Book Section:

Rambeau, Claire, Finlayson, Bill, Smith, Sam et al. (2011) Palaeoenvironmental reconstruction at Beidha, Southern Jordan (ca. 18,000-8,500 BP): Implications for human occupation during the Natufian and Pre-Pottery Neolithic. In: Mithen, Steven and Black, Emily, (eds.) Water, Life & Civilisation. International Hydrology Series. Cambridge University Press, Cambridge, pp. 245-268.

16 Palaeoenvironmental reconstruction at Beidha, southern Jordan (*c*. 18,000–8,500 BP): Implications for human occupation during the Natufian and Pre-Pottery Neolithic

Claire Rambeau, Bill Finlayson, Sam Smith, Stuart Black, Robyn Inglis and Stuart Robinson

ABSTRACT

The Beidha archaeological site in Southern Jordan was occupied during the Natufian (two discrete occupation phases, *c*. 15,200–14,200 cal. BP and *c*. 13,600–13,200 cal. years BP) and Pre-Pottery B Neolithic periods (*c*. 10,300–8,600 cal. years BP). This chapter reconstructs the palaeoenvironments at Beidha during these periods, using sedimentological observations and the stable isotopic composition (oxygen and carbon) of carbonate deposits. Age control is provided by uranium-series and radiocarbon dating. Detailed analysis of a carbonate stratigraphic section related to a fossil spring close to the site, and a sequence of carbonate nodules from a section on the western edge of the archaeological site, permits a reconstruction of climatic variations between *c*. 18,000 and *c*. 8,500 years BP. The results of the palaeoenvironmental study are compared with the archaeological evidence, to explore the relationship between human occupation and climatic variability at Beidha. The results indicate a marked correspondence between more favourable (wetter) environmental conditions and phases of occupation at Beidha, and provide clues to the likely sources of water that sustained the settlement during the Late Pleistocene and early Holocene.

16.1 INTRODUCTION

Climate change during the Late Pleistocene–early Holocene is often seen as a key factor in the transition to sedentism and stable, agricultural societies in the Middle East, given the background of major events such as the start of the Younger Dryas and the Holocene (e.g. Moore and Hillman, 1992; Mithen, 2003; Cordova, 2007, see also Feynman and Ruzmaikin, 2007). Even more abrupt climatic events, such as the '8.2 ka BP cooling event', recognised in various parts of the globe, may also have had an influence on Levantine societies (e.g. Staubwasser and Weiss, 2006; Weninger *et al*., 2006; Berger and Guilaine, 2009).

The regional and local impacts of past climatic events on societies remain largely unknown, and detailed studies are required to compare palaeoenvironmental data and archaeological information. The southern Levant is a key area for this type of investigation because of its transitional character between arid zones to the south and east and more favourable, wetter climates to the north and west (e.g. EXACT (Executive Action Team Middle East Water Data Banks Project), 1998; Cordova, 2007). The various regions of the southern Levant receive contrasting amounts of mean annual rainfall (Figure 16.1). Inter-annual variations in rainfall also increase with decreasing annual precipitation (e.g. Sanlaville, 1996). The eastern and southern parts of the Levant experience low annual precipitation rates that are highly variable from year to year. This is produced by a dominant source of moisture from the Mediterranean (e.g. Enzel *et al*., 2008), combined with extreme topographic gradients, and results in the juxtaposition of different bioclimatic zones within a limited geographical area (Zohary, 1962; Al-Eisawi, 1985, 1996; EXACT, 1998).

It is likely that past populations living on the fringe of arid areas were especially susceptible to the impact of climate change, since such locations are more vulnerable to environmental variations (e.g. Neumann *et al*., 2007). As such, the southern Levant provides a particularly good case study for exploring the relationship between the transition to settled farming societies and climate change, especially in marginal areas. In this chapter we present a study centred on the Beidha

Water, Life and Civilisation: Climate, Environment and Society in the Jordan Valley, ed. Steven Mithen and Emily Black. Published by Cambridge University Press.

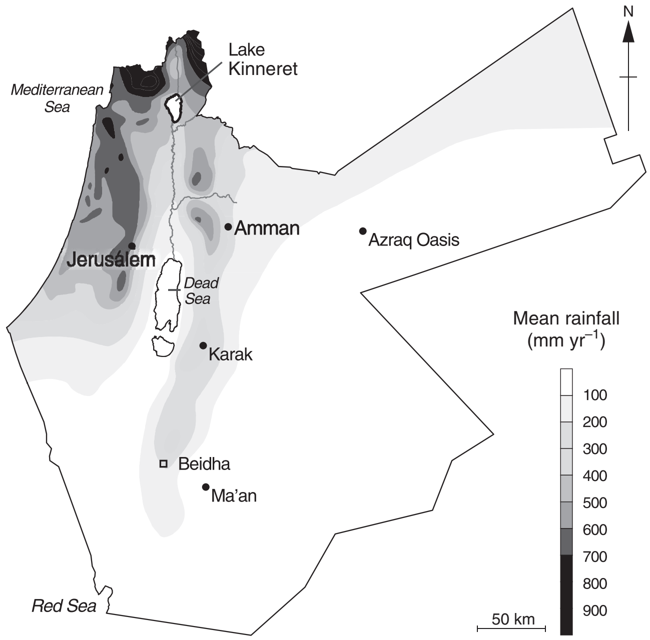

Figure 16.1. Map of the southern Levant showing average annual rainfall (modified from EXACT, 1998) and the location of the study area.

archaeological site, located in the arid zone of southeast Jordan (Figure 16.1), which compares localised changes in the environment across the Late Pleistocene/early Holocene transition with the known history of occupation.

Beidha is an important prehistoric archaeological site situated *c*. 4.5 km north of the well-known Nabataean city of Petra, with occupation phases during the Natufian (Levantine term corresponding to the later Epipalaeolithic) and the Pre-Pottery Neolithic B (PPNB) (e.g. Byrd, 1989, 2005). At the time of its discovery by Diana Kirkbride in 1956, the site appeared as a low tell, created by Neolithic deposits on a remnant alluvial terrace, and was covered by Nabataean(/Roman) agricultural terraces (Kirkbride, 1989). When Kirkbride began excavations at Beidha in 1958, very little was known about the early Neolithic of the Near East. One of Kirkbride's major objectives was to 'spread sideways rather than to dig deeply' (Kirkbride, 1960, p. 137). This modern approach of open area excavation is one of the reasons her excavation remains so important because a relatively large area of the settlement was uncovered. Her other chief objective was to reconstruct the Neolithic economy, looking at the 'practice of agriculture and the domestication of animals' (Kirkbride, 1960, p. 137). This of course remains an important research issue. The project ran under Kirkbride's direction with field seasons (and publication of interim reports) almost every year between 1958 and 1967, with a final season in 1983. She was joined in that year by Brian Byrd, who subsequently took on the role of bringing the project to publication (Byrd, 1989, 2005). Beidha is now one of many PPNB sites excavated in the southern Levant, but Kirkbride's fieldwork has made the site one of the best-known early villages in the world (Byrd, 1989). The site remains a key location for our understanding of Neolithic origins and development.

Previous studies at Beidha have tentatively reconstructed Late Pleistocene–Holocene palaeoenvironmental changes and correlated these with periods of human occupation (Raikes, 1966; Field, 1989; Comer, 2003; see also Helbaek, 1966 and Fish, 1989, and section 16.4 below). Such studies were, however, reliant on limited sources and quantities of information about the palaeoenvironmental evolution and had to contend with limited knowledge about the chronology of settlement.

Our new study uses a combination of geomorphological and sedimentological observations and stable isotopic (C, O) analysis of spring-carbonates (tufas) and pedogenic nodules collected around the site, to examine past environments at Beidha during the Late Pleistocene to early Holocene (*c*. 18,000–8,000 BP). Age control is provided by uranium-series dating of carbonate deposits and radiocarbon dating of organic remains. The new data are compared to, and integrated with, previous studies from Beidha and elsewhere in the southern Levant in order to provide a multi-proxy reconstruction of past environments that can be compared with changes in the archaeological record over the same period.

16.2 PRESENT-DAY ENVIRONMENTAL SETTING

Beidha is situated at *c*. 1,020 m above mean sea level (amsl) and *c*. 4.5 km north of the Nabataean city of Petra, within the alluvial valley created by the Wadi el-Ghurab ('Valley of the Ravens'; also spelled Wadi Ghuraib, Wadi Gharab, Wadi Ghrab; e.g. Byrd, 1989, 2005; Helbaek, 1966; Kirkbride, 1966; Kirkbride, 1968). The valley is bordered by steep cliffs of Cambrian/Ordovician sandstone (Figure 16.2) and is dissected by a modern wadi bed currently dry except during major rain (flash-flood) events (Comer, 2003). The valley drains the Jebel Shara (also spelled Jebel Shara' or Gebl Sharah; Mount Seir of the Bible), an upland area of Cretaceous limestone, situated a few kilometres to the east of Beidha, with altitudes up to 1,700 m amsl (Byrd, 1989; Comer, 2003). The Wadi el-Ghurab, generally flowing northeast to southwest, reaches the Wadi Araba (Kirkbride, 1985; Byrd, 1989, 2005) after a drop of over 400 m less than 2 km downstream of the site (Kirkbride, 1985).

Generally, the sandstone area in which Beidha and Petra lie forms a shelf interrupting the east-to-west abrupt altitudinal descent from the high Jordanian plateau (including Jebel Shara) to the low, desertic lands of the Wadi Araba. The N–S orientated sandstone shelf is about 4 km wide at Petra and 6 km wide at Beidha (Kirkbride, 1985; Byrd, 1989). Beidha is therefore situated in the midst of an area of abrupt variations in elevation and geology that determine a variety of natural plant (and animal)

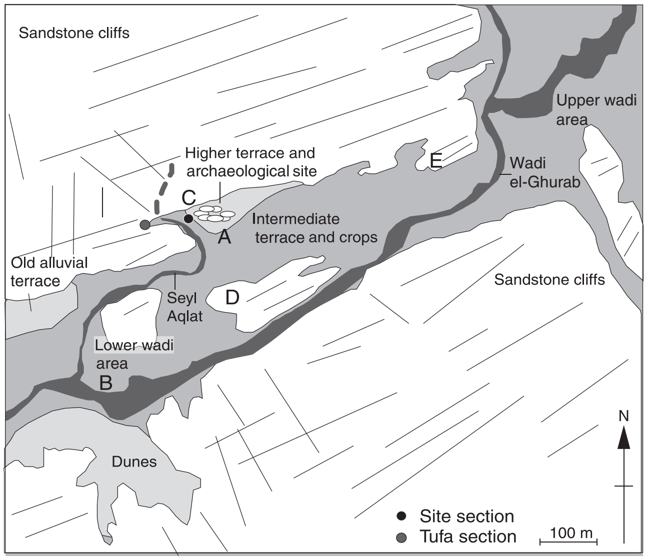

Figure 16.2. Schematic map showing the surroundings of the archaeological site of Beidha. The letters A to E refer to the locations from which the panoramic pictures presented in Figure 16.3 were taken.

communities: from the forested, Mediterranean highlands of Jebel Shara (Zohary, 1962; Helbaek, 1966), to the steppic zone of the sandstone and alluvial valleys where Beidha itself is situated, and ultimately to the desert settings of the Wadi Araba (Byrd, 1989). This particular situation is believed to have played a major role in the initial human occupation of the site, as it would have provided for a variety of edible plants and herd animals, distributed along an altitudinal gradient within a reduced catchment area (Byrd, 1989).

The alluvial valley harbouring Beidha is aligned on a roughly east–west axis (Figure 16.2). The site itself is situated on the northern side, on an elevated area interpreted to be an ancient alluvial terrace (the 'upper terrace' of Raikes, 1966; Field, 1989). Above the surface of this terrace the Neolithic village has created a low tell (Kirkbride, 1989; Byrd, 1989). An intermediate valley base is located south of the site, with elevations dropping gently from the upper to this lower alluvial terrace, where the cultivable soils are located (Raikes, 1966; Byrd, 2005). At present the Wadi el-Ghurab dissects these lower alluvial deposits and runs alongside the sandstone cliffs on the southern side of the valley (Figure 16.2).

A seasonal channel, the Seyl Aqlat, additionally drains the sandstone cliffs just northwest of the site (e.g. Kirkbride, 1960, 1989) before joining the Wadi el-Ghurab. The Seyl Aqlat cuts over 18 m through the high bank upon which the archaeological site is located and appears to have dissected or removed the western part of the site (Figure 16.3), probably after its abandonment in *c.* 8,500 BP (Kirkbride, 1968; Kirkbride, 1985; Byrd, 1989; Kirkbride, 1989; Field, 1989). Two large sand dunes have developed against sandstone cliffs in the southwest of the valley (Figures 16.2 and 16.3).

Springs are nowadays scarce in the area near Beidha (Kirkbride, 1966) and occur notably at the geological transition between the limestone and sandstone formations. About four kilometres east of Petra is the strong spring of 'Ain Musa (the biblical spring of Moses; Byrd, 1989). With the exception of the 'Ain Musa spring, none of the springs described in the Beidha area are particularly powerful nowadays (Kirkbride, 1966). The nearest water source to the site today is the spring of Dibadiba (or Dibadibah), situated *c.* 3 km east of the Beidha settlement on the slope towards the Cretaceous limestone uplands, at an elevation of 1,320 m amsl and near the contact between the limestone and the Cambrian/Ordovician sandstone (Kirkbride, 1966, 1968; Byrd, 1989). Kirkbride (1968) (see also Raikes, 1966) had assumed this to be the nearest perennial source of water during the Neolithic occupation, although she mentioned the possibility of rock pools and catchment areas near the village to provide for additional, intermittent water sources.

Mean annual rainfall in the area varies greatly between the Jebel Shara (*c.* 300 mm year^{-1}) and the Wadi Araba (less than 50 mm year^{-1}). It is *c.* 170 mm year^{-1} at Wadi Musa and has been estimated to average 170–200 mm year^{-1} at Beidha (Raikes, 1966; Byrd, 1989; see also Banning and Kohler-Rollefson, 1992). In the region, rainfall occurs principally in winter, with a dry summer (e.g. Henry, 1997; EXACT, 1998). Raikes (1966) further indicates the extreme range of variation in mean annual rainfalls over a 20-year period at Wadi Musa (1940–1960 period, −60% to +82% around the mean value of 170 mm year^{-1}). Predominant winds are from the west (Banning and Kohler-Rollefson, 1992).

Present-day vegetation at Beidha belongs to the steppe category (Helbaek, 1966; Gebel and Starck, 1985), but may have been strongly affected by human-induced environmental degradation during the past 9,000 years (Byrd, 1989). On the sandstone shelf, the alluvial valleys themselves contain no trees, although better-watered niches within the sandstone massifs harbour tree species such as oaks and junipers. The soil of the valley is composed of a mix of calcareous alluvium from Jebel Shara and wind-blown particles from the sandstone cliffs and Wadi Araba, and is considered as highly permeable and unable to retain winter rain for long (Helback, 1966). Dry farming in settings similar to that of Beidha is usually associated with a minimum of 200 mm average annual rainfall (Raikes, 1966), and Helback (1966) notes that nowadays 'only hollow patches with a comparatively high groundwater table can bear a crop and then only in years of a favourably distributed winter rain and snow'. Comer (2003) indicates that water is now brought to the Beidha area and used to replenish Nabataean cisterns. However, this water is not used for irrigation. Instead, it provides drinking water for goats, and cooking and washing water for the Bedouin families. Agriculture at Beidha is therefore still dependent, as it was *c.* 40 years ago, on sufficient and well-distributed rainfall. On a good year, herds of goats owned by the Bedouin tribes will be allowed to eat stubble after the harvesting; the entire plants will be consumed by the animals if the absence of rainfall at the appropriate moment induces crop failure.

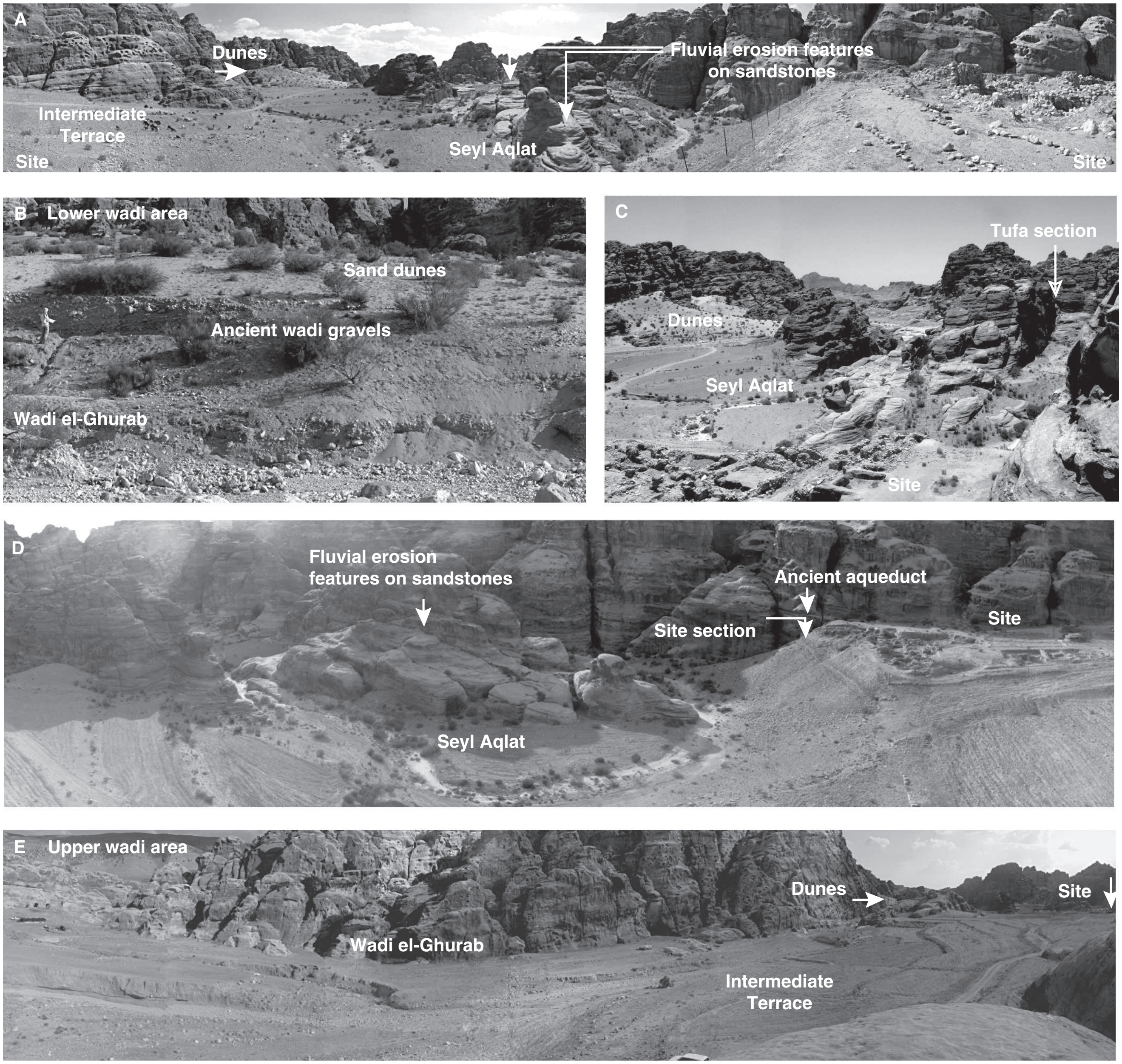

Figure 16.3. (A) Panoramic view from the site, looking southwest. (B) View of ancient gravel terraces, looking south-southwest. Robyn Inglis for scale. (C) View from the site on the tufa section and the dunes, looking southwest. (D) View from a sandstone outcrop on the site and the Seyl Aqlat, looking north-northwest. (E) View from a sandstone outcrop on the alluvial plain and the present-day bed of the Wadi el-Ghurab. Looking southeast. Picture credits: C. Rambeau and R. Inglis, May 2006.

16.3 HUMAN OCCUPATION AT BEIDHA: CHRONOLOGICAL FRAMEWORK

The site of Beidha appears to have been occupied by an Early Natufian camp, with some later Natufian occupation after a short break (Byrd, 1989). There was then a long period of abandonment before its reoccupation in the Pre-Pottery Neolithic (Byrd, 2005).

Complementary to archaeological observations, such as the nature of the lithic assemblage and architectural types, the absolute chronology of occupation at Beidha (Figure 16.4; Table 16.1) has been previously determined by radiocarbon dating techniques (Byrd, 1989; Byrd, 2005). All dates are presented here as calendar years before present (cal. BP) re-calibrated from the original radiocarbon dates using the Oxcal 4.0 programme online (IntCal 04, 95.4%).

Table 16.1 *All radiocarbon dates from Beidha*

In bold: this study (three dates). All other dates from Byrd (1989, 2005a), recalibrated. Calibration was carried out using the Oxcal 4.0 programme online (IntCal 04, 95.4%).

Period	Deposit	Lab. reference	Date uncal. BP	±	Date cal. BP	±
Natufian (1)		AA-1463	12,910	250	15,155	861
Natufian (1)		AA-1465	12,450	170	14,549	540
Natufian (1)		AA-1464	12,130	190	14,225	605
Natufian (2)	**site section**	**beta 235214**	**11,820**	**70**	**13,645**	**176**
Natufian (2)	**site section**	**beta 235215**	**11,260**	**60**	**13,156**	**120**
Natufian (2)		AA-1462	10,910	520	12,584	1315
Neolithic	**site section**	**beta 235216**	**9,110**	**50**	**10,302**	**108**
Neolithic	L4:11	P-1380	9,128	103	10,262	321
Neolithic	F4:300	GrN-5062	9,030	50	10,104	166
Neolithic	L4:13	K-1086	8,940	160	9,984	428
Neolithic	F4:300	P-1382	8,892	115	9,925	315
Neolithic	L4:11	GrN-5136	8,810	50	9,913	242
Neolithic	E2/P:24	BM-111	8,790	200	9,911	469
Neolithic	J4:16	AA-13036	8,830	70	9,907	272
Neolithic	K3:16	K-1410	8,850	150	9,892	344
Neolithic	K3:17	K-1411	8,770	150	9,866	336
Neolithic	L4:13	P-1381	8,765	102	9,851	304
Neolithic	J13:41	AA-13038	8,765	80	9,850	300
Neolithic	E1:30	K-1082	8,710	130	9,842	323
Neolithic	E2/P:24	K-1084	8,730	160	9,842	356
Neolithic	E1:30	P-1378	8,715	100	9,841	310
Neolithic	K3:17	K-1412	8,720	150	9,838	344
Neolithic	L4:11	K-1083	8,640	160	9,752	432
Neolithic	L4:51	AA-14109	8,646	69	9,694	194
Neolithic	F4:300	K-1085	8,550	160	9,643	507
Neolithic	E1:30	GrN-5063	8,640	50	9,630	103
Neolithic	E1:30	P-1379	8,546	100	9,593	293
Neolithic		AA-1461	8,390	390	9,398	978
Neolithic	J13:30	AA-13037	7,720	130	8,649	333
Neolithic	J4:16	AA-13035	6,535	70	7,443	127

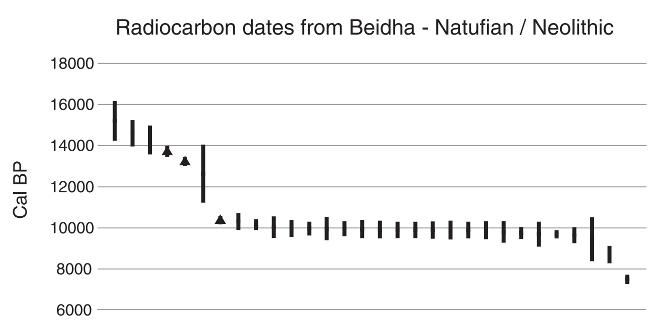

Figure 16.4. Chronological framework at Beidha. Dates marked by triangles: this study. Black lines: data from Byrd (1989, 2005), recalibrated. Ages calculated using Oxcal 4.0 (Int Cal 04, 95.4%).

16.3.1 The Natufian period

Natufian (e.g. Byrd, 1989; Bar-Yosef, 1998; Byrd, 2005; Boyd, 2006) populations have been described as semi-sedentary complex hunter-gatherer groups, exploiting natural resources such as wild cereals and the products of hunting. While there are a small number of apparently long-term Natufian settlements that indicate an increase in sedentary behaviour, many sites still appear to fall into the classic hunter-gatherer range of base camps with smaller, shorter-lived special purpose camps (Olszewski, 1991). It appears that the increase in sedentism and complexity mostly occurred during the Early Natufian, whereas during the Late Natufian there was an increase in mobility and a reduction in group size. This is often thought to reflect the harsher environmental conditions of the Younger Dryas (e.g. Mithen, 2003).

At Beidha, soundings below the Neolithic village and trenches revealed the presence of Natufian deposits in six areas of the site. During the earlier seasons (1958–1967; Byrd, 1989) a continuous sequence of about 0.4–0.6 m thickness was recorded, and subdivided into three depositional phases. In 1983, a trench was

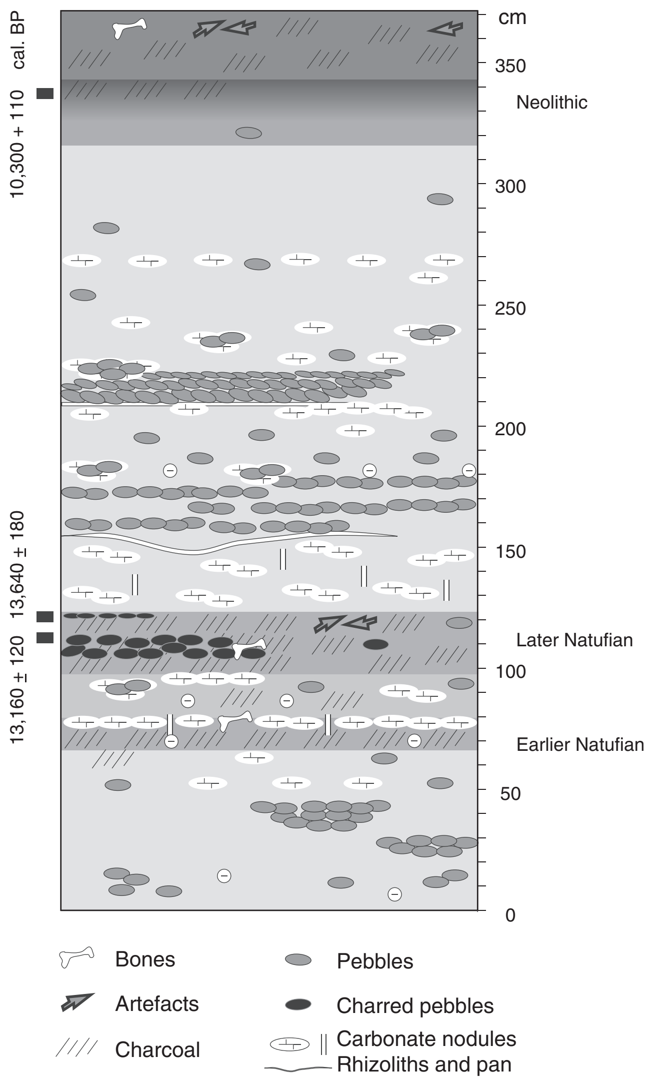

Figure 16.5. Schematic succession of sedimentary layers at the site section, as illustrated in Figures 16.2 and 16.3, and location of the levels from which new radiocarbon dates have been obtained.

opened on the northwestern (eroded) slope of the site (Figure 16.3A and D). There, two discrete horizons of Natufian occupation were discovered (*c*. 0.15 m and 0.4 m thick) separated by a sterile layer (0.4 m of paler sand with diffused charcoal and carbonate nodules but no artefacts or bones; Figure 16.5). The lower, thinner occupation layer contains a lithic assemblage comparable to the Natufian deposits discovered in the other excavation areas, whereas the upper layer had an extremely low density of artefacts with a different character. Five dates were obtained from this trench (Byrd, 1989). The oldest occupation horizon was dated between 15,155 ± 861 cal. BP and 14,225 ± 605 cal. BP (three dates; Figure 16.4; Table 16.1), placing this layer within the Early Natufian. The younger Natufian horizon yielded two dates, one of which (12,584 ± 1,315 cal. BP) definitely corresponds to the later Natufian settlement: the other (9,398 ± 978 cal. BP) has been considered as intrusive from the Neolithic (sample AA-1461; Figure 16.4; Table 16.1). Byrd (1989) therefore placed the later Natufian occupation at Beidha at the juncture between the Early and Late Natufian. The date used to justify this is, however, associated with a significant error bar of ±1,315 years (Figure 16.4; Table 16.1).

The Early Natufian at Beidha has been described as composed of at least three phases of semi-permanent, complex hunter-gatherer settlement (Byrd, 1989). Evidence for hunting is abundant, whereas evidence for plant collecting and consumption is limited; no architectural features such as walls, storage facilities or burials were discovered. Byrd (1989) suggests that the Early Natufian occupation Beidha represents a short-term/seasonal campsite, with recurrent occupation during an extended time period. Byrd (1989) proposes that occupation occurred either during winter or mid-summer, at times when plant resources were less abundant and hunting may have represented a favoured procurement strategy.

The later Natufian period has only been recorded on the northern edge of the site and seems to correspond to more ephemeral occupation – maybe representing a short period of transient occupation. No definite human activity is then recorded for *c*. 3,500 years, but the presence of a small structure made of sandstone slabs – 'such as children at play might make', *c*. 20 cm below the start of PPNB occupation layers, hints at an occasional occupation of the site (Kirkbride, 1968).

16.3.2 Pre-Pottery Neolithic A (PPNA) – Early Pre-Pottery Neolithic B (EPPNB)

There has been considerable debate regarding the early Neolithic in the southern Levant, especially concerning the character of the transition from the PPNA to the PPNB. No structural phase clearly pre-dating the Middle PPNB (MPPNB) was reported from Beidha, but there is some evidence for earlier occupation. Byrd notes that some material from the site initially thought to be Natufian is Neolithic in character, and 'may well predate the Middle PPNB' (Byrd, 2005, p. 17). This was associated with a mudbrick structure, unlike the stone architecture associated with the MPPNB. There are further structural remains that pre-date the first well-known architectural phase (i.e., wall-less, outdoor courtyards deposits, extending to *c*. 20 cm below the first houses; Kirkbride, 1968). In addition El Khiam points (diagnostic of the PPNA) and Helwan points (diagnostic of EPPNB) were discovered during Kirkbride's excavation in the earliest layers (Mortensen, 1970). Byrd suggests that examination of the earliest Neolithic layers still requires further field investigation and sampling. Even the well-known first architectural phase (A, characterised by curvilinear architecture) conventionally associated with the MPPNB poses some questions as the style of architecture is typical of that associated with the EPPNB in the northern

Levant, for example at Jerf el-Ahmar (Stordeur *et al*., 1997). Furthermore, the earliest radiocarbon date for the Neolithic occupation from the excavations (Phase A) appears to lie on the boundary between the EPPNB and MPPNB (Figure 16.4; Table 16.1).

16.3.3 Pre-Pottery Neolithic B (PPNB)

In the Levant, the PPNB is a period of settlement expansion and development of animal herding strategies, following the beginning of plant cultivation that occurred during the PPNA. Large permanent settlements became established during the MPPNB in the Levantine region, Beidha being a classic example although others, such as 'Ain Ghazal, became substantially larger, especially in the Late PPNB (Rollefson and Köhler-Rollefson, 1989). It has been argued that around 8,500 BP, large PPNB settlements in the southern Levant abruptly collapsed, and were replaced by the smaller settlements of the PPNC, which marked a return towards nomadic pastoralism (Rollefson and Köhler-Rollefson, 1989).

There is no evidence to indicate abandonment and reoccupation at any point in the Neolithic occupation of the site (Byrd, 2005). Byrd argues that occupation was largely restricted to the MPPNB (*ibid*.) although the radiocarbon dates suggest a longer sequence from *c*. 10,300 and 8,600 cal. BP, with a recent review suggesting that the MPPNB ran from 10,100 to 9,250 cal. BP, with the Late PPNB dating to 9,250–8,700 cal. BP (Kujit and Goring-Morris, 2002). Kirkbride recorded a complicated stratigraphic sequence, which Byrd (2005) simplified into three major phases, reflecting both stratigraphic relationships and architectural styles. The earlier Phase A is characterised by semi-subterranean single-room round stone buildings built around wooden pole frames. In Phase B the walls become straighter with rounded corners and the buildings more subrectangular, but they are still single-room and generally semi-subterranean. In Phase C the buildings become rectangular, with ground (or possibly basement) floors divided into a series of cells by massive piers that probably supported upper floors. Beidha has always been seen as an archetypal model of the transition from round single-roomed to rectangular multi-roomed buildings that occurred during the Neolithic. This probably reflects a greater density of settlement occupation, increasing population, and more storage on a household level.

Barley was the main cereal recovered from the farming community of PPNB Beidha, but domestic emmer wheat has also been identified in the plant assemblage (Helback, 1966; Perkins Jr, 1966); wild plant species were also collected. There are strong indications for the domestication of goats, while hunting remained an important subsistence strategy (Perkins Jr, 1966).

Most of the published dates (22 out of 23) related to this period fall between 10,262 ± 321 cal. BP and 8,649 ± 333 cal. BP (Figure 16.4; Table 16.1). This implies an abandonment of the site shortly after the youngest date. One date has been, however, obtained at Beidha at 7,443 ± 127 cal. BP (Figure 16.4; Table 16.1). This is an outlier with no other supporting dates or cultural remains distinctive to this date, and hence its validity is questionable. It must be noted here, additionally, that Rollefson (1998, 2001) has argued that Beidha Phase C is PPNC (*c*. 8,800–8,200 cal. BP; Staubwasser and Weiss, 2006), mostly on the base of architectural arguments.

It is difficult to determine whether the abandonment of the village was a gradual or sudden event. Refuse dumping patterns within the uppermost layers of the Neolithic occupation seem to indicate a gradual abandonment of buildings and, more generally, of the site (Byrd, 2005), yet the destruction of part of the younger Neolithic deposits by Nabataean terracing renders the pattern of abandonment difficult to interpret. After the site's abandonment, the Seyl Aqlat cut through the western part of the site, probably removing a considerable area of both the Natufian and Neolithic occupation (e.g. Kirkbride, 1966; Kirkbride, 1985; Byrd, 1989; Field, 1989; Byrd, 2005). Although the extent of the erosion is impossible to determine, it has been estimated that up to half of the Neolithic village may have been destroyed (Field, 1989).

16.3.4 Nabataean and Roman time periods

There is no evidence for subsequent use of the valley until the Nabataean/Roman period. During the Nabataean, the Wadi el-Ghurab was terraced with a series of stone walls, marking fields that are still used today by local Bedouin communities for rain-fed cultivation. The Nabataeans also terraced the tell area more than 6,000 years after its abandonment, destroying part of the upper cultural layers in the process (Kirkbride, 1968; Byrd, 2005). There are badly weathered remains of rock-cut aqueducts, also presumed to date from this period, running around the sandstone outcrops of Seyl Aqlat. Numerous Nabataean cisterns, linked to an elaborate system of runoff water collection and storage, are present in the Beidha area (Helback, 1966; Comer, 2003) and are still used today as water storage facilities by the local Bedouin communities.

16.4 THE PALAEOENVIRONMENTAL CONTEXT

16.4.1 Environmental conditions in the southern Levant (*c*. 20,000–7,000 cal. BP)

The general background for this study is provided by a regional assessment of climate and palaeoenvironmental changes in the eastern Mediterranean, derived from various critical reviews of the available evidence (Chapter 6, this volume; see also Sanlaville, 1996; Henry, 1997; Sanlaville, 1997). It seems that the Last Glacial Maximum (LGM, *c*. 23,000 to 19,000 cal. BP) period in the Levant was characterised by cooler temperatures than present; there is still some debate about whether it was also a drier period. After a period of transition possibly marked by a short-term climatic event at *c*. 16,000 cal. BP (Heinrich Event 1), the Bølling–Allerød warm interval (*c*. 15,000 to 13,000 cal. BP) was a period of increased rainfall and higher temperatures in the eastern Mediterranean region, as evidenced by palynology, speleothems and marine sediments from the Red Sea. The Bølling–Allerød was directly followed by the Younger Dryas (*c*. 12,700 to 11,500 cal. BP), a cold and arid period of major importance in the North Atlantic region. It has been argued that this event had a major impact on Levantine climates and populations (e.g. Bar-Matthews *et al*., 1997, 1999, 2003; Mithen, 2003; Robinson *et al*., 2006; Cordova, 2007; Chapter 6 of this volume). The dominant view of an arid and cold Younger Dryas in the eastern Mediterranean, and its influence on human communities, are, however, disputed by several authors (Tchernov, 1997; Stein *et al*., 2010; Stein *et al*., in press). The warm and wet characteristics of the following early Holocene period (*c*. 9,500 to 7,000 cal. BP) are clearly shown in pollen records, isotopic records, fluvial deposits and soil sequences (Chapter 6, this volume). Around 8,200 cal. BP, cold and arid conditions seem to settle in the eastern Mediterranean (e.g. Staubwasser and Weiss, 2006; Weninger *et al*., 2006; Berger and Guilaine, 2009) although, considering the scarcity of data in the region, it is still unclear if this relates to an abrupt climatic event or is part of a more gradual trend towards climate deterioration starting globally at *c*. 8,600 cal. BP (Rohling and Palike, 2005).

Of all the proxies available for the reconstruction of palaeoclimates in the Levant during the periods of occupation at Beidha, speleothem isotopic records are possibly the most informative, as they offer a continuous and well-dated sequence. In particular, speleothems from the Soreq Cave (Bar-Matthews *et al*., 1996, 1997, 1999, 2000, 2003) have allowed for high-resolution records dated by ^{230}Th–^{234}U (TIMS) methods. The oxygen isotopes variations at Soreq clearly show variations that probably correspond to major climatic events such as the LGM, the Bølling–Allerød and the Younger Dryas (see also Chapter 6, this volume). Bar-Matthews *et al*. (2003) indicate a close variation between planktonic foraminiferal and speleothem δ^{18}O values during the past 250,000 years, which suggest a link between marine and terrestrial records. They therefore used sea surface temperature (SST) reconstructions as an approximation for land surface temperature variations. This information was employed to refine Bar-Matthews and colleagues' previous interpretations of the oxygen-isotopic record and calculate both the isotopic composition ($\delta^{18}O_{rain}$), and, for certain periods, the amount, of 'palaeo annual rainfall'. The calculated $\delta^{18}O_{rain}$ is more positive during the Younger Dryas, suggesting low rainfall and enhanced aridity. Prior to this period, and during the early Holocene (11,000–7,500 cal. years BP), wetter and warmer conditions are suggested by a more negative $\delta^{18}O_{rain}$ record. Recently, Affek *et al*. (2008) have used the 'clumped isotope' thermometry technique (which is based on the number of ^{13}C–^{18}O bonds within the carbonate lattice and can be utilised to calculate temperatures at the time of the carbonate growth) on Soreq speleothems. The temperatures calculated have been proved similar to those estimated for the eastern Mediterranean SST. The calculated temperatures are 6–7 °C colder than for the present-day during the LGM (20,000–19,000 cal. BP), whereas they are slightly higher than, or similar to, those of today for the early Holocene (10,000–7,000 cal. BP).

In climatic settings closer to those at Beidha, i.e. in the semi-arid and arid regions of the southern Levant, a series of proxies, including soil and fluvial deposits and pollen information from archaeological sites, indicate a similar history. In the Wadi Faynan area (western Jordan, *c*. 30 km north of Beidha), drier conditions are attested by aeolian deposits in the Wadi Dana around the LGM (McLaren *et al*., 2004). During the period *c*. 18,300–12,900 cal. BP, flora and fauna assemblages from archaeological sites in Eastern and Southern Jordan (Azraq, Judayid) and within the Jordan Valley (Wadi Fazaël) seem to indicate overall favourable climatic conditions (Sanlaville, 1996 and references therein; dates recalibrated), interrupted by a short, dry incursion (dated at *c*. 13,900 cal. BP at Judayid; Sanlaville, 1996). A short, moderately dry episode at *c*. 15,400–13,900 cal. BP following better climatic conditions is also recorded in pollen studies from Wadi Hisma (southern Jordan; Emery-Barbier, 1995; Henry, 1997; Sanlaville, 1996; dates recalibrated).

In the Negev, dune-dammed lakes that appeared during this phase of overall increased humidity (coeval with a phase of pedogenesis) were transformed into sebkhas at *c*. 12,900–11,500 cal. BP (Sanlaville, 1996 and references therein). The size and isotopic compositions of terrestrial gastropods in the Negev also hint at an arid episode during the interval *c*. 12,900–12,500 cal. BP (Magaritz and Heller, 1980; Sanlaville, 1996). The accumulation of drift sand on top of Early Natufian layers, at both Wadi Judayid and Beidha, has been interpreted as suggesting a dry episode (Henry, 1997).

During the early Holocene, the expansion of PPNB sites (in particular, Middle and Late PPNB sites) in settings that are now hyper-arid (Azraq Basin, the Black Desert in Eastern Jordan, Wadi Hisma) seem to correspond to a major pluvial episode (Henry, 1997 and references therein). In the Azraq basin, domestic-type einkorn and barley were exploited since the early PPNB (Jilat 7; Garrard *et al*., 1996; Henry, 1997) in locales receiving far less rainfall (i.e., about half) than necessary for rain-fed agriculture, and without spring-water supply. C3 grasses are present at the site of Ain Abu Nukhayla in Wadi Rum, *c*. 90 km south of Beidha, during the PPNB, whereas such plants are uncommon in the modern, steppic and desertic vegetation of the area (Portillo *et al*., 2009). A southward shift in the distribution of pure C3-plant communities is recorded by the $\delta^{13}C$ composition of fossil land snails in the northern Negev during the early Holocene (*c*. 11,000–6,800 cal. BP), indicating wetter conditions then than during the middle Holocene and today (Goodfriend, 1999). In Wadi Faynan, palynological, plant macrofossils and molluscs studies indicate a much more humid environment during the early Holocene than at present (Hunt *et al*., 2004). A rainfall value of about 200 mm (compared with the modern 120 mm; see Chapter 15, this volume) is proposed for the time period before 8,000 BP. Decreased rainfall and desiccation, coeval with variations in global temperature, is evidenced in Wadi Faynan at *c*. 8,000 BP, followed by a return to increased rainfall after 7,400 BP (the then absence of coeval forest regeneration may have been due to human inhibition). Meandering, perennial rivers are recorded at Wadi Faynan prior to 6,000 cal. BP (Hunt *et al*., 2004). The early Holocene optimum seems to be marked in the Jordan Valley by warm and humid conditions compatible with a geomorphological record of marshlands, wide flood plains and travertine deposition. The following phase begins with a marked climate instability with torrential flows and erosion, then stability under a cold and humid climate, before renewed erosion and the establishment of a semi-arid, Mediterranean climate in the Jordan Valley in the mid-Holocene (Hourani and Courty, 1997).

16.4.2 Previous environmental studies at Beidha

Most of the detailed studies about the environmental changes at Beidha were produced during the excavation seasons. In particular, Raikes (1966) and Field (1989) produced preliminary reports on the geomorphology and palaeoenvironments at Beidha. Fish (1989) presented a preliminary study of the pollen record. Observations made during the excavations by Kirkbride and her colleagues provide further information about the palaeoenvironment. Later studies around the Beidha area (Comer, 2003) also provide useful remarks and observations.

Geomorphologically, the archaeological site of Beidha is located on an ancient alluvial fill terrace bordered by sandstone cliffs on the northern edge of the valley. To the south, elevations slope gently to an intermediate terrace level (Figure 16.2). To the west, the steep descent (*c*. 18 m) towards the modern bed of the Seyl Aqlat results from the considerable erosion that this seasonal watercourse inflicted to the western part of the site (Byrd, 2005; Figure 16.3).

Overall, the sedimentation at the site can be summarised as follows: a sandy sediment is deposited prior to the first level of the Natufian occupation (on average 0.4–0.6 m throughout the site, *c*. 0.15 m on the western edge where the second Natufian level is recorded; Byrd, 1989), then *c*. 0.4 m of sterile sand overlies this cultural layer in the northwestern part of the site, then *c*. 0.4 m related to the second Natufian occupation. This is surmounted by over 1.5 m of sterile sand, on which the Neolithic village was constructed (Figure 16.5). The pollen assemblage, albeit patchy, with probable localised biases and difficult to interpret, indicates an open, steppe-like vegetation in both sterile and cultural horizons, with arboreal pollen always less than 20% (Fish, 1989).

16.4.3 Environmental conditions during the Earlier Natufian occupation

Raikes (1966) identifies two terrace systems around Beidha. The upper terrace bears the archaeological site, whereas the lower terrace (intermediate valley base) contains the ancient agricultural soils (Figure 16.2). The upper terrace, following Raikes' interpretation, would be the remnant of a valley fill created during an interpluvial phase, at a 'very remote period of long duration' (Raikes, 1966). Raikes identifies an erosional phase, postponing the creation of the upper terrace and responsible for the creation of the lower terrace. He attributes this phase to downward faulting activity in the rift, which would have resulted in lowered drainage datum and increased erosion. The lower terrace was then itself eroded during another episode of downfaulting. The upper and lower terraces, following Raikes' scenario, may have already been isolated during the Natufian.

Travertine deposits have been discovered at Bir Abu Roga, less than 1 km downstream of Beidha (Kirkbride, 1966; Raikes, 1966). Raikes postulates that the spring at Bir Abu Roga – situated at the level of the lower terrace – and/or other springs in the region may have represented the drinking water supply for the Natufian people of Beidha. He further suggests that this period may be characterised by higher rainfall, perhaps as much as 400 mm year^{-1} on average.

Field (1989) proposes a slightly different story. He studied a composite sedimentary section from two areas of the site and interprets the Natufian occupation to have occurred during a time of aggradation of the Wadi el-Ghurab. Sediments would have been accumulated by stream deposition. Interestingly, a lens of gravels, pebbles and sand related to wadi deposition, uncovered 3 m below the surface on the southeastern gentle slope of the tell, contains artefacts of probable Natufian origin; it has been suggested that they may originate from the erosion of Natufian layers further to the north or the west (Byrd, 1989). This deposit confirms wadi deposition at the same elevation as, and thus probably contemporaneous with, Early Natufian deposits on the western slope (*c*. 2.3 m under the Neolithic).

Field relates the creation of a higher valley floor, prior to the erosion event that isolated the terrace on which the site is located, to a period of greater sediment supply to the wadi system, such as may occur during a time of less intense (fewer storm events, and more regular but not necessarily greater) rainfall. Field therefore postulates that different rainfall patterns during the Natufian may have created a more favourable environment, with enhanced vegetation cover. It has been suggested that during the Early Natufian, vegetation cover was more developed in the alluvial valleys of the sandstone shelf, and that the Mediterranean forest of Jebel Shara extended further down its slopes (Byrd, 1989). Low contents of phosphorus, nitrogen and organic matter indicate limited human impact on the environment during Natufian times (compatible with low intensity occupation; Field, 1989).

Comer (2003), in his 'cultural site analysis' of Beidha and its surrounding, notes a close correspondence between the Natufian occupation and the Bølling–Allerød amelioration with increased temperature and humidity, and suggests (as well as for the Neolithic) increased runoff as a means to provide enhanced water supply to the valley.

16.4.4 The Later Natufian and the Natufian/Neolithic sterile interval

Raikes (1966) interprets the sterile layer between the Natufian and PPNB occupation layers, and probably the sterile layer covering the Neolithic as well, as being aeolian in origin, within which current-bedded forms were created by storm-related outwash from the sandstone cliff. In contrast, Field (1989) postulates that the sterile interval between the Natufian and the Neolithic was deposited by ephemeral streams, and not by aeolian deposition. He bases his argument on the fact that several fining-upward sequences, made of gravelly sands and capped up by siltier deposits and carbonate build-up, are observable in the sedimentological section: such sequences form in stream deposition settings, with a short period of non-deposition at the end of the sequence. There is a non-negligible gravel component, and cross-bedded sands are visible near the base of the sterile interval; all these indications point towards ephemeral stream deposition.

Fish (1989) studied pollen assemblages within the same areas investigated by Field (1989). She noticed higher frequencies of chenopod and amaranth pollen in three samples, one from the intermediate layer between the two Natufian occupations, and two from the base of the sterile horizon overlying the upper Natufian layer (highest frequencies). This may represent the local expression of a more widespread cool, dry interval during the Natufian in the southern Levant (Fish, 1989). Interestingly, Kirkbride (1968) mentions an erosion gully cutting through Early Natufian levels, which was first interpreted as being a human-made structure (Kirkbride, 1968). Byrd (1989) further mentions that this erosional gully may cut from the top of the Early Natufian deposit, or from a slightly higher level. At the base of the sterile interval, pollen also indicates permanently damp habitats in the vicinity.

At the top of the sterile interval, below the Neolithic occupation horizons, the pollen assemblage is quite different from the base – no increase in chenopod or amaranth is recorded, whereas relatively high grass values suggest a rather mesic steppe assemblage (Fish, 1989). Raikes (1966) notes equally that the top layer of the sterile sand between the Natufian and the PPNB bears marks of organic material, hinting at relatively important vegetation coverage at the site before the Neolithic settlement. Kirkbride (1968) similarly records shadows in the sand just underneath the Neolithic layers, suggestive of areas where a cover of shrubs has been removed prior to the village construction.

16.4.5 The Neolithic

According to Raikes (1966), at the time of the Neolithic occupation, the settlement was located on a high terrace remnant, adjacent to a wide valley floor composed of loamy sand, with a more intensive vegetation cover protecting it from erosion.

Field (1989) identifies an erosional phase, after the Natufian but prior to or coeval with Neolithic occupation, that isolated, among others along the Wadi el-Ghurab, the alluvial terrace on which the Neolithic village was constructed. This erosion phase may have been related to increased rainfall intensity and a flash-flood regime. Field suggests that such climatic conditions may have reigned during the PPNB occupation; the settlement, situated on a higher terrace, may have been protected from flash-flood events (Field, 1989). In this context, the presence of a village wall constructed during the earliest phase of the village (Phase A), with steps connecting the wall to an upper layer where the houses themselves were situated (Kirkbride, 1968; Byrd, 2005), seems to indicate that the terrace was already isolated at the start of the Neolithic occupation. Bar-Yosef (1986) suggested that this wall may have been a protection from floods, although Byrd (2005) notes that flooding may not have represented a considerable issue if the Wadi el Ghurab was following a course on the southern side of the valley during the PPNB as it does today.

According to Field (1989), no aggradation occurred during the Neolithic occupation itself, but thin cross-bedded sands, probably caused by stream deposition at minor tributaries coming from the sandstone cliffs bordering the site, are observable in a few places. The higher concentrations of phosphorus, nitrogen and organic matter during the PPNB are coherent with reduced sedimentation and increased human occupation.

No water harvesting or storage techniques were apparently in use during the Neolithic. In light of this, Helbaek (1966) proposed a palaeo-rainfall of 300–350 mm year^{-1} during the occupation, based on estimated requirements for the growth of wild wheat (wild species are considered to require substantially higher annual rainfall than the 200 mm limit usually associated with dry farming; Raikes, 1966). Raikes (1966) alternatively proposed that changes in the characteristics of soil cover, or a similar/slightly higher rainfall (but less intense and with a better distribution throughout the year, and accompanied by higher soil retention), would have made agriculture at PPNB Beidha possible without a major change in the climate conditions. Kirkbride (1968) reiterated this conclusion and declared that since the Neolithic village was first constructed there has probably been no major climate change; enhanced human activity (clearance, grazing and cultivation) and intensified erosion (maybe worsened by down-faulting of the drainage datum) are made responsible for gradual environmental degradation. Raikes (1966) and Kirkbride (1966, 1968) postulate that the tributary drainage of the Seyl Aqlat, responsible for the destruction of the western side of the site after its abandonment, was not in existence during the time of occupation or was just starting, and was therefore of minor influence to the settlement.

Raikes (1966) views the wadi system during the Neolithic as sub-perennial at best (mid-winter to early summer), even if the local rainfall had increased to 300 mm yearly average. He suggests that most of the drinking water during the Neolithic must come from the spring at Dibadiba. Permanent sources of water (springs or pools) during the Neolithic are, however, attested by the pollen record (*Typha/Sparganium*; Fish, 1989). Moreover, trench excavations near the sandstone cliff edge, *c*. 80 m east of the village, have uncovered possible travertine deposits just over a metre under the surface (Kirkbride, 1966, 1968; Byrd, 1989, 2005). The presence of a spring in the immediate vicinity of the settlement is interpreted as a factor that may have influenced settlement location (Byrd, 1989).

Comer (2003) notes a good correspondence between the time of Neolithic occupation at Beidha and the wetter and warmer conditions of the early Holocene Climatic Optimum, suggesting that water may have been present near the site owing to increased runoff. His study demonstrates that, considering the geographical position of Beidha, any runoff produced by sufficient rainfall would be channelled towards the site. Comer (2003) argues that the depletion of certain natural resources, as they were increasingly and more effectively exploited, triggered the abandonment of Beidha. He bases this proposal on the claim that Beidha was deserted well before a period of climate deterioration in terms of significant decreases in temperature and rainfall, which he places at roughly 7,000 BP.

16.5 MATERIAL AND METHODS

The area around Beidha offers numerous sedimentary outcrops and carbonate precipitations that can be used for palaeoenvironmental reconstruction. This study focused on two major sedimentary sections:

1. A sedimentary section containing a series of pedogenic nodules, located directly on the western side of the site (Figure 16.5);
2. A sequence of carbonate deposits, related to an ancient spring, outcropping near the site in a small canyon (Figure 16.6).

We also use observations resulting from a geomorphological survey conducted around Beidha in 2006, which aimed to identify major episodes of wadi aggradation/downcutting along with changes in the sedimentation patterns.

16.5.1 Sedimentary sections and sample preparation

A section of 372 cm, directly situated on the western side of the Beidha archaeological site, where it has been exposed by stream-cutting erosion, was cleaned and sampled for carbonate concretions, bulk sediment and charcoal. It is mainly composed of sandy deposits and comprises black/grey layers with charcoal, burnt pebbles and bones that were believed to correspond to Natufian and EPPNB occupation layers (Figure 16.5). A complementary section of 251 cm, situated inside the archaeological site and encompassing the rest of the PPNB occupation layers, was sampled for carbonate concretions and bulk sediment.

A 2-m-thick sequence of spring carbonates outcrops less than 100 m away from the site on the western side of the Seyl Aqlat (Figures 16.3 and 16.6). It consists of thin layers of sand-rich carbonates, with occasional reed imprints. Collected samples were mechanically cleaned, including the removal of all altered surfaces, then cut into *c*. 1-cm-thick slices.

Carbonate samples from both the site section and the spring carbonate sequence were ground to a fine powder using an agate planetary ball mill.

16.5.2 Dating methods

Three fragments of charcoal from the site section have been dated by radiocarbon methods (AMS analysis, Beta Analytic Radiocarbon Dating Laboratory, Miami, Florida). Two of the samples originate from a level attributed to the Later Natufian horizon described by Byrd (1989), and the third belongs to the start of the Neolithic occupation layers (Figure 16.5). The two samples related to the Natufian horizon (beta 235214 and beta 235215; Table 16.1) failed to yield separable charcoal fractions and were analysed as organic sediment fractions following pre-treatment by acid washes. The sample from the start of the Neolithic occupation layers was treated as charred material with a pre-treatment by acid and alkali washes, following Beta Analytic pre-treatment standards.

Selected samples from the spring sequence have been dated using uranium series (U-series). Using the ^{230}Th–U disequilibrium

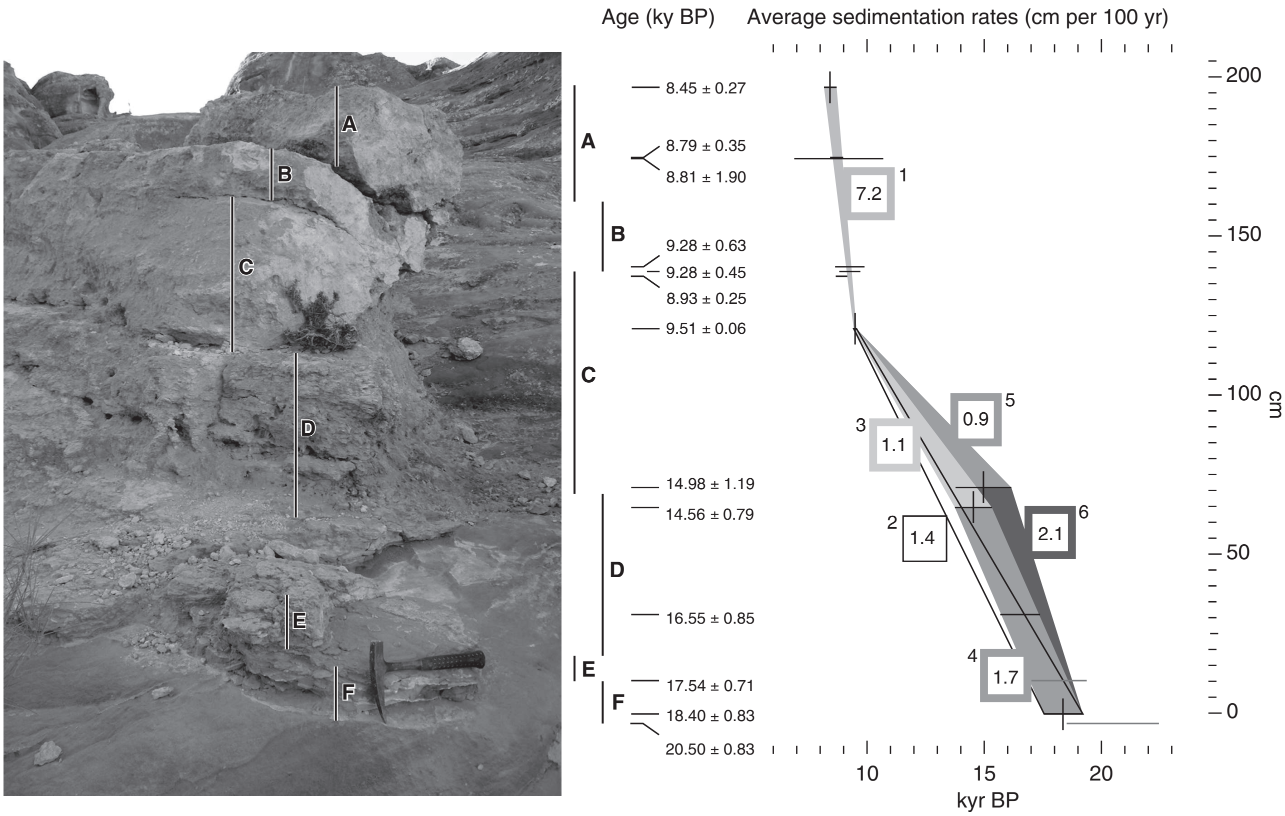

Figure 16.6. Spring carbonate (tufa) sequence, U-series dates and average sedimentation rates. Italic numbers refer to dates obtained on one sub-sample only; other dates were obtained with the isochron technique on multi sub-samples. Numbers 1–6 relate to sedimentation rates as calculated in Table 16.3.

method to date carbonates implies that at the time of precipitation the sample was free from ^{230}Th, which, along with ^{232}Th, predominantly adsorbs onto clay minerals. The spring carbonate ^{230}Th/^{232}Th ratios indicate extensive detrital contamination (Table 16.2). We therefore used an isochron method to correct for the detrital component. Isochron methods for impure carbonates described in Candy *et al*. (2005) and Candy and Black (2009) (see also Ludwig and Titterington, 1994; Ludwig, 2001; Hercman and Goslar, 2002 and references therein; Garnett *et al*., 2004 and references therein. We used several sub-samples from the same layer, which supposedly contain different ratios of a single carbonate and a single detrital phase. A 2-D isochron is constructed with the results for each sub-sample (Table 16.2), using ^{238}U/^{232}Th and ^{230}Th/^{232}Th activity ratios (S. Black; see also Chapter 9 of this volume for further details about instrumentation).

16.5.3 Granulometric analyses

Selected sediment samples from the site section were analysed for their granulometry (Coulter LS 230 laser granulometer) to determine potential changes in the sedimentation type within the sedimentological sequence, notably to discriminate between aeolian and fluvial deposits. Selected bulk sediments were also sampled from different settings (dunes, ancient terraces, wadi sedimentary sequences) for granulometry analysis and comparison with sediments from the site section.

16.5.4 Stable isotope (C, O) analyses

Bulk samples from both the site and the spring carbonate section were analysed for stable isotopes (carbon and oxygen) using a SIRA II stable isotope ratio mass spectrometer (SIRMS) after careful calibration with international standards. A maximum error of ±0.1‰ has been determined for the measurements of calcite δ^{18}O, using a series of duplicated samples and systematic measures of an internal standard (CAV-1, standardised against NBS-19).

16.5.5 Mineralogy and facies analyses

Mineralogical compositions of spring carbonate samples were determined by X-ray diffraction using a Siemens D5000 X-ray diffraction spectrometer, together with major and trace elements after dissolution of powders with mineral acids and analysis via a Perkin Elmer Elan 6000, inductively coupled plasma mass spectrometer (ICP-MS). Six thin sections were also obtained from different levels of the spring carbonate sequence.

Table 16.2 *Uranium-series dates from the tufa series*

Uranium/thorium isochron ages (in bold; e.g. **SB1**) are calculated using information from a series of sub-samples (e.g. SB1a-d). Dates based on one sample only (uncorrected ages; e.g. Bei-Ee) are shown not in bold. Uncertainties on U and Th concentrations (average SDs calculated on all the data) are ± 0.45% and ± 0.67%, respectively.

Sample	Distance from the base (mm)	U (μg kg^{-1})	Th (μg kg^{-1})	$^{234}U/^{238}U$	$^{230}Th/^{238}U$	$^{230}Th/^{232}Th$	U/Th isochron age
SB1a	200	908	1,366	1.015±0.012	0.031±0.002	0.064±0.019	
SB1b	200	820	830	2.288±0.014	0.043±0.005	0.131±0.024	
SB1c	200	637	423	3.261±0.014	0.056±0.007	0.257±0.026	
SB1d	200	1,145	551	3.753±0.025	0.060±0.005	0.382±0.029	
SB1							**8,435±270**
SB2a	178	95	174	1.382±0.037	0.035±0.023	0.059±0.011	
SB2b	178	118	344	0.766±0.021	0.008±0.030	0.010±0.010	
SB2c	178	128	282	1.126±0.020	0.027±0.021	0.038±0.013	
SB2d	178	90	161	1.403±0.018	0.037±0.029	0.066±0.015	
SB2							**8,790±350**
Bei-A3a	178.3	949	1,506	2.332±0.029	0.073±0.000	0.141±0.003	
Bei-A3a-1	178.3	472	999	1.843±0.039	0.071±0.001	0.102±0.002	
Bei-A3a-2	178.3	773	1,687	2.646±0.050	0.072±0.062	0.101±0.088	
Bei-A3a-4	178.3	423	906	1.774±0.040	0.068±0.051	0.098±0.073	
Bei-A3a-5	178.3	659	1,616	2.931±0.018	0.072±0.035	0.090±0.045	
Bei-A3a							8,811±1,899
Bei-B3	143.8	539	965	1.822±0.008	0.081±0.001	0.140±0.002	
Bei-B3–1	143.8	2,498	7,136	2.651±0.066	0.082±0.002	0.088±0.002	
Bei-B3–2	143.8	1,385	2,608	3.004±0.008	0.083±0.001	0.135±0.003	
Bei-B3							**9,282±628**
Bei-BC	142.3	1,216	994	1.725±0.009	0.083±0.000	0.313±0.001	
Bei-BC-1	142.3	972	2,110	1.299±0.029	0.083±0.001	0.118±0.001	
Bei-BC-2	142.3	798	1,328	1.626±0.030	0.087±0.001	0.160±0.003	
Bei-BC							**9,282±450**
Bei-C1	140.8	675	965	1.860±0.013	0.086±0.001	0.184±0.003	
Bei-C1–1	140.8	930	2,017	1.751±0.024	0.089±0.001	0.125±0.002	
Bei-C1–2	140.8	865	1,683	1.496±0.030	0.088±0.001	0.139±0.002	
Bei-C1							**8,928±248**
Bei-C2–1	124.3	805	1,001	1.600±0.045	0.087±0.003	0.215±0.005	
Bei-C2–2	124.3	1,249	623	2.169±0.048	0.084±0.001	0.518±0.009	
Bei-C2–3	124.3	763	1,684	2.275±0.005	0.085±0.006	0.118±0.010	
Bei-C2–4	124.3	884	1,093	1.442±0.024	0.085±0.004	0.210±0.011	
Bei-C2							**9,507±59**
Bei-C5a	74.3	748	1,106	2.360±0.027	0.123±0.001	0.255±0.000	
Bei-C5a-1	74.3	877	1,426	1.516±0.018	0.135±0.001	0.255±0.004	
Bei-C5a-2	74.3	827	1,617	1.943±0.017	0.128±0.001	0.200±0.002	
Bei-C5a-3	74.3	641	1,454	1.472±0.016	0.127±0.001	0.171±0.003	
Bei-C5a							**14,984±1,190**
SB3a	68	639	524	2.120±0.002	0.038±0.009	0.141±0.024	
SB3b	68	814	1,010	1.634±0.020	0.051±0.010	0.125±0.009	
SB3c	68	1,181	230	2.902±0.021	0.019±0.018	0.293±0.007	
SB3d	68	744	381	2.504±0.022	0.029±0.018	0.171±0.009	
SB3e	69	637	1,068	1.153±0.017	0.066±0.012	0.121±0.014	
SB3f	70	451	431	2.044±0.021	0.042±0.019	0.134±0.019	
SB3g	71	492	430	2.055±0.029	0.040±0.023	0.140±0.020	
SB3							**14,555±790**
SB4a	34	773	214	3.304±0.029	0.010±0.008	0.109±0.028	
SB4b	35	834	328	3.007±0.024	0.010±0.010	0.078±0.021	

Table 16.2 (*cont.*)

Sample	Distance from the base (mm)	U (μg kg^{-1})	Th (μg kg^{-1})	$^{234}U/^{238}U$	$^{230}Th/^{238}U$	$^{230}Th/^{232}Th$	U/Th isochron age
SB4c	36	821	119	3.677±0.029	0.012±0.008	0.259±0.018	
SB4d	37	717	613	1.833±0.015	0.003±0.008	0.010±0.012	
SB4e	38	564	442	1.955±0.020	0.003±0.002	0.013±0.020	
SB4f	39	206	131	2.365±0.020	0.006±0.003	0.029±0.008	
SB4g	40	487	340	2.207±0.019	0.005±0.002	0.020±0.007	
SB4h	41	423	231	2.625±0.021	0.007±0.001	0.038±0.006	
SB4							**16,550±850**
Bei-Ee	13.5	914	497	1.3156±0.0061	0.1493±0.0004	0.8419±0.0081	17,543±709
Bei-F6a	3	1,098	1,697	1.6696±0.0435	0.1573±0.0027	0.3121±0.0077	
Bei-F6a-1	3	1,993	5,908	1.1380±0.0320	0.1621±0.0025	0.1676±0.0037	
Bei-F6a-2	3	580	2,021	2.2713±0.0795	0.1564±0.0044	0.1377±0.0033	
Bei-F6a							**18,400±826**
Bei-F7	0	733	699	1.9167±0.0105	0.1722±0.0005	0.5532±0.0015	20,504±829

16.6 RESULTS AND INTERPRETATION

16.6.1 Site section: chronology of occupation

Three new ^{14}C dates have been obtained from bulk charcoal collected within the slope section on the western edge of the Beidha settlement (Figures 16.3, 16.5). A black layer corresponding to the later Natufian phase previously identified (Byrd, 1989) yielded two dates of 13,645 ± 176 and 13,156 ± 120 cal. BP (Figures 16.3 and 16.6). The sample from the base of the subsequent PPNB occupation layer gave an age of 10,302 ± 108 cal. BP (Figures 16.3 and 16.6). These new dates refine our knowledge of the timescale of human settlement at Beidha, particularly the later Natufian occupation, which falls within the Early Natufian time period (Bar-Yosef and Belfer-Cohen, 1999), contrary to Byrd's (1989) preliminary conclusions about a second occupation at the transition between the Early and the Late Natufian. The new ^{14}C dates also support arguments for an earlier start for Neolithic occupation than previously thought. The new Neolithic date obtained at Beidha falls within the same range of previously acquired dates following their recalibration (Figure 16.3), but is better constrained. It actually suggests an EPPNB, or very early MPPNB occupation at Beidha. This is compatible with the architectural style of the earliest Beidha Neolithic, and with the dates obtained for similar architecture in the northern Levant.

16.6.2 Site section: sedimentological analysis, and geomorphological observations around the site

Granulometry analysis and sedimentological observations have been performed on a composite sedimentological section on the western side of the Beidha terrace and within the Beidha tell. Results of the granulometry analysis are presented in Figure 16.7. Overall, these results are rather inconclusive, as samples from the dunes and certain levels of the wadi sequence are indistinguishable. They are mostly composed of a fine fraction usually attributed to wind-blown deposits, and are potentially the result of local weathering of the sandstone. This renders the differentiation between aeolian and fluvial deposits very difficult on the basis of the granulometry alone (Figure 16.7). However, a shift in sedimentation type is noticeable between the Natufian occupations (sediments aligned on the same composition trend than sediments from the main wadi system and dunes; Figure 16.7) and later deposits (sediments richer in clay; Figure 16.7). This apparent shift in sedimentation seems at odds with Field's (1989) conclusions, which suggest a similar type of deposition before, during and after the Natufian, with continuous aggradation. It is, however, compatible with an erosional phase before the Neolithic levels (also suggested by Field, 1989), which would have induced incision in the wadi bed and isolation of the terrace from the wadi system. The sedimentation mechanism of the sterile interval remains unclear – possible interpretations include deposition from ephemeral streams washing material from the cliffs and/or an increase in aeolian input (Raikes, 1966; Field, 1989).

The presence of pebbles within the site terrace sedimentary sequence aligned on a major flow direction towards the west to west-northwest indicate the episodic incursion of meandering channels under Natufian deposits. Before the Early Natufian, the sedimentary system thus appears to function mostly in an aggradation mode, as suggested by Field (1989). Root concretions just under the Natufian levels at the site section reflect vegetation colonisation and possibly relatively mesic conditions, maybe indicative of a riverine setting.

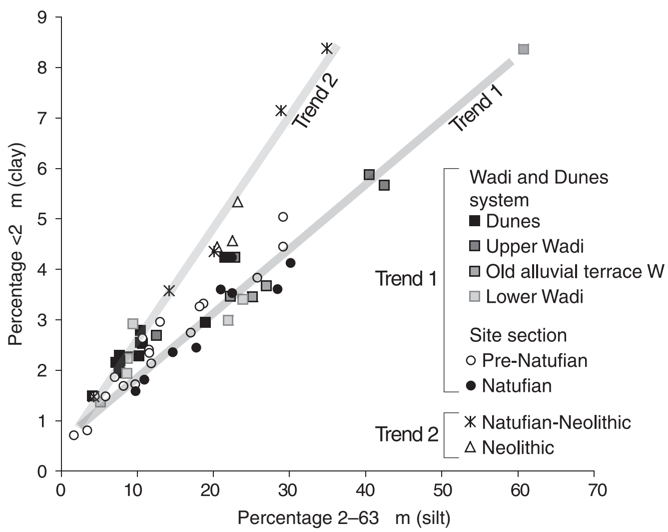

Figure 16.7. Granulometry analysis from the site section and other sediments from the valley.

Geomorphological features west of the site, in particular rounded sandstone terraces at a lower elevation than the Natufian layers (Figure 16.3), suggest previous burial under fluvial sediments. These features are compatible with a valley filled to Natufian occupation levels, then subjected to erosional processes at a later time.

16.6.3 Spring carbonate section: chronology, sedimentology and sedimentation rates

The oxygen isotopic composition of the spring carbonate sequence suggests that these carbonates precipitated from ambient-temperature waters (see, e.g., Andrews, 2006). This is further supported by the low sedimentation rates and abundance of plant encrustations, such as reed imprints, observable in the spring carbonate sequence of Beidha (Ford and Pedley, 1996; Pentecost, 1995). The term tufa, following the definition of Pedley (1990) (see also Ford and Pedley, 1996, and Pedley *et al*., 2003), can be used to describe the Beidha carbonate sequence. The mineralogical composition of the carbonate phase of the tufa deposits is essentially calcitic, with traces of dolomite for certain samples. An important detrital phase is always present, dominated by quartz grains. Thin sections derived from the Beidha spring carbonate series show a predominantly micritic fabric, including a significant amount of wind-blown sand particles. The depositional setting at the Beidha tufa sequence can be described as a spring-fed shallow-water marshy environment, probably in close proximity to the spring outlet, but corresponding to a calm depositional environment with low-velocity water flows.

The use of U-series to date impure carbonates such as tufa has been widely discussed in the literature (e.g. Geyh, 2001; Mallick and Frank, 2002; Garnett *et al*., 2004; Candy *et al*., 2005; Geyh, 2008 and references therein). Tufa deposits have been recently dated using U-series (e.g. Eikenberg *et al*., 2001; Soligo *et al*., 2002; O'Brien *et al*., 2006). It has been suggested that the best kind of tufa deposits for dating purposes are those of low porosity (typically, micritic facies), thus avoiding problems linked with secondary sparitic cementation within big pores (e.g. Garnett *et al*., 2004). At Beidha, although the micritic facies is an advantage for U-series dating techniques, the presence of a significant detrital phase forced the use of the isochron dating method.

The independent dating of vertically adjacent samples from the spring carbonate section (separated by no more than a few centimetres; Figure 16.6) shows very good consistency. However, large error bars obtained with the isochron method for certain layers (Figure 16.6) hint at complicating processes within the sedimentary sequence. One possible explanation is the mixing of successive layers of precipitation during the sample preparation. If the sedimentation rate is particularly low, grouping these layers will result in an average, less accurate date. Another possibility is the presence of secondary carbonate, after the main phase of precipitation, filling voids. Considering the dominantly micritic facies at the spring carbonate sequence, this hypothesis is less likely. Other explanations include phases of meteoric alteration/reprecipitation, especially for the upper layers directly exposed to the atmosphere and for now-internal layers that may have been exposed for an unknown amount of time following a precipitation hiatus and mixing in groundwater sources. However, no correlation was found between Mg, Sr, Mg/Ca and either the carbon or oxygen isotopic ratios. This suggests an open and fluid system, with no significant changes in the groundwater source through time.

Dates obtained from the Beidha tufa series using U-series techniques indicate that sedimentation probably started just after the LGM (Figure 16.6), although the older date obtained by U-series at Beidha is based on one sub-sample only and is therefore less reliable than dates obtained from multiple sub-samples and the isochron technique. Carbonate precipitation then continued with variable sedimentation rates until *c*. 8,450 BP. The spring carbonate record at Beidha therefore spans more than 10,000 years, which is unusual for tufa deposits (Andrews, 2006), although a Czech Republic tufa sequence has been shown to span *c*. 7,000 years (Zak *et al*., 2002). Tufas in more northern latitudes are usually rapidly accumulating systems and can, therefore, record short-time variations such as seasonality. At Beidha the sequence is much more condensed and such a resolution is probably impossible to attain.

Sedimentation rates at the Beidha tufa sequence can be calculated using the U-series dates obtained (Figure 16.6; Table 16.3), although large error bars associated to some of the dates render them less accurate. Additionally, a potential error of ±5 cm has been attributed to sampling depths. Sedimentation rates calculated using mean dates and sampling depths are shown in

Table 16.3 *Sedimentation rates calculated for various intervals of the tufa section*

Intervals are numbered 1–6 as presented in Figure 16.6. Ranges of sedimentation rates include potential errors on both dates and sampling depth.

	Sample age (years BP)	Distance from the base (cm)	Sedimentation rate (cm per 100 yr) Average	Range
1	8,450 ± 270 9,507 ± 59	200.3 ± 5 124.3 ± 5	7.2	4.8–11.8
2	9,507 ± 59 18,400 ± 826	124.3 ± 5 3.0 ± 5	1.4	1.1–1.6
3	9,507 ± 59 14,555 ± 790	124.3 ± 5 68.0 ± 5	1.1	0.8–1.6
4	14,555 ± 790 18,400 ± 826	68.0 ± 5 3.0 ± 5	1.7	1.0–1.9
5	9,507 ± 59 14,984 ± 1190	124.3 ± 5 74.3 ± 5	0.9	0.6–1.4
6	14,984 ± 1190 18,400 ± 826	74.3 ± 5 3.0 ± 5	2.1	1.1–5.8

Figure 16.6. Values calculated using both extremities of the ranges given by uncertainties on dates and sampling depths are also presented in Table 16.3.

Sedimentation rates are significantly different between the lower and upper parts of the sections (Figure 16.6; Table 16.3). The higher sedimentation rates at the upper part of the section (*c*. 9,500–8,450 cal. BP) reflect higher spring activity, probably in link with higher meteoric precipitation and aquifer recharge during the early Holocene wet period. The lower sedimentation rates related to the lower part of the section (*c*.18,500–9,500 cal. BP) may reflect aquifer recharge after the end of the LGM (during which the spring did not appear to have been flowing) but drier conditions than during the following early Holocene. The period between *c*. 15,000/14,500 and 9,500 cal. BP seems to show a relative decrease in sedimentation rates compared to the period *c*. 18,500–15,000 cal. BP (Figure 16.6; Table 16.3). This may reflect the influence of a dry period, possibly related to the Younger Dryas, although potential errors related to dating imprecision render this difficult to assess with certainty.

16.6.4 Spring carbonate and site section: stable isotopic composition of carbonates

Oxygen and carbon isotopes have been measured both at the site and the spring carbonate sections. The oxygen curves of both sections exhibit significant variations, which may be related to fluctuations of the local environmental conditions (Figure 16.8). The major excursions seem to be synchronous in both records, considering the U-series and radiocarbon dates available for the spring-carbonate and site section, respectively. The more noticeable events are a marked increase in both oxygen isotopic records at *c*. 13,000 BP, followed by more negative values from *c*. 10,500–9,500 BP. This positive excursion seems to correspond in time with the Younger Dryas period (*c*. 12,700–11,500 BP), whereas the more negative values before and after this period can be associated with the Bølling–Allerød interval (*c*. 15,000–13,000 BP) and the onset of the early Holocene. These three major divisions of the record seem to generally correspond to specific times of occupation (Early Natufian during the Bølling–Allerød, PPNB during the early Holocene) and abandonment of the site. A shift towards more favourable climatic conditions (more negative $\delta^{18}O$) seems to be recorded at the site section even before the first known date of occupation (*c*.10,300 BP; Figure 16.8). A shift towards more positive ratios around 8,800–8,500 BP is coeval with the end of PPNB occupation at the site (Figure 16.8). Overall, the good correlation between occupation phases and the evolution of the oxygen isotopic composition of carbonates suggest a climatic control over periods of settlement at Beidha. In this context, more negative $\delta^{18}O$ values would correspond to more favourable climatic conditions at Beidha, whereas more positive values would mark periods of climatic deterioration, inducing the abandonment of the site (see discussion).

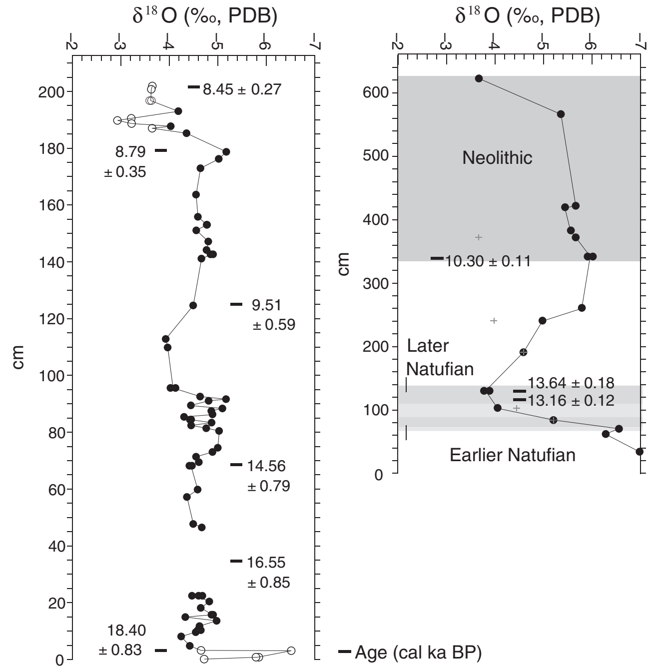

Figure 16.8. Oxygen stable isotope curves for the tufa (left) and site (right) sections. Grey highlights refer to times of occupation at the archaeological site (Natufian and Neolithic). White dots in the tufa section correspond to isotopic compositions potentially influenced by disequilibrium effects (e.g. evaporation).

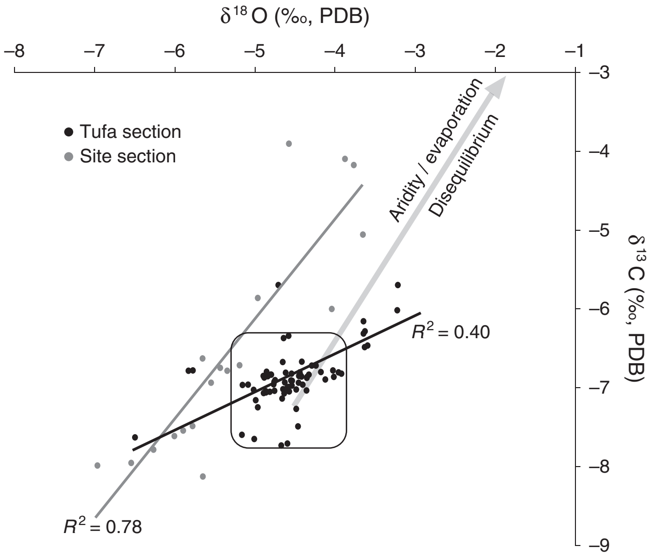

Figure 16.9. Oxygen and carbon isotopic composition and covariation (trend lines) for the site and tufa sections at Beidha. Evaporation/disequilibrium trend from Andrews (2006). The black box contains the samples that may be considered independent from disequilibrium effects.

A maximum in δ^{18}O values, following a sharp increase of the ratio, at the site section seems coeval with the last level of Natufian occupation (Figure 16.8). This may suggest that the Natufian population, facing increasingly degraded climatic conditions, nevertheless came back to Beidha and tried to settle for a short period (the more ephemeral occupation of the Later Natufian noticed by Byrd, 1989). Alternatively, it is possible that the soil carbonate nodules, from which the isotopic record is derived, developed slightly after the site abandonment (see discussion).

At about that time, increased climate variability is recorded in the tufa series by alternating lower and higher δ^{18}O values in the carbonates after an initial shift towards more negative ratios (Figure 16.8). This may indicate quickly changing conditions that would have allowed a brief return to Beidha for the Natufian population, during a short period of climatic improvement within a general trend towards a less favourable environment.

A marked correlation between C and O isotopic composition of carbonate precipitates is usually interpreted as reflecting the influence of evaporative processes (e.g. Smith *et al.*, 2004; Andrews, 2006; O'Brien *et al.*, 2006). At Beidha, a strong correlation ($R^2 = 0.78$; Figure 16.9) between the carbon and oxygen isotopic records is noticeable for soil carbonates deposited within the site section, whereas the spring carbonate series shows a far less marked covariation (Figure 16.9). Most of the samples from the spring carbonate sequence seem actually independent of an evaporative trend (black box, Figure 16.9). However, the uppermost samples seem to record an increasing influence of evaporative processes, probably linked with the cessation of the spring flow shortly afterwards.

16.7 DISCUSSION

16.7.1 Beidha spring: related aquifer and groundwater residence time

Springs in Jordan today are related to either water-table or confined aquifers. Springs related to confined aquifers tend to have steadier, larger flows than water-table springs and show little sensitivity to climate change. Water-table springs generally present small and highly variable flows and show great sensitivity to climatic conditions; they may stop flowing during times of low rainfall (EXACT, 1998). The former spring studied at Beidha only flowed during a limited period of time (*c*. 20,000–8,500 cal. BP) and presents slow and variable sedimentation rates throughout this period. Considering the average sedimentation rates of *c*. 1.4 cm per 100 years and *c*. 7.2 cm per 100 years for, respectively, the lower part and the upper part of the section (Figure 16.6; Table 16.3), and the average thickness of the samples analysed (1 cm), each sample should represent between *c*. 14 and 71 years of deposition, with a maximum of 167 years given by the lowest sedimentation rate calculated at the section (Table 16.3). The fact that clear variations are observable in the isotopic record therefore suggests that the residence time of the aquifer related to the relict spring is lower than this upper figure.

This points to a spring related to a water-table aquifer, highly sensitive to climatic variations. This would also explain the good correlation between the spring isotopic record and the isotopic record derived from the carbonate nodules at the site section, which do not relate to spring waters. We therefore take the view that, even if the exact time of residence of the aquifer waters is unknown, the spring system reacted promptly to climate changes and the isotopic record derived from the spring carbonates reflects these variations.

16.7.2 The isotopic record at Beidha: potential interpretations and palaeoenvironmental implications

ISOTOPIC VARIATIONS IN CARBONATES

Carbonate precipitates can reflect a range of the environmental conditions present during the time of their formation. These include the temperature and isotopic composition of the parent water from which the carbonate formed, as well as other factors that can affect the carbonate precipitation equilibrium, such as evaporation.

The relation between water temperature, the isotopic composition of the parent water and the isotopic composition of calcite precipitates can be summarised, in equilibrium conditions, by equations derived from the Craig palaeotemperature relationship (Craig, 1965; Andrews, 2006) such as (amongst others) presented in O'Neil *et al.* (1969) or Hays and Grossman (1991). The isotopic composition of the parent water, however, is itself dependent on a series of parameters including mean air temperature, the source and amount of precipitations, evaporation, and in the case of precipitates related to groundwater systems, on residence time and groundwater mixing. A good correlation, for example, has been proved between surface air temperatures and the oxygen isotopic composition of rainfall (Rozanski *et al*., 1993).

Soil carbonate nodules have been interpreted to reflect changes in the bulk soil water composition, and, for shallow soils, evaporation (e.g. in the Rio Grande area, New Mexico; Deutz *et al*., 2001). Palaeoclimatic changes, however, may only be recorded in carbonate nodules related to rapidly buried soils (Deutz *et al*., 2001 and references therein). Several studies have suggested that pedogenic carbonate $\delta^{18}O$ compositions can be indicative of the $\delta^{18}O$ values of local rainfall (e.g. Cerling, 1984; Cerling and Quade, 1993; Amit *et al*., 2007), although other parameters influencing the $\delta^{18}O$ composition of soil water must not be neglected (e.g. Deutz *et al*., 2001 and references therein). Air temperatures, for example, can have an important impact: Zanchetta *et al*. (2000) interpreted an abrupt shift of about $-1‰$ in $\delta^{18}O$ of pedogenic carbonates of the Somma-Vesuvius in Italy as related to a cooling of about 2 °C after the Avellino eruption (3.8 ka BP). Quade *et al*. (2007) listed three major factors influencing the $\delta^{18}O$ of soil carbonates in the Atacama desert: the $\delta^{18}O$ value of local rainfall (itself dependent on temperature, and potentially other parameters such as the amount and source of rainfall, altitude and continentality; Rozanski *et al*., 1993; Rowe and Maher, 2000 and references therein; see also Zanchetta *et al*., 2000); soil temperature; and soil water evaporation before the formation of soil carbonates. In arid environments, evaporation seems to be the main control on soil carbonate $\delta^{18}O$ composition (Quade *et al*., 2007). Zanchetta *et al*. (2000) also mention dewatering soil processes prior to carbonate precipitation, owing to evaporation, as a way of increasing pedogenic $\delta^{18}O$ values in arid and semi-arid environments, potentially to a point masking the rainfall signature (Zanchetta *et al*., 2000 and references therein). On lake margins in an evaporative system in Tanzania, higher $\delta^{18}O$ values in rhizoliths have been recorded during dry periods while lower values have been interpreted as reflecting meteoric water composition in times of increased precipitation (Liutkus *et al*., 2005). The data of Liutkus *et al*. (2005) also shows a strong covariation between $\delta^{13}C$ and $\delta^{18}O$ values.

In tufa deposits, variations of the oxygen isotopic records can be interpreted in terms of temperature variations and/or variations of the isotopic composition of the parent water, including precipitation sources and air temperature variations (e.g. Andrews *et al*., 2000; Andrews, 2006; O'Brien *et al*., 2006 and references therein; Smith *et al*., 2004; see also the discussion about interpretations of the isotopic record in Chafetz and Lawrence, 1994).

The consensus view seems to be that short-term variations (e.g. seasonal) in the isotopic record of tufas are dominantly controlled by stream temperatures (i.e. lower isotopic values corresponding to higher temperatures), when the isotopic composition of waters can be considered essentially invariant (Andrews *et al*., 2000; Matsuoka *et al*., 2001; Andrews, 2006; O'Brien *et al*., 2006; Brasier *et al*., 2010). By contrast, longer-term variations (on millennial scales, such as, for example, between the mid-Holocene and the present day) are thought to be mainly controlled by changes in the meteoric water composition in the aquifer catchment area (e.g. Andrews *et al*., 1997; Smith *et al*., 2004). Andrews *et al*. (1997) have demonstrated that modern tufa $\delta^{18}O$ values are closely linked to the isotopic composition of precipitations, while moderated by other factors such as water temperature, evaporation and residence time. Rainwater composition is in turn controlled by, amongst others, latitude, changes in the air-mass sources, air-mass temperature, altitude and rainout/amount effects (Andrews *et al*., 2000). Higher values of $\delta^{18}O_{calcite}$ may then be caused by higher $\delta^{18}O_{recharge}$ (higher air temperatures or variations in the source of airmasses; Andrews *et al*., 2000).

Overall, it has been suggested that mean air temperature variations exert the strongest influence on the long-term $\delta^{18}O$ composition of tufas (e.g. Andrews *et al*., 1994, 2000; Andrews, 2006; O'Brien *et al*., 2006). The relationship between temperature and the $\delta^{18}O$ composition of tufas is then complicated by the fact that air temperature and calcite precipitation temperature dependence exert opposite influences on the isotopic composition ($\delta^{18}O_{water}$ increases with rising air temperature; *c*. $+0.58‰$ per °C in Europe; Andrews, 2006; whereas $\delta^{18}O_{calcite}$ decreases with rising water temperature; *c*. $-0.24‰$ per °C; Andrews, 2006). The final signal is dominated by the air temperature effect but 'damped' by the water temperature influences (Andrews *et al*., 1994, 2000; Andrews, 2006). In Europe, it has been claimed that *c*. 40% of the air temperature variation is finally recorded in the tufa $\delta^{18}O$ signal, with rising air temperatures inducing an increase in $\delta^{18}O$ values (Andrews, 2006). Following the same line of interpretation, O'Brien *et al*. (2006) have inferred the mean isotopic change in their tufas from the Grand Canyon area between the mid-Holocene and the modern day ($-0.5‰$) to correspond to a shift of *c*. -1 °C, while Andrews (2006) cites variations of $-1‰$ in the $\delta^{18}O_{tufa}$ corresponding to *c*. $-3.5‰$ between 9.5 and 8.2 ka BP in the United Kingdom and Czech republic.

Short-term variations in the $\delta^{18}O$ of precipitations can also result from events such as intense rainfall (the 'amount effect'), seasonal variability (more negative precipitations during the cooler period of the year), and temporal changes in the air-mass sources (Andrews, 2006). In strongly evaporative settings, evaporation processes can also influence the oxygen isotopic composition of the tufas (e.g. O'Brien *et al*., 2006; Andrews, 2006; Chafetz and Lawrence, 1994 and references therein). It is believed that seasonal evaporation in arid climates can shift

$\delta^{18}O$ compositions of tufas up by at least 1‰ (Andrews and Brasier, 2005). Andrews *et al*. (2000) also indicate that O and C isotopes covariation can be related to climatic factors such as aridity.

THE ISOTOPIC RECORD AT BEIDHA

Overall, both the relict spring carbonate system near the archaeological site of Beidha, and the carbonate nodules sampled directly at the site, seem to coevally record changes in climatic conditions. However, it may be difficult to determine precisely which parameters are mainly responsible for the fluctuations of the Beidha record. The interpretation of the spring carbonate sequence at Beidha is further complicated by the fact that the spring itself is no longer in existence (e.g. Smith *et al*., 2004; Andrews, 2006 and references therein). This means that a comparison between the composition of modern carbonate precipitates, spring water values and climate parameters such as temperature and rainfall (as notably realised at Soreq Cave; Bar-Matthews *et al*., 1996), is not directly possible at Beidha.

Pedogenic nodules at Beidha form part of a relatively fast-accumulating sequence (Figures 16.5 and 16.8) and therefore may be recording environmental conditions at the time of their formation. In this study, we take the view that isotopic variations in the pedogenic nodules and carbonates are mainly controlled by evaporation, as evidenced by the significant correlation between C and O isotopes (Zanchetta *et al*., 2000; Liutkus *et al*., 2005; Quade *et al*., 2007). As such, positive shifts of the isotopic record will correspond to periods of more intense evaporation linked to increased aridity, while lighter compositions will correspond to wetter periods (such as suggested by Liutkus *et al*., 2005, for lake-margin rhizoliths in Tanzania). This interpretation is coherent with the increased presence of aridity indicators in the pollen record during and after the Later Natufian occupation (Fish, 1989), the presence of a later erosion gully cutting through Early Natufian levels (Byrd, 1989; Kirkbride, 1989), and the change in sedimentation suggesting a shift in the climate regime following a time of wadi aggradation at the site (Figure 16.7).

Both shifts towards heavier isotopic values at the top of the tufa and site sequence are consistent with increased evaporation ($\delta^{13}C$ and $\delta^{18}O$ covariation; Figures 16.7, 16.8) just before the site's abandonment, coherent with the cessation of spring activity shortly afterwards. A major phase of erosion took place after the site abandonment, also suggestive of a shift towards a drier climate. Considering the covariation of tufa and pedogenic carbonate oxygen isotopes, and the indication of increased aridity and evaporation at the top of the tufa sequence, a cessation of spring activity linked with a sudden tectonic event that would have changed the groundwater trajectory is unlikely.

In the rest of the tufa record, it is difficult to know exactly how the other isotopic shifts, corresponding in time to the Bølling–Allerød, the Younger Dryas and the start of the early Holocene, relate to climatic variations. At Beidha, the sampling resolution (samples of *c*. 1 cm thickness), coupled with low sedimentation rates, means that decades/centuries of climatic variations are averaged out; therefore an interpretation in terms of water temperature changes (mainly valid on a seasonal timescale) is probably invalidated. An overall control of mean air temperature variations is possible in the long term, i.e. between the start and the end of sedimentation at the Beidha spring. It is possible (although difficult to prove) that the general trend towards less negative $\delta^{18}O$ (*c*. 1‰ over the whole section), on which the shorter time variations such as related to the Bølling–Allerød, the Younger Dryas and the early Holocene are superimposed, is linked with generally increasing mean air temperatures through time (*c*. 3.5 °C, following the estimates of Andrews, 2006). Since the spring at Beidha seems to have started flowing after the end of the LGM, such an interpretation would be coherent with the general increase in temperatures (6–7 °C; Affek *et al*., 2008) recorded at Soreq between the LGM (20,000–19,000 cal. BP) and the early Holocene (10,000–7,000 cal. BP). However, it is difficult to interpret the medium-term variations (during the Bølling–Allerød and Younger Dryas, and at the start of the early Holocene) as purely dependent on air temperature variations, since they would imply higher temperatures during the Younger Dryas and colder temperatures during both the Bølling–Allerød and the early Holocene, at odds with all other palaeoclimatic interpretations of the region.

We therefore suggest, as a working hypothesis, that medium-term variations in the Beidha tufa record are related to changes in the $\delta^{18}O$ composition of spring water, themselves related to shorter-term effects than mean air temperature changes, such as the amount of rainfall, seasonality or changes in the rainfall sources. The marked shift towards lighter compositions during the early Holocene clearly corresponds to more extended sedimentation rates (more recharge, hence wetter conditions). Earlier shifts towards, successively, lighter and heavier compositions may therefore correspond to alternate wetter and drier periods: respectively, the Bølling–Allerød and the Younger Dryas. In this context, the correlation between times of lighter isotopic composition and times of increased sedimentation points in favour of a general control by rainfall amounts or distribution. The very negative values recorded at the start of the Beidha sequence (Figure 16.8) may be related to isotopically light snow-melt waters feeding the groundwater system after the termination of the LGM.

On this topic, certain similarities between the Beidha and Soreq $\delta^{18}O$ isotopic records are worth considering (Figure 16.10). In particular – and even if the magnitude of variations is quite different – both records show a shift towards heavier $\delta^{18}O$ during the time period corresponding to the Younger Dryas, bracketed by two periods of lighter isotopic values. The Soreq isotopic record has been interpreted by Bar-Matthews and

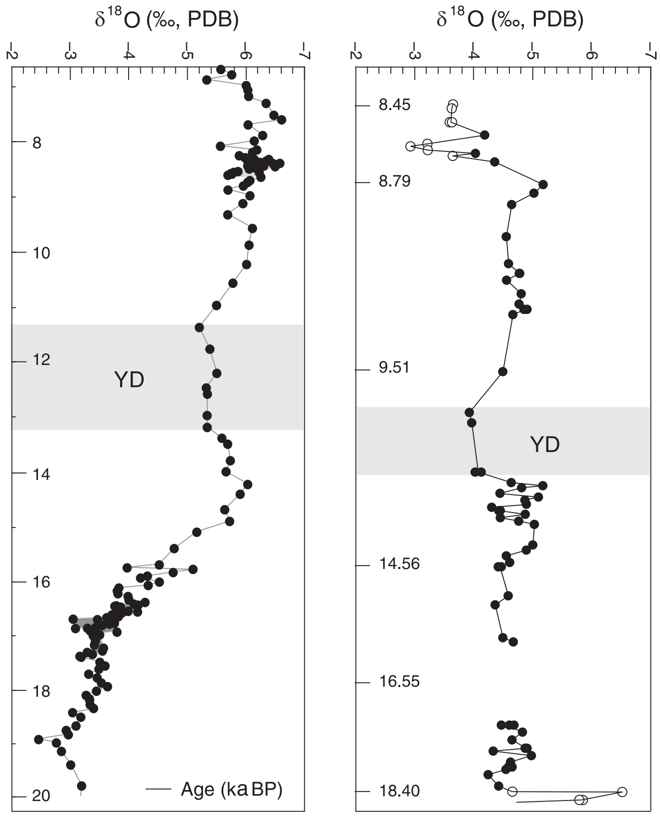

Figure 16.10. Comparison between the Soreq isotopic record (left; modified from Bar-Matthews *et al*., 1999) and the Beidha spring-carbonate record (right; this study). Open dots correspond to samples from the Beidha record that show potential disequilibrium effects (e.g. evaporation). Light grey highlights indicate the probable time of the Younger Dryas (YD).

colleagues as primarily reflecting changes in the isotopic composition of the cave waters, related to rainfall amounts (Bar-Matthews *et al*., 1996, 1997, 1999, 2003). The fact that speleothem records (Soreq), pedogenic carbonates and tufa deposits (Beidha) seem to record similar trends in oxygen isotopes may be an important piece of information for the interpretation of such records, and hints at a common controlling climatic parameter. Further studies are needed to better understand this control.

16.7.3 Source of water to the settlements

It appears unlikely that the former spring studied in this work was ever sufficient to support a large Neolithic settlement by itself. However, the presence of other (albeit undated) former springs in the area has been attested by previous studies; they may have represented collectively a significant source of water to both the Natufian and Neolithic settlements. Geomorphological and sedimentological studies seem to suggest that the wadi system may have been wider and more perennial during occupation periods. The sedimentation rate of the tufa, and possibly the oxygen isotope variations, suggest wetter conditions during both times of occupation; this may have resulted into a more stable riverine environment, with more vegetation cover and less flash-floods (see also the study at Wadi Faynan by Smith *et al*., this volume, Chapter 15). During the earlier Natufian level at least, wadi-type sedimentation, with meandering channels, is attested in the immediate vicinity of the archaeological site. This suggests a wider, less-incised valley floor, possibly supporting a more widespread river system. The position of the wadi itself is unknown during Neolithic times, but there are suggestions that the major erosive processes occurred after the site abandonment at *c*. 8,500 BP, coeval with climate change, and are marked, for example, by the deep incision of the Seyl Aqlat. In this case, it is possible that the valley floor, albeit slightly lower than during Natufian time, was still relatively large during the Neolithic, and supported a river system not confined to a single, flash-flooding, deeply incised wadi bed as it is at present. During the entire occupation history of the site, and even (at least partially) during the interval between Natufian and Neolithic occupations, the spring near Beidha was flowing, indicating overall wetter conditions at the site, or better recharge in the highlands, than those of today. Permanent sources of water near the settlement are suggested by the pollen record (Fish, 1989) and other tufa deposits may have deposited in the immediate vicinity of the site (Kirkbride, 1966, 1968; Byrd, 1989, 2005). In the light of this new study and observations, we therefore postulate that it is unlikely that the people at Beidha were travelling the *c*. 5 km to the spring at Dibadiba to get their water; they probably had water resources, either from the wadi itself or from the numerous springs in the area, closer at hand. It is also possible that a wider, less incised and better-watered floodplain was present, which was attractive to early agricultural practices.

16.7.4 Neolithic settlement at Beidha

A more favourable climate seems to have settled at Beidha sometime before the first known time of occupation (*c*. 10,300 BP; Figure 16.4; Table 16.1), as indicated by more negative $\delta^{18}O$ in carbonate nodules from the site section (Figure 16.8). This change in environmental conditions may have encouraged people to settle at Beidha earlier than previously thought. This hints at the possibility of an earlier than MPPNB occupation at Beidha, coeval with an improvement in the environmental conditions. This may explain the earliest, undated structures found at Beidha (Kirkbride, 1968; Byrd, 2005) as well as some features of the lithic assemblage from the lower levels (Mortensen, 1970). The new date obtained from the section, at *c*. 10,300 cal. BP (EPPNB/very early MPPNB), also revives the debate about the architectural style of Phase A, which may be related to EPPNB rather than MPPNB.

16.8 SUMMARY AND CONCLUSIONS

This new integrative study, based on oxygen isotopic data from two sections (pedogenic carbonate and tufa deposits) as well as sedimentological observations, and rigorously time-constrained (U-series at the tufa section, new radiocarbon dates and archaeological levels at the site section), allows for a better understanding of the palaeoenvironmental conditions at Beidha during the Natufian (Early Natufian) and Neolithic (PPNB) times of occupation. We have interpreted the isotopic record as showing primarily changes in the water isotopic composition and evaporative processes, with more negative values corresponding to wetter periods and more positive values related to increased aridity. This is in accordance with observations from the sedimentation rates at the tufa section and previous observations at the site, notably the pollen record (Fish, 1989). Temperature information remains inconclusive, although we suggest that the spring section may record an overall increase of temperature of *c*. 3.5 °C between the start and the end of the depository sequence, a gradual change generally coherent with previous studies (Affek *et al*., 2008). Overall, the coincidence between times of occupation and environmental changes recorded in the isotopic composition of carbonates, as well as in other proxies, suggests that the population at Beidha responded strongly to environmental variations during both the Natufian and Neolithic.

The new radiocarbon dates suggest that both Natufian occupations at Beidha occurred during the Early Natufian. The first period of Natufian occupation occurred during a time of wadi aggradation, as suggested by the granulometric analyses (Figure 16.7) and previous observations at the site (Field, 1989; contrary to the views of Raikes, 1966). Environmental conditions seem to have been more favourable, with higher rainfall (less positive $\delta^{18}O$ values at both the site and the tufa sections; Figure 16.8). These conclusions are in accordance with previous studies at the site and elsewhere in the Levant that suggested wetter conditions, with a more extended vegetation cover at Beidha (Byrd, 1989), corresponding to the Bølling–Allerød wet and warm interval (e.g. Bar-Matthews *et al*., 2003; Robinson *et al*., 2006; Chapter 6, this volume). The presence of a wider, more perennial wadi system is proposed for that time period.

A shift towards more arid conditions is recorded around the time of the second Natufian occupation, with more positive $\delta^{18}O$ values in the pedogenic carbonates hinting at increased evaporation (site section, Figure 16.8). This is coherent with the increase of aridity indicators in the pollen record before and after the second Natufian occupation layer (Fish, 1989). In the tufa section, increased climate variability is recorded by alternating lower and higher $\delta^{18}O$ values in the carbonates, after an initial shift towards more negative ratios (Figure 16.8). This climate variability during the Early Natufian at Beidha may correspond to the short, dry spell indicated by flora and fauna records in the southern Levant that interrupts overall favourable conditions (e.g. Sanlaville, 1996). It is possible that, in a climate of generally degrading conditions, the brief, later Natufian occupation represents a last try for the population to settle at Beidha – maybe during a short period of climatic improvement – before the environment became too hostile.

The sterile interval between the Natufian and Neolithic occupation seem to correspond to an arid event that settled in by *c*. 13,000 BP (more positive $\delta^{18}O$ values at both the tufa and site section; Figures 16.6 and 16.8). This is coherent with the change of sedimentation at the site section (granulometry analyses, Figure 16.7), the pollen record (Fish, 1989) showing higher frequencies of aridity indicators at the base of the interval, the isolation of the terrace on which the Neolithic site is built, and the marks of erosion in the sterile sediments between the two levels of occupation (Byrd, 1989; Kirkbride, 1989), but at odds with Field's (1989) interpretation of continuous wadi aggradation. Our results are in accordance with previous studies indicating drier (and probably cooler) conditions during the Younger Dryas in the Levant (e.g. Bar-Matthews *et al*., 2003; Robinson *et al*., 2006; Chapter 6, this volume).

The site section records a shift towards less positive isotopic composition even before the first known date of occupation (i.e. *c*. 10,300 cal. BP, this study; Byrd, 2005), coherent with other observations of renewed, denser and more mesic vegetation cover (Raikes, 1966; Kirkbride, 1968; Fish, 1989). The hypothesis of an earlier (PPNA/EPPNB) settlement at Beidha would fit with some of the archaeological evidence, such as the lithic material uncovered from the earlier levels, and possibly early architectural structures (Kirkbride, 1968; Mortensen, 1970; Byrd, 2005).

Generally, during the early Holocene and the PPNB occupation, high sedimentation rates in the tufa sequence, as well as more negative $\delta^{18}O$ values at both the site and the tufa sections (Figures 16.6, 16.8) indicate wetter conditions at Beidha, such as suggested for the Levant in general during the Climatic Optimum (e.g. Chapter 6, this volume; Bar-Matthews *et al*., 2003; Henry, 1997). We propose, contrary to Field's (1989) interpretation of a flash-flood regime during the PPNB, that the wadi flow at that time may have been more perennial and could have supplemented water resources available from the spring we investigated, and others in the area (see Kirkbride, 1966; Raikes, 1966; Kirkbride, 1968; Byrd, 1989, 2005). A wide floodplain, with better water availability, may have been decisive for the start of agricultural practices at Beidha.

Towards the end of the tufa and site sections, the isotopic records indicate a shift towards more arid conditions. Shortly after that, the spring stopped flowing, coeval with the Neolithic site final abandonment, at around 8,500 cal. BP. We interpret this shift to be responsible for the progressive abandonment of Beidha (Byrd, 2005). Subsequently, a major phase of erosion destroyed part of the site, probably in relation with the new, drier climatic conditions. A similar phase of aridity, generalised erosion and flash-flood regime has been recorded elsewhere in the region (e.g. Hourani and Courty, 1997; Hunt *et al*., 2004).

Overall, the conditions at Beidha seem to have been wetter than today during both Natufian and Neolithic times of occupation, and probably during part of the interval in between, as attested by the spring activity and the pollen indicators of perennial water sources around the site (Fish, 1989). It is unlikely, therefore, that the populations at Beidha used the spring at Dibadiba as a main supply for their water, as suggested by previous studies (Raikes, 1966; Kirkbride, 1968), or that greater water supply was provided solely by increased runoff (Comer, 2003).

The stable isotopic composition of carbonates has proved to be a powerful tool for the reconstruction of palaeoenvironments in a semi-arid setting. However, the exact parameters controlling their variations in such an environment remain hidden. In this context, the similarity of trends, in the southern Levant, between oxygen isotopic variations from speleothems (Soreq, Central Israel; Bar-Matthews *et al*., 1997, 1999, 2003), tufas and pedogenic carbonates (Beidha, this study) is an important observation. This should trigger additional studies about the specific climatic variations (in particular, changes in rainfall amounts, rainfall sources, or seasonality) that can direct such covariations.

REFERENCES

Affek, H. P., M. Bar-Matthews, A. Ayalon, A. Matthews and J. M. Eiler (2008) Glacial/interglacial temperature variations in Soreq cave speleothems as recorded by ‘clumped isotope’ thermometry. *Geochimica et Cosmochimica Acta* **72**: 5351–5360.

Al-Eisawi, D. (1985) Vegetation in Jordan. In *Studies in the History and Archaeology of Jordan II*, ed. A. Hadidi. Amman: Department of Antiquities pp. 45–58.

Al-Eisawi, D. (1996) *Vegetation of Jordan*. Cairo: UNESCO Regional Office for Science and Technology for the Arab States.

Amit, R., J. Lekach, A. Ayalon, N. Porat and T. Grodek (2007) New insight into pedogenic processes in extremely arid environments and their paleoclimatic implications – the Negev Desert, Israel. *Quaternary International* **162**: 61–75.

Andrews, J. E. (2006) Palaeoclimatic records from stable isotopes in riverine tufas: synthesis and review. *Earth-Science Reviews* **75**: 85–104.

Andrews, J. E. and A. T. Brasier (2005) Seasonal records of climatic change in annually laminated tufas: short review and future prospects. *Journal of Quaternary Science* **20**: 411–421.

Andrews, J. E., M. Pedley and P. F. Dennis (1994) Stable isotope record of palaeoclimate change in a British Holocene tufa. *Holocene* **4**: 349–355.

Andrews, J. E., R. Riding and P. F. Dennis (1997) The stable isotope record of environmental and climatic signals in modern terrestrial microbial carbonates from Europe. *Palaeogeography Palaeoclimatology Palaeoecology* **129:** 171–189.

Andrews, J. E., M. Pedley and P. F. Dennis (2000) Palaeoenvironmental records in Holocene Spanish tufas: a stable isotope approach in search of reliable climatic archives. *Sedimentology* **47**: 961–978.

Banning, E. B. and I. Kohler-Rollefson (1992) Ethnographic lessons for the pastoral past: camp locations and material remains near Beidha, Southern Jordan. In *Pastoralism in the Levant: Archaeological Materials in Anthropological Perspectives*, ed. O. Bar-Yosef and A. Khazanov. Madison WI: Prehistory Press pp. 181–204.

Bar-Matthews, M., A. Ayalon, M. Gilmour, A. Matthews and C. J. Hawkesworth (2003) Sea-land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. *Geochimica et Cosmochimica Acta* **67**: 3181–3199.

Bar-Matthews, M., A. Ayalon and A. Kaufman (1997) Late quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Research* **47**: 155–168.

Bar-Matthews, M., A. Ayalon and A. Kaufman (2000) Timing and hydrological conditions of Sapropel events in the Eastern Mediterranean, as evident from speleothems, Soreq cave, Israel. *Chemical Geology* **169**: 145–156.

Bar-Matthews, M., A. Ayalon, A. Kaufman and G. J. Wasserburg (1999) The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel. *Earth and Planetary Science Letters* **166**: 85–95.

Bar-Matthews, M., A. Ayalon, A. Matthews, E. Sass and L. Halicz (1996) Carbon and oxygen isotope study of the active water-carbonate system in a karstic Mediterranean cave: implications for paleoclimate research in semiarid regions. *Geochimica et Cosmochimica Acta* **60**: 337–347.

Bar-Yosef, O. (1986) The walls of Jericho: an alternative interpretation. *Current Anthropology* **27**: 157–162.

Bar-Yosef, O. (1998) The Natufian culture in the Levant, threshold to the origins of agriculture. *Evolutionary Anthropology* **6**: 159–177.

Bar-Yosef, O. and A. Belfer-Cohen (1999) Facing environmental crisis – societal and cultural changes at the transition from the Younger Dryas to the Holocene in the Levant. In *The Dawn of Farming in the Near East*, ed. R. T. J. Cappers and S. Bottema. Berlin: ex Oriente pp. 55–66.

Berger, J. F. and J. Guilaine (2009) The 8200 cal BP abrupt environmental change and the Neolithic transition: a Mediterranean perspective. *Quaternary International* **200**: 31–49.

Boyd, B. (2006) On ‘sedentism’ in the later Epipalaeolithic (Natufian) Levant. *World Archaeology* **38**: 164–178.

Brasier, A. T., J. Andrews, A. D. Marca-Bella and P. F. Dennis (2010) Depositional continuity of seasonally laminated tufas: implications for $\delta^{18}O$ based palaeotemperatures. *Global and Planetary Change* **71:** 160–167.

Byrd, B. F. (1989) *The Natufian Encampment at Beidha: Late Pleistocene Adaptation in the Southern Levant Moesgard*. Arhus: Jutland Archaeological Society.

Byrd, B. F. (2005a) *Early Village Life at Beidha, Jordan: Neolithic Spatial Organization and Vernacular Architecture*. Oxford: Oxford University Press.

Byrd, B. F. (2005b) Reassessing the emergence of village life in the Near East. *Journal of Archaeological Research* **13**: 231–290.

Candy, I. and S. Black (2009) The timing of Quaternary calcrete development in semi-arid southeast Spain: investigating the role of climate on calcrete genesis. *Sedimentary Geology* **218**: 6–15.

Candy, I., S. Black and B. Sellwood (2005) U-series isochron dating of immature and mature calcretes as a basis for constructing Quaternary landform chronologies for the Sorbas basin, southeast Spain. *Quaternary Research* **64**: 100–111.

Cerling, T. E. (1984) The stable isotopic composition of modern soil carbonate and its relation to climate. *Earth and Planetary Science Letters* **71**: 229–240.

Cerling, T. E. and J. Quade (1993) Stable carbon and oxygen isotopes in soil carbonates. In *Proceedings of the Chapman Conference, Jackson Hole, Wyoming*, ed. J. Swart, J. A. McKenzie and K. C. Lohman. Oxford: Elsevier Science Ltd pp. 217–231.

Chafetz, H. S. and J. R. Lawrence (1994) Stable isotopic variability within modern travertines. *Geographie Physique et Quaternaire* **48**: 257–273.

Comer, D. C. (2003) Environmental history at an early prehistoric village: an application of cultural site analysis at Beidha, in southern Jordan. *Journal of GIS in Archaeology* **1**: 103–116.

Cordova, C. (2007) *Millennial Landscape Change in Jordan: Geoarchaeology and Cultural Ecology*. Tucson: University of Arizona Press.

Craig, H. (1965) The measurement of oxygen isotope palaeotemperatures. In *Stable Isotopes in Oceanographic Studies and Palaeotemperatures*, ed. E. Tongiorgi. Pisa: Consiglio Nazionale Della Richerche, Laboratorio de Geologia Nucleare pp. 161–182.

Deutz, P., I. P. Montanez, H. C. Monger and J. Morrison (2001) Morphology and isotope heterogeneity of Late Quaternary pedogenic carbonates:

implications for paleosol carbonates as paleoenvironmental proxies. *Palaeogeography Palaeoclimatology Palaeoecology* **166**: 293–317.

Eikenberg, J., G. Vezzu, I. Zumsteg *et al*. (2001) Precise two chronometer dating of Pleistocene travertine: the Th-230/U-234 and Ra-226(ex)/Ra-226 (0) approach. *Quaternary Science Reviews* **20**: 1935–1953.

Emery-Barbier, A. (1995) Pollen analysis: environmental and climatic implications. In *Prehistoric Cultural Ecology and Evolution: Insights from Southern Jordan*, ed. D. O. Henry. New York: Plenum Press pp. 375–384.

Enzel, Y., R. Arnit, U. Dayan *et al*. (2008) The climatic and physiographic controls of the eastern Mediterranean over the late Pleistocene climates in the southern Levant and its neighboring deserts. *Global and Planetary Change* **60**: 165–192.

EXACT (Executive Action Team Middle East Water Data Banks Project) (1998). *Overview of Middle East Water Resources – Water Resources of Palestinian, Jordanian, and Israeli Interest*. http://water.usgs.gov/exact/overview/index.htm

Feynman, J. and A. Ruzmaikin (2007) Climate stability and the development of agricultural societies. *Climatic Change* **84**: 295–311.

Field, J. (1989) Appendix A: geological setting at Beidha. In *The Natufian Encampment at Beidha, Late Pleistocene Adaptation in the Southern Levant*, ed. B. F. Byrd. Aarhus: Jutland Archaeological Society pp. 86–90.

Fish, S. K. (1989) Appendix B: The Beidha pollen record. In *The Natufian Encampment at Beidha, Late Pleistocene Adaptation in the Southern Levant*, ed. B. F. Byrd. Aarhus: Jutland Archaeological Society pp. 91–96.

Ford, T. D. and Pedley, H. M. (1996) A review of tufa and travertine deposits of the world. *Earth Science Reviews* **41**: 117–175.

Garnett, E. R., M. A. Gilmour, P. J. Rowe, J. E. Andrews and R. C. Preece (2004) Th-230/U-234 dating of Holocene tufas: possibilities and problems. *Quaternary Science Reviews* **23**: 947–958.

Garrard, A., S. Colledge and L. Martin (1996) The emergence of crop cultivation and caprine herding in the 'marginal zone' of the southern Levant. In *The Origins and Spread of Agriculture and Pastoralism in Eurasia*, ed. D. R. Harris. London: University College pp. 204–226.

Gebel, H. G. K. and J. M. Starck (1985) Investigations into the Stone Age of the Petra Area (Early Holocene Research): a preliminary report on the 1984 campaigns. *Annual of the Department of Antiquities of Jordan* **29**: 89–114.

Geyh, M. A. (2001) Reflections on the ^{230}Th/U dating of dirty material. *Geochronometria* **20**: 9–14.

Geyh, M. A. (2008) Selection of suitable data sets improves ^{230}Th/U dates of dirty material. *Geochronometria* **30**: 69–77.

Goodfriend, G. A. (1999) Terrestrial stable isotope records of Late Quaternary paleoclimates in the eastern Mediterranean region. *Quaternary Science Reviews* **18**: 501–513.

Hays, P. D. and E. L. Grossman (1991) Oxygen isotopes in meteoric calcite cements as indicators of continental palaeoclimate. *Geology* **19**: 441–444.

Helbaek, H. (1966) Appendix A – Pre-Pottery Neolithic farming at Beidha: a preliminary report. *Palestine Exploration Quarterly* **98**: 61–66.

Henry, D. O. (1997) Prehistoric human ecology in the southern Levant east of the Rift from 20 000–6 000 BP. *Paleorient* **23**: 107–119.

Hercman, H. and T. Goslar (2002) Uranium-series and radiocarbon dating of speleothems – methods and limitations. *Acta Geological Polonica* **52**: 35–41.

Hourani, F. and M.-A. Courty (1997) L'évolution climatique de 10 500 à 5500 B.P. dans la vallée du Jourdain. *Paleorient* **23**: 95–105.

Hunt, C. O., H. A. Elrishi, D. D. Gilbertson *et al*. (2004) Early-Holocene environments in the Wadi Faynan, Jordan. *The Holocene* **14**: 921–930.

Kirkbride, D. (1960) The excavation of a Neolithic village at Seyl Aqlat, Beidha, near Petra. *Palestine Exploration Quarterly* **92**: 136–145.

Kirkbride, D. (1966) Five seasons at the Pre-Pottery Neolithic village of Beidha in Jordan. *Palestine Exploration Quarterly* **98**: 8–72.

Kirkbride, D. (1968) Beidha: Early Neolithic village life south of the Dead Sea. *Antiquity* **42**: 263–274.

Kirkbride, D. (1985) The environment of the Petra region during the Pre-Pottery Neolithic. In *Studies in the History and Archaeology of Jordan II*, ed. A. Hadidi. Amman: Department of Antiquities pp. 117–124.

Kirkbride, D. (1989) Preface. In *The Natufian Encampment at Beidha, Late Pleistocene Adaptation in the Southern Levant*, ed. B. F. Byrd. Aarhus: Jutland Archaeological Society pp. 7–8.

Kujit, I. and A. N. Goring-Morris (2002) Foraging, farming and social complexity in the Pre-Pottery Neolithic of the South-Central Levant: a review and synthesis. *Journal of World Prehistory* **16**: 361–439.

Liutkus, C. M., J. D. Wright, G. M. Ashley and N. E. Sikes (2005) Paleoenvironmental interpretation of lake-margin deposits using δC-13 and δO-18 results from early Pleistocene carbonate rhizoliths, Olduvai Gorge, Tanzania. *Geology* **33**: 377–380.

Ludwig, K. R. (2001) *ISOPLOT/Ex Rev. 2.49*. Boulder, CO: United States Geological Survey.

Ludwig, K. R. and D. M. Titterington (1994) Calculation of ^{230}Th/U isochrons, ages, and errors. *Geochimica et Cosmochimica Acta* **58**: 5031–5042.

Magaritz, M. and J. Heller (1980) A desert migration indicator – oxygen isotopic composition of land snail shells. *Palaeogeography Palaeoclimatology Palaeoecology* **32**: 153–162.

Mallick, R. and N. Frank (2002) A new technique for precise uranium-series dating of travertine micro-samples. *Geochimica et Cosmochimica Acta* **66**: 4261–4272.

Matsuoka, J., A. Kano, T. Oba *et al*. (2001) Seasonal variation of stable isotopic compositions recorded in a laminated tufa, SW Japan. *Earth and Planetary Science Letters* **192**: 31–44.

McLaren, S. J., Gilbertson, D. D., Grattan, J. P. *et al*. (2004) Quaternary palaeogeomorphologic evolution of the Wadi Faynan area, southern Jordan. *Paleogeography Paleoclimatology Paleoecology* **205**: 131–154.

Mithen, S. J. (2003) *After the Ice: A Global Human History, 20,000–5000 BC*. London: Weidenfeld and Nicolson.

Moore, A. M. T. and G. C. Hillman (1992) The Pleistocene to Holocene transition and human economy in Southwest Asia: the impact of the Younger Dryas. *American Antiquity* **57**: 482–494.

Mortensen, P. (1970) A preliminary study of the chipped stone industry from Beidha. *Acta Archaeologica* **41**: 1–54.

Neumann, F. H., E. J. Kagan, M. J. Schwab and M. Stein (2007) Palynology, sedimentology and palaeoecology of the late Holocene Dead Sea. *Quaternary Science Reviews* **26**: 1476–1498.

O'Brien, G. R., D. S. Kaufman, W. D. Sharp *et al*. (2006) Oxygen isotope composition of annually banded modern and Mid-Holocene travertine and evidence of paleomonsoon floods, Grand Canyon, Arizona, USA. *Quaternary Research* **65**: 366–379.

O'Neil, J. R., R. N. Clayton and T. K. Mayeda (1969) Oxygen isotope fractionation of divalent metal carbonates. *Journal of Chemical Physics* **30**: 5547–5558.

Olszewski, D. I. (1991) Social complexity in the Natufian? Assessing the relationship of ideas and data. In *Perspectives on the Past: Theoretical Biases in Mediterranean Hunter-Gatherer Research*, ed. G. Clark. Philadelphia: University of Pennsylvania Press pp. 322–340.

Pedley, H. M. (1990) Classification and environmental models of cool freshwater tufas. *Sedimentary Geology* **68**: 143–154.

Pedley, M., J. A. G. Martin, S. O. Delgado and M. G. Del Cura (2003) Sedimentology of Quaternary perched springline and paludal tufas: criteria for recognition, with examples from Guadalajara Province, Spain. *Sedimentology* **50**: 23–44.

Pentecost, A. (1995) The Quaternary travertine deposits of Europe and Asia Minor. *Quaternary Science Reviews* **14**: 1005–1028.

Perkins Jr, D. (1966) Appendix B – Fauna from Madamagh and Beidha: a preliminary report. *Palestine Exploration Quarterly* **98**: 66–67.

Portillo, M., R. M. Albert and D. O. Henry (2009) Domestic activities and spatial distribution in Ain Abu Nukhayla (Wadi Rum, Southern Jordan): the use of phytoliths and spherulites studies. *Quaternary International* **193**: 174–183.

Quade, J., J. A. Rech, C. Latorre *et al*. (2007) Soils at the hyperarid margin: the isotopic composition of soil carbonate from the Atacama Desert, Northern Chile. *Geochimica et Cosmochimica Acta* **71**: 3772–3795.

Raikes, R. (1966) Appendix C – Beidha: prehistoric climate and water supply. *Palestine Exploration Quarterly* **98**: 68–72.

Robinson, S. A., S. Black, B. Sellwood and P. J. Valdes (2006) A review of palaeoclimates and palaeoenvironments in the Levant and Eastern Mediterranean from 25,000 to 5000 years BP: setting the environmental background for the evolution of human civilisation. *Quaternary Science Reviews* **25**: 1517–1541.

Rohling, E. J. and H. Palike (2005) Centennial-scale climate cooling with a sudden cold event around 8,200 years ago. *Nature* **434**: 975–979.

Rollefson, G. (1998) The Aceramic Neolithic of Jordan. In *The Prehistoric Archaeology of Jordan*, ed. D. O. Henry. Oxford: British Archaeology Reports pp. 102–126.

Rollefson, G. (2001) The Neolithic period. In *The Archaeology of Jordan*, ed. B. MacDonald, R. Adams and P. Bienkowski. Sheffield: Sheffield University Press pp. 67–105.

Rollefson, G. and I. Köhler-Rollefson (1989) The collapse of early Neolithic settlements in the southern Levant. In *People and Culture in Change: Proceedings of the Second Symposium on Upper Palaeolithic, Mesolithic and Neolithic Populations of Europe and the Mediterranean Basin*, ed. I. Hershkovitz. Oxford: Oxbow pp. 73–89.

Rowe, P. J. and B. A. Maher (2000) 'Cold' stage formation of calcrete nodules in the Chinese Loess Plateau: evidence from U-series dating and stable isotope analysis. *Palaeogeography Palaeoclimatology Palaeoecology* **157**: 109–125.

Rozanski, K., L. Araguas-Araguas and R. Gonfiantini (1993) Isotopic patterns in modern global precipitation. In *Climate Change in Continental Isotopic Records*, ed. P. K. Swart, K. C. Lohman, J. A. McKenzie and S. Savin. Washington, DC: American Geophysical Union pp. 1–36.

Sanlaville, P. (1996) Changements climatiques dans la région levantine à la fin du Pléistocène supérieur et au début de l'Holocène. Leurs relations avec l'évolution des sociétés humaines. *Paleorient* **22**: 7–30.

Sanlaville, P. (1997) Les changements dans l'environnement au Moyen-Orient de 20 000 BP à 6 000 BP. *Paleorient* **23**: 249–262.

Smith, J. R., R. Giegengack and H. P. Schwarcz (2004) Constraints on Pleistocene pluvial climates through stable-isotope analysis of fossil-spring tufas and associated gastropods, Kharga Oasis, Egypt. *Palaeogeography Palaeoclimatology Palaeoecology* **206**: 157–175.

Soligo, M., P. Tuccimei, R. Barberi *et al*. (2002) U/Th dating of freshwater travertine from Middle Velino Valley (Central Italy): paleoclimatic and geological implications. *Palaeogeography Palaeoclimatology Palaeoecology* **184**: 147–161.

Staubwasser, M. and H. Weiss (2006) Holocene climate and cultural evolution in late prehistoric-early historic West Asia – Introduction. *Quaternary Research* **66**: 372–387.

Stein, M., A. Torfstein, I. Gavrieli and Y. Yechieli (2010) Abrupt aridities and salt deposition in the post-glacial Dead Sea and their North Atlantic connection. *Quaternary Science Reviews* **29**: 567–575.

Stordeur, D., D. Helmer and G. Willcox (1997) Jerf el ahmar, un nouveau site de l'horizon PPNA sur le moyen Euphrate syrien. *Bulletin de la Société préhistorique française* **94**: 282–285.

Tchernov, E. (1997) Are late Pleistocene environmental factors, faunal changes and cultural transformations causally connected? The case of the southern Levant. *Paleorient* **23**: 209–228.

Weninger, B., E. Alram-Stern, E. Bauer *et al*. (2006) Climate forcing due to the 8200 cal yr BP event observed at Early Neolithic sites in the eastern Mediterranean. *Quaternary Research* **66**: 401–420.

Zak, K., V. Lozek, J. Kadlec, J. Hladikova and V. Cilek (2002) Climate-induced changes in Holocene calcareous tufa formations, Bohemian Karst, Czech Republic. *Quaternary International* **91**: 137–152.

Zanchetta, G., M. Di Vito, A. E. Fallick and R. Sulpizio (2000) Stable isotopes of pedogenic carbonates from the Somma-Vesuvius area, southern Italy, over the past 18 kyr: palaeoclimatic implications. *Journal of Quaternary Science* **15**: 813–824.

Zohary, M. (1962) *Plant Life of Palestine: Israel and Jordan*. New York: Roland Press.