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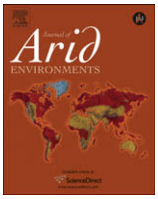

Palaeoecological analysis of a Late Quaternary sediment profile in northern Oman

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ABSTRACT

High resolution palaeoecological studies of the Arabian Peninsula for the late Quaternary period are scarce. Consequently, little is known about time-dependent relationships between vegetation, environment and the development of human settlements in this area. To help fill this gap for the arid Hajar mountains of northern Oman, a 20 m deep profile in a sediment-filled depression near an oasis settlement was analysed for its physico-chemical properties, pollen and spores and other palynomorphs. Charcoal frequencies in combination with geochemical data provided evidence of an Early Holocene increase of rainfall. The onset of dryer conditions at about 8 ka was indicated by charcoal frequencies and geochemical data as were previously unrecognised short humid periods dated to 5.7, 5 and 4.4 ka. The upper 4 m of sediments contained a 4300 year-old pollen profile reaching into the archaeologically important Umm al-Nar period characterized by increased settlement activities throughout Oman. Variation in mollusc shell frequency and periodic peaks of NH_4-N suggested only minor local variations of rainfall throughout the last 2000 years. The sudden appearance of *Olea spec*., *Ziziphus* and *Fabaceae* pollen since about 500 years ago points to a late onset of oasis agriculture nearby.

1. Introduction

A large number of palaeoclimatic records have been published in the last few years aimed at unraveling the possible effects of albedo changes in the temperate zone of the northern hemisphere and of fluctuations in the ITCZ-related Indian Ocean Monsoon (IOM) on the long-term climate history of the Arabian Peninsula. Valuable climate records have been derived from the geomorphology of dunes (Glennie and Singhvi, 2002; Preusser et al., 2002, 2005; Bray and Stokes, 2004), speleothems and cave fillings (Burns et al., 2002; Cremaschi and Negrino, 2005; Fleitmann et al., 2003, 2007) and, most importantly, from lake and ocean sediments (Szabo et al., 1995; Overpeck et al., 1996; Reichart et al., 1999; von Rad et al., 1999; Gasse and Van Campo, 1994; Gasse, 2000; Lézine et al., 2002, 2007; Gupta et al., 2003; Naidu and Niitsuma, 2003; Kröpelin and Soulié-Märsche, 1991; Radies et al., 2005). Taken together these records indicate that over the last 23,000 years numerous shifts between wet and dry periods have had a major impact on the landscape of the Arabian Peninsula causing large changes in its vegetation composition (such as switches of dominance from C_3 to C_4 plants, Parker et al., 2006) and the appearance and disappearance of lakes in what today is the world's largest sandy desert (Radies et al., 2005; Lézine et al., 2007). Mainly as a consequence of a northwards movement of the IOM, periods wetter than today seem to have prevailed from 17,000 to 16,000 BP, from 15,000 to 14,500 (Gasse, 2000) and from 9000 to 7500 BP or even to 6000 BP (Overpeck et al., 1996; Naidu and Niitsuma, 2003; Lézine et al., 2007; Fleitmann et al., 2007). There is also consensus in the published work that latest by 4000 BP the climatic conditions on the Arabian Peninsula have become very arid leading to today's typical desert landscape.

Despite the above mentioned body of literature, a few major gaps of knowledge remain to be filled. One relates to the rather coarse (millennia-scale) resolution of most data and another one to the fact that most published palaeoclimatic records are limited to the late Pleistocene and early Holocene periods and lack continuity to today's climate and vegetation conditions. Important exceptions are varved sediment records from the Pakistani shore of the Arabian Sea floor (von Rad et al., 1999) and speleothem data from southern Oman (Burns et al., 2002). In view of these limitations, the aim of our study was to analyze a pollen and charcoal containing sediment record of high resolution in an effort to reconstruct the vegetation history over the time span that is important for the development of irrigation agriculture in Oman. While it seems evident that the development of the famous *aflaj*-based irrigation systems of Oman were triggered by a combination of technological, social and climatic factors, the latter may be objectively dated by palaeoclimatic records. In this context the period from 2000 to

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2000 BP is of particular interest as since at least 2500 BP the first *aini-aflaj* canal networks and underground *falaj* systems (Costa, 1983; Dutton, 1986; Norman et al., 1998; Omezzine and Lokman, 1998; Wilkinson, 1974) channeled water to Omani oases, often over many kilometers. The dominant crops were traditional wheat varieties (*Triticum dicoccon*, *Triticum aestivum* L. and *Triticum durum* Desf.; Al-Maskri et al., 2003; Hammer et al., 2003), date palm (*Phoenix dactylifera* L.), banana (*Musa* spp.) and vegetables.

Fisher (1994) suggested that the many centuries old extended juniper (*Juniperus excelsa* subsp. *polycarpos*) tree populations on the mountain range of Al Jabal al Akhdar may be used for annual-ring analyses. However, results of Sass-Klaasen et al. (2008) indicated that under the conditions of Oman *Juniperus excelas* occasionally formed multiple rings per year and considerable work would thus be required before short-range tree-based climatic records could perhaps be established.

A major problem with past pollen-analytical (palynological) efforts to reconstruct long-term climatic records of Oman, except for a study on coastal mangrove swamps (Lézine et al., 2002), has been the lack of appropriate undisturbed sediments. In most places, erratic but often strong rainfall events have led to heavily eroded, rocky landscapes except for the intensively cropped terrace soils of oases. This has precluded the preservation of suitable material for analysis. However, in 2003 a large depression with an undisturbed sediment profile was identified in the Jabal Bani Jabir of the southern Hajar Mountains. The site, which is situated just below the recently discovered 4000–5000 year old, monumental tower tombs of the Shir plateau in northern Oman, has provided a largely undisturbed sediment profile which was dated by OSL measurements of quartz particles (Fuchs et al., 2007; Fuchs and Buerkert, 2008). Results of the age determinations and sedimentation rates provide a reliable time frame for the reconstruction of the palaeoenvironmental conditions throughout the Late Glacial and Holocene. This frame is filled with data about the vegetation history of the region since the time of the towers' construction as derived from results of a multi-proxy physico-chemical and palynological analysis. Together they allow to examine whether major environmental changes have occurred since the Shir towers were built.

2. Methodology

2.1. Description of the study site and field methods

The site is located 150 m above the central housing area of the mountain oasis of Maqta (22.83°N, 59.00°E; 1050 m asl) in the arid Wadi Khabbah of the Jabal Bani Jabir, which is part of the Northern Omani Hajar ash-Sharqi range receiving today on average about 100 mm of rainfall annually (Fig. 1). Maqta comprises 16 tiny terrace systems that total 4.5 ha of which 2.9 ha are planted to date palm (*P. dactylifera* L.) and 0.4 ha to wheat landraces (Triticum spp.) all clustered around 22 springs. The sediment profile was excavated in an ellipsoid, flat, natural depression about 200 m × 500 m in size possibly the collapsed remains of an ancient cave. Over the ages the depression has been partly filled with sediments suspended in wadi water flowing down from the surrounding mountains during rainfall events (see also photograph in Fig. 1). There may also have been a contribution of eolian elements during occasional dust storms but this component most likely was only of minor importance given the protected nature of the depression surrounded on three sites by 500 m high mountain cliffs.

Presently the surface of the depression supports some *Acacia* trees, an old landmark *Sisyphus spina-christi* (L.) Willd. tree and the dry shoots of apparently heavily grazed perennial grasses which provide temporary fodder after the very occasional rainfall events. As indicated by the existence of an old irrigation canal (Arabic 'falaj', pl. 'aflaj'), whose age was radiocarbon dated to 425 ± 30 years BP, a small portion of this depression, 350 m to the north of the sediment profile, had formerly been temporarily irrigated following rainfall events. Evidence for the past temporary agricultural use of the depression was the observed appearance of indigo (*Indigofera tinctoria* L.), a traditional dye crop, after thunderstorms in 2003, 2005 and 2006. According to the local farmers' oral tradition, the water of this falaj vanished in ancient times following a quarrel within the village that ended with a mythical animal approaching the spring supplying the falaj and consuming all of its water.

The centre of the depression was chosen to prepare the sediment profile for subsequent analysis. To this end a 20 m deep pit was dug by hand into the bone dry clayey soil and 40 u-shaped containers of 50 mm × 20 mm × 500 mm, custom-made from stainless steel, were hammered one below each other vertically into the profile. This allowed sampling of the full depth of the pit. Care was taken to avoid compression of the extracted sediment column. The sediment-filled containers were covered in the pit with stainless steel lids, sealed with tape and subsequently transported to Germany for analysis. After removal of the monolith, the profile was cleaned and examined for the occurrence of mollusc shells and pieces of charcoal which were counted and collected for further analysis.

Four of the mollusc shells, 5–8 cm in length, from 80, 130, 160 and 400 cm profile depth were ^{14}C-dated using accelerated mass spectrometry (AMS) at the Poznań Radiocarbon Laboratory, Poznań, Poland. Results are reported as uncalibrated and calibrated dates (Figs. 2 and 3) whereby the true (calibrated) ages of the samples are displayed with probabilities of 68% and 95%. Calibrations were made with the OxCal software (Bronk Ramsey, 1995, 2001, 2005) assuming a marine reservoir age R (global mean) + ΔR (local correction), where $\Delta R = 250 \pm 50$ years (Hughen et al., 2004).

In recognition of the well known errors of the reservoir effect of secondary carbonates, detailed sampling for optical stimulated luminescence (OSL; Aitken, 1998) was also carried out. Sediment samples collected at 50 cm intervals, except for the middle section of the profile where sampling intervals were adjusted to apparent changes in particle size distribution, were taken from 9 p.m. to 2 a.m. during two moon-less nights using a rope-ladder of aluminum steps and steel ropes, wrapped in several aluminum foil and light-proof black plastic sheets, shipped to Bayreuth, Germany. Optical stimulated luminescence (OSL) dating (Aitken, 1998) of sediments was performed as described by Fuchs et al. (2007) and Fuchs and Buerkert (2008) with the most important steps being as follows: In a first step the quartz coarse grain fraction (90–200 μm) was extracted. After removal of carbonates and organics from the samples with HCl and H_2O_2, heavy liquid density separation with lithium-heteropolytungstate (LST) was used to separate the quartz from any heavy minerals ($>2.75\ \mathrm{g\,cm^{-3}}$) and feldspars ($<2.62\ \mathrm{g\,cm^{-3}}$). Finally, the samples were etched for 1 h in 40% HF to remove the alpha irradiated outer layer of the quartz grains and to eliminate any potential feldspar contamination. During all steps of the sample preparation, subdued red light (640 ± 20 nm) was used. Luminescence measurements were carried out on a RisØ-Reader TL/OSL-DA-15, equipped with blue LEDs (470 ± 30 nm) for stimulation and a Thorn-EMI 9235 photomultiplier combined with a 7.5 mm U-340 Hoya filter (290–370 nm) for detection. β-irradiation was performed by a ^{90}Y/^{90}Sr source ($8.94 \pm 0.4\ \mathrm{Gy\,min^{-1}}$).

For D_e determination, a single aliquot regenerative dose protocol (SAR) was applied (Murray and Wintle, 2000). Therefore, six regeneration cycles were used and the shine-down curves were measured for 20 s at elevated temperatures (125 °C) after a preheat of 240 °C (10 s) for the natural and regeneration signals and 160 °C for the test dose signals. The integral of 0–0.4 s of the shine-down curves, after subtracting the background signal from the mean of the 16–20 s integral, was used for D_e determination. Feldspar contamination of the aliquots was checked by stimulating the

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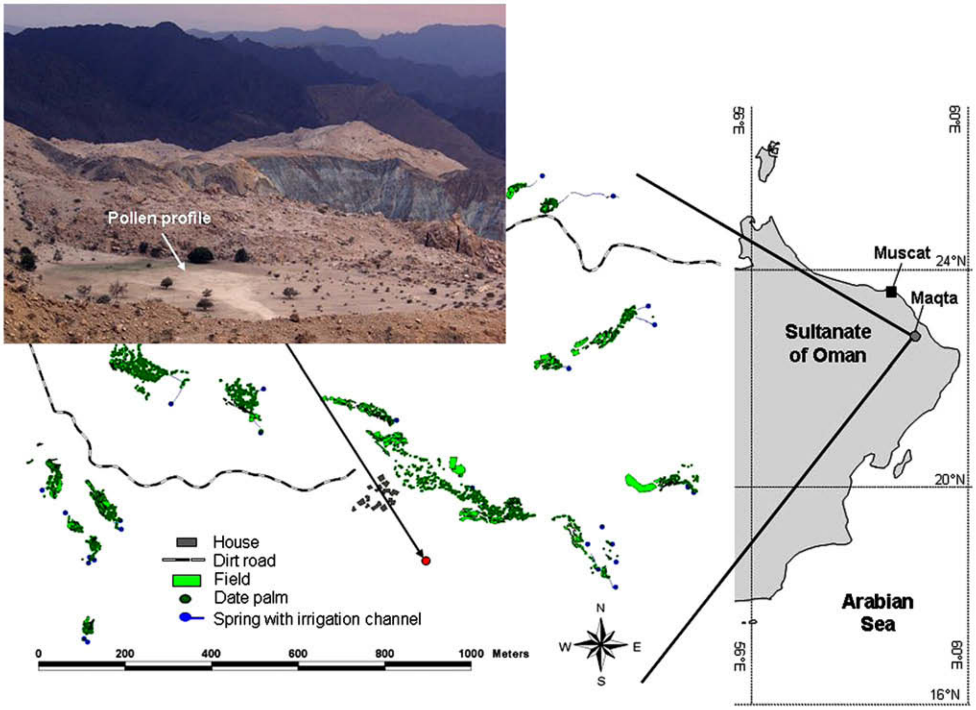

Fig. 1. Map of the Sultanate of Oman indicating the location of the mountain oasis of Maqta and the profile used for sediment and pollen analysis.

sample with infrared light (IRSL) after artificial dosing. To detect possible insufficient bleaching, all measurements were carried out on small multiple grain aliquots containing ca. 200 grains per aliquots (Fuchs and Wagner, 2003), mounted on aluminum cups (12 mm diameter) using silicon oil. D_e calculation was based on the measurements of 24–100 aliquots per sample, following the procedure suggested by Fuchs et al. (2007).

Low level γ-spectrometry was applied to determine the dose rate ($\dot{D}$) of the sediments and cosmic-ray dose rates were calculated according to Prescott and Hutton (1994). The water content of the samples was determined using the average value of the possible water content range, based on the porosity of the samples. An error for the water content value was chosen, which included the possible water content range. The values used for the water content were checked by measuring the *in situ* water contents of the samples, showing conformity within errors. Based on OSL age determinations, sedimentation rates were calculated for every section of the sediment profile, using linear regression.

2.2. Laboratory analyses

The texture of carbonate free samples of the 0–2000 cm deep profile, each comprising between 25 and 40 cm depth intervals, was determined by the hydrometer method (Van Reeuwijk, 1992).

For physico-chemical analysis, samples were taken at 20 cm intervals for the top 200 cm, at 25 cm intervals from 200 to 400 cm and at appropriate levels with reference to sediment properties further down the profile. They were analyzed for their pH in a 1:2.5, 0.01 M $CaCl_2$-suspension, for their carbonate content (gasometric determination according to Scheibler; VDLUFA, 1991) and for organic carbon (Corg) according to the Walkley–Black procedure (Page et al., 1982). From 6 to 200 cm profile depth, a total of 39 samples were taken at 3 cm intervals and analysed for mineral nitrogen (N_{min} as NO_3-N and NH_4-N; VDLUFA, 1991) and H_2CO_3-extractable Olsen phosphorus (P; Page et al., 1982).

For palynological analysis including charcoal particles, 97 samples, each weighing about 7 g, were taken at 10 cm intervals (from 5 cm to 200 cm depth) and at 10–12 cm intervals (from 210 cm depth down the profile). All of these were treated by standard methods, including 10% NaOH, to initially disperse the sediments, 10% HCl to remove carbonates, flotation to separate the organics from the inorganic matrix using sodium metatungstate ($3Na_2 \cdot WO_4 \cdot 5 \cdot WO_2 \cdot H_2O$) and acetolysis to dissolve cellulose and to darken the palynomorphs for ease of recognition (Faegri and Iversen, 1989; Moore et al., 1991). Prepared residues were embedded in glycerine on microscope slides over which coverslips of 18 × 24 mm were sealed with Entellan®. The slides were subsequently counted, mostly at ×400 magnification. For detailed morphological studies, an oil immersion lens (×1000) was used. For identification of pollen spores the atlases of Reille (1992a–d), Moore et al. (1991), Beug (1961), Faegri and Iversen (1989) and a reference collection of the Laboratory of the Division of Soil Science and Biology at LEUPHANA University of Lüneburg, Campus Suderburg, Germany were consulted. The guide and reference literature of Van Geel (1978, 2001) was used to identify fungal remains.

Pollen calculation and diagram construction were performed with the software package Tilia, Tiliagraph & Tiliaview (Grimm, 1990) whereby the reported pollen sum (100%) refers to phanerogams only. Taxa which belonged to the cryptogams, fungal remains that could not be identified and charcoal particles were percentaged outside the pollen sum. For each sample the total sum of all palynomorphs was based on the counting of at least one microscope slide. Pollen, spores, fungal remains and micro-charcoal are furthermore presented as absolute counts at all analysed depths.

3. Results

3.1. Mollusc shells and profile age

Mollusc shells, which were all identified as *Zootectus insularis* Ehrenberg (*Subulinidae*) except for three individuals of *Mordania*

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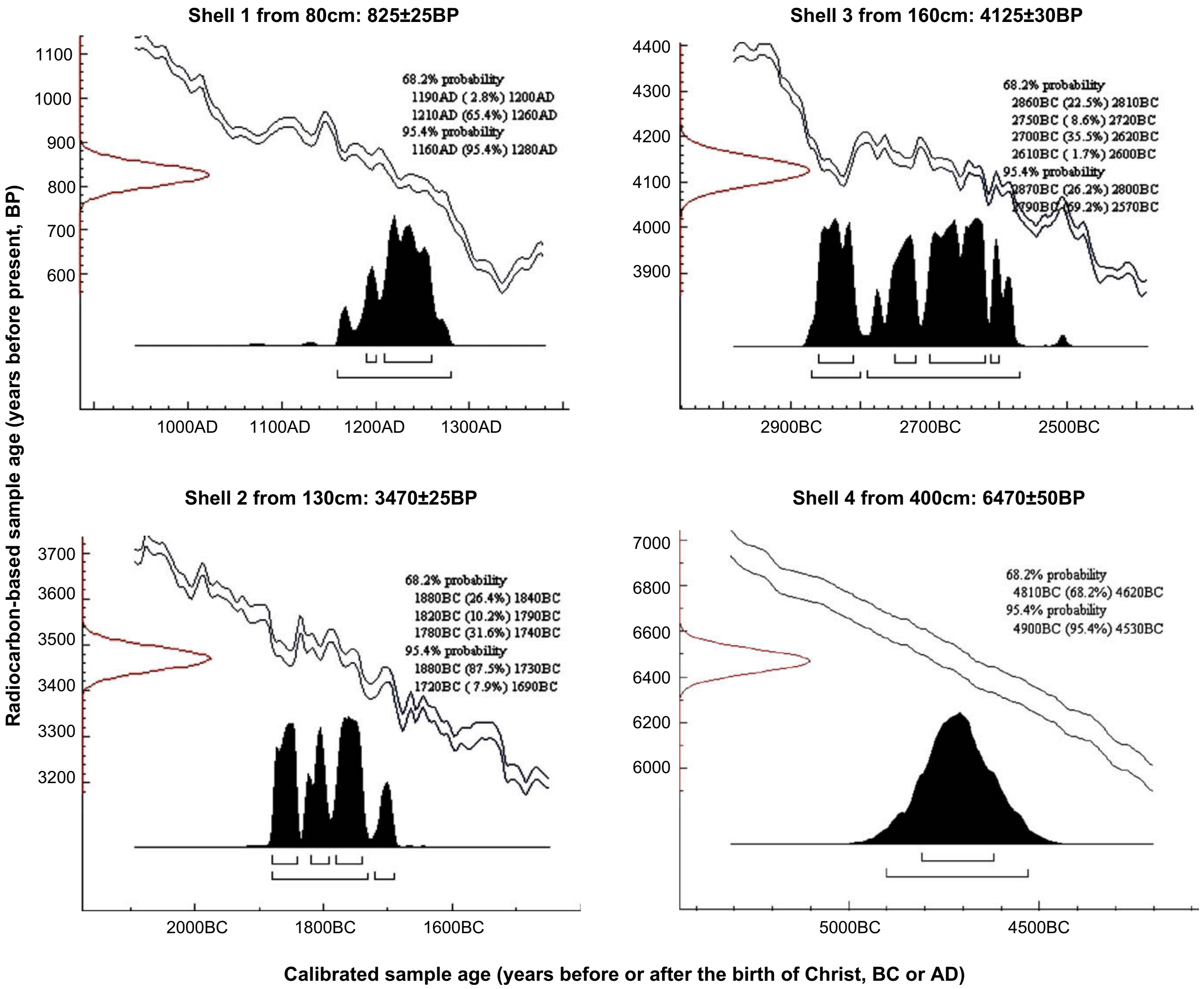

Fig. 2. Uncorrected and corrected age values of the mollusc shells from a sediment profile above the mountain oasis of Maqta (Oman) as determined by ^{14}C accelerated mass spectrometry (AMS). For the ^{14}C data intervals of calendar age are given, where the true (calibrated) ages of the samples are shown with probabilities of about 68% and 95%. Calibrations were made with the OxCal software (Bronk Ramsey, 1995, 2001, 2005) assuming a marine reservoir age R (global mean) $+ \Delta R$ (local correction), where $\Delta R = 250 \pm 50$ years (Hughen et al., 2004).

omanensis (Smith) (*Buliminidae*) at 80 and 275 cm were found throughout the profile but their frequency peaked at 150–160 cm and at 400 cm depth (Fig. 3). The ^{14}C analysis of the four selected shells yielded for 80, 130, 160 and 400 cm depth uncalibrated ages of 825 (±25), 3470 (±25), 4125 (±30) and 6470 (±50) years BP, respectively. When converted to calibrated ages at the 95.4% probability level these values translated into ranges of 1160–1280AD, 1880–1690BC, 2870–2570BC and 4900–4530BC (Fig. 2 and 3). The order of the uncalibrated ages of the shells as well as those of the calibrated ones followed curvi-linear relationships which made it precarious to use these values for dating of the sediments even if the true size of the assumed reservoir effects were smaller than expected and OSL values of the sediments from the upper 400 may be somewhat under-estimated because of insufficient bleaching.

3.2. OSL chronology of the profile

Across the upper part of the profile (0–400 cm) the calculated OSL ages were in strong stratigraphic order with standard errors typical for such measurements (Fig. 3). None of the samples had a significant radioactive disequilibrium. Due to a high inter-aliquot scatter (Fuchs and Wagner, 2003), most of the samples showed insufficient bleaching and D_e calculations were therefore performed according to the method described by Fuchs et al. (2007). The high r^2 value suggested that in contrast to the ^{14}C data for the mollusk shells the OSL values allow a reliable dating of the sediments. These values were therefore used to construct a time scale (BP) for all figures showing profile properties (Figs. 4–7; Fuchs and Buerkert, 2008).

3.3. Sediment texture (particle size), chemical properties and micro-charcoal (0–2000 cm)

Based mainly on its particle size and charcoal distribution and for some depth intervals its geochemical properties as well as palynological features, the sediment profile was subdivided into six units (a–f from bottom to top; Fig. 4) whereby the pH varied with 7.6–7.8 remarkably little throughout the different layers.

Unit a (2000–1475 cm) covering approximately the time span 19–13 ka and characterized by a sedimentation rate of about 0.8 mm a^{-1} (Fuchs and Buerkert, 2008) had a relatively high

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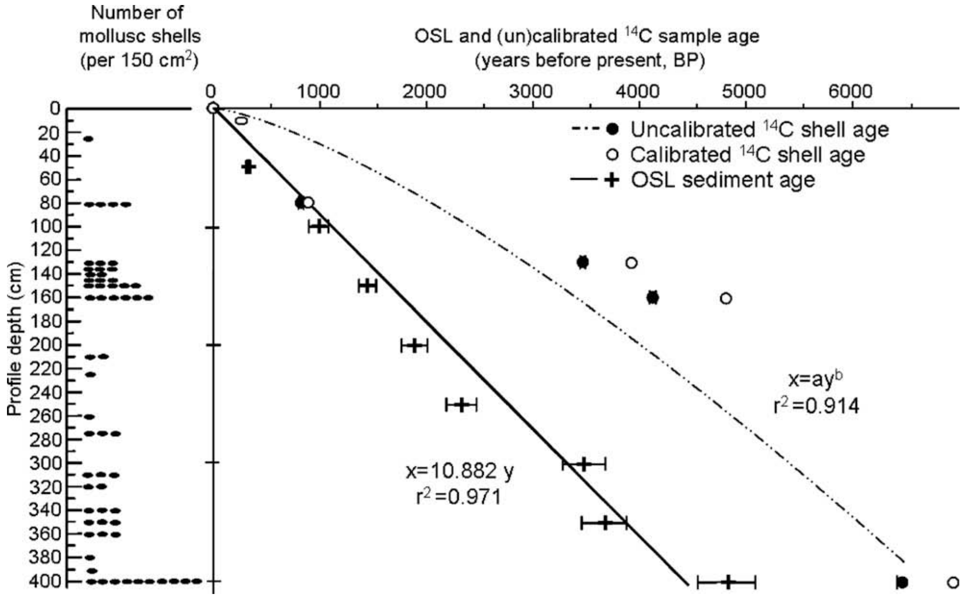

Fig. 3. Left: Distribution of mollusc shells (*Zootectus insularis* and *Z. omanensis*) found in a 15 × 10 cm sampling layer in the upper 400 cm of a sediment profile above the mountain oasis of Maqta (Oman). Right: Uncorrected age of the mollusc shells as determined by ^{14}C accelerated mass spectrometry (AMS) and sediment age as determined by Optically Stimulated Luminescence (OSL). In all cases data are displayed with their analytical standard errors which, where not visible, were smaller than the symbol.

amount of sand, a clay content of about 20% and the highest carbonate content of the entire profile. Organic carbon levels were highest at 1775 cm where also the sand fraction increased. Low to medium amounts of micro-charcoal particles were found from 1575 cm upwards. A strong decrease of the sand fraction and a marked increase of the silt fraction, followed by an increase of the clay content marked the boundary between profile units a and b.

Unit b (1475–1000 cm) was characterized by the highest clay contents of the entire profile, a nearly continuous decrease of the $CaCO_3$ curve, with lowest amounts at 1100 cm where Corg and Nmin values peaked. Those findings, indicating increasing moisture conditions and biomass production, are in good agreement with a major increase of the micro-charcoal curve peaking at 1250 cm and maintaining highest values during the upper part of unit b (1175–1000 cm; Fig. 4). These results correspond to the findings of Fuchs and Buerkert (2008) about the profile features during the Late Glacial to Holocene transition, which shows a short phase of strongly reduced sedimentation (0.2 mm a^{-1}) at 1450–1400 cm followed by an increase to 3.8 mm a^{-1} at 1400–800 cm and a late period of high sedimentation (6.3 mm a^{-1}) at 1200–800 cm (8.7–8.07 ka) thereby reflecting a marked increase of humidity during the Early Holocene.

Unit c (1000–600 cm) showed increases in the sand fraction and the carbonate content. Conversely, the levels of C_{org}, N_{min} and micro-charcoal particles decreased, though discrete charcoal peaks at 821, 721, 661 and 641 cm are noteworthy. Fuchs and Buerkert (2008) described a decline in the sedimentation rate at 800 cm to 0.9 mm a^{-1} (equivalent to 8 ka) which then persisted for the last 8000 years.

Unit d (600–400 cm), OSL-dated to 6–4 ka, was characterised by a major increase in charcoal particles, a decrease in the sand fraction and a consistent increase in C_{org} and N_{min} throughout the remainder of the unit. The very high values of charcoal at 541, 521, 481, 451 and 421 cm may reflect extreme events of seasonal biomass burning such as by man-made fires.

Unit e (400–200 cm) had a homogenous clay and fine silt content. At 300 cm (3.25 ka OSL age; Fig. 4) a minor change in particle size distribution occurred. The charcoal content was comparably low, while the C_{org} values increased from 0.22% at the base of this stratigraphic unit to 0.33 at its top and 0.54% at 160 cm depth in unit f indicating an increase of plant dry matter production at the time of origin of this sediment layer.

Unit f (200–0 cm, equivalent to about 1.6 ka) showed a strong decrease in medium silt and a simultaneous increase in coarse sand at 150 cm. Throughout this stratigraphic unit the carbonate concentration declined strongly between 200 and 130 cm, recovered at 110 cm and remained constant thereafter (Fig. 4). At 150 cm the amount of charcoal particles slightly rose again. Within the unit, the concentration of NO_3-N exponentially rose from 1.3 mg kg^{-1} at 200 cm to 71.3 mg kg^{-1} at 7 cm, whereas NH_4-N concentrations, averaging 0.75 mg kg^{-1} sediment, showed a pronounced peak between 96 and 104 cm (1.1 ka; Fig. 5). Through the upper 30 cm of the profile, the sediment contained a total of about 96 kg NO_3-N ha^{-1}. Averaging only 0.5 mg kg^{-1} throughout unit f, H_2CO_3-extractable P was remarkably low except for the upper 15 cm.

3.4. Palynological features

Both the preservation of pollen and spores and their quantities strongly varied throughout the profile (Fig. 6). Only 16 out of 46 analysed samples in the upper 400 cm part of the profile (in stratigraphic units e and f) provided palynomorph amounts sufficient for analysis (Fig. 7), though spores and fungal remains as well as certain pollen taxa were frequent. Among the pollen of terrestrial plant communities, the profile was dominated by herbs and grasses, whereas among the cryptogams, the amounts of fern and moss spores showed great variation. Most of the fungal spores in unit f derive from Ascomycetes while the upper part of unit e was dominated by Chlamydospores of *Glomus* (Figs. 6 and 7), indicating erosion possibly as a result of burning (Van Geel, 2001). Pollen of *Cichoriaceae* and *Asteraceae* predominated throughout the profile while *Poaceae* was the only other consistently recorded taxon.

Upper profile samples contained a greater diversity of taxa, particularly trees and shrubs, than lower sediment layers. Lamiaceae, Fabaceae, Scrophulariaceae, cf. *Plantago, Artemisia,* Rhamnaceae cf. *Ziziphus* and *Olea spec.* were recorded only from the topmost sample. It is likely that poor preservation conditions have

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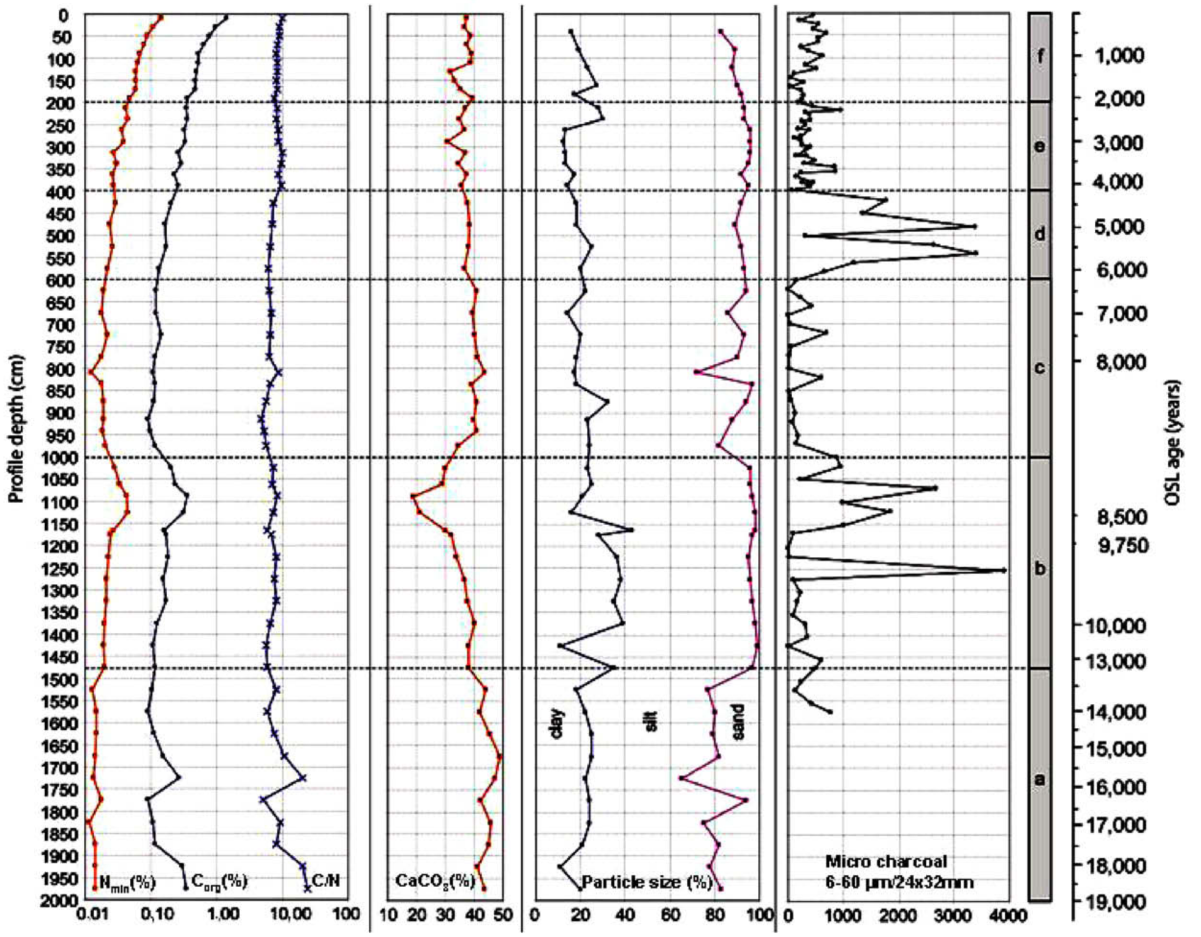

Fig. 4. Organic carbon (C_{org}), mineral nitrogen (N_{min}), C/N ratio, $CaCO_3$, particle size and micro-charcoal distribution of the 2000 cm deep sediment profile at Maqta (Oman). The time scale (years BP) on the right *y*-axis is based on Optically Stimulated Luminescence (OSL) of quartz particles (Fuchs and Buerkert, 2008).

inhibited representation or identification at greater depths for some of these taxa. Other taxa restricted to the upper half of the diagram are *Asphodelus spec., Ephedra (Ephedra distachya* type *and Ephedra fragilis* type), cf. *Phoenix dactylifera* and cf. *Juniperus.* The lack of *Juniperus* pollen in the topmost sample is consistent with the absence of this genus in the vegetation of the area today, although the earlier occurrences could also have been the result of long distance transport (Fig. 7).

The only taxa that remained sporadically represented in the lower part of the sequence were Chenopodiaceae, Rosaceae, *Cerealia* type and cf. *Tamarix.* Given their rare occurrence, pollen counts were small in the lower part (220–400 cm) of the profile and are therefore not displayed in the percentage diagram. At 219 cm Chenopodiaceae amounted to 4%, *Ephedra* to 2%, Cichoriaceae to 35% and Asteraceae to 30% (based on a sum of 99 pollen and spores per slide). An inverse relationship between pollen and spore occurrence on the one hand and charcoal on the other was found at 219 and 346 cm. *Ephedra* pollen peaked at 346 cm (Fig. 6).

Spores and other remains of Cryptogams were most frequent at 70–145 cm, but also occurred in upper layers. Most of the spores appeared to be from unidentified Bryophyta, Selaginellaceae, Pteridophyta and from fungi.

4. Discussion

Based on the OSL chronology the 2000 cm long sediment profile spans about the last 19 ka whereby for the upper 400 cm the reliability of sediment dating may suffer from the effects of insufficient bleaching, making the samples systematically younger than they really are. In contrast, the radiocarbon dates from the mollusc shells with their unknown reservoir effects (Phelan, 1999, Petchey et al., 2004; Nakamura et al., 2007), regardless of using calibrated or uncalibrated values, were of little use in establishing a reliable chronostratigraphy for the upper part of the profile though they suggest a sudden increase in sedimentation rate at about 140 cm depth (Fuchs and Buerkert, 2008).

Only the uppermost part of the profile retained pollen, spores and non-pollen palynomorphs, mainly from fungi. The distribution of microscopic charcoal, the contents of C_{org}, N_{min} and carbonate as well as its relatively high sand content indicate that unit a (19–13 ka OSL ages) represents a period of high aridity when wind activity enhanced aeolian particle transport on a widely bare soil surface. The sharp increase of silt at 1475–1400 cm and the strong drop of charcoal at 1425 cm within the "transitional phase" characteristic of a reduced sedimentation rate (TP: Late Glacial–Holocene transition) might reflect the dry and cold spell from 13.200–11.400 BP, well known as the Late Glacial (LG) Younger Dryas paleoclimatic deterioration in the North Atlantic region.

Unit b was characterized by a higher sedimentation rate at 1400–1000 cm. Very high charcoal amounts accompanied by decreasing carbonate content and increasing C_{org} and N_{min} values at 1225–975 cm together with a period of pronounced sedimentation rate (6.3 mm a^{-1}) at 1200–800 cm (8.7–8.07 ka) provide evidence for the onset of the Early Holocene humid period and may reflect

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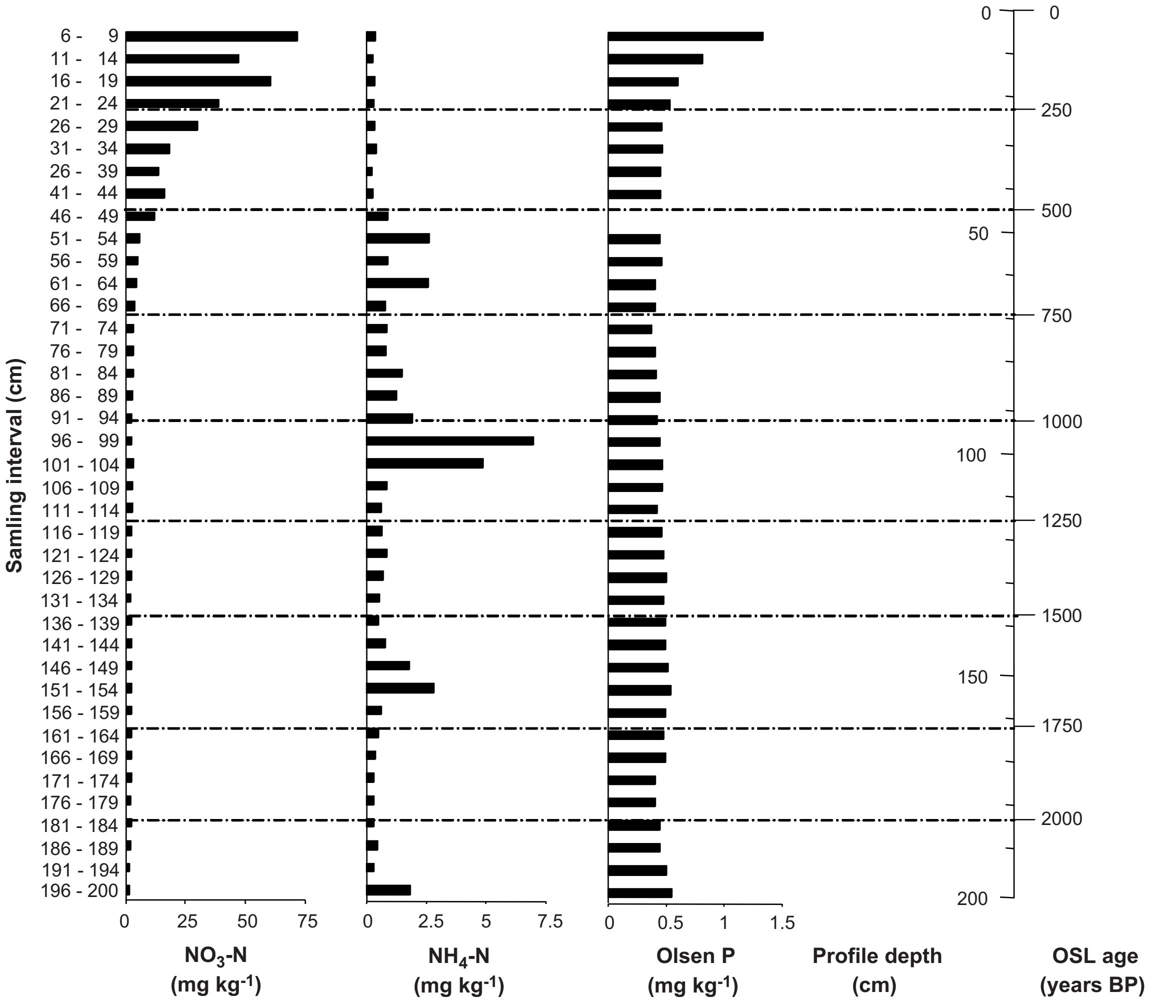

Fig. 5. Concentrations of nitrate (NO_3), ammonium (NH_4) and H_2CO_3-extractable phosphorus (Olsen P) of the upper 200 cm of the sediment profile at Maqta (Oman). The time scale on the right (years BP) *y*-axis is based on Optically Stimulated Luminescence (OSL) of quartz particles (Fuchs and Buerkert, 2008).

a denser vegetation cover leading to initial soil development. Among other studies, δ^{13}C data of speleothems of Soroq Cave (Israel; Bar-Matthews et al., 2003) pointed to torrential rainfall events during the period dated 8.5–7 ka which was interrupted by a drier period around 8.25–8 ka.

Within unit c (1000–600 cm) distinctive troughs and peaks in the charcoal curve and repeated increases of the profile's sand content indicated a non-uniform change to a period of decreasing precipitation. Within the uncertainties of the age model (Fuchs and Buerkert, 2008), our observations seem to correlate well with previous data from southern Oman (Fleitmann et al., 2003) and Yemen (Lézine et al., 2007) that date the onset of dryer conditions to about 8 ka.

At 600–400 cm (6.2–4.2 ka) within unit d another significant increase of charcoal with three distinctive peaks (at 5.7, 5 and 4.4 ka) point to periods of higher humidity assuming that the presence of charcoal particles reflects increased burning effects of a denser woody vegetation cover. Periods of higher lake level in the Dead Sea reconstructed from speleothems (Frumkin et al., 2001) and palynological data indicate phases of relative high precipitation/evaporation ratios at around 5 and 3.2 ka in the Near East and also the δ^{18}O data of spaleotherms presented by Fleitmann et al. (2007) support the existence of at least the first two short more humid periods derived from our sediment record.

The relatively high concentrations of NO_3-N and H_2CO_3-extractable P but also of C_{org} in the upper sediment layers (Fig. 4) likely reflect the combined effects of plant growth and mixing of small particles of organic debris from the surface into the topsoil. The decreasing P and C_{org} level with profile depth may also mirror recent faecal additions from donkeys and small ruminants grazing the depression after rainfall events. Higher concentrations of NH_4-N likely indicate the effects of water logging-induced anaerobic soil conditions as its accumulation likely occurs whenever temporary water saturation inhibits nitrification (Urban, 1993). More humid conditions may also be indicated by the accumulation of mollusc shells at 130–160 cm (equivalent to 1.5 ka).

Van Zeist and Bottema (1991) concluded from their work on the Arabian Peninsula that the regional climate has become steadily more arid during the Holocene leading to today's very sparse herb cover compared to that of the early Holocene. Deil and Al Gifri (1998) stated that most of the Arabian grassland was of secondary origin, having gradually replaced the original *Juniperus* and *Acacia* woodlands and that the evergreen *Olea–Barbeya–Tarchonanthus* woodlands were destroyed by man-induced cutting and burning. Today, annual rather than perennial grasses together with shrubs are the most important source of fodder for livestock in Arabia, particularly at higher altitudes. Nevertheless, a reconstruction of the local fauna at Al-Buhais (U.A.E.) indicates that the typical Arabian desert fauna around 4.7 ka might not have been much different from today's (Uerpmann et al., 2000).

Previous work has provided archaeological evidence of five millennia of transhumant landuse in the Maqta territory (Siebert et al., 2005). It was heavily influenced by traditional trade routes

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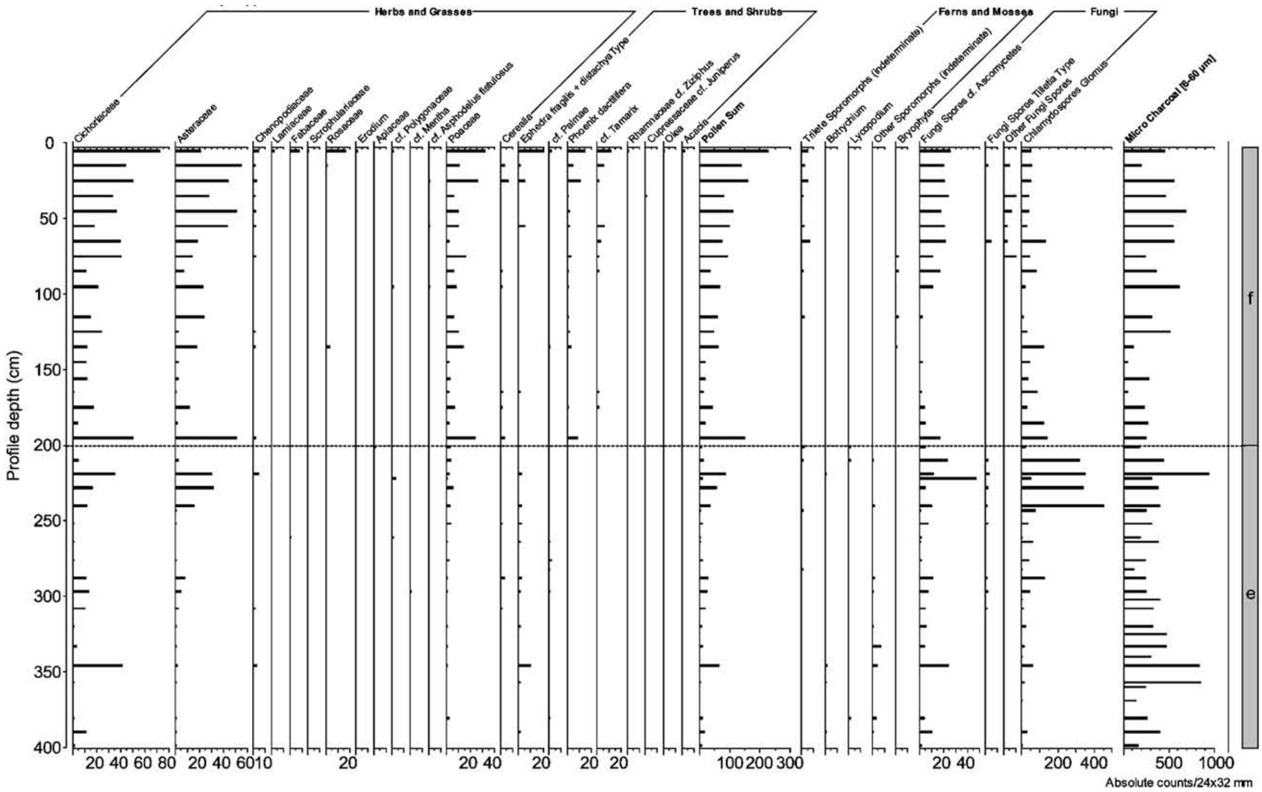

Fig. 6. Pollen, spores and non-pollen palynomorphs plotted in absolute counts (0–400 cm) of the sediment profile at Maqta (Oman). The time scale (years BP) on the right *y*-axis is based on Optically Stimulated Luminescence (OSL) of quartz particles (Fuchs and Buerkert, 2008).

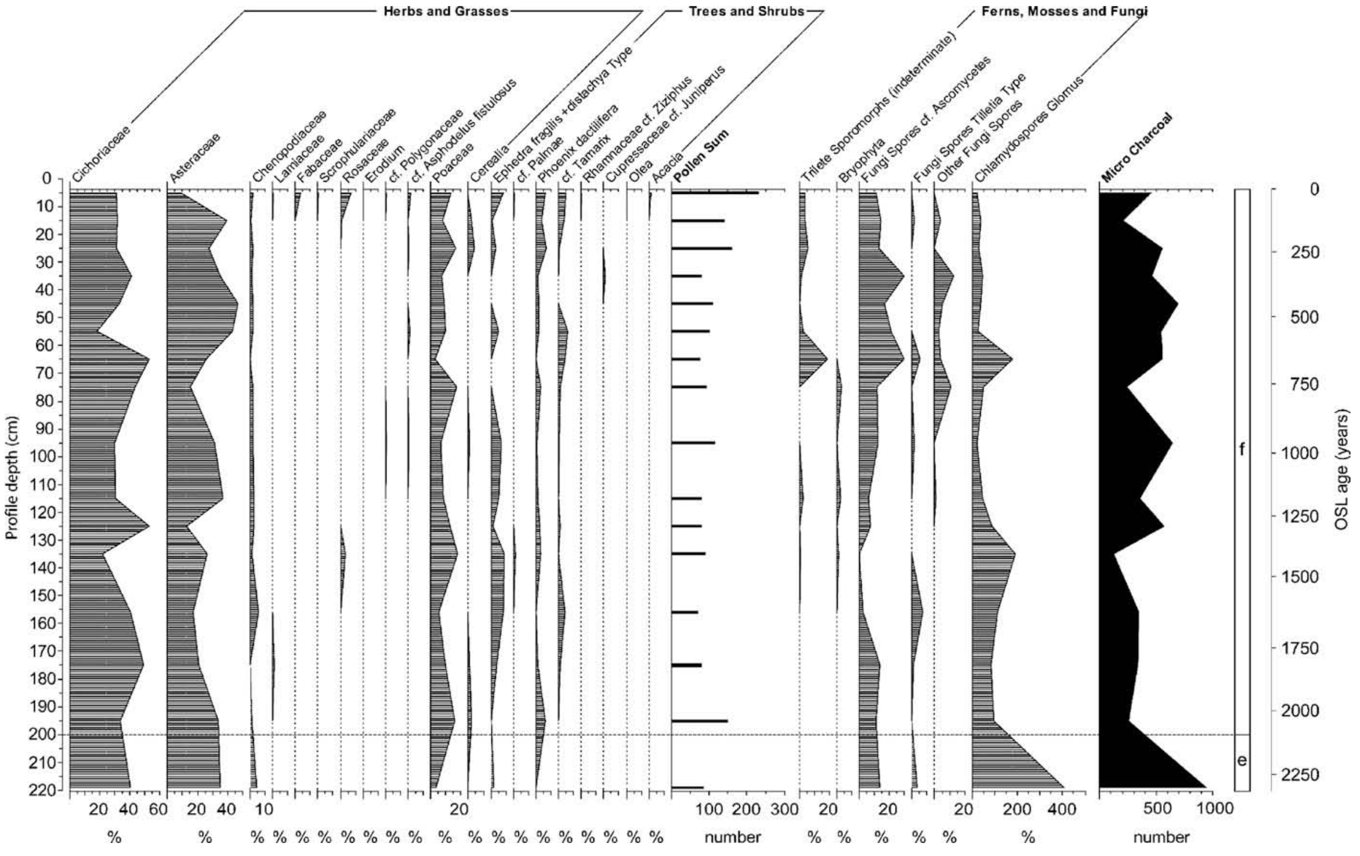

Fig. 7. Pollen percentage diagram (0–200 cm) of the sediment profile at Maqta (Oman). The time scale (years BP) on the right *y*-axis is based on Optically Stimulated Luminescence (OSL) of quartz particles (Fuchs and Buerkert, 2008).

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that led from the Wadi Khabbah west across the Jabal Bani Jabir to the important port of Tiwi on the Arabian Sea. The effects of human activities and climatic fluctuations should have had a substantial impact on the vegetation at the local level and therefore the profile at Maqta plays an important role in better understanding the agroecological environment of northern Oman. It seems to have been dominated by herbs and grasses at least for the last 4 ka, among which *Cerealia* is of particular interest. Unfortunately it is still unclear whether this pollen find is from wild species or from cultivated cereals. Another interesting feature is the late reappearance of *Ephedra* pollen at 65 cm depth (600 BP; Fig. 6). *Ephedra pachyclada* is typically associated with open *Juniperus-Olea* woodlands at altitudes of 2000 m in the Jabal Akhdar range (Ghanzanfar, 1992), whereas *Ephedra ciliata* is a very common plant growing on gravel foothills and plains. As both species are often associated with drought-ridden open vegetation types, the increasing occurrence of their pollen – together with that of *Tamarix*, a well known desert pioneer plant – might suggest a local increase in aridity at about 1.6 ka, 600 and 200 BP. For the 600 BP peak this is supported by the findings of von Rad et al. (1999) who reported a precipitation minimum in varved sediments at about 700–400 BP. The older peak of *Ephedra* occured at 346 cm, equivalent to about 3600 BP (Fig. 6). Alternatively *Ephedra* pollen could have been wind-transported to the area from other parts of the Arabian Peninsula or even the hyperarid parts of (north)western Africa. However, at Maqta, the main wind direction is from the east rather than from the west and *E. pachyclada* and *E. ciliata* have been described earlier as important components of the recent local flora (Ghazanfar, 1992, 1998). Some support for increased aridity during this time may be provided by a slight reduction in microscopic charcoal from the time of representation of *Ephedra*, if decreased burning indeed reflects reduced cover with woody species.

The appearances of pollen from *Olea spec*., Rhamnaceae (cf. *Ziziphus*) and Fabaceae within the last 500 years could well indicate the advent of oasis agriculture in the inhospitable Maqta area especially as they correspond well with the charcoal-^{14}C dated age of construction of the abandoned *aflaj* located close to the investigated site. Compared to other recently described oases in the northern Oman mountains which bear vivid testimony to continuous agricultural activities over the last three millennia (Nagieb et al., 2004), the advent of irrigation agriculture at Maqta may have been very late likely reflecting the ecologically difficult environmental conditions for a growing agropastoral population in search for new territories.

5. Conclusions

The geochemical and charcoal records of the alluvial depression above Oasis Maqta in Northern Oman provide previously unknown insights into environmental conditions and regional climatic development during the Last Glacial Maximum (LGM), the Late Glacial (LG) and the Holocene period. After the dry period at the end of the LGM and subsequent climatic amelioration, another period of climatic deterioration was identified that might relate to the "Younger Dryas" event (around 11.6 ka). Very high charcoal frequencies in combination with geochemical data are indicative of an Early Holocene increase of rainfall. In accordance with previous sedimentological investigations and OSL dating of the entire profile, our data reflect well the subsequent onset of dryer conditions at about 8 ka. Previously underinvestigated in the climatic record of the region is the occurrence of three periods (at 5.7, 5 and 4.4 ka OSL age) of higher humidity as deduced from high charcoal frequencies and geochemical data which may merit further study.

The combination of chemical and palynological features of the studied upper part of the profile with its surprisingly well preserved pollen indicates that changes in local rainfall and human impact on the vegetation were relatively minor over the last four millennia. Nevertheless, variations in NH_4-N concentrations and mollusc shell accumulations suggest the occurrence of occasional moist periods of unknown length.

The absence of pollen from agricultural crops, with the possible exception of cereals and *Phoenix dactilifera* until about 500 years ago likely reflects the harsh ecological conditions of the area enforcing a largely pastoral way of life. Overall, the results of pollen analysis provide little evidence for a major climate change over the past 4300 years, the time-span of the Shir towers' existence. An exception may be a minor increase in aridity as indicated by *Ephedra* pollen within the last 600 years.

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