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Mangroves of Oman during the late Holocene: climatic implications and impact on human settlements

Anne-Marie Lézine[1], Jean-François Saliège[2], Robert Mathieu[3], Thibaut-Louis Tagliatela[3], Sophie Mery[4], Vincent Charpentier[4] and Serge Cleuziou[4]

1 FRE 2400-CNRS, Jussieu, Boîte 106, F-75252 Paris cedex 5, France, e-mail: lezine@ccr.jussieu.fr
2 LODYC, Jussieu, Boîte 100, F-75252 Paris cedex 5, France
3 Département de Géologie Sédimentaire, Université Paris VI, Jussieu, Boîte 117, F-75252 Paris cedex 5, France
4 UMR 7041-CNRS, Maison René Ginouvès, 21 rue de l'Université, F-92023 Nanterre cedex, France

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Abstract. Pollen and micropalaeontological analyses carried out on mangrove swamp sediments of Suwayh, Oman (22°05.589'N, 59°40.033'E) reveal environmental changes linked both to climate (monsoon) and geomorphological (sea-level) variations during the Late Holocene. A *Rhizophora* mangrove developed at Suwayh around 6000 years B.P. under climate conditions marked by an increased tropical influence as compared to the modern situation, with dominant summer rains. The later extension of *Prosopis cineraria* at Suwayh provides evidence for a different rainfall pattern, with a winter rainy season. Pollen and micropalaeontological composition shows three episodes influenced by the sea water at Suwayh. The most important corresponded to the mangrove episode centred ca. 6000 B.P. This was followed by two episodes of slight seawater incursion at ca. 5100 and 4500 B.P. responsible for the formation of a brackish lagoon. Comparison based on ^{14}C measurements on shell recovered from both the sedimentary sequence of Suwayh and the nearby archaeological sites demonstrates that close relations existed between man and mangroves during the Neolithic and the Early Bronze Age.

Key words: Mangrove – Pollen – Foraminifera – Palaeoclimate – Palaeoenvironment – Human settlements – Oman – Holocene

Introduction

Mangrove ecosystems are very sensitive to climate change. The two main limiting factors to their distribution are the air temperature of the coldest month (around 16°C) (Chapman 1975) and aridity (Marius 1985). As a consequence, mangrove ecosystems are mainly found in equatorial and tropical areas, where they benefit from high air temperature and abundant input of fresh water. Their floristic composition decreases with latitude northwards. If they are at all present in sub-tropical desert zones, such as those along the coasts of the Arabian Peninsula, it is only as impoverished formations containing a single species, *Avicennia marina*, which is adapted to highly saline and evaporitic conditions (Tomlinson 1986). Other components of the mangrove found southward along the East African coast, for example *Brughiera gymnorrhiza, Ceriops tagal, Sonneratia alba* and *Rhizophora mucronata* (White 1983), are absent in Arabia, except for the latter which is known from restricted areas of the southernmost part of the Red Sea coasts (Ghazanfar and Fisher 1998). During the late Quaternary, mangrove areas have undergone large fluctuations in extent (e.g. Lézine 1997) directly related to variations in monsoonal rainfall in the tropics. Geomorphological changes of the littoral linked to sea-level fluctuations have also played an important role, by increasing or diminishing the large muddy areas necessary for mangrove establishment.

We investigate here environmental changes in the coastal zone of Oman since 6000 years B.P. (ages are expressed as calibrated age B.P. or B.C. according to Stuiver et al. 1998a). Correspondence between conventional and calibrated ages B.P. and B.C. is given (Table 1). Pollen and micropalaeontological analyses of a sediment core recovered in the palaeomangrove of Suwayh (22°05.589'N, 59°40.033'E) (Fig. 1a) are presented with the aim of reconstructing the influence of sea level and climate variations on the evolution of the littoral ecosystem of south eastern Oman, and the implications of these for human populations. Environmental data are scarce in southern and eastern Arabia for this period (Lézine et al. 1998), which probably has to be regarded as one of increased human population densities (Wilkinson 1999). Along the littoral of the Arabian Sea, human occupation intensified from the middle of the 6th millennium B.C. (Charpentier et al. 2000). This is indicated by several hundred archaeological sites dating from 5500 B.C. to 1600 B.C. identified in the Ja'alan Region at the eastern edge of Oman (Fig. 1b) during the course of the archaeological "Joint Hadd Project" (Cleuziou and Tosi 2000). In the Suwayh area, several archaeological excavations and soundings have been carried out at various Neolithic sites identified as SWY-1, SWY-2, SWY-10, SWY-11 and BJD-1 (6th to 4th millennium B.C.). The Early Bronze Age period (ca. 3000-2000 B.C.),

Correspondence to: Anne-Marie Lézine

Table 1. Radiocarbon ages for Suwayh. Radiocarbon ages were corrected using a ΔR = 235±30 reservoir correction and then converted to calendar ages using the Calib 4.1.2 calibration routine (Stuiver et al., 1998a). Calendar ages are bracketed by the 1σ range value. They are expressed as B.P. and B.C. in order to facilitate correlation between sedimentary and archaeological records. Species analysed were *Amiantis umbonella, Saccostra cucculata* and *Lunella coronatus*

Site	Laboratory number	Conventional Age ^{14}C B.P.	Standard deviation	Calibrated Age B.P. (1σ)	Calibrated Age B.C. (1σ)	^{13}C PDB	^{18}O PDB	Species analysed
SWY-3	Pa 1775	4240	40	4081-3926	2132-1977	2.16	0	*A. umbonella*
SWY-3	Pa 1772	4265	40	4115-3968	2166-2019	1.72	-0.6	*A. umbonella*
SWY-3	- Pa 1677	4270	40	4126-3972	2177-2023	1.09	-0.7	*A. umbonella*
SWY-3	- Pa 1684	4315	40	4177-4058	2228-2109	1.12	-0.6	*A. umbonella*
SWY-3	- Pa 1679	4315	40	4177-4058	2228-2109	1.69	-0.6	*A. umbonella*
SWY-3	- Pa 1674	4325	40	4211-4066	2262-2117	1.44	-0.5	*A. umbonella*
SWY-3	Pa 1777	4395	50	4318-4140	2369-2191	2.39	0	*A. umbonella*
SWY-3	- Pa 1710	4505	40	4425-4314	2476-2365	1.62	-0.5	*A. umbonella*
SWY-3	- Pa 1718	5020	40	5126-4959	3177-2010	1.34	0.23	*A. umbonella*
SWY-3	Pa 1723	5410	60	5593-5465	3643-3515	1.23	-0.5	*A. umbonella*
SWY-3	Pa 1721	5705	40	5901-5765	3952-3816	-1.2	-0.2	*A. umbonella*
HD-6	Pa 1719	4945	60	5027-4839	3077-2889	1.3	0.4	*A. umbonella*
SWY-2	Pa 1708	5165	40	5306-5238	3357-3289	1.68	0.36	*A. umbonella*
SWY-2	Pa 1788	5975	40	6201-6098	4252-4149	1.09	-1.2	*S. cucculata*
SWY-11	Pa 1787	6970	45	7037-7219	5358-5270	1.24	-0.9	*S. cucculata*
SWY-11	Pa 1716	7275	60	7577-7461	5627-5511	0.37	-0.4	*L. coronata*
Suwayh drill 1 –35 cm	Pa 1767	4570	60	4530-4390	2580-2440	1.67	-0.8	*A. umbonella*
Suwayh drill 1 –69.5 cm	Pa 1765	5045	35	5211-4992	3262-3043	0.77	0.38	*A. umbonella*
Suwayh drill 1 –185 cm	Pa 1794	5760	100	5990-5769	4040-3819	1.14	-0.4	*S. cucculata*
Suwayh drill 2 –230 cm	Pa 2029	5605	60	5842-5646	3892-3696	1.1	0	Shells undiff.

better known in the north from sites HD-1, HD-6, RJ-1 and RJ-2, is documented at SWY-3 near Khawr Bani Bu Ali (Méry and Marquis 1998, 1999).

Modern features

Climate and vegetation

The climate of Oman covers a wide range from a mean annual rainfall of less than 50 mm in the interior of the Rub' al-Khali desert to ca. 350 mm with occasional snowfalls at 3000 m in the north-eastern Hajar mountains. Rainfall occurs in summer due to the south-western monsoon circulation and also in winter due to the penetration of eastern Mediterranean troughs in the Persian Gulf following the Zagros topographical barrier (Fig. 1a). The northern penetration of summer monsoon fluxes in Oman (for example to the southernmost part of the country in the Dhofar region) is greatly limited by the strong influence of the North-westerlies which advect dry and hot air over Arabia and are responsible for important dust transport into the mid-troposphere. The mean annual temperature ranges between 29°C at the sea level to 18°C at 1755 m altitude, sometime falling to freezing during winter at higher levels.

As a consequence, the lowland vegetation of Oman is mainly of semi-desert type containing *Acacia* spp., *Prosopis cineraria* and *Ziziphus spina-cristi*, while desert areas are characterised by the occurrence of *Calligonum crinitum*, *Cyperus conglomeratus*, *Dipterygium glaucum*, *Tribulus arabicus* and *Artemisia monosperma*. In summer rain areas, the tropical, "Somalia-Masai" (White 1983) influence is well recorded in Dhofar where *Acacia-Commiphora* woodlands occur, but is progressively replaced toward altitudes above 500 m by mixed assemblages dominated first by *Boswellia*, *Dracaena* and *Euphorbia* then by semi-evergreen woodlands dominated by *Anogeissus dhofarica*. To the north-east, where rainfall is lower and the precipitation mainly occurs in winter *Prosopis cineraria* dominates the coastal plains and lower foothills. Here the vegetation shows strong floristic links with the eastern side of the Persian Gulf and belongs to the "Omano-Makranian sub-zone" of the Nubo-Sindian centre of endemism (Ghazanfar and Fisher 1998). The altitudinal distribution of vegetation associations therefore includes mixed assemblages dominated by *Euphorbia larica*, *Convolvulus acanthocladus*, semi-evergreen woodlands with *Dodonaea viscosa, Ebenus stellatus, Olea europaea* subsp. *africana* and *Monotheca buxifolia*, and at the top of the Hajar mountains, evergreen needle-leaved woodlands dominated by *Juniperus excelsa* subsp. *polycarpos* associated with *Ephedra pachyclada, Cotoneaster nummularia* and *Daphne mucronata*.

Mangrove vegetation occurs only as a restricted formation located at the mouth of wadis (at Quriyat or Qurum) and in brackish lagoons fed by underground freshwater or seasonal freshwater inflows (at Sur and Khawr al-Jaramah). *Avicennia* thickets grow on sandy mud or rocky soils in the intertidal zone. They are bordered on the landward side by herbaceous plant communities composed of salt-tolerant species mainly belonging to the Chenopodiaceae, Frankeniaceae, Asteraceae and Plumbaginaceae. *Phragmites australis* may occur in mangroves when the salinity is very low, and in association with *Typha australis* and the submerged species *Ruppia maritima* it characterises predominantly freshwater environments.

Modern pollen deposition and micropalaeontological characterisation: methods

Sixteen surface samples were taken in coastal lagoons and temporary ponds; at Quriyat (23°16'N, 58°55'E), Sur (22° 33'N, 59°32'E), Khawr al-Jaramah (22°29'N, 59°43'E) along the coast of the Gulf of Oman, and at Khawr Bani Bu Ali (22°02'N, 59°39'E) on the Indian Ocean shore (Fig. 2). Samples were processed using the standard HF method (Faegri and Iversen, 1975) and sieved on a 5-µm mesh for pollen. Pollen counts ranged from 61 to 8943 and 80 taxa were identified. Identifications were done using the photograph collection of the African Pollen Database (http:\\medias.meteo.fr) and various atlases of pollen morphology (El Ghazali 1991; Reille 1992; Bonnefille and Riollet 1980).

Results (Figs. 2 and 3)

Surface samples from mangroves at Quriyat, Sur and Khawr al-Jaramah reveal similar assemblages, with Amaranthaceae/Chenopodiaceae, Asteraceae, Cyperaceae and Poaceae dominating the herbaceous taxa. *Zygophyllum simplex* and *Artemisia* are also present as significant percentages, reflecting the regional dry and hot environmental conditions. Trees occurring both locally (*Avicennia* and *Tamarix*) and regionally (*Acacia, Prosopis, Ziziphus*) are under-represented in the pollen assemblages, their presence never exceeding 10%. *Avicennia marina* pollen percentages are surprisingly low, even in the immediate proximity of the trees from which they come (for example at Khawr al-Jaramah). This clearly indicates that *Avicennia* pollen grains are poorly dispersed into the atmosphere and are not transported over long distances. The occurrence of this taxon, even as a single grain, is thus indicative of the presence of the corresponding trees in the immediate surroundings.

The occurrence of fern spores and *Typha* pollen grains at Quriyat and Khawr al-Jaramah indicates local fresh-water input from seasonal wadis. Sea-water influence is indicated at Khawr al-Jaramah and Sur by the predominance of the foraminiferal species *Ammonia beccarii, Quinque-*

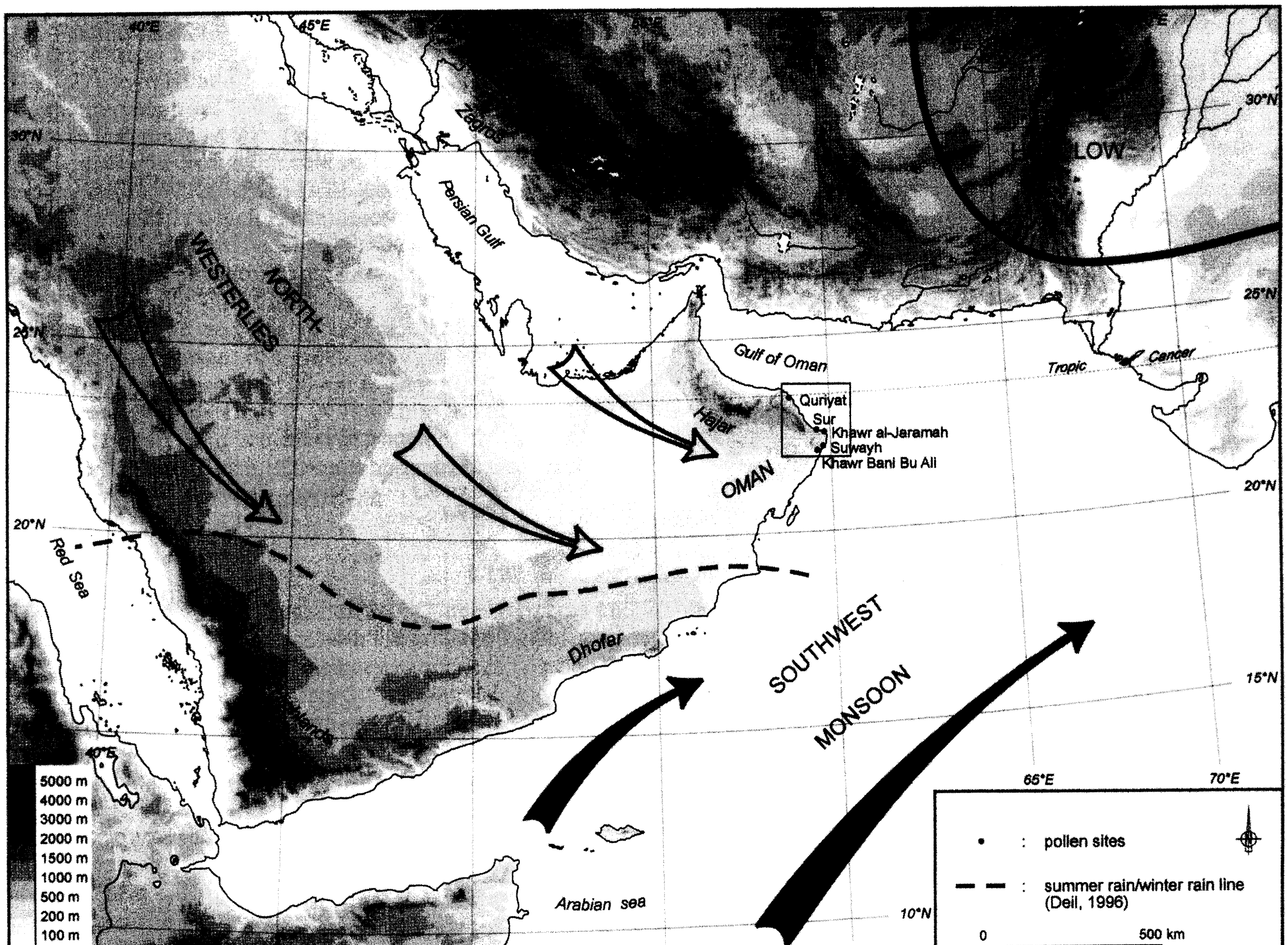
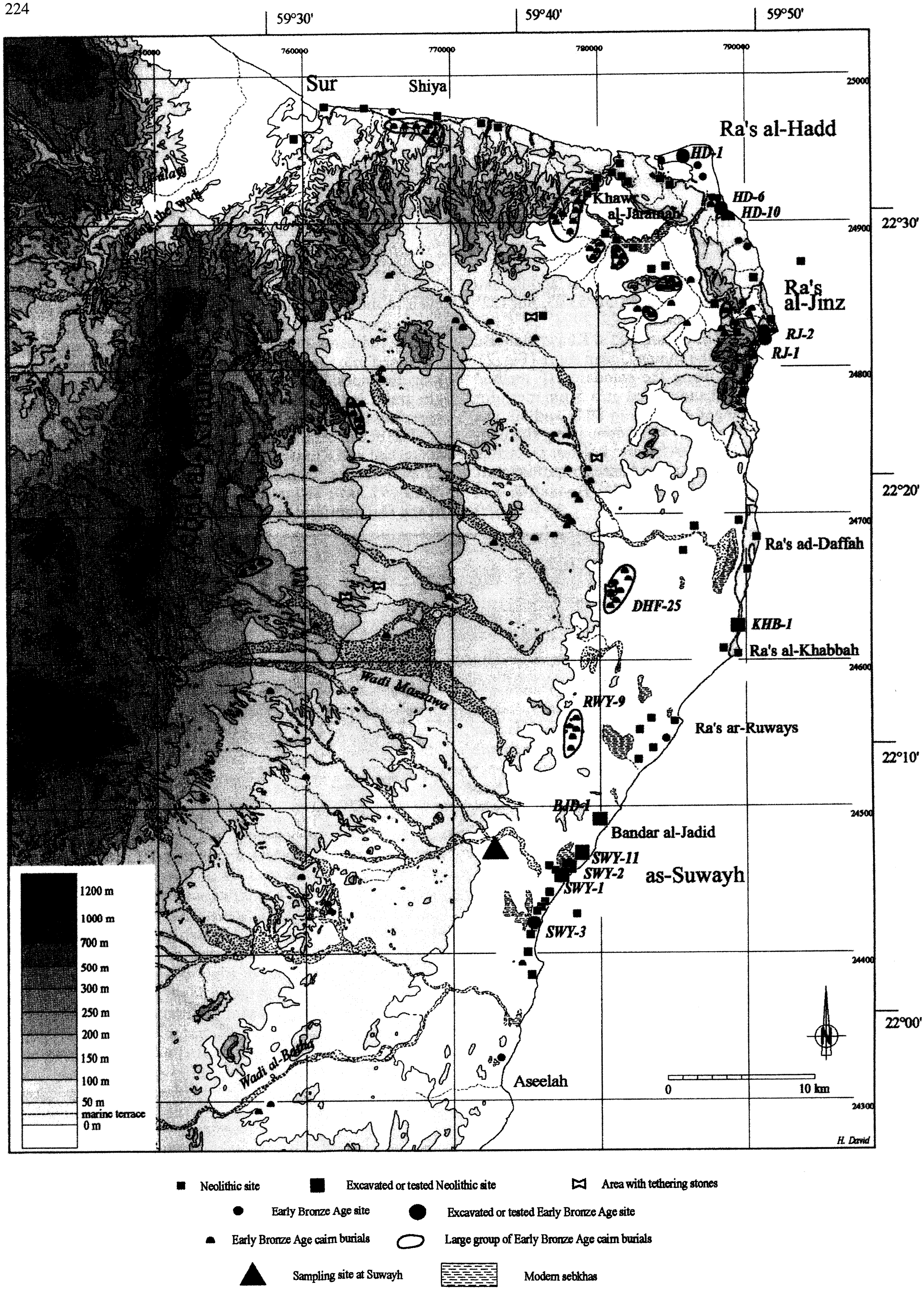


Fig. 1a. Location map of pollen and archaeological sites referred to in the text. This figure shows the main features of the regional atmospheric circulation. The boundary between summer and winter rain is drawn after Deil (1996)


59°30'
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22°10'
22°00'
Sur
Shiya
Ra's al-Hadd
HD-1
HD-6
HD-10
Khawr al-Jaramah
Ra's al-Jinz
RJ-2
RJ-1
Ra's ad-Daffah
DHF-25
KHB-1
Ra's al-Khabbah
Wadi Masawa
RWY-9
Ra's ar-Ruways
BJD-1
Bandar al-Jadid
SWY-11
SWY-2
SWY-1
SWY-3
as-Suwayh
Wadi al-Batha
Aseelah
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10 km
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H. David
1200 m
1000 m
700 m
500 m
300 m
250 m
200 m
150 m
100 m
50 m
marine terrace
0 m
Neolithic site
Excavated or tested Neolithic site
Area with tethering stones
Early Bronze Age site
Excavated or tested Early Bronze Age site
Early Bronze Age cairn burials
Large group of Early Bronze Age cairn burials
Sampling site at Suwayh
Modern sebkhas

loculina jugosa, *Q. seminulum* and *Alphidium crispum*, whereas a continental influence is locally marked at Sur and Quriyat by the presence in high percentages of *Ammonia tepida*, *Sinoculina rotundata*, *S. bosciana* and *Nonion depressulum*. A clearly different pattern is recorded at Khawr Bani Bu Ali, where *Ruppia maritima* reaches 86% reflecting the brackish to fresh water local environment. This pattern is also seen in the micropalaeontological association with the near absence of foraminifera (except for some test fragments) and the dominance of fresh-water ostracods of the Cyprididae family.

The fossil record

The mangrove deposits were sampled at some 3 km from the coastline (22°05.289'N, 59°40.033'E, 16 m asl) in two sections, a few metres apart from each other, in the Suwayh depression. This depression belongs to a series of fossil lagoons extending along the Indian Ocean coast south of Ra's al-Hadd (Fig. 1b). These lagoons are separated from the sea by sand bars and are occasionally fed by freshwater from wadis flowing from the Jebel al-Khamis (the easternmost part of the Hajar mountain range). The present-day vegetation surrounding the depression is composed of semi-desert steppes with some *Prosopis* trees.

Sampled were taken at 2 cm to 5 cm intervals from a 187 cm vertical face in a pit (Drill 1). A 350 cm deep core (Drill 2) provided additional samples which were taken at 10 cm intervals from 350 cm up to 140 cm in beds of mangrove sediments (Fig. 4). Two different sedimentary units can be distinguished. The first of these is the base of the sequences (up to 130 cm in Drill 1 and from 350 cm up to 160 cm in Drill 2) which is characterised by homogeneous green sandy clay with oyster shells (*Saccostrea cucullata*) in Drill 1 and undifferentiated fragments in Drill 2. The second overlying unit consists of alternating brown to green clays, sand and gravel layers. Shells of *Amiantis umbonella* are present in a green, sandy clayey level at 70 cm in Drill 1 and around 100 cm in Drill 2. They are also present at 40 cm in Drill 2. A few thin layers of gravel, brown clay and sand are recorded toward the top of the sequence (40 cm - 0 cm). This unit has not been sampled in Drill 2.

Chronological control

Chronological control is based on 20 ^{14}C measurements on marine shells recovered from both the archaeological sites (SWY-2-3-11) and the sedimentary sequences (Table 1). Since the study area is directly influenced by strong upwellings caused by the south-western monsoon circulation (Prell 1984), the reservoir effect (ΔR) has to be discussed and the mean value of 400 years used for the global ocean (Stuiver et al. 1998a,b) reconsidered.

In our study, the estimation of ΔR is based on comparison between ^{14}C measurements on *Amiantis* shells (samples Pa-1684 and 1674) and on pottery fragments from the same layer of SWY-3 dated from the Early Bronze Age.

←

Fig. 1b. Location map of archaeological sites in the Ja'alan region. Sites referred to in the text are in bold characters

We assume that these shells were collected from the nearby coastal areas and are adequate to evaluate the local reservoir effect. The characteristics of the pottery (fabric and morphology), which are well studied in the Ja'alan region, have led to the assignment of an age of 2100-2200 B.C. to these fragments (Méry and Marquis 1998, 1999). This age has been used to re-calculate the theoretical age of contemporary shells from the same archaeological layer using the model developed by Stuiver and Braziunas (1993) for CO_2 exchanges between the atmosphere and the surface marine waters (0-75 m). We assume that the difference between the result of this calculation (4040-4112 B.P.) and our ^{14}C conventional measurements (4315±40 B.P. and 4325±40 B.P. respectively) represents the ΔR, which can thus be evaluated as around 235±30 years.

The pollen content

Sixty samples were prepared. Only 30 of them yielded a pollen content sufficiently diverse to form reliable pollen spectra. In these samples pollen counts ranged from 139 to 957 including 96 different pollen and fern taxa. Percentages were calculated based on these sums. They are expressed in a pollen diagram (Fig. 5). Two distinct pollen zones have been identified. They are separated by a sterile section, that between 130 cm and 35 cm in Drill 1:

Lower Zone. From 350 cm up to 170 cm in Drill 2 and from 187 up to 130 cm in Drill 1 is a Mangrove zone. The pollen assemblages are characterised by the continuous occurrence of *Avicennia* and *Rhizophora* pollen grains in significant percentages (maximum = 18% and 8%, respectively). *Rhizophora* pollen grains are present from the base of Drill 2 up to 200 cm, while *Avicennia* also occurs in Drill 1, up to 140 cm (maximum = 5%). The other tree pollen grains mainly come from Afromontane ecosystems (*Juniperus, Podocarpus, Ericaceae, Myrica, Olea, Dodonaea, Ephedra*). The low and mid-altitude trees are represented only by *Acacia*. Amaranthaceae/Chenopodiaceae, Cyperaceae and Poaceae reach the highest percentages as might be expected. They are associated with other herbaceous taxa from semi-desert communities (*Tribulus, Calligonum, Dipterygium* etc). Fresh-water indicators such as *Typha* are regularly present, while fern spores occur sporadically. The foraminiferal assemblages (Fig. 4) confirm the marine influence with the littoral/marine taxa, *Ammonia beccari* in association with *Quinqueloculina semilunum, Q. akneriana, Elphidium crispum* reaching 19% to 50%.

Upper zone. From 35cm up to 0 cm in Drill 1 the pollen assemblages show a rather different composition. *Avicennia* pollen grains are only present at two levels (21.25 cm and 15.5 cm) in low percentages. *Dodonaea* and *Prosopis*-type characterise the tree pollen association. The latter reaches 22%. The herbaceous association does not differ significantly from the preceding pollen zone except for one taxon, *Ruppia*, which occurs in the uppermost level. This zone is interrupted between 15 cm and 11 cm by

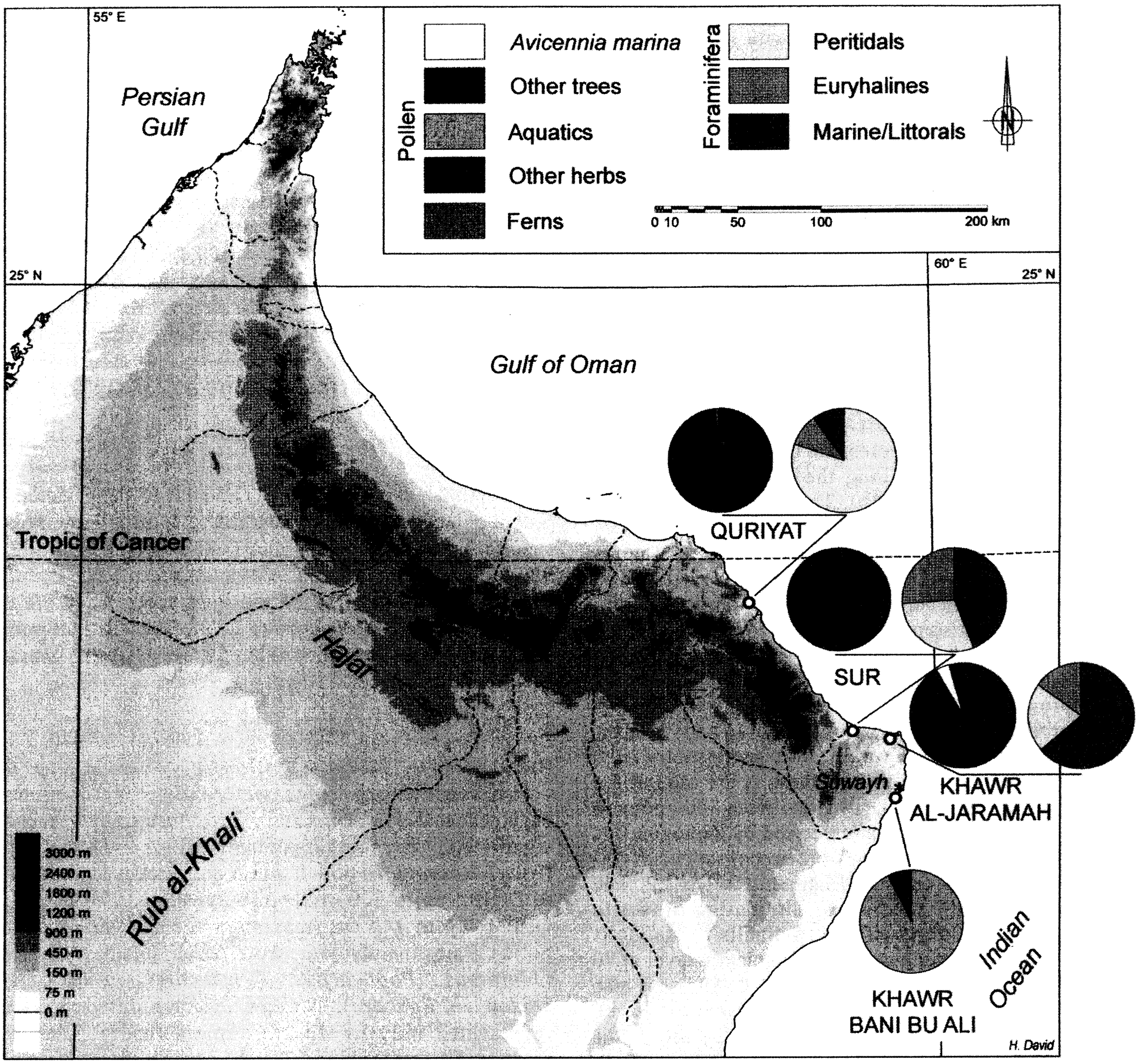

Fig. 2. Summary diagrams of pollen and foraminifera assemblages in the modern samples from the littoral of Oman. Data shown in each diagram correspond to the mean value of each site. *Avicennia* pollen percentages are very low, even in sites under well marked marine influence (Sur). The only site where *Avicennia* pollen is noticeable is Khawr al Jaramah. Khawr Bani Bu Ali is a fresh-water dominated depression; foraminifera are absent from this sample

a reworked layer characterised by exotic pollen grains: *Pinus*, *Podocarpus*, Ericaceae and ferns, and among the foraminifera by the occurrence of the planktonic species *Globigerinoides sacculifer*. Littoral/marine foraminifera (*Ammonia beccarii* and *Quiqueloculina akneriana*) are also present at 40 cm (4530-4390 B.P.) confirming that the Suwayh depression was under the influence of sea-water at that time. However, the dominance of peritidal species of foraminifera in the upper levels of Drill 1 (*Ammonia tepida, Sinuloculina bosciana, S. rotunda*), particularly at the highest level, indicates that the marine influence was sporadic and that the mangrove was replaced by a brackish to fresh-water lagoon, confirmed by the dominance of *Ruppia* in the pollen assemblage.

Environmental implications

Past vegetation and climate
A mangrove extension around 6000 B.P.

The pollen diagram clearly shows that the mangrove was present at the core site around 6000 B.P. It was composed of two dominant tree species *Rhizophora* and *Avicennia* This suggests a more pronounced tropical influence at the time, since only *Avicennia* is found in the present-day mangroves of Arabia, whilst *Rhizophora* extends southward in more humid areas. *Rhizophora* pollen grains are known to be produced in great abundance by their source plants (Muller 1959) and predominantly dispersed by air

(Tomlinson et al. 1979). However, studies of modern pollen deposition in soil surface samples have demonstrated that their percentages decrease rapidly with distance (Edorh 1986). Consequently, we can suggest that the *Rhizophora* plants, which are nowadays restricted to the south-westernmost coastal areas of the Arabian Peninsula in Yemen, extended at that time about 2500 km to the East, up to Suwayh. They were probably located to seaward of the core site, whereas *Avicennia,* the percentages of which were higher than in the present-day *Avicennia* population of Oman (see above), grew closer to the site as developed populations. The occurrence of fresh-water taxa (*Typha*) and ferns moreover suggests that fresh-water inputs were constant. The influence of open sea water in the area of Suwayh near 6000 B.P. is also demonstrated by the presence at the same levels of oysters and marine species of foraminifera, particularly *Ammonia beccarii, Quinqueloculina seminulum*, and *Bolivina striatula.*

A dominant tropical influence during this mangrove episode can also be inferred, indirectly, from the composition of the two other plant associations; the lowland association and the Afromontane association.

In the lowland vegetation association *Prosopis* was surprisingly absent (only one grain was found at these levels in Drill 1). As an element of the "Omano-Makranian sub-zone" of the Nubo-Sindian centre of endemism, it nowadays dominates the lowlands of eastern Oman where winter rains occur. According to Ghazanfar and Fisher (1998), the presence of *Prosopis* in Oman testifies to the existence of a migration route from the eastern side of the Gulf during the Pleistocene, when the sea-level was low. *Prosopis*-type represents up to 9% of the pollen content of the modern soil surface samples throughout the country (Gajewski et al. in prep) and up to 7.4% in the mangroves as detailed above (sample O98-06). The near absence of *Prosopis*-type pollen grains in the levels dated around

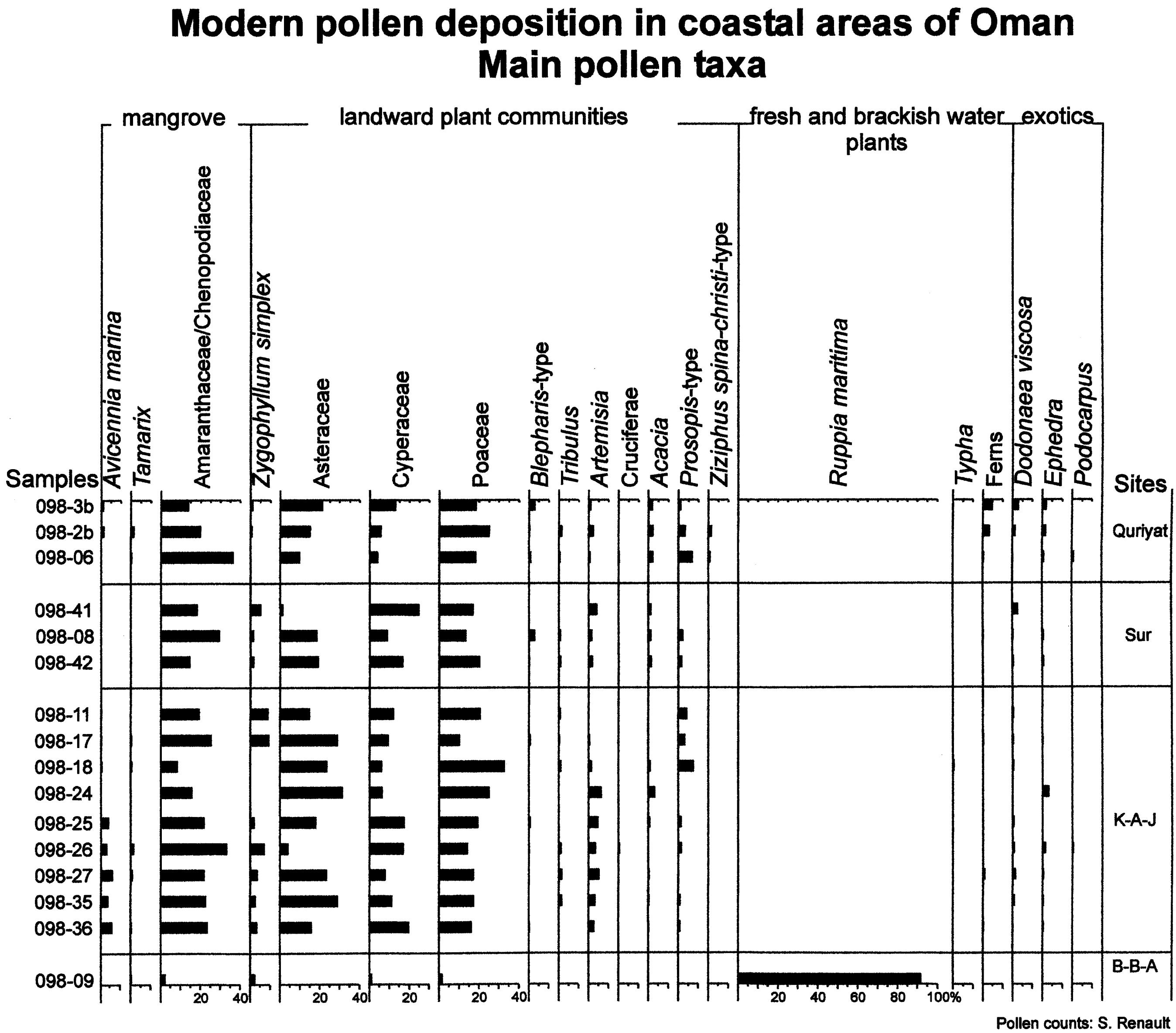

Fig. 3. Summary pollen diagram for modern pollen samples from the littoral of Oman (from North to South: Quriyat, Sur, Khawr al Jaramah (K-A-J), and Khawr Bani Bu Ali (B-B-A). Pollen taxa are grouped according to the ecological affinity of their source plants. Percentages are based on the sum of all the pollen grains and spores counted

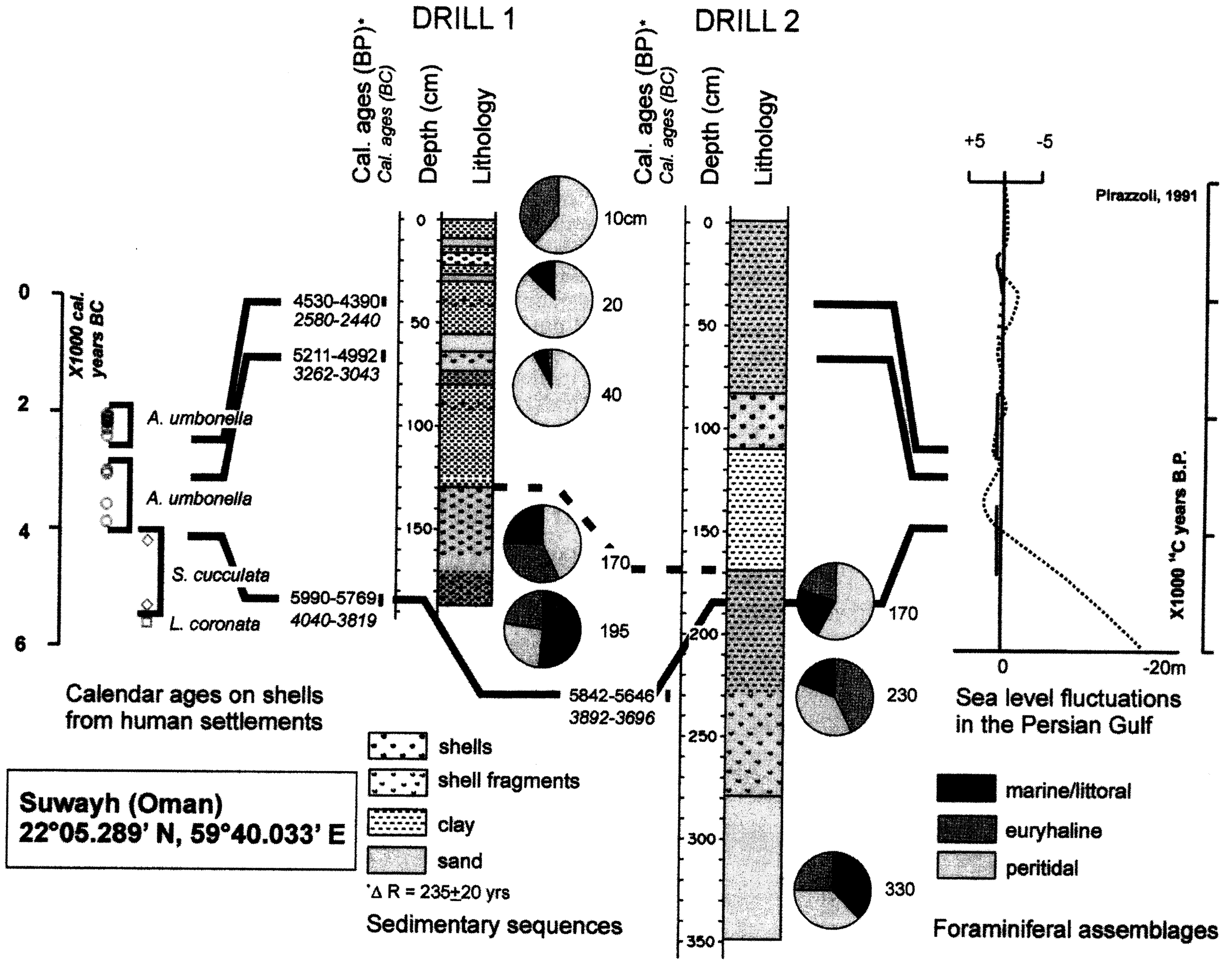

Fig. 4. Correspondence between ^{14}C measurements on shells recovered in the archaeological sites surrounding the Suwayh depression and the sedimentary sequences Drill 1 and 2. The oldest ages are obtained on *Saccostrea cucculata* in both environments. In the sedimentary sequences, they correspond to an episode of mangrove extension at Suwayh as indicated by the foraminiferal assemblages. The more recent ages are obtained on *Amiantis* recovered in two well defined episodes of slight marine incursion in a general peritidal context. They are contemporary with shell accumulations in the nearby archaeological sites. On the right, the figure shows the correlation between our data and the general trend of sea level fluctuations as synthesised by Pirrazoli (1991) in the Persian Gulf

6000 B.P. at Suwayh thus suggests that the Omano-Makranian floristic influence did not expand south-westward to the core site and that winter rains were therefore considerably less than today.

The Afromontane association is composed of numerous taxa partly absent from the modern flora of Oman. They could have been transported over long distances by the South-Western Indian monsoon fluxes since their source plants are nowadays common in the highlands of Ethiopia (*Myrica*, *Podocarpus*, Ericaceae) (White 1983) or Yemen (Ericaceae, *Myrica*) (Hepper and Wood 1979). Their expansion in the mountains of Oman at that time might also be indicated.

The replacement of the mangrove by a brackish or fresh-water lagoon at Suwayh after 5000 yr B.P.

The upper levels of Drill 1 provide evidence for different, more unstable, local conditions in a semi-desert regional environment closer to the modern one. The sedimentary sequence shows successive periods of saline water penetration, as indicated by the presence of *Amiantis* shells at 70 cm and 40 cm, dated respectively from 5211-4992 B.P. and 4530-4390 B.P. *Amiantis* is nowadays found in brackish lagoons with salinity from 38‰ to 44‰ such as Khawr al-Jaramah, where mangroves occur as relict populations. Pollen grains are unfortunately not preserved in these levels, suggesting a period of successive drought and rainfall. Environmental conditions remained unstable up to the present day as is illustrated by a reworked layer dominated by marine species of foraminifera together with *Pinus* and *Podocarpus* pollen grains around 20 cm, possibly related to a storm event. The regional conditions were close to those of today with *Acacia-Prosopis* thorn woodlands of semi-desert type. The local hydrological conditions closely corresponded to those of Kwar Bani Bu Ali (sample O98-09) with seasonal flooding of fresh-water allowing the *Ruppia* population to extend. *Avicennia* definitively disappeared from Suwayh recently, since it is recorded up to 15.5 cm.

Sea-level variations

Incursion of marine water and mangrove development 3 km from the modern shoreline in the Suwayh depression ca. 6000 yr B.P. is coeval with a slight transgression in the Gulf as recorded by evidence from numerous authors (in Pirazzoli 1991) (Fig. 4). According to these and other studies the altitudinal position of the corresponding shoreline differed from 2 to 3 metres below the present level (Lambeck 1996) to 1 to 2 metres above (Dalongeville and Sanlaville 1987; Sanlaville and Paskoff 1986). In our study, the corresponding levels are located from 1.6 m to almost 3.5 m lower than the modern surface which is situated at roughly 16 m in altitude. This observation suggests that vertical movements could have affected the eastern Arabian Peninsula during the late Quaternary (Vita-Finzi 1986) up to recent times. More data are needed to measure these precisely, particularly along the coasts of the Indian Ocean and the Gulf of Oman. This event has been followed by two marine incursions of shorter duration at ca. 5101 and 4460 B.P. as indicated by the presence of *Amiantis* shells and marine foraminifera in the sediments. After this date only storm events could have periodically allowed marine water to penetrate inland.

Human exploitation of the palaeo-mangrove

Shell and fish remains are numerous in the archaeological sites from Eastern Oman confirming the continuous importance of lagoon and marine food sources for Neolithic populations. The earliest evidence of shells from the mangrove ecosystem dates from the middle Holocene. Typical mangrove species of gastropods *Terebralia palustris, Isognomon ephippium* and *Telescopium telescopium* (Plaziat 1995), associated with the more ubiquitous species of oyster, *Saccostrea cuccullata*, locally attached to *Avicennia* roots, have been found in many archaeological sites from the coast of the Gulf of Oman and the Indian Ocean (Glover 1998). Near Suwayh at SWY-11, *Terebralia palustris* shells, broken to extract the flesh of the mollusc for eating, have been found in levels dated from the archaeological assemblage to the 5th millenium B.C. (Charpentier et al. 2000). *Isognomon ephippium* and *Saccostrea cuccullata* were also present, but in smaller quantities. Shells of *Saccostrea* have been dated from 5304-5227 B.C. and 4248-4144 B.C. at SWY-2 and 11, respectively (Table 1). In the more recent habitats from SWY-2 and 3, such mangrove species disappeared and shells of *Amiantis* became dominant. They have been dated from 3940 to 1980 B.C. These shells probably come from the nearby Suwayh lagoon since the ^{14}C measurements correspond in both the sedimentary sequence and the archaeological sites (Fig. 4). This confirms that the food resources of Neolithic populations in the Suwayh area were closely dependent on local environmental conditions. However, the presence of a particular species on a site may not be a direct reflection of its abundance in the environment, as consumption choices were made by all groups of late prehistoric foragers. Moreover, the results of a limited excavation cannot easily be extended to a whole archaeological site. Accepting these caveats, it can safely be concluded that the presence of tropical mangroves and their resources provided ideal conditions for food procurement for local populations and allowed human settlement to expand throughout the area.

Conclusion

Changes in regional climate and vegetation

A tropical climate prevailed around 6000 yr B.P. when the mangrove developed at Suwayh. As a result the present day boundary between summer and winter rains (Fig. 1a) was probably shifted by approximately 3° towards the north and reached 22° along the Indian Ocean coast. The change from a summer rain dominant (tropical) to a winter rain dominant climate, similar to that of the present day, occurred after 5000 B.P., the vegetation landscape in the Ja'alan region being similar to the modern one after 4460 B.P. Our data agree well with previous studies which suggest that the climate became dry after 4500 B.P. in the north tropical areas, notably in the Arabian sea region (Van Campo 1983; Sirocko et al. 1993). However, it was not possible, because of the truncated and probably discontinuous nature of the sedimentary sequence of Suwayh, to identify any abrupt aridification event such as that documented in core M5-422 from the Gulf of Oman between 4025 B.P. and 3625 B.P. It has been suggested that this event was responsible for the collapse of the Akkadian empire (Cullen et al. 2000), which at its maximum size extended from the headwaters of the Tigris-Euphrates rivers to the Persian Gulf near to the present study site. The only abrupt catastrophic event recorded later is a probable storm event recorded around 10 cm - 20 cm in Drill 1 and unfortunately not dated; the event could have been very local. New sedimentological and geomorphological data from the nearby "Wahiba Sands" in Oman have shown that the only arid event during the late Holocene responsible for increased dune activity occurred later than 2000 yr B.P. (Radies et al. 2001).

Changes in littoral environment linked to sea level movements

The marine influence strongly diminished after 5600 B.P. as a brackish lagoon, such as that nowadays located to the north at Khwar al-Jaramah on the Oman sea shore, developed at Suwayh. Two intervals of marine incursion, probably linked to slight marine transgressions (Pirazzoli 1991), are successively dated from 5101 B.P. and 4460 B.P.

Adaptation of human population

The evolution of human populations, as reconstructed by archaeology in eastern Arabia, can be matched with these climatic and environmental data. By the Middle Holocene, groups of foragers were moving seasonally through various ecological niches between the coastlands (in winter) and mountain valleys (in summer), occupying various campsites on the way. Plant gathering, combined with fishing and shell harvesting on the coast, plus hunting and herding in the interior formed the subsistence basis (Uerpmann et al. 2000). Most of the coastal sites found in

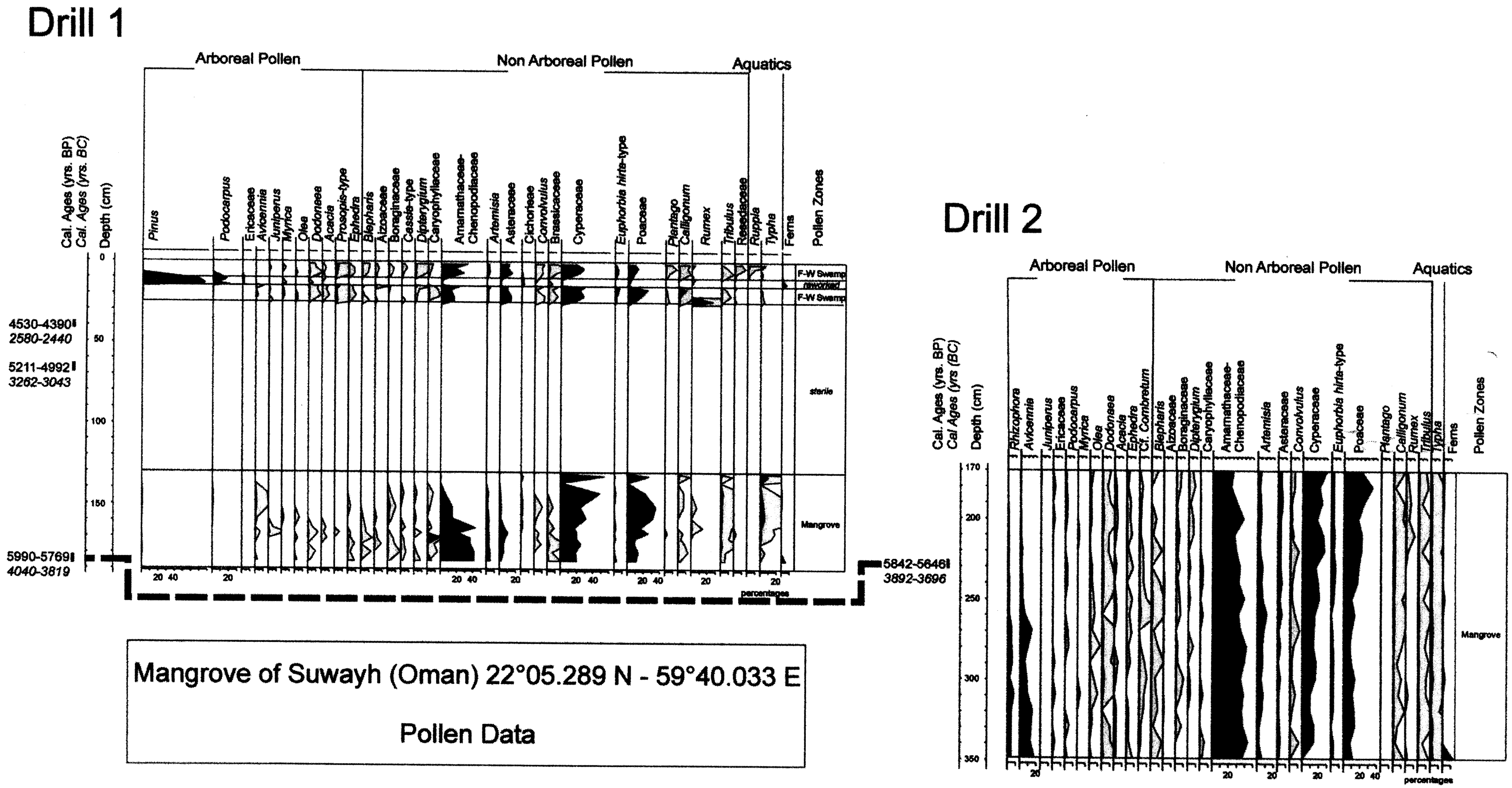

Fig. 5. Pollen diagrams from Suwayh Drill 1 and 2 showing the percentages of arboreal, non-arboreal and aquatic pollen and fern taxa against depth. Percentages are based on the sum of all the pollen grains and spores counted. The dashed line indicates correlation between the two sequences. Grey curves indicate exaggerated percentages (x10)

the Ja'alan (Fig. 1b) are likely to correspond to such a general pattern, which probably still applied during the Early Bronze Age, but they may have varied considerably through space and time with local conditions.

Archaeological surveys in the Ja'alan have taken place mainly along the present coastline and we can assume that the available data for these areas is representative of the past situation, but away from the coastline the region remains insufficiently known. 5th and 4th millennium B.C. campsites are abundant on the limestone terraces (KHB-1) and sand bars that separated the lagoons from the sea, concentrated particularly near the outlets such as SWY-1 and SWY-2, on both sides of the entrance of the Suwayh lagoon. Ongoing analyses of shells and fish bones suggest both the resources of sea and lagoons were exploited, with a probable trend towards the exploitation of larger fish, including pelagic species, during the 4th millennium B.C. Our knowledge is however biased by the absence of any detailed survey along the inner side of the lagoons. This is due to obvious difficulties in finding these vanished coastlines in the landscape; various changes, such as sedimentary accumulation, may have hidden any early sites in these areas, preventing any reconstruction of local complexity and complementarity of settlement patterns around the lagoons. Large mangroves and more favourable vegetation and climatic conditions may have allowed more permanent forms of settlement during the 5th millennium B.C. but the implications of this conclusion remain to be tested. A few bones of domestic caprines found on the sites also suggest that herding took place in the interior, and the inferred denser vegetation cover may account for the presence of "tethering stones" on the nowadays barren gravel surfaces of the sedimentary terraces. These stones can be associated with hunting or early forms of domestication (Cremaschi et al. in prep).

Rich archaeological data indicate that the second part of the 4th millennium B.C. in Oman was a period of intensive economical and social transformations (Cleuziou 2001). Copper exploitation was introduced from southeastern Iran together with various other pyrotechnologies, while the first oasis system based on palm tree cultivation and linked to the development of irrigation systems appeared slightly before 3000 B.C. These transformations are well dated and definitely occur after the climatic change documented above, a clear demonstration that social evolution cannot be linked to environmental changes in a simplistic way although it obviously cannot be disconnected. Intensification of food production in man-made environments (oases) and of regional exchanges is to some extent a response to the deterioration of environmental conditions (Cleuziou 1998).

The population in the area increased and territories became marked by cemeteries of tower-like collective burials on the crests overlooking the oases, the grasslands, the freshwater ponds and the fishing grounds. Some of these, according to excavations at cemeteries RJ-6 and HD-7, could have contained over two dozen individuals. Some 2500 burials in such situations are known from the Ja'alan, indicating a population of the whole ecological zone by groups that may have, at times, been relatively important. The only site excavated for this period is HD-6, located between a small lagoon and the sea. Its inhabitants intensely exploited large sea fish including pelagic species. Archaeology indicates that these were not only eaten immediately but were also processed by drying, smoking or salting for later consumption and exportation to the interior. Green turtles (*Chelonia mydas*) and dolphins were also slaughtered, notably for their fat. The village may have housed one or two hundred individuals, whose ancestors were buried in some twenty-five graves on the overlooking cliff, covering a period of at least three centuries between 3000 and 2600 B.C. Particularly interesting in our perspective is the presence of large cemeteries at DHF-25 (over 250 monuments) and RWY-9 (over 150 monuments) along the inner shore of a large dried lagoon, that would correspond to the marine incursion documented at 4460 B.P., or the 260 monuments grouped in five cemeteries on the hills dominating the southern shore of the Khor al-Jaramah. This may indicate the existence of rather large sites nearby, exploiting the resources of the lagoons rather than those of the open sea, although coastal sites such as HD-6 or RJ-1 and associated cemeteries along the rocky sections of the coast at Ra's al-Jinz or Shiya, indicate that rocky shores were also exploited.

The last three centuries of the 3rd millennium B.C. are the period when the Early Bronze Age cultures of Oman reached their greatest achievements, and it can be assumed that changes like the documented drying-up of the lagoons had no direct impact on the system, except at local level. Extraction of food from the marine environments concentrated on the coast itself, as evidenced from sites like RJ-2 and SWY-3, where the available technologies and abundance of fish could sustain the demand, both for local subsistence and exportation. Later periods are poorly documented, both in the archaeological and environmental record, and any matching of the little data at hand would be pure speculation.

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