generalize since so much depends on the degree to which the bones had been buried and thus protected from both dispersal and weathering. Four categories of bones could be identified:

1. Bones buried for the whole monitoring period, from 1974 to 1998, and not seen until the final clearing of the site. For example, the small cluster of vertebrae on the south side of the channel at 4.6 m along the datum line (Figure 9) were found below the surface; they were stained light brown in colour; they had extensive root marking on all surfaces; and they showed little evidence of weathering, having light cracking following the fibre structure of the bones. One of the vertebrae had the surface bone heavily modified by chemical corrosion resulting from the extensive root etching similar to, but not as extreme, as that shown in Andrews (1990, figure 1.11A). This type of surface degradation arising from chemical processes below the ground results from subsurface weathering in that it is the consequence of temperature and moisture fluctuations in a biologically active soil. It has different effects on the bone from surface weathering as defined by Behrensmeyer (1978).
2. Some bones were partly buried and were visible on the surface of the ground, and they had differential weathering on their two surfaces. One side was stained light brown as seen above, and this side usually also had root marks and low levels of weathering. The other side of the same bone was either unstained or lightly stained and typically had extensive splitting and some flaking of surface

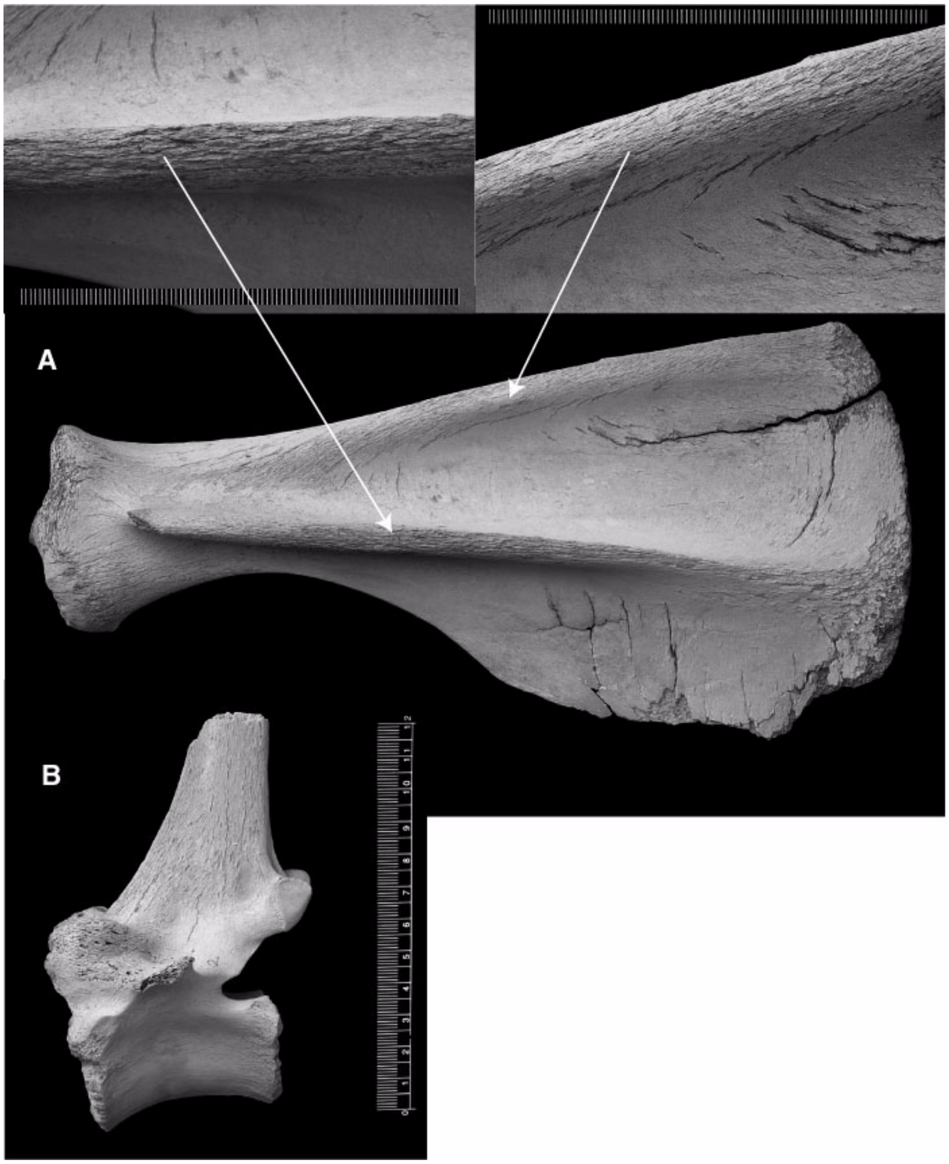


Figure 8. Above, right scapula collected March 6, 1995, 13.5 m down gully, with two close-up views to show the extensive splitting and incipient flaking due to weathering. Below, lateral view of vertebra collected on March 6, 1995, showing the greatest extent of weathering similar to the 1994 specimen shown in Figure 7. Scale is millimeters.

bone, identified as stage 2 weathering following Behrensmeyer (1978). The topmost vertebra in the cluster mentioned above was in this position, as was the isolated vertebra 9 m to the north of channel (Figure 9).

3. Two ribs had one end or one corner buried and the rest of the bone exposed at the surface. The buried end was stained as above, and it showed little evidence of weathering, while the exposed end had extensive cracking and flaking consistent with stage 2-3 weathering (Figure 10).

4. Several bones had never been buried at any stage. For example, the calcaneus from the left leg had been seen on every occasion the camel skeleton was surveyed, and it moved very little from its original resting place. It was weathered on all surfaces, with extensive splitting and flaking of bone along the bottom edge and processes, stage 3 at least, and it had no staining or root marks (Figure 10). On the other hand, the half pelvis recovered from the north side of the channel had fine splitting and minor flaking over the whole surface at

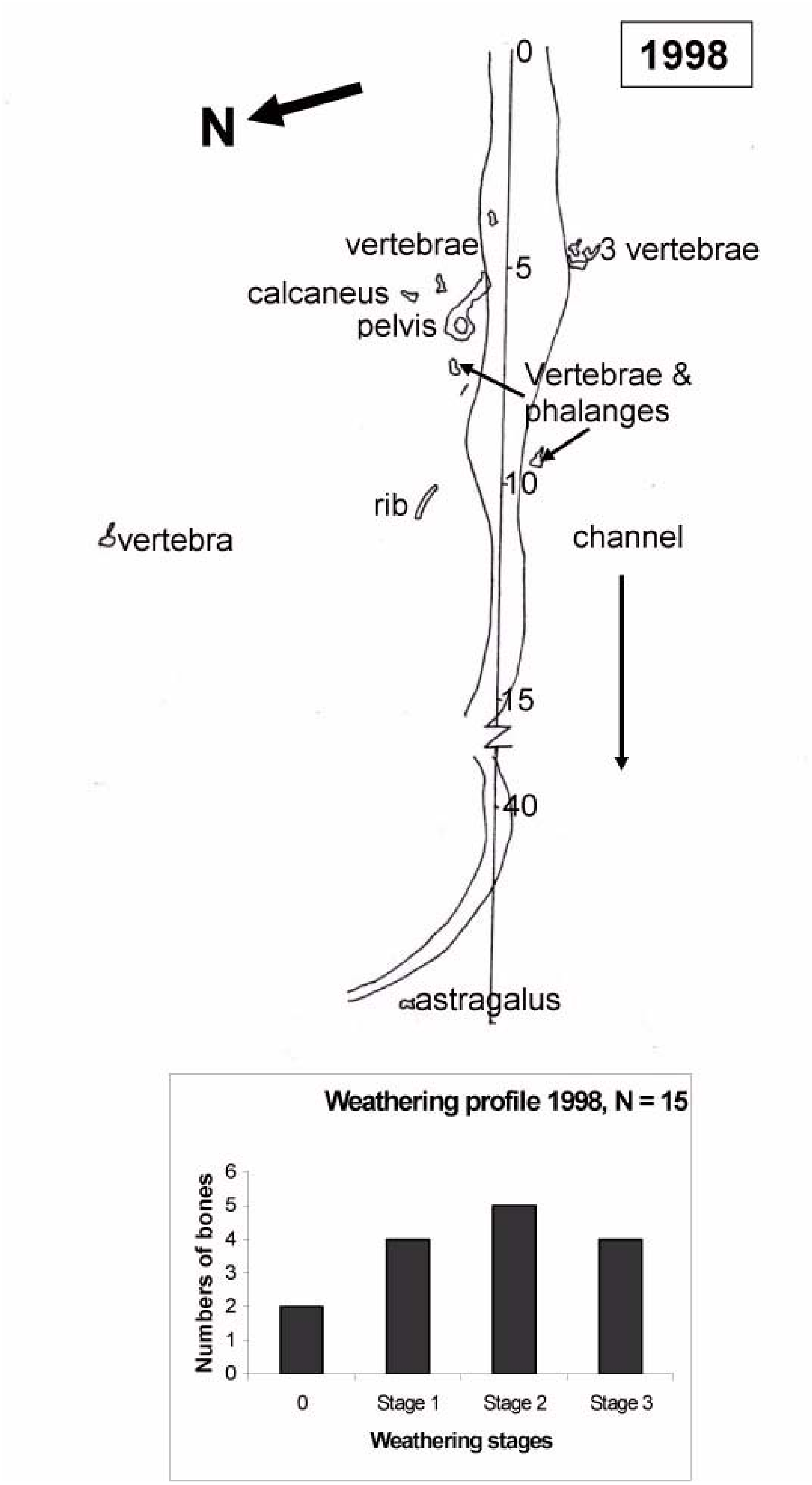


Figure 9. Plan view of camel skeleton made on November 8, 1998. The main bone cluster has moved down slope about 5 m, and a single bone was found 45 m down the wadi. Nothing was found between 12 and 45 m and so again the scale has been truncated. Below is the weathering profile (Behrensmeyer 1978) of the bones that could be located at this time.

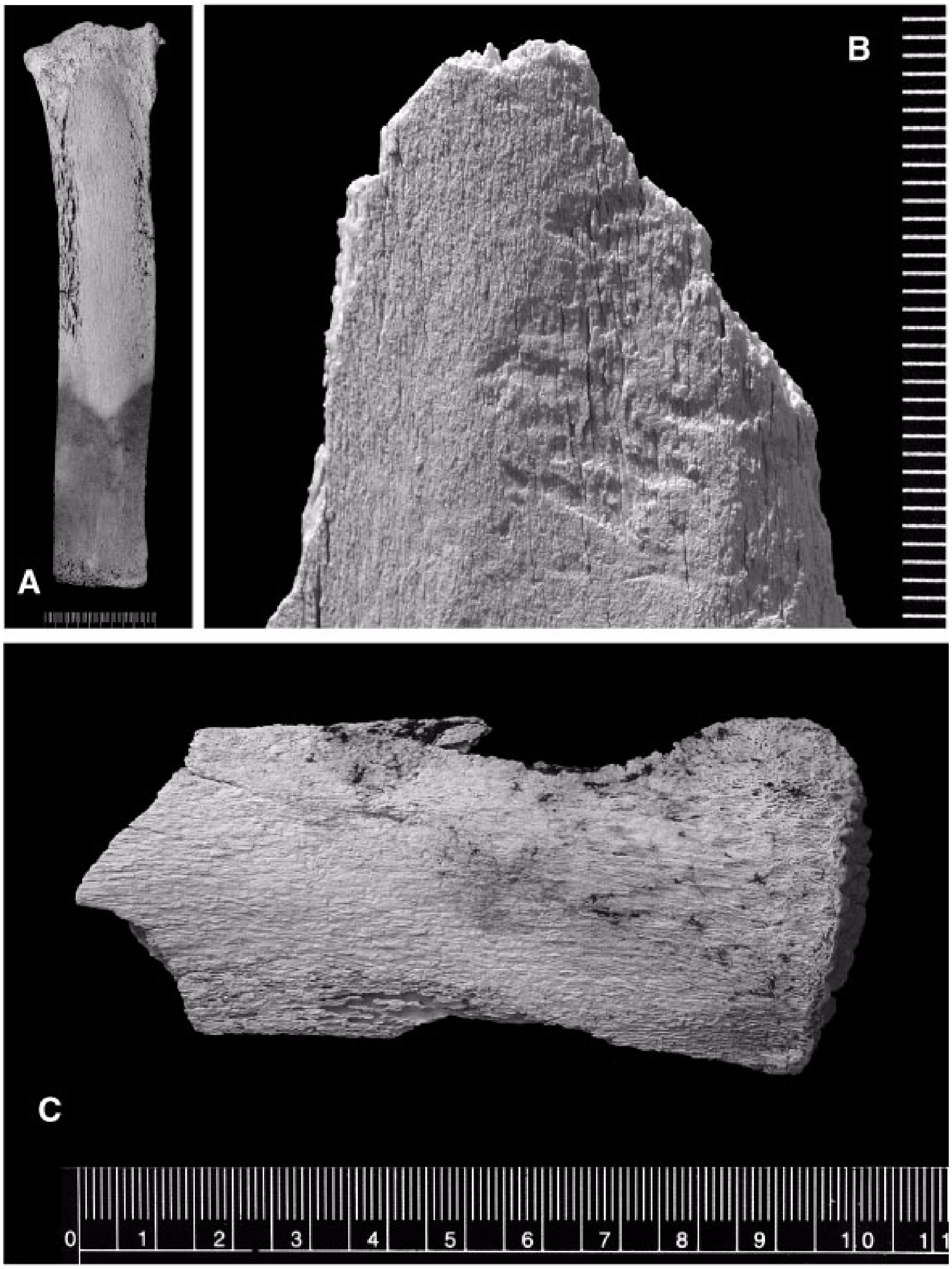


Figure 10. Above, left, one of the ribs that was partially buried and recovered on 1998, the lower part stained as a result of burial. Above, right, close-up of broken end of a rib fragment showing carnivore chew marks. Below, the calcaneus collected in 1998, inferior view showing stage 3 weathering. Scale is millimeters.

stage 1 only, yet it had been exposed on the surface for the whole period of the survey.

One additional observation concerns the astragalus found 45 m down the wadi bottom (Figure 9). This specimen was not stained and had no root marks, but it showed only very early stages of stage 1 weathering. It was not seen during earlier surveys, and it is possible that it is intrusive, carried there from another skeleton. If it belongs to the monitored skeleton, it may have in fact been buried for much of the 15 years of the monitoring, but some time between 1994 and 1998, the years of the last two surveys, it was washed out of its burial place and transported down the wadi. During this period of up to four years it was exposed to the elements and any staining was removed.

DISCUSSION

When rainfall occurs in this part of Abu Dhabi it can be extremely violent, resulting in flash floods in gully systems. It might be expected, therefore, that burial of bones would be slow, transport of bones in gullies would be rapid, and that the extremes of weathering would result in the rapid breakdown of bones exposed on the surface. The aim of this monitoring survey was to gain some understanding of the rates of dispersal and weathering of bones in a sub-tropical desert environment. There have been few long-term studies of this nature published, and none at all in this kind of environment, so that even though this study is based on a single skeleton, we feel it offers some insight into taphonomic processes.

The period of the survey was 15 years, from January 1984 to November1998, and this is the minimum time the bones from the camel skeleton were exposed in the Arabian desert. Total exposure was probably closer to 17 years, since the camel was already largely disarticulated and soft tissues had almost totally decayed. By analogy with other dead animals that we observed in Abu Dhabi, we estimate that it probably died at least two years before the monitoring began.

Weathering

Weathering has been defined by Behrensmeyer (1978) as destruction of bone by physical and chemical agents operating either on the surface or within the soil. We distinguish between surface weathering, where bone is exposed to variations in heat, moisture and solar radiation, and subsurface weathering, where chemical solution and plant action are more important (Trueman et al. 2004). Behrensmeyer (1978) considered the physical stresses of heating/cooling and wetting/drying to be the primary causes of surface weathering, and more recent work on chemical and physiological changes in bones exposed to weathering (Trueman et al. 2004) has stressed the heating and cooling effect as instrumental in the breakdown of collagen. For bones buried in soil or in close contact with soil, Trueman et al. (2004) have additionally proposed a mechanism for replacement of chemical elements in bone by means of water flow whereby water is wicked up from the underside of the bone and evaporated from the exposed side, leading to deposition of authigenic minerals in the pore spaces left open from the collagen decay.

It is clear from the work of Trueman et al. (2004) that greater precision of environmental variables is needed for a better understanding of the effects of weathering. Their study on mineralization changes in bone was carried out in semi-arid conditions in East Africa, at Amboseli, where rainfall was from 350 to 400 mm per year (Trueman et al. 2004). The rainfall at Jebel Barakah averaged just under 100 m per year for the study period (Figure 2), and temperature varied from 12 to 40º during the year (and sometimes varied by almost as much within a 24 hour period). These climate conditions are probably more extreme than at Amboseli, although comparative data are not available, but it is likely that moisture is less of an issue in the Arabian Desert where rainfall is so much lower. In addition, the sandy substrate does not hold moisture well, and so while it is likely that the effects of temperature are greater at Jebel Barakah than at Amboseli, the effects of mineral replacement by water transport are probably less. We are currently undertaking a programme investigating mineralogical changes in this and other non-tropical environments (Fernandez-Jalvo and Andrews, personal commun., 2005), and the following discussion is restricted to surface modifications of the camel skeleton that were observed in the field and subsequently in the laboratory.

Surface Weathering

Over the period of 15 years (17 assuming an additional two years before observations began), weathering of the bones can be categorized in three modes.

1. For bones exposed on the surface, weathering after eight years (10 years estimated) had barely reached stage 1. After 10 years (12 years estimated), most bones were intermediate between stages 1 and 2, with at least one bone with its most exposed area at stage 3. Little change was seen in the following year, and by 1998, after 15 years exposure (17 years estimated), weathering was well advanced on most bones, with extensive splitting and flaking characteristic of stage 3 surface weathering. This pattern was present mainly on the most exposed parts of the bones, that is those bones that were on the surface all the time and were not buried for any of the time; bones that were stabilized on the surface so that only one side was exposed to weathering; and those parts of the bones that were more vulnerable, such as alveolar bone and processes.
2. Lesser degrees of surface weathering were seen on bones that were subject to movement, although in general one side was more weathered than the other. After 15 years (17 years estimated), stage 2 weathering was the

maximum seen, with the less weathered side intermediate between stages 1 and 2. The same degree of surface weathering was also seen on bones that had been buried for part of the time, or had only a shallow covering of sand.

3. Bones more deeply buried had little or no weathering on any surface, so that even after 15 years (17 years estimated) there were two bones that showed no evidence of weathering and several more that were only at stage 1 (Figure 10).

Comparisons can be made with the Amboseli data set of 35 large mammal carcasses on which Behrensmeyer (1978) based her work. Her study provided a good sample for determining rates of weathering in tropical environments, and the one individual sampled here, albeit for a longer period, is not sufficient to establish a sound time scale for weathering outside the tropics. What can be inferred from this one individual are as follows:

After 2-4 years, most bones visible on the camel skeleton were not weathered, and only two bones had incipient stage 1 weathering, whereas the Amboseli skeletons were all at stages 1 and 2 (see Figure 11);

From years 4 to 8, the bones from the camel skeleton were still mainly unweathered, with less than one quarter at stage 1, whereas the majority of skeletons from Amboseli had reached stages 3-4 (Figure 11);

From years 10 to 15, the majority of bone from the camel skeleton were at stage 2, with a range from 0 to 3, while the Amboseli skeletons had all reached stage 3, with a range from 3 to 5 (Figure 11).

The earliest that any single bone from the camel skeleton had reached stage 3 was by year 12, and no greater degree of weathering was observed after 17 years. In the Amboseli sample, the first skeletons had reached stage 3 by years 4-5, stage 4 by years 6-7, and stage 5 by years 10-15 (Behrensmeyer 1978). It is evident from this data that the climate conditions in Abu Dhabi promote far less rapid weathering than those at Amboseli, but what are these climatic differences? The daily temperature fluctuations in the desert conditions of Abu Dhabi are likely to be greater than at Amboseli, indicating temperature is not a significant factor. If high daily temperature variation was a factor in weathering, the degree and rate of weathering should be more rapid in the desert environment than in tropical savanna, but this is clearly not the case. Seasonal moisture variation would appear to be lower at Jebel Barakah, for rainfall is sporadic and restricted to less than half the year at Jebel Barakah, and daily moisture variation is also less, for there is little dew formed on sandy substrates. Solar radiation is also less at Jebel Barakah, for although the apparent radiation is high in the desert, which makes life quite unpleasant in the absence of any shade, Jebel Barakah is at 24º latitude compared with Amboseli at 2.5º latitude. It would appear likely that the combination of less solar radiation and moisture variation are two of the factors that result in slower weathering in Abu Dhabi.

Subsurface Weathering

Subsurface weathering was readily distinguished from surface weathering. The bones from the camel skeleton that had been underground for any period had light staining and root marks, a phenomenon common to many environments (Andrews and Armour-Chelu 1998). Bones more deeply buried were more deeply stained and had extensive root etching, with roots penetrating below the surface and splitting the bone and spalling off surface bone. Both the splitting and the flaking are deeper than is seen in stages 1-3 of surface weathering, and they are more localised while at the same time exterior bone on other parts of the bone may be little altered. Unfortunately there are too few data on which to set up objective criteria for identifying stages of subsurface weathering, although this is obviously important.

Bone Dispersal

When first observed, the camel skeleton was dispersed over 18 m along the shallow sloping gully with a lateral spread of just under 3 m (Figure 3). This was virtually unchanged after eight years, with an apparently contracted range of dispersal probably as a result of burial of some of the bones (Figure 4). In 1994, 10 years after the skeleton was first monitored, there were several parts of the skeleton 21 to 24 m down the gully (Figure 6), both ribs and limb bones, and these were complete and showed no evidence of carnivore action or rounding. The bones were in or near the line of the channel cutting through the bottom of the gully, and it is most likely that they were transported down the gully by water flow, although there is no direct evidence of this. There was some movement of bones 2-3 m up the gully, and this seems most likely to be due to scavengers or trampling. Four years later, when the monitoring of the camel skeleton finished, there were bones 45 m down the gully (Figure 9). Throughout most of this period, however, the central cluster of bones close to where the camel died remained within the original

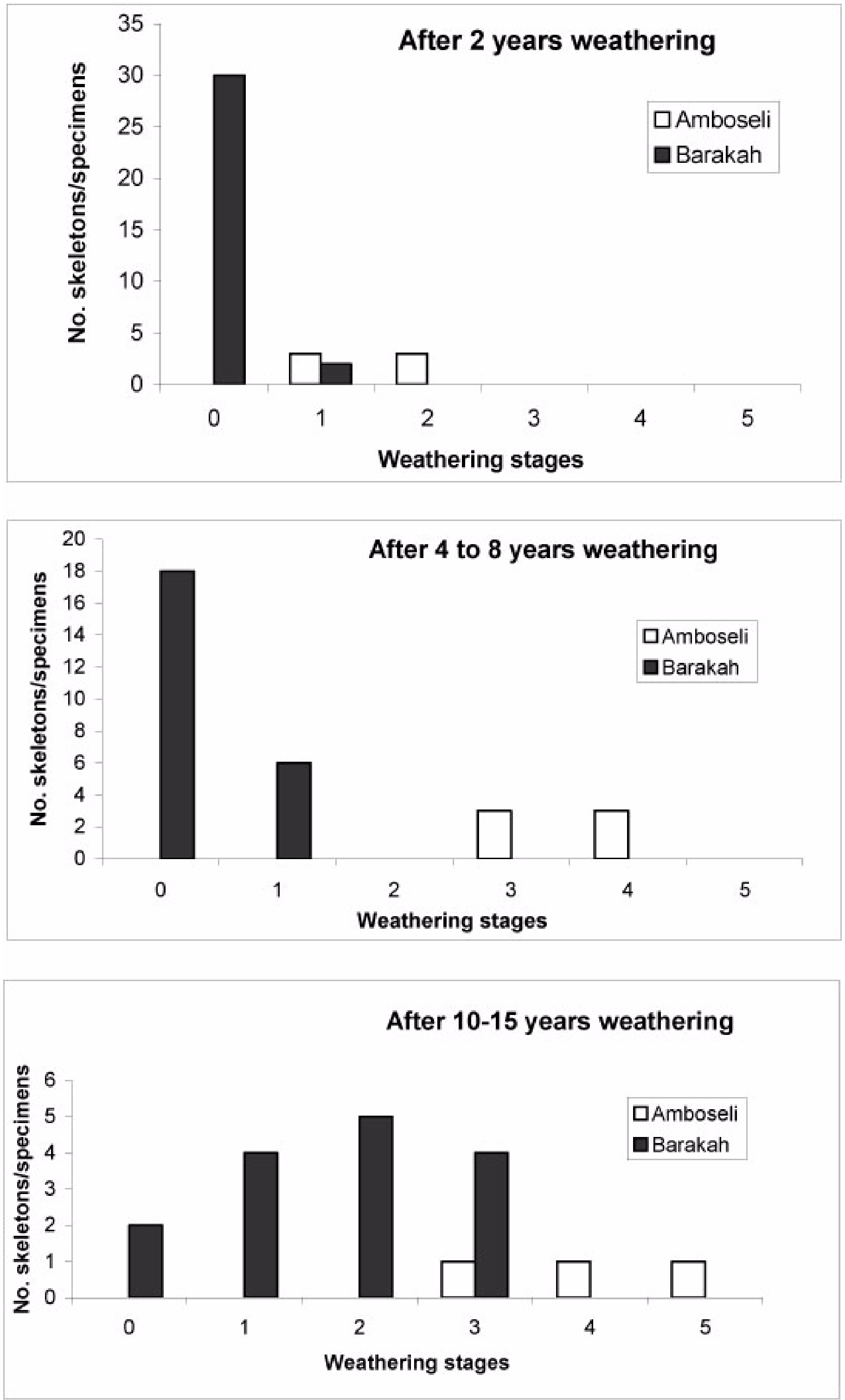


Figure 11. Comparison of weathering stages between the camel skeleton from Jebel Barakah and 35 bovid skeletons monitored at Amboseli, Kenya. Six weathering stages are shown (Behrensmeyer 1978), and the comparison is between *numbers of bones* for the Barakah camel and *numbers of skeletons* for Amboseli.

dispersal area of 14 m and were not transported. This cluster consisted mainly of ribs and vertebrae, which according to experimental work on bone transport are the bones most likely to be moved by water transport (Voorhies 1969, Lyman 1994).

Rain in Abu Dhabi can be torrential, and flash floods in gully systems are commonplace. There

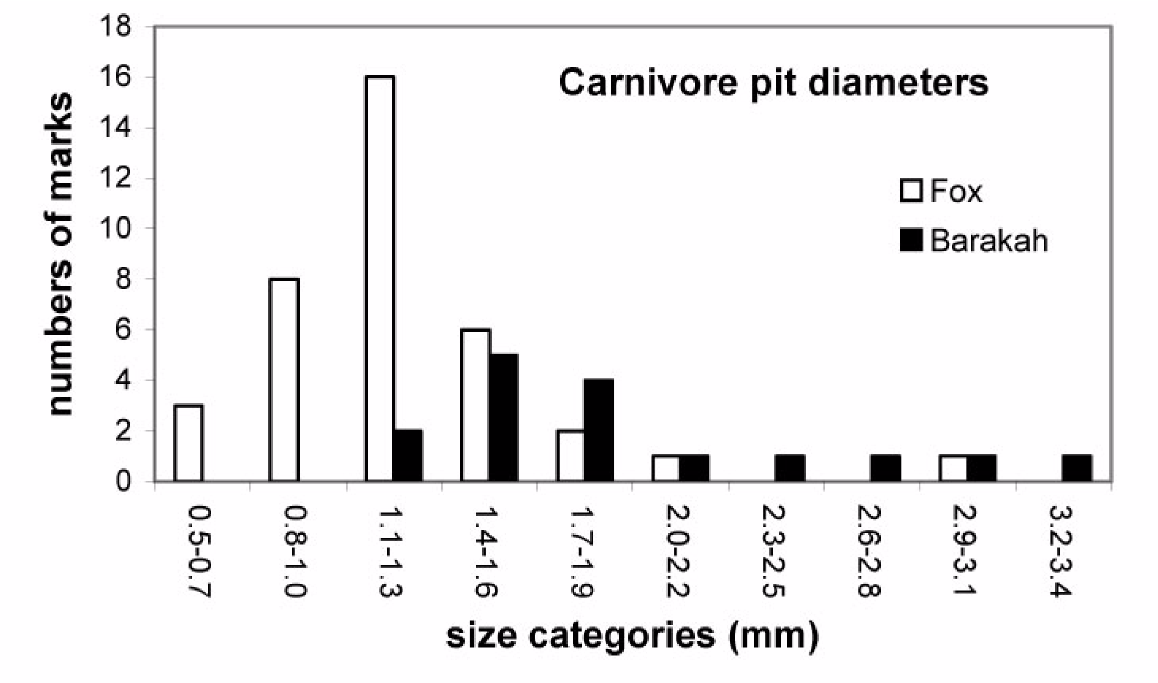


Figure 12. Size distribution of carnivore pit marks (category 'a' of Andrews & Fernandez-Jalvo 1997) on all bones from the Jebel Barakah camel (N = 16) compared with the distribution of pit sizes on bone diaphyses made by foxes in southern England (N = 37).

were several periods of heavy rain during the monitoring period, and clearly this had the effect of transporting some of the bones down the gully, but many of the skeletal elements that were moved the furthest (maxilla, astragalus and radioulna), were the ones that in experimental work moved least (Voorhies 1969). The bones remaining at the death site, by contrast, were the ones that are most susceptible to water transport.

Bone Orientations

Orientations of the bones were influenced by their position on the surface, which in turn would be related to surface run-off of water. The bones on the north side of the gully aligned to the south and west, at 221º to 280º, following the slope of the side of the gully towards the channel. The data have been provided in Figures 3, 4, 6 and 9, but they do not provide evidence independent of topographical slope.

Carnivore Action

There was surprisingly little evidence of carnivore activity on the camel bones. It was assumed that skeletal elements missing from the skeleton had been removed by scavengers, which in northwestern Abu Dhabi would be most likely to be jackals and foxes, hyaenas being absent from the area now (Harrison and Bates 1990). Chewing was confined to broken edges and near the ends of bone processes and vertebral spines (Figure 10), and the size distribution of pits on diaphyseal surfaces (category a of Andrews and Fernandez-Jalvo 1997) shows a range overlapping but exceeding that of a larger sample of foxes from southern England (Figure 12). This is consistent with the probable identity of the scavengers being jackals and foxes, but it does not exclude the possibility of larger predators being involved. We have observed at other sites that carnivores of all sizes can make small diameter chewing marks on bones, but small carnivores cannot make large marks, so that it is not so much the range of sizes of marks that distinguish between carnivore chew marks as the greatest size of the marks. The size of the largest carnivore chewing marks on the Jebel Barakah camel skeleton therefore indicate a predator larger than a fox, but unfortunately there is little information on the size of jackal chewing marks. No rodent chewing was observed.

Trampling

Many of the camel bones were unbroken, even after 15 to17 years of exposure. Breakage of vertebral lateral processes and spines was common, most ribs were broken, and the pelvis was broken into two pieces although still complete. This is a type of breakage that even a large carnivore would find difficult, and since the bone was minimally transported it is most likely that the breaks were the result of trampling by a large mammal, most probably other camels, which graze over Jebel Barakah.

CONCLUSIONS

1. The 15 year monitoring of a camel skeleton at Jebel Barakah, United Arab Emirates, has shown that rate and degree of weathering was slower than in tropical Africa. At comparable yearly intervals the camel skeleton was 1 to 2 weathering stages behind the skeletons from Amboseli, Kenya. Bones protected from weathering by burial predictably showed little evidence of surface weathering, but there were root marks on some of the bones caused by the extensive root systems of the desert grasses.
2. Dispersal of bones was irregular, and it almost certainly reflects the uneven distribution of rain, with no rain at all some years. Bones were transported up to 45 m down the gully, but many of the ribs and vertebrae were not moved at all. The pattern of movement of skeletal elements differs from that indicated by experimental work on fluvial transport of bone.
3. There was some evidence of carnivore action, with the maximum pit size indicating a scavenger larger than fox. No hyaenas are present in the area today, and it is likely that the marks were made by jackals.

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