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Alluvial deposition and lake-level fluctuations forced by Late Quaternary climate change: the Dead Sea case example

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Abstract

Based on geomorphic observations, we discuss lake-level fluctuations, alluvial deposition and river entrenchment in the Dead Sea–Wadi Araba area. The bulk of alluvium in the northern Wadi Araba was probably deposited before the Lisan period of lake transgression that started at about 70 kyears B.P. The lake reached a maximum elevation about 150 m below sea level (b.s.l.), possibly around 15 cal. kyears B.P. as indicated by the highest preserved beach ridges. Cosmogenic exposure dates show that the ridge material consists mainly of remobilized Pleistocene gravel indicating little sediment supply during most of the Lisan period. During this period, a reduced sediment flux fed subaquatic fan deltas along the margin of the Dead Sea. Wetter conditions settled at the end of this period, the water level rose to about 280 m b.s.l. around 15 kyears B.P. and prevailed in the early Holocene (10.5–7 cal. kyears B.P.). Following that humid period, the lake level dropped and two major episodes of fluvial aggradation occurred during periods of relative low lake level. The first aggradational episode took place between about 7.0 and 6.2 cal. kyears B.P. Beach bars indicate a subsequent lake transgression between 6.2 and 4.4 kyears B.P. up to 350 m b.s.l. The second aggradational episode happened between 4.4 and 2.0 cal. kyears B.P., and was also followed by a late transgression up to 375 m b.s.l., dated to 1960–1715 cal. years B.P. The correlation between low lake level and fluvial aggradation is taken to reflect the synchronous change of the fluvial regime and of the lake hydrologic balance, forced by climate changes, rather than a base-level control. We also exclude large tectonic forcing on fan emplacement and river entrenchment. Alluviation appears in this setting as a very irregular process, characterized by long periods of quiescence alternating with periods of fan build-up, reflecting the transient response of the water drainage system to climate change.

Keywords: Alluviation; Climate; Fluvial

1. Introduction

The history of sediment flux might constitute some proxy for climatic fluctuations (e.g., Goodbred and Kuehl, 2000), particularly in arid environments, which are known to be highly sensitive to climate changes (e.g., Bull, 1991; Harvey, 1997; Harvey et al., 1999), but relationships are in no manner clear. Factors other than a direct effect of climate on hydrology may, however, also influence aggradation/incision processes. They include base-level changes induced by sea-level or lake-level changes or tectonics (e.g., Merritts et

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al., 1994), changes in the sediment production delivered to the fluvial system induced by climate changes or by active tectonics (e.g., Tucker and Slingerland, 1996) or internal geomorphic adjustment within the catchment and fan system, a response that depends on the size and lithology of the system (Bull, 1991). In addition, the history of sediment flux depends upon the spatial extent and timing of aggradation and incision phases that are, in turn, modulated by the vegetation and its evolution in response to climate change (Knox, 1984; Bull, 1991). Nearby watersheds may respond very differently to climate change and slightly different climate changes might produce very different geomorphic responses. Such complexity might totally obscure the climatic control on the timing and extent of episodes of aggradation and incision. In this paper, we address this question on the basis of geomorphic observations around the Dead Sea.

The Dead Sea area has long been recognized as a particularly appropriate area to investigate the geomorphic impact of Late Quaternary climate change (e.g., Grossman and Gerson, 1987; Bull, 1991). The Dead Sea rift has formed a lacustrine closed basin (e.g., Garfunkel et al., 1981). Dissection of the steep flank of the rift has fed alluvial fans that interfinger downstream with lacustrine sediments and bear cross-cutting relationships with shoreline features. This particular setting makes it possible to assess to what extent fan alluviation may have been driven by lake-level fluctuations or tectonic uplift of the rift flanks, rather than by climate changes (e.g., Frostick and Ried, 1989). This study takes advantage of previous investigations of lake-level fluctuations, geomorphology and stratigraphy (e.g., Klein, 1982; Begin et al., 1985; Frumkin et al., 1991; Yechieli et al., 1993; Bowman, 1971; Sneh, 1979; Goodfriend et al., 1986; Bowman and Gross, 1992). We also report some new ^{14}C dates, U/Th dates and exposure ages derived from ^{10}Be cosmogenic isotopes. This study aims primarily at a better understanding of the geomorphic impact of climate change but is also of importance for active tectonic investigations. Assessing the climatic control on morphogenesis is indeed a major issue in that respect because slip rates on faults are often determined from offset of geomorphic features (e.g., Ginat et al., 1998; Klinger et al., 2000; Niemi et al., 2001). A clear correlation between morphogenetic episodes and fluctuations of regional climate might help provide chronological constraints in addition to direct dating (e.g., Noller et al., 2000).

In the following sections, we briefly describe the geomorphic setting and then report some results from local investigations at a few key sites. We present these data in the context of variations in lake level, and we suggest a temporal scheme for the emplacement of the different alluvial surfaces in this region. Although internal adjustment of the geomorphic system is probably responsible for some of the complexity of the geomorphic record, we show that climate change has left a major and identifiable geomorphic signature.

2. Geomorphic setting

The study area encompasses the Dead Sea basin, a pull-apart basin on the Dead Sea transform fault system. The basin is bordered by steep normal fault scarps (e.g., Freund et al., 1968; Garfunkel et al., 1981; Ben-Avraham, 1997). The northern Wadi Araba valley, to the south of the Dead Sea, is bounded to the east by a main strike-slip strand of the Dead Sea fault (Fig. 1). The alluvial surfaces in the study area were initially mapped on aerial and satellite views (SPOT and Landsat). These surfaces were classified based on their relative elevation, their morphological facies and their color tone, which is mainly indicative of the degree of development of desert pavement and varnish. Three main classes are generally distinguished in the region (e.g., Grossman and Gerson, 1987) and can indeed be identified on the images (Fig. 2). Smooth and well-developed desert pavement with weathered boulders and pebbles characterizes the first group of surfaces, of presumed Pleistocene age. They can be identified from their dark chromatic signature. Active flood plains, consisting of bare gravel with no desert pavement or varnish, forming braided channels, are also easily identifiable from their relatively bright signature on the images. The third group of terraces, which are intermediate in age and elevation, are characterized by a bar-and-swale morphology, poorly developed desert pavement, little varnish and low to moderate weathering of pebbles. They are assigned Holocene ages.

Around the Dead Sea lake margin, the alluvial surfaces, which are confined to the very coastal area, mainly fall into the intermediate category. They consist

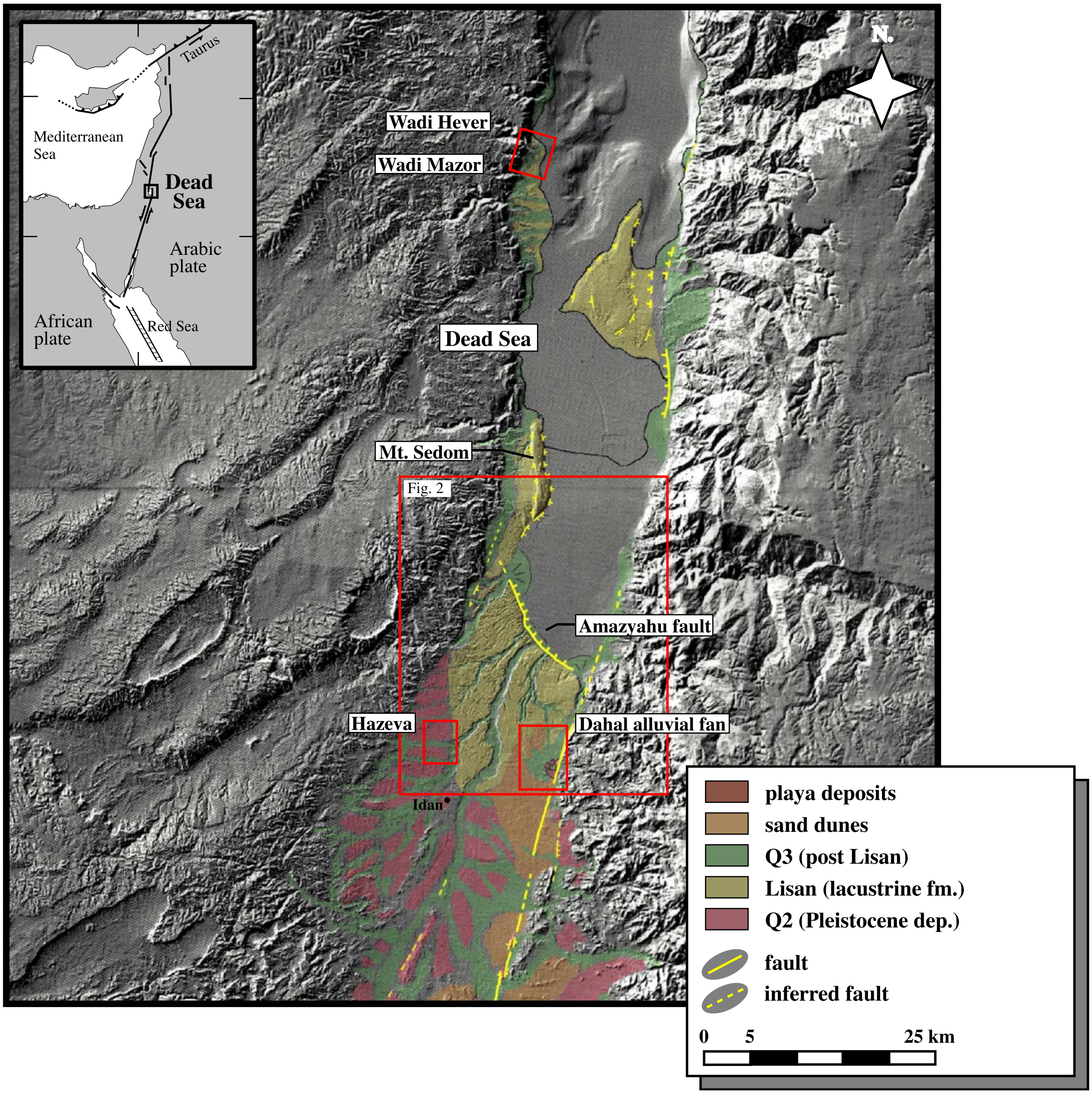

Fig. 1. Morphotectonic map of study area. Shaded topography adapted from Hall (1994). Tectonic features and geomorphic interpretation are derived from Garfunkel et al. (1981), complemented by satellite images, air photos and field survey. Boxes show locations of (Figs. 2, 3, 5 and 7), respectively.

of a narrow talus apron at the base of the cliffs and well-individualized fans at the outlet of the major canyons. The upper terrace treads overlie, or are inset, into subaquatic fan delta deposits (e.g., Sneh, 1979; Bowman, 1988). In contrast, the Wadi Araba valley, just south of the Dead Sea Lake, is floored with well-preserved Pleistocene surfaces, with some patches of more recent alluviums lying at about the same elevation. It suggests that no large aggradational episode has occurred there since the Pleistocene terraces were

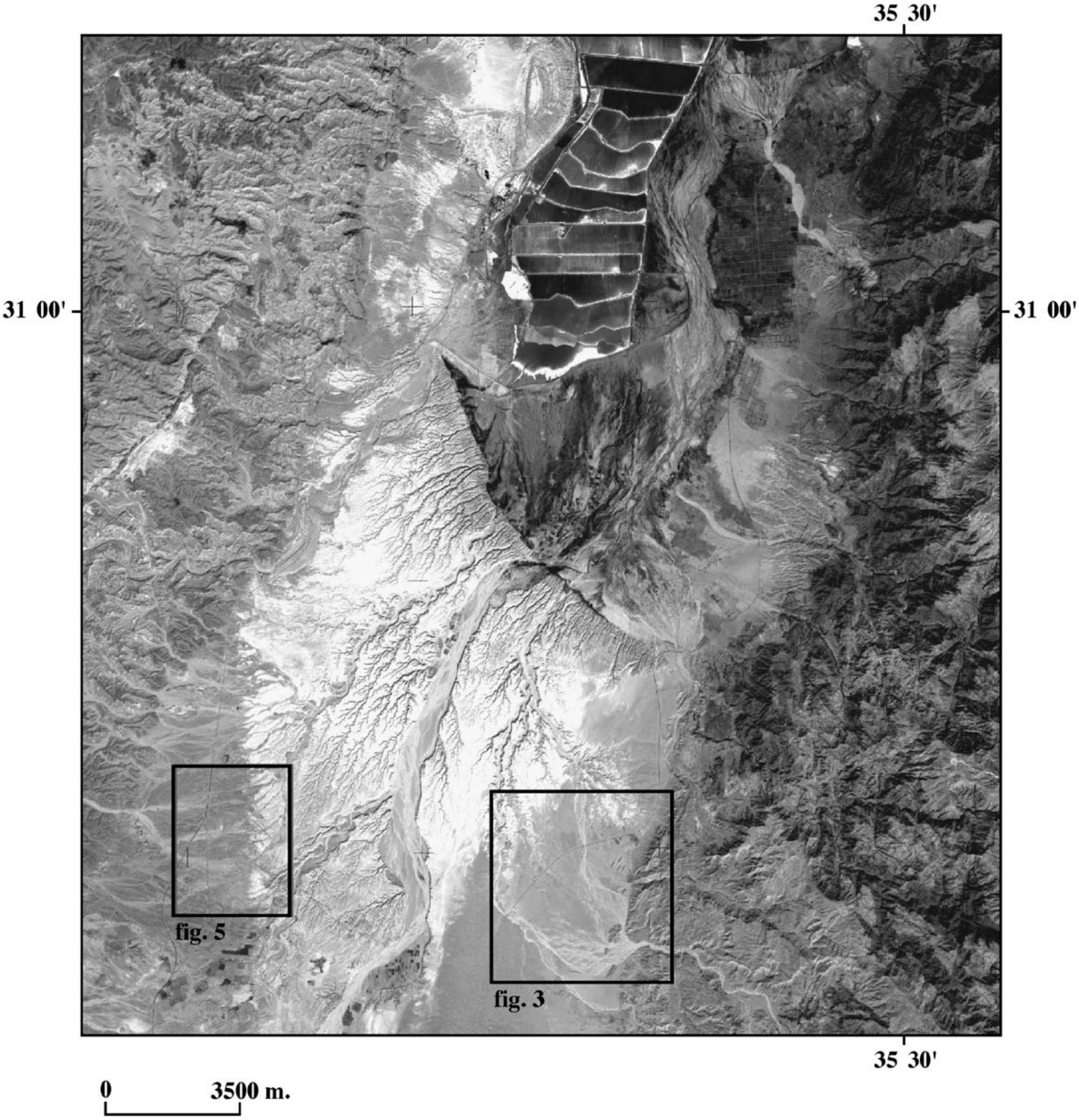

Fig. 2. Satellite image of the Northern Wadi Araba. The different colors of the surfaces allow to differentiate the terraces and to recognize the stratigraphic relationship between different units. Boxes show location of Figs. 3 and 5.

abandoned, and that there have been no large vertical motions. At the southern tip of the Dead Sea, the alluvial surfaces merge with extensive outcrops of yellow-white lacustrine sediments (Fig. 2). These sediments belong to the Lisan Formation that was deposited during the late Pleistocene high stand of the Dead Sea (Druckman et al., 1987; Kaufman et al., 1992).

Based on the air photo survey, we selected a few key sites for field investigations. Two sites were chosen south of the Dead Sea basin. Site 1 is located on the largest alluvial fan in the study area, which lies at the outlet of Wadi Dahal on the eastern side of the Araba valley (Figs. 1 and 2). This site was selected because in this area, Pleistocene alluviums merge with lacustrine sediments, allowing for some investigation of how Pleistocene aggradation relates to lacustrine sedimentation. The second site lies on the western side of the valley, near En Hazeva. This is where the highest known coastal features around the Dead Sea have been observed (Bowman and Gross, 1992). Visible on the SPOT images (Figs. 1, 2 and 5), they consist of beach ridges left at an elevation of up to 150 m b.s.l. (Figs. 1, 2 and 5) over the pediment alluvium. A third site that lies close to the coastline of the Dead Sea, the Wadi Hever alluvial fan, was chosen to address the lower water level period.

Fieldwork was conducted to check the photo-mapping and to clarify the relationships between the different units. Various dating methods have been used, according to the material available, including ^{10}Be cosmogenic isotopes dating, U/Th series dating and ^{14}C dating, to place additional constraints on the age of the different surfaces exposed.

3. Results from local investigations

3.1. The Dahal alluvial fan (Site 1), Northern Wadi Araba

The Wadi Dahal is an ephemeral stream incising the eastern flank of the Araba valley. This large

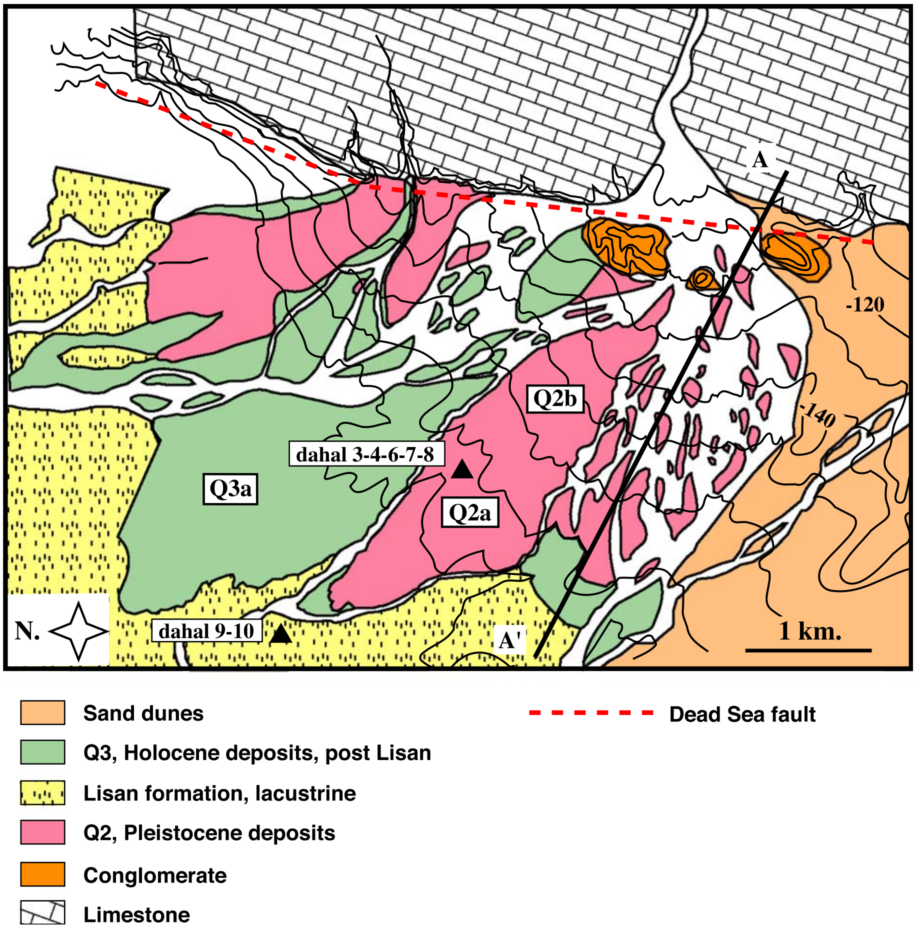

Fig. 3. The Wadi Dahal fan shows a Pleistocene terrace overlapped by lacustrine sediments from the Lake Lisan. During the Holocene, the Q3 terraces have prograded on the top of the lacustrine sediments.

alluvial fan (Fig. 3) covers an area of about 11 km^2. Some parts of this fan are still drained by ephemeral channels, but the large areas of alluviums preserved from recent wash are probably rather old. These patches are indeed paved with weathered limestone cobbles and pebbles (Q2b in Fig. 3). A more recent surface (labeled Q3a in Fig. 3) is slightly inset into Q2a. The fan is only slightly dissected, except near its toe where the few streams that reach the Dead Sea have incised narrow channels, probably by headward erosion in response to Holocene Dead Sea level changes. A section following one of those streams (AA′ in Fig. 3) was surveyed. The fanglomerates interfinger downstream with lacustrine sediments (Fig. 3) characterized by aragonite laminae. Although the lacustrine sediments are always interlayered with some gravel layers, the bulk of the subaerial fan deposits Q2 can be traced downstream below the lacustrine dominated sediments. The transition is marked by a break-in-slope at an elevation of about 160 m b.s.l. (Fig. 4). The Lisan Formation, thus, appears to be transgressive over the Q2 fanglomerates that form the bulk of the Dahal fan. The Q3a alluvium that is inset into Q2, grades downstream into a gravel sheet that caps the lacustrine Lisan deposits. It indicates that Q3 was emplaced after the lacustrine period.

We sampled aragonite laminae at two sites, DAHAL-10 at an elevation of about 190 m b.s.l. and DAHAL-9 at an elevation of 200 m b.s.l. These samples were dated by U/Th, following the radiochemical procedure of Ku (1976). The highest sample, DAHAL-10, yields an age of 26.6 ± 1.8 kyears. DAHAL-9, sampled about 10 m lower, yields an age of 31.5 ± 2 kyears (Table 1). Those two ages are consistent with their relative stratigraphic position and with the ages reported by Kaufman et al. (1992) for the Lisan formation, between 63 and 15 kyears B.P. These results place a minimum age of about 31 kyears for the deposition of Q2 on the Dahal fan.

Rocks samples were collected at the undisturbed surface of the fan in a site located above the Lisan

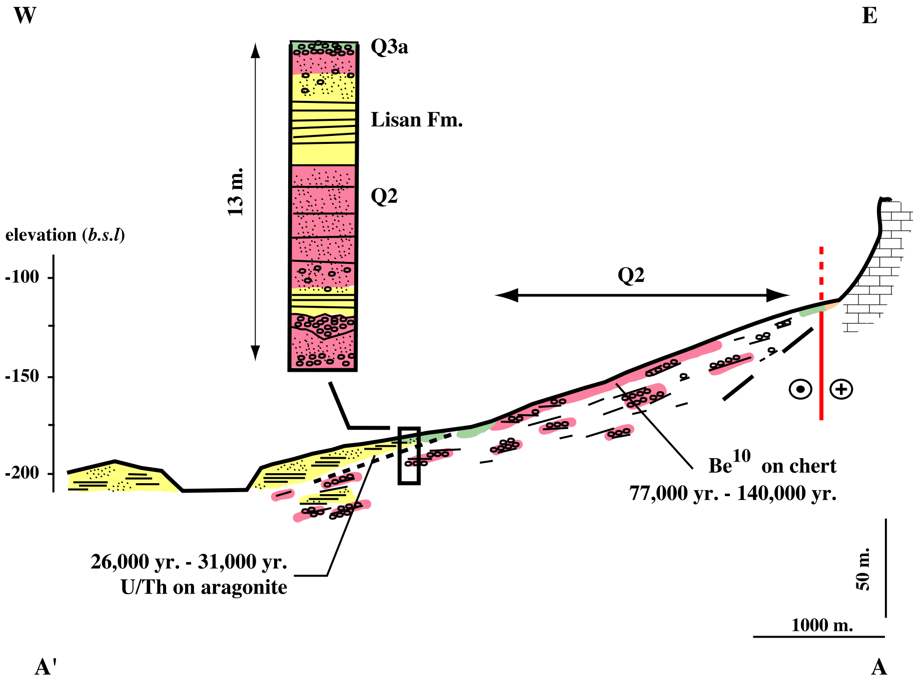

Fig. 4. Topographic cross-section of the Wadi Dahal fan (located on Fig. 3). The break-in-slope indicates the beginning of the lacustrine units on top of the Pleistocene fan. The section has been reconstituted from field observations and dated samples have been reported. Topography from 1/50,000 Jordan topographic maps (sheet 3051 I).

Table 1
U/Th ages of aragonites from the Dahal alluvial fan

Sample	Age (kyears B.P.)	Error (kyears)
DAHAL-9	31.5	2
DAHAL-10	26.6	1.8

transgression (Fig. 3). The duration of their exposure to cosmic rays was estimated using ^{10}Be isotopes (e.g., Gosse and Philips, 2001). The technique applies best to quartz but due to of the dominantly limestone lithology, we collected cherts.

In this arid setting, we suspect that the effect of erosion on the fan surface, far from any recent dissection, has been small. Because the data are not sufficient to estimate properly the effect of surface erosion and predeposition exposures, the data listed in Table 2 were computed assuming no erosion. Ages might be biased toward younger ages, however. The samples collected at the surface of the fan (DAHAL 3, 4, 6, 7) yield ages between 32 ± 7 and 140 ± 31 kyears B.P. DAHAL 8 is corrected for sampling depth (60 cm) using a density of 2 g cm^{-3} for the overlying material; the in situ-produced ^{10}Be concentration corresponds to a surficial exposure age of 140 ± 31 kyears B.P. We, therefore, suspect that the dispersion of exposure ages most likely reflect post-alluvial fan surface abandonment processes rather than significant exposure prior to deposition. Since in cases of post-depositional processes, which are generally not uniform across a fan surface, the oldest age in the distribution is closest to the true age (Brook et al., 1993), the upper bound for the surface Q2 abandonment is given by the ^{10}Be age at 140 ± 31 kyears B.P. On the other end, the U/Th ages of the transgressive lacustrine sediments on Q2 imply that the Q2 unit on the Dahal fan was deposited at least 31.5 ± 2 kyears B.P. ago. Finally, the inset fan surface, Q3, was emplaced after the Lisan high stand, which is dated at about 15 kyears B.P. (Kaufman et al., 1992).

3.2. Alluvial pediment and beach ridges in the Hazeva area (Site 2), Northern Wadi Araba

Well-preserved coastal geomorphic features are abundant around the Dead Sea. Among the most conspicuous ones are the wave-cut shore terraces located along the western Dead Sea margin (Bowman, 1971). High beach ridges were also reported and surveyed at the southern tip of the Dead Sea near Hazeva (Bowman and Gross, 1992) on the opposite side of the Araba valley relative to the Wadi Dahal. They form a sequence of arcuate bars built over an alluvial pediment made of coalescent fan terraces (Fig. 5a and b). The best-developed ridges are about 3 m high (Fig. 6). They can be traced over several hundred meters to several kilometers on the SPOT image (Fig. 5a).

The ridges are mainly built of well-sorted sandy and gravely layers dipping away from the basin, forming backsets. Such a structure, which is typical of beach ridges, probably reflects gradual incorporation of material brought by wave run-up during lake-level rising periods (Thompson, 1992). Beach ridges may have formed preferentially at the southern tip of the Dead Sea because at this location, the lake was transgressive over a smooth and gently sloping alluvial pediment. This configuration, added to the hairpin geometry of the southern tip of the lake, may indeed have contributed to a local amplification of waves.

The uppermost ridge lies at an elevation of 150 m b.s.l. (Fig. 5b), which is significantly higher than the

Table 2
^{10}Be concentrations and apparent exposure ages of the cobbles collected on the Dahal fan

Sample	Number of events	^{10}Be concentration (at/g)	^{10}Be error (at/g)	Sampling depth (cm)	Surficial ^{10}Be concentration (at/g)	T_{min} (corrected) (years B.P.)	T_{min} error
DAHAL-3	63	5.13e+05	6.95e+04	0	5.13e+05	120,000	2.9e+04
DAHAL-4	105	1.42e+05	1.56e+04	0	1.42e+05	32,000	7.4e+03
DAHAL-6	145	5.9e+05	5.71e+04	0	5.90e+05	140,000	3.1e+04
DAHAL-7	100	3.34e+05	3.73e+04	0	3.34e+05	77,000	1.8e+04
DAHAL-8	99	2.63e+05	2.95e+04	60	5.86e+05	140,000	3.1e+04

According to the site elevation, 150 m b.s.l., and latitude: 30°50N, the production rate is 4.43 at/g/year. Uncertainties based on analytical errors.

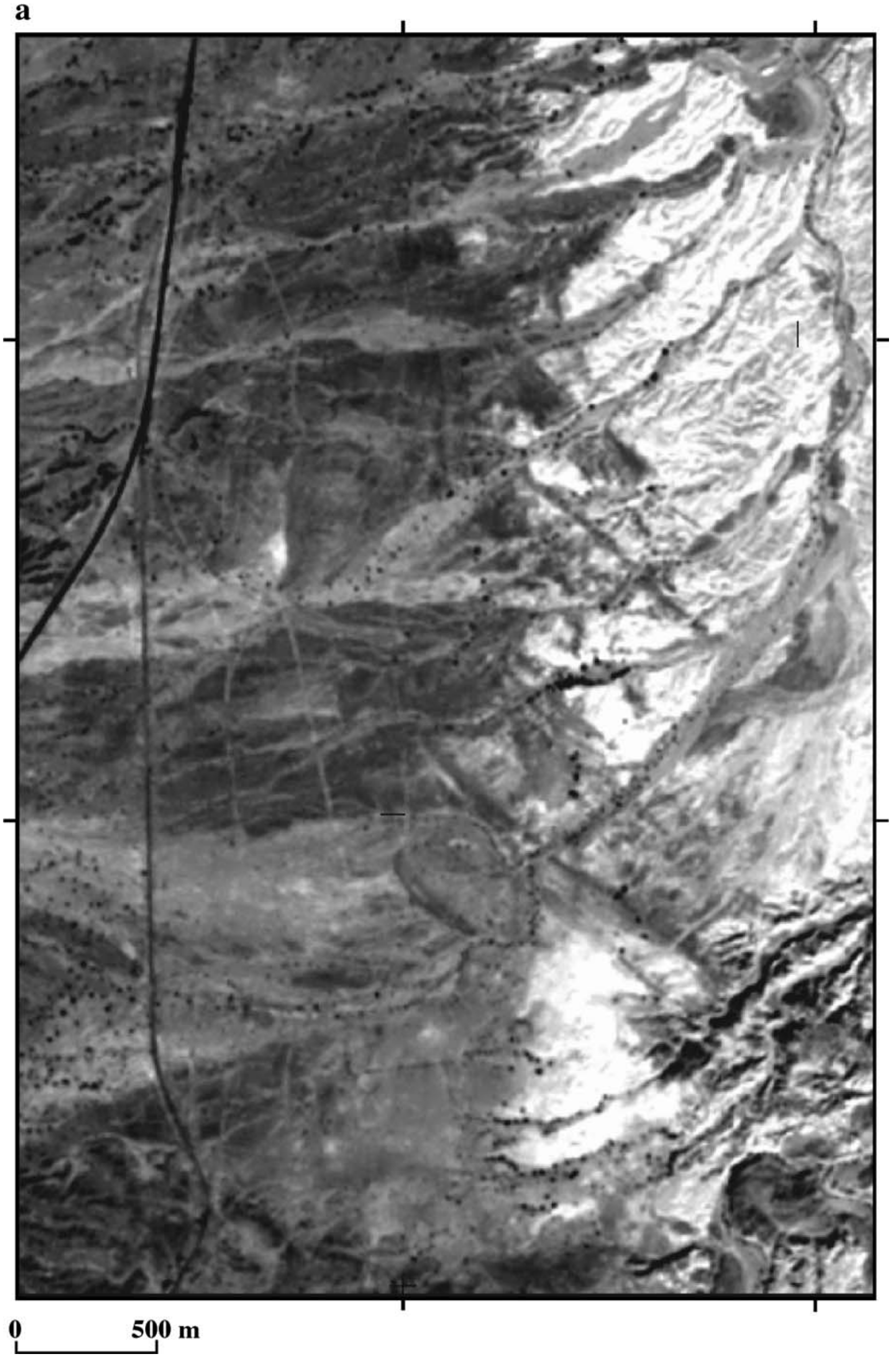

Fig. 5. SPOT view (a) and interpretative map (b) of En Hazeva area. The surfaces of different age can be distinguished from tonal differences. The linear features oriented NW–SE are beach ridges. See Fig. 2 for location.

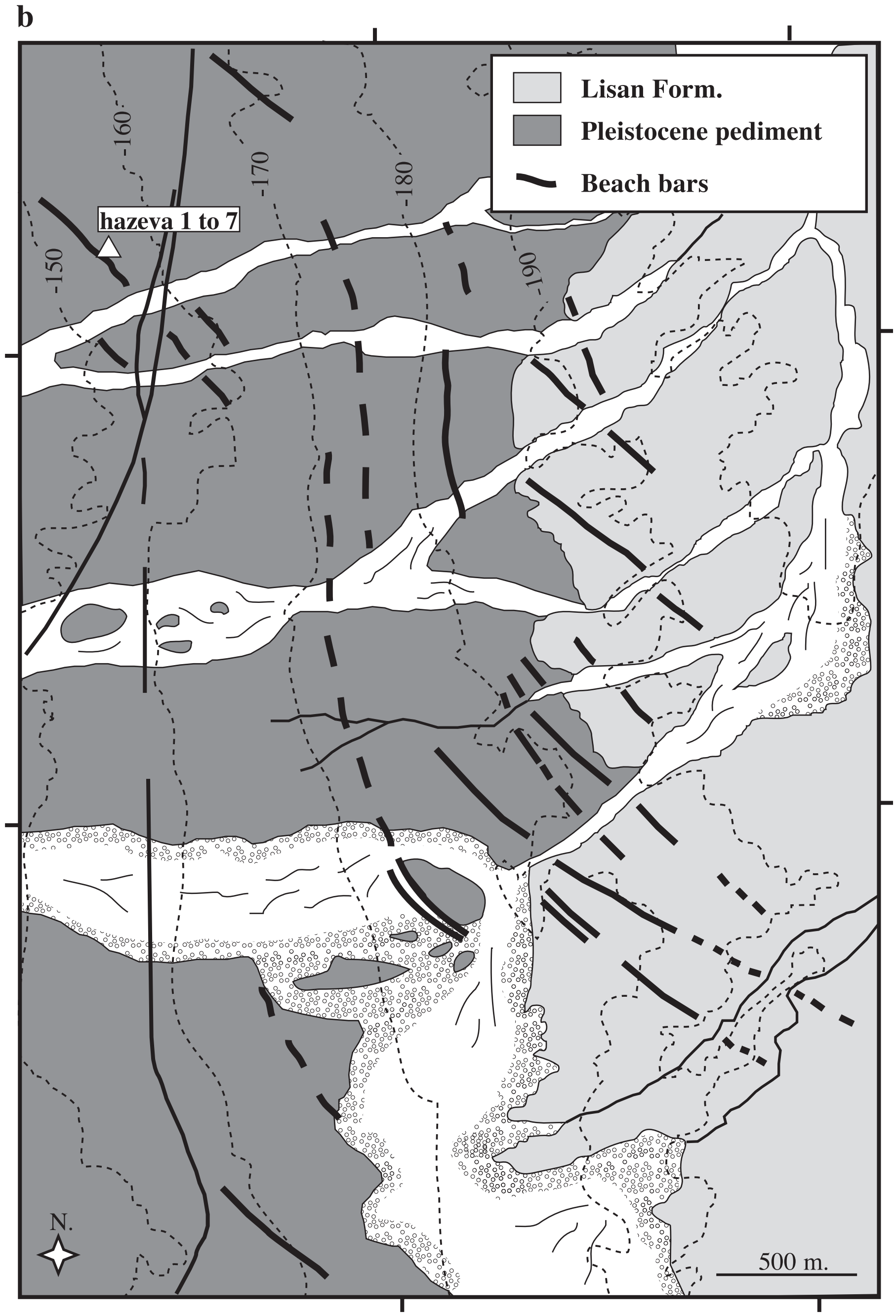

Fig. 5 (*continued*).

elevation generally ascribed to the uppermost level of the Lake Lisan of 180 m b.s.l. (Neev and Emery, 1967; Begin et al., 1974; Druckman et al., 1987; Goldberg, 1994), but close to the 140–150 m b.s.l. elevation of shore features observed at the northern edge of the Dead Sea and interpreted as uplifted by

Fig. 6. Typical view of a beach ridge at Hazeva site.

tectonics (Macumber and Head, 1991). The location of the site of Hazeva, north of the Idan fault (located just south of the city of Idan) (Fig. 1), makes it improbable that the site could have been uplifted significantly by active deformation because the site lies at the base of normal fault scarps bounding the pull-apart basin. Moreover, the alluvial pediment merges with the intensely dissected Lisan formation at about the same elevation (180 m b.s.l.) as the transgressive Lisan lacustrine over the Dahal fan on the other side of the valley.

Bowman and Gross (1992) have shown that the Hazeva beach ridges are characterized by soil characteristics in the early stage of Reg development (e.g., Amit and Gerson, 1986), consistent with an electric conductivity typical of Holocene surfaces. They, therefore, proposed that although the beach ridges lie 20 m above the previously accepted highest level of the Lake Lisan, they would be related to the Lake Lisan highest stand rather than to some older episode of lake-level high stand.

Some chert samples were collected to determine their cosmic ray exposure ages. Each sample consists of several (5–10) centimetric pebbles collected at the surface within an area 1 m^2 in size near the crest of the ridge (HAZEVA 1–5). Sand layers at depth of 60 and 160–180 cm from the ridge crest were also sampled (HAZEVA-6 and HAZEVA-7, respectively). The minimum exposure ages (erosion is neglected) calculated from the measured in situ-produced ^{10}Be concentrations vary from 18 up to 96 kyears for the samples collected at the surface (Table 3). Ages are, however, consistently increasing with depth. This distribution strongly suggests that the ridge was built by remobilization of material that has been previously exposed to cosmic rays. It gives a maximum age for the ridge of 18 kyears, slightly younger that the 25 kyears age of the last high stand of the Dead Sea (higher than 164 m b.s.l.) proposed by Bartov et al. (2002).

The way the ridge has been emplaced is consistent with the observation that the Lisan formation is transgressive over the pediment. It suggests that little aggradation has taken place over this pediment during the Lisan period. This pediment might be correlated, based on elevation, with the upper terrace, Q2, of the Dahal fan. The only significant episode of aggradation in the area after the development of this Pleistocene pediment corresponds to the gravel sheet Q3 spread on top of the Lisan formation that is observed both at sites 1 and 2.

Table 3
^{10}Be concentrations and apparent exposure ages of the cobbles collected near En Hazeva on a beach ridge (Fig. 5b)

Sample	Number of events	^{10}Be concentration (at/g)	^{10}Be error (at/g)	Sampling depth (cm)	Surficial ^{10}Be concentration (at/g)	$T_{\min}$ (corrected) (years B.P.)	$T_{\min}$ error
HAZEVA-1	111	1.29e+05	1.38e+04	0	1.29e+05	30,000	6800
HAZEVA-2	101	1.47e+05	1.64e+04	0	1.47e+05	34,000	7300
HAZEVA-3	54	7.77e+04	1.13e+04	0	7.77e+04	18,000	4400
HAZEVA-4	116	4.08e+05	4.30e+04	0	4.08e+05	96,000	2200
HAZEVA-5	108	8.53e+04	9.25e+03	0	8.53e+04	20,000	4500
HAZEVA-6	164	2.41e+05	2.23e+04	50	4.69e+05	56,000	12,000
HAZEVA-7	130	5.02e+05	5.07e+04	170	4.84e+06	120,000	27,000

According to the site elevation, 155 m b.s.l., and latitude: 30°50N, the production rate is 4.43 at/g/year. Uncertainties based on analytical errors.

3.3. The Wadi Hever fan sequence (Site 3), western Dead Sea margin

The fan sequences observed along the western shore of the Dead Sea (Sneh, 1979; Amit and Gerson, 1986; Bowman, 1988; Frostick and Ried, 1989) are small fan deltas deposited at the mouth of the major streams draining the fault scarp along the western flank of the Dead Sea Basin. They generally cover an area smaller than 6 km^2. Numerous inset terraces that formed during Late Pleistocene–Holocene entrenchment characterize these alluvial fans (Bowman, 1988). The fan sequence is quite comparable when different rivers are considered. For example, a very similar fan sequence is observed at the mouth of Wadi Mazor and Wadi Hever (Fig. 7a and b). Since the smaller Wadi Mazor fan sequence was deposited much higher in elevation, the similarity cannot be interpreted as due to a common base-level control.

We focused on the Wadi Hever fan sequence (Fig. 7a and b). At this site, conspicuous shorelines were cut into the talus apron at the base of the cliffs. They form nearly horizontal wave-cut terraces (Fig. 8) that lie at elevation higher than 210 m b.s.l. Given that such a high lake level was never reached during the Holocene period (Frumkin, 1997), they were most probably cut during the late Pleistocene lake regression that followed the high stand recorded by the beach ridges at Hazeva site. This puts a minimum age for the development of the talus apron. The section cut by stream incision along the Wadi Hever reveals coarse clastic sediments interbedded with fine-grained lake sediments. The proportion of lacustrine sediments increases downstream (Sneh, 1979; Frostick and Ried, 1989). Basinward, the fan delta grades into carbonates and evaporites (Sneh, 1979). The coarse alluvium forms meter-thick gravel sheets, which were probably laid down during flash flood (Frostick and Ried, 1989). As reported by many authors (e.g., Sneh, 1979), highly localized Gilbert-type foresets and prograding beach bars (Fig. 9) were incorporated into the fan delta. These observations suggest that the fan delta was emplaced under the influence of a rising lake level, probably at the end of the Lisan period, with a relative quiescence in alluvial aggradation (see also Frostick and Ried, 1989).

Younger terraces are clearly inset into the fan delta. These terraces consist only of fluvial gravel up to 5 m thick. Because they do not bear any mark of Late Pleistocene wave-cut shorelines (Fig. 7a and b), they must post-date the Lake Lisan regression. Three principal inset terraces may be distinguished from tonal differences on air photography (Fig. 7a and b). They are labeled Q3a, Q3b and Q3c in reference to the Q3 terrace of the Wadi Dahal fan as they also post-date the Lake Lisan regression. The schematic cross-section of Fig. 9 shows the main relationships between the different terraces. Their geometry suggests that they must have developed during periods of relatively low lake level. They also bear evidence for minor lake transgressions suggesting that periods of alluviation and lake level rise have alternated as depicted in Fig. 10.

Q3b consists of about 5 m of fluvial material overlying fan delta material, as indicated by the foresets and the lacustrine facies with aragonite laminae. A shell collected at a depth of about 6 m below the Q3b gravel (MAZOR-6 in Figs. 7b and 9 and

Fig. 7. (a) Air photo of the Wadi Hever and Wadi Mazor fans along the western coast of the Dead Sea showing the succession of inset terraces, erosional benches on the talus apron and beach ridges. (b) Interpretative map of Wadi Hever and Wadi Mazor fan sequences. The spatial relationship between fluvial terraces and beach ridges constraints the timing of emplacement of the different units. It is noteworthy that whatever the distance to the shoreline and the size, all fans have a similar depositional pattern, denoting of a common factor controlling their evolution.

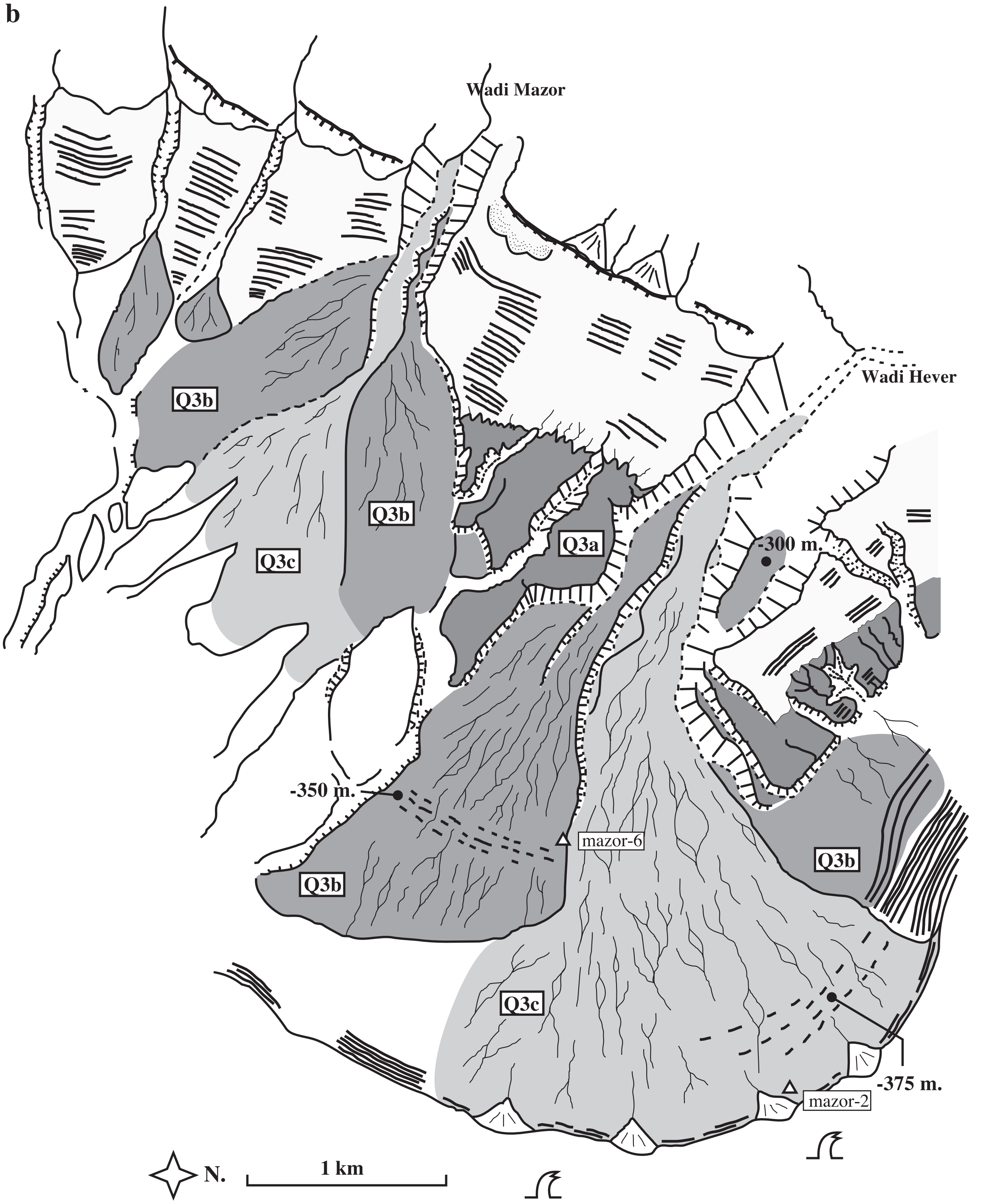

Fig. 7 (*continued*).

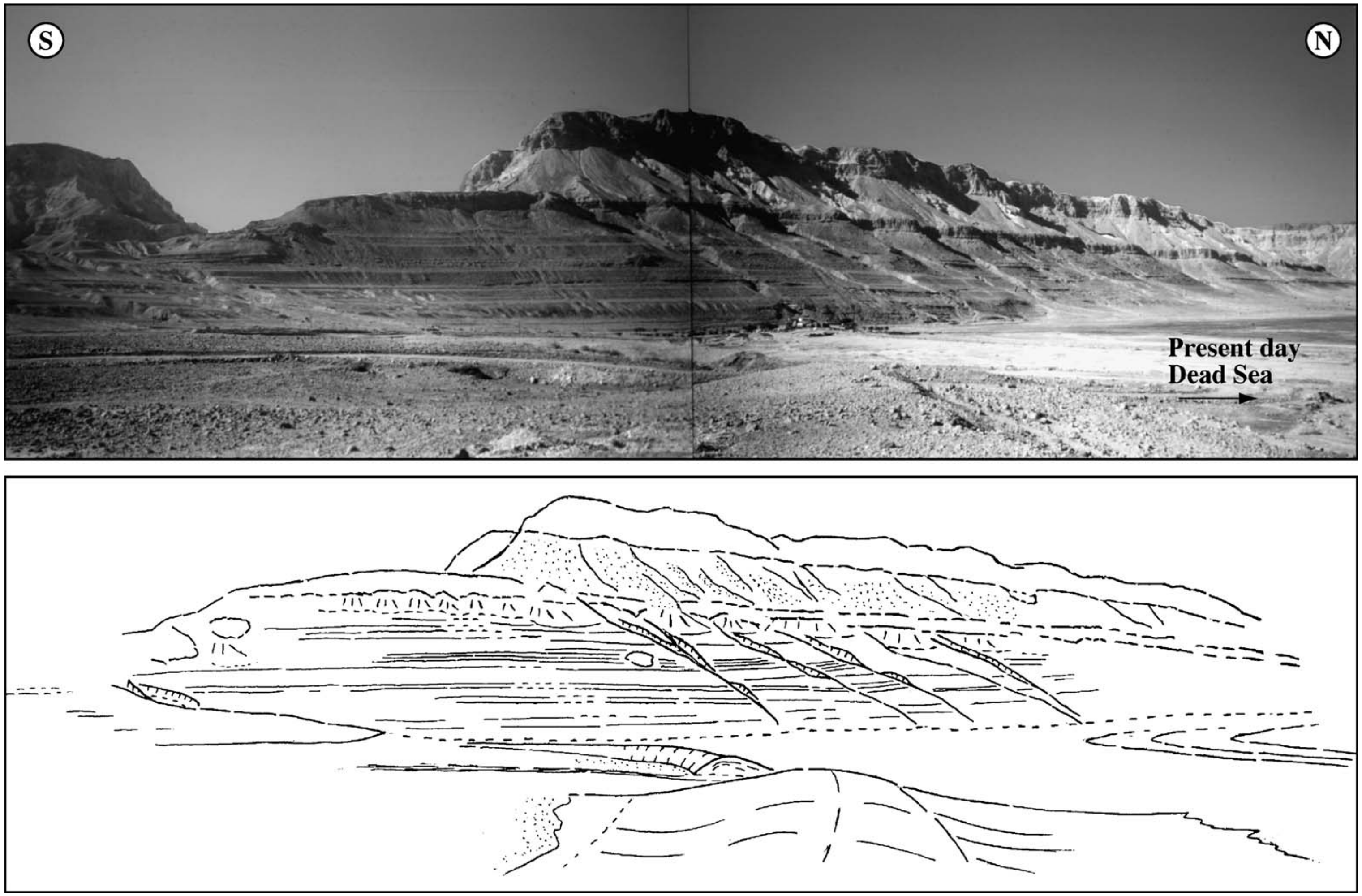

Fig. 8. Field view of one beach ridge on Q3b on the Wadi Hever fan (in foreground) with numerous wave-cut shorelines on the talus apron (background) corresponding to the flank of the Dead Sea basin.

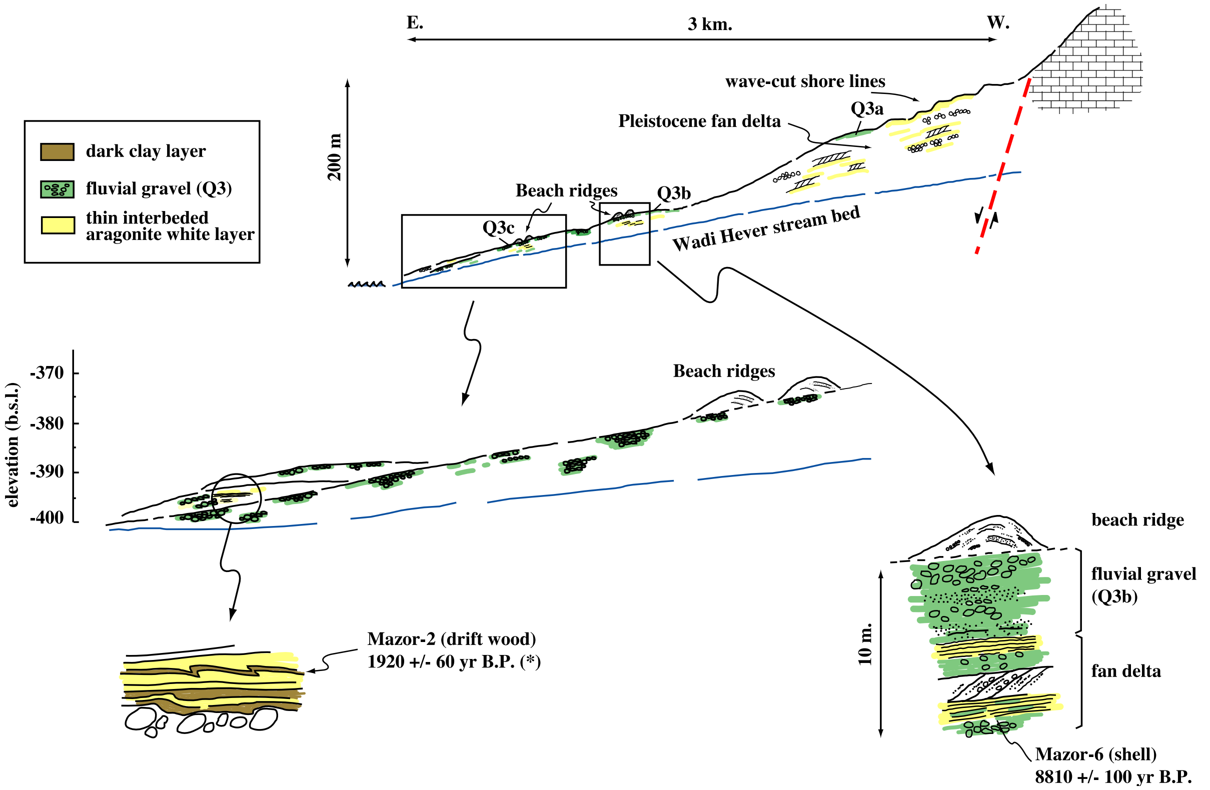

Fig. 9. Schematic section of the Wadi Hever fan describing the main relationships between the different units. A drift wood sample (Mazor-2) was collected in a convoluted lacustrine level transgressive on Q3c alluviums. (*) Aragonite younger than 2000 cal. years B.P. is also reported in similar environment by Kaufman et al. (1992).

Table 4) yields a ^{14}C age of 8810 ± 160 years B.P. (9970–9540 cal. years B.P.). Beach bars built on Q3b terraces at an elevation of about 350 m b.s.l. show that Q3b experienced a minor lake transgression.

Q3c is inset into Q3b. It did not experience the 350 m b.s.l. lake transgression since the beach bars on Q3b cannot be traced across Q3c. Q3c did experience a minor lake transgression, however, as indicated from beach bars left at an elevation of about 375 m b.s.l. Closer to the shore of the Dead Sea, modern lowering of the lake level has induced 1–3 m of incision. This recent entrenchment provides cross-sections at the toe of Q3c alluviums (Fig. 9). The gravely toe is overlain by some lacustrine sediments (clay mixed with some sands and with some aragonite laminae). We collected a sample of driftwood (MAZOR-2 in Fig. 9 and Table 4) in a dark clay layer level draping the Q3c gravel at the toe of the fan. This sample yields a ^{14}C age of 1920 ± 60 years B.P. (1960–1715 cal. years B.P.).

4. Comparing morphological and sedimentological records with lake-level fluctuations

On the basis of our observations and the data available in the literature, we propose some scenario describing the Late Quaternary geomorphic evolution in the study area. All ages are reported as they are found in the literature for easier traceability (calibrated ages are indicated by cal.).

Along the Wadi Araba, most alluvial surfaces, including the Dahal fan at site 1 and the pediment at site 2, have been deposited essentially before the transgression of the Lisan Formation. Based on the ages obtained from this study and the ^{130}Th/^{234}U

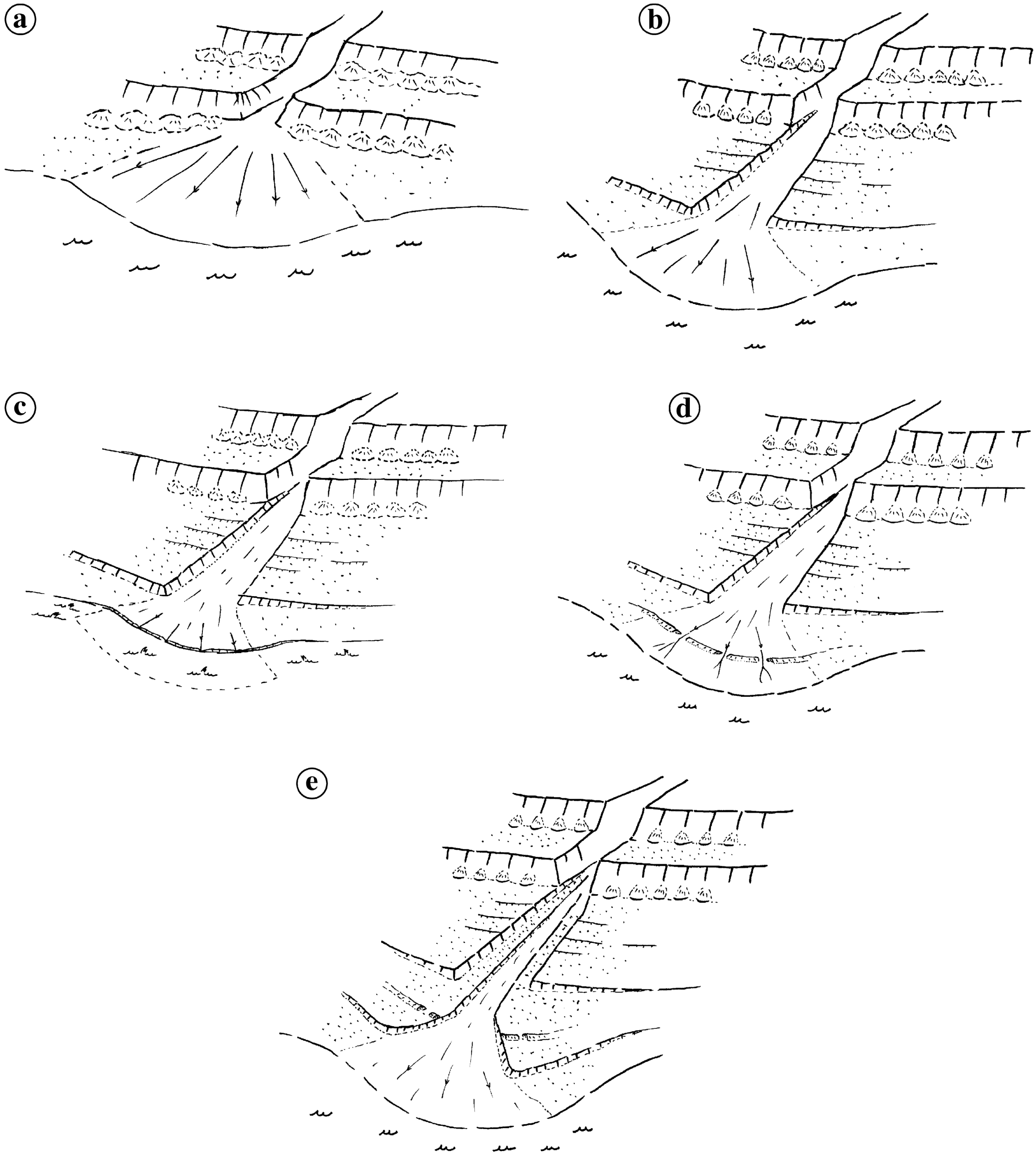

Fig. 10. Sketches showing the emplacement of the different geomorphic features. (a) At time t_0, one fluvial surface is active, which could be assigned to Q3a for example. (b) The lake level drops down. Some wave-cut benches have been carved in the Q3a surface during the recessing of the lake. At some point, the stream just incises the Q3a surface and a new prograding surface, Q3b, is built in front of Q3a. (c) The lake level starts to rise again, flooding the previously active fluvial surface. Beach ridges form on the top the fluvial unit. (d) During a new recessing stage of the lake, parts of the beach ridges are eroded off and new wave-cut are carved in the fluvial surfaces. (e) Eventually, the level of the lake decreases so much that the previously active surface is partly eroded and a new fluvial surface is built in front, Q3c, leaving a perched beach ridge on the abandoned Q3b surface.

Table 4
^{14}C ages measured at the AMS facility of Gif-Sur Yvette (Raisbeck et al., 1994)

Sample	Laboratory number	Type	Fraction	Age[a] (years B.P.)	Error (year)	Calibrated age[b] (years B.P.)
MAZOR-2	GifA98119	Driftwood		1920	60	1960–1715
MAZOR-6	GifA98222	Shell	CACO3	8810	100	9970–9540

[a] Uncalibrated age.
[b] Calibrated according to Stuiver and Pearson (1993), Kromer and Becker (1993) and Stuiver and Reimer (1993).

dates of the Lisan lacustrine between 63 and 15 kyears B.P. (Kaufman et al., 1992; Table 1), we propose that these alluviums were emplaced between 140 and 70 kyears B.P.

The lake probably reached its maximum extent at the end of the Glacial Maximum, with an elevation of at least 180 m b.s.l. indicated from the distribution of lacustrine sediments (Neev and Emery, 1967, Begin et al., 1974), the oolithic deposits (Druckman et al., 1987) and archeological sites (Goldberg, 1994). The beach bars near Hazeva suggest that lake Lisan actually rose to a maximum elevation of about 150 m b.s.l., at the end of this period, probably after 18 cal. kyears B.P. (Fig. 11), based on cosmogenic exposure ages of pebbles from the beach bars. This lake-level high stand is consistent with shorelines observed at the same elevation on the other side of the Wadi Araba valley, just north of the Wadi Dahal (Site 1) dated to 16–15 kyears B.P. (Figs. 2 and 3 in Niemi et al., 2001), and also with shore features located at the northern edge of the Dead Sea in the Wadi-al-Hammeh, which stand about 140–150 m b.s.l. and have been dated to 12 kyears B.P. (Macumber and Head, 1991).

The sand and gravel incorporated into the beach bar of Hazeva were mainly fed from underlying

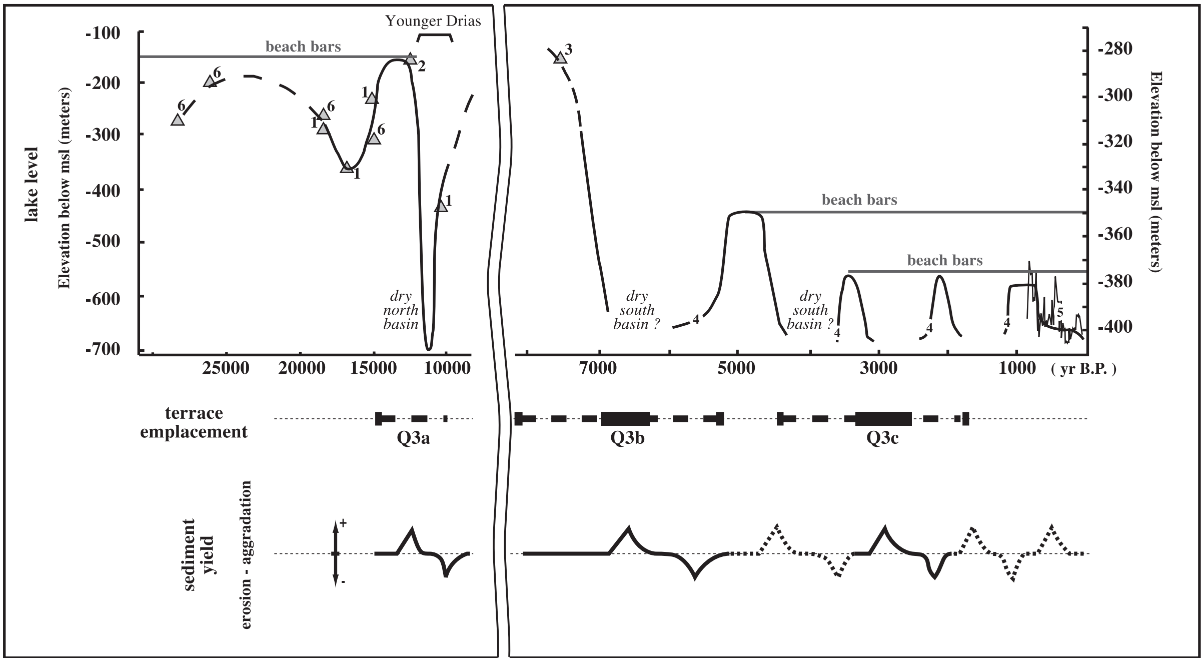

Fig. 11. Synthesis of lake fluctuations and terrace emplacement (age are in years B.P.). Lake level fluctuations are derived from (1) Begin et al. (1985), (2) Macumber et al. (1991), (3) Goodfriend et al. (1986), (4) Frumkin (1997), (5) Klein (1982), (6) Bartov et al. (2002) and the elevation of the beach bars.

Pleistocene material suggesting that little aggradation occurred on the Pleistocene pediment during the Lisan period. The subaquatic fan deltas along the margin of the Dead Sea were fed during this period relative quiescence in alluvial aggradation. The gravel veneer (Q3a) that has prograded on top of Lisan lacustrine material is evidence for an episode of alluviation post-dating the Late Pleistocene lake regression, probably before the Younger Dryas dry spell.

Borehole data from the Zeelim alluvial fan (just south of the Wadi Mazor on Fig. 1) shows a large layer of halite, denoting a period of low lake level correlated with the Younger Dryas (Neev and Emery, 1967). Based on ^{14}C dating of the upper and lower layers, Yechieli et al. (1993) have indeed proposed that the halite layer formed between 11315 ± 80 and 8440 ± 95 years B.P. This layer probably is the same as the one identified by Ben-Avraham et al. (1999) from seismic reflection profiles in the Dead Sea basin, and dated about 8 to 7 kyears B.P. It is probably during this regression that lake Lisan formed the numerous wave-cut shorelines carved into the talus apron and terraces on top of the Late Pleistocene fan delta at the base of the cliff flanking the Dead Sea. The dry spell possibly led to a total shrinking of the lake with the development of a drainage system at the bottom of the lake at an elevation of 700 m b.s.l. (Neev and Emery, 1967). This episode is thought to coincide with the worldwide documented Younger Dryas cold event (Fairbanks, 1989).

After the Younger Dryas to about 7–6 kyears B.P., wetter conditions seems to have prevailed according to pollen records (Horowitz, 1979) and isotopic studies of land carbonates and snails (e.g., Goodfriend, 1990, 1991). These conditions have maintained a higher lacustrine level that probably rose to a maximum of about 280 m b.s.l. at the end of this period, attested by the salt deposits on shells of land snails that are younger than 6660 ± 70 years B.P. (Goodfriend et al. 1986). Other lakes in the Arabian desert experienced a coeval lacustrine optimum between 8800 ± 90 and 6100 ± 70 years B.P. (McClure, 1976). During that period, a new generation of subaquatic fan deltas were built into the previously dissected Late Pleistocene fan delta. Based on the morphology of the karst system in the diapir of salt of Mt. Sodom and numerous radiocarbon dates, Frumkin (1997) has shown that this lake high stand should have already decreased by 5.9 kyears B.P. (6.8 cal. kyears B.P.).

Q3b was probably deposited after this early–middle Holocene lacustrine optimum because it overlies subaquatic fan delta material dated to 8810 ± 160 years B.P. and does not bear any trace of the Early–Middle Holocene lake transgression when the lake level rose to 280 m b.s.l. Q3b was probably deposited and abandoned after that period, i.e. after 7000 cal. years B.P. This alluvium could correlate with the fluvial gravel layer reported at depth between 14 and 9.5 m in the Zeelim cores, and also inferred to have been deposited during a low-stand lake level at about this period (Yechieli et al., 1993).

The beach bars on Q3b indicate a subsequent lacustrine transgression that could correlate with the deposition of the clay layer dated to about 4.3 kyears B.P. (Neev and Emery, 1967). During that period, the lake level is known to have reached its maximum at about 4.4 kyears B.P. (4.9 cal. kyears B.P.) (Frumkin, 1997). We infer that the Q3b terrace probably formed earlier, during the low lake-level stand, between about 7.0 and 6.2 cal. kyears B.P. (Fig. 11). Incidentally, we derive that the maximum lake level reached during the 4.9 cal. kyears B.P. lake transgression is about 350 m b.s.l. This minor lacustrine optimum seems to coincide with a period of generally more humid and cooler climate than at present (see review by Issar et al., 1992). A large increase in alluviation was inferred at several sites in the Negev area and probably marks the end of this period at about 4 cal. kyears B.P. ago (Rosen, 1986; Issar et al., 1992; Goldberg, 1994). Q3c could correlate with this period.

Q3c is inset into Q3b and did not experience the 4.9 cal. kyears B.P. lake transgression since the beach bars abandoned at 350 m b.s.l. are standing on Q3b and cannot be traced across Q3c. Since that period, the Dead Sea seems to have been continuously shrinking with only three possible significant high stands at 3400, 2010 and 630 cal. years. B.P. (Frumkin, 1997) (Fig. 11). The latest prominent Holocene fan terrace was deposited most likely during the low stand, between 3400 and 2100 cal. years B.P., as indicated by the overlying beach bars, which stand at about 395 m b.s.l. (Fig. 11), and the transgressive lacustrine deposits dated between 1960 and 1715 cal. years B.P. (Table 4) at the toe of the fan.

5. Discussion–Conclusion

The particular setting of the Dead Sea area, thus, offers some unique opportunity to study the relationship between tectonics, lake-level fluctuation and fluvial aggradation or entrenchment.

Since all alluvial fans around the Dead Sea show a similar morphology, one may tempted to ascribe this similarity to a common base-level control related to the Dead Sea lake-level variations. This hypothesis was rejected by Bowman (1988), who has documented the fan sequence at the mouth of Wadi Zeelim where the inset terraces show no tendency for a slope increase with entrenchment. Although Bowman's interpretation is questionable because the terraces geometry might be alternatively interpreted in terms of a retreating knickpoint, the fact that about the same fan sequence is observed at different elevations (Wadi Hever, Wadi Mazor) also advocates for a forcing factor other than direct base-level control.

The geometry and location of fans were certainly constrained to some extent by tectonics since they formed at the base of cumulative normal fault scarps. However, a tectonic control on episodes of fan aggradation and river entrenchment seems doubtful for our period of interest, as a maximum of 10 m of vertical motion due to tectonics is estimated along the Dead Sea shore for the post-Lisan period (Bartov et al., 2002). Our observation that periods of fan aggradation have alternated with periods of lake relative high stand makes a climatic control a much more plausible explanation. Climate may drive aggradation or entrenchment at the outlet of a drainage basin depending on the amount of sediment delivered to the drainage by hillslope processes compared to water discharge. The two major Holocene fan terraces described in this study, Q3b and Q3c consist of subaerial gravel that can be traced at elevations well below the transgressive shorelines. This means that they must have been emplaced during time of relatively low lake-level stand. Our preferred scenario is that the bulk of Q3b aggradation took place at the end of the wet early Holocene phase that lasted until about ca 6.5 ka (Leroi-Gourhan and Darmon, 1987; Horowitz, 1992) marked by a lake-level high stand (Fig. 11). The return of more arid conditions would have reduced the vegetation cover, making more regolith, formed by weathering during the wet period, suddenly available for transport, leading to some aggradation (Howard and Kerby, 1983; Bull, 1991). After depletion of the stock of regolith, a return to weathered-limited hillslope may have reduced the sediment supply from hillslopes, leading to river entrenchment into its previous fill. Such a scenario, though not unique, would fit the chronologic and the stratigraphic constraints obtained from our study. It implies that aggradation and river entrenchment would essentially mark transient response of the water drainage system to climate change (Whipple and Tucker, 1999). The chronology of aggradation of fan terraces and subsequent river incision would then be tuned to climate changes, although some time lag and some variability in the response of the drainage basin might be expected depending on the size and dominant lithology of the watershed (Bull, 1991).

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