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Reconstructing low levels of Lake Lisan by correlating fan-delta and lacustrine deposits

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Abstract

Reconstruction of paleo-shorelines of Lake Lisan, the late Pleistocene precursor of the Dead Sea, is based on sequence stratigraphy of fan-delta and lacustrine deposits that are exposed at the Perazim Valley, southwest of the Dead Sea. The shoreline sediments are physically correlated with lacustrine aragonites, their ages are determined by U-series dating, to establish a lake-level curve for the time interval between 55 and 35 kyr. During most of this period, Lake Lisan was at a relatively low level, which fluctuated between 280 and 290 m below sea level (m bsl). The minimum lake stand (~ 330 m bsl) was reached at 47 kyr and lasted for 3–4 kyr. This episode is marked by a depositional hiatus in the section, and formation of an erosional channel. The studied period correlates with the global marine isotope stage 3. The low stand of Lake Lisan during most of this period indicates relative dry climatic conditions in the region.

1. Introduction

Reconstruction of paleo-lake levels is important in the evaluation of paleohydrologic and paleoclimatic conditions in continental environments (cf. Benson, 1978; Street-Perrott and Harrison, 1985; Benson and Thompson, 1987; Wohl and Enzel, 1995).

Data for reconstruction of lake levels are obtained from two principal environments: (a) the shore and near-shore environment, and (b) the main lake water body. The shore environment provides the best information on paleo-lake area and elevation (cf. Wells et al., 1989; Oviatt et al., 1994; Adams and Wesnousky, 1998). The deep-water environment may provide continuous information on the chronology and paleolimnology, but only limited information on the absolute magnitude of lake-level changes. Complementary studies from both environments are desirable because together they can provide a comprehensive understanding of a lake's history. However, this combination is seldom achieved (cf. Wohl and Enzel, 1995).

During the Pleistocene to the Holocene several lakes occupied the basins along the Dead Sea Transform. The sediments that were deposited in these lakes compose the Samra, Lisan and Ze'elim Formations (cf. Neev and Emery, 1967; Begin et al., 1974; Yechieli, 1993; Stein et al., 1997; Ken-Tor et al., submitted). In this study, we focus on the lake-level history of Lake Lisan, which existed in the Dead Sea basin between ~ 70 and 17 kyr (Kaufman, 1971; Kaufman et al., 1992; Schramm et al., 2000). Outcrops of the Lisan Formation are distributed from Hazeva in the south to the Sea of Galilee in the north (Fig. 1). Around 17 kyr Lake Lisan started to recede toward the present level of the Dead Sea (Begin et al., 1974; Schramm et al., 2000; Ken-Tor et al., submitted). The rate of water decline and the elevation of the lowest lake stand are not known, but Yechieli et al. (1998) concluded that the water level never dropped below 500 m below sea level (m bsl). Following the definition of Street-Perrott and Harrison (1985), the late Pleistocene Lake Lisan and the Holocene Dead Sea can both be considered amplifier lakes, which experienced rapid fluctuations in lake level by tens to hundreds of meters.

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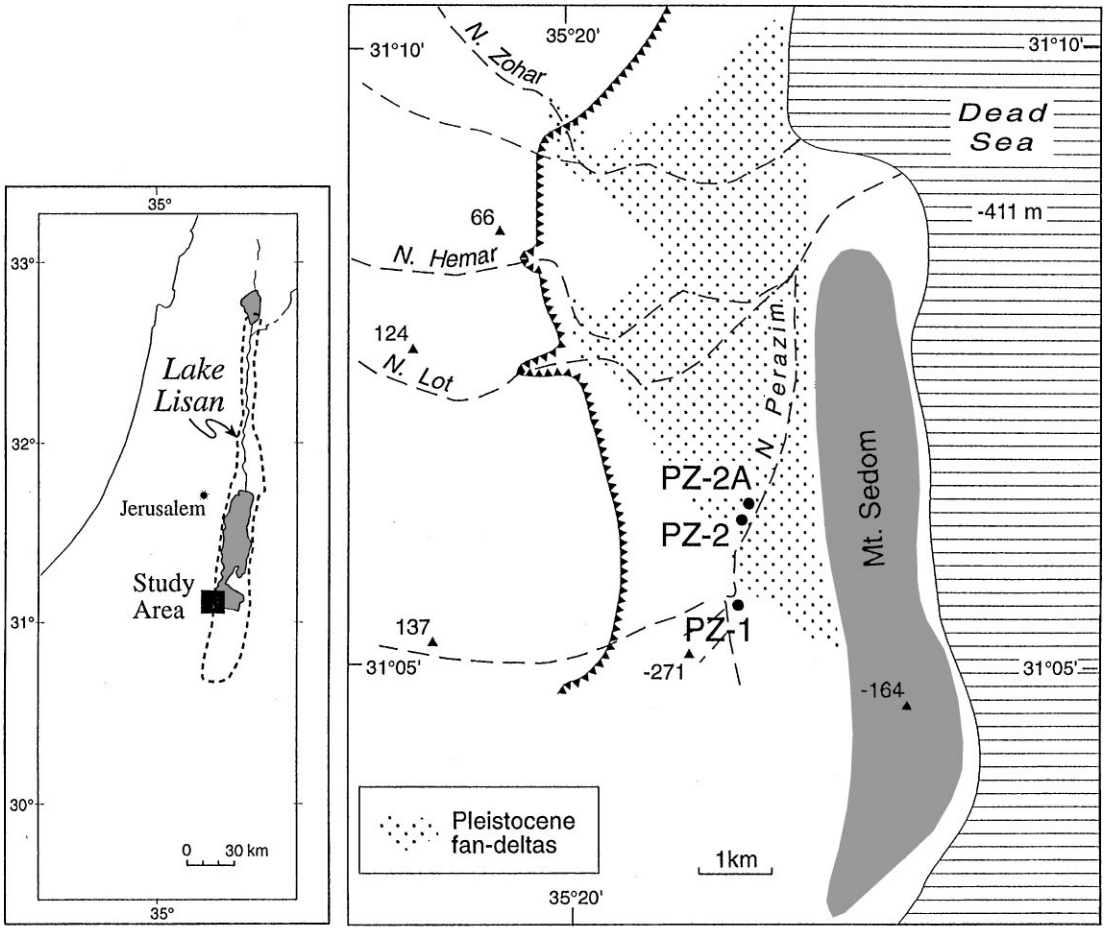

Fig. 1. Location map showing studied sections PZ-1, PZ-2 and 2A and distribution of Lake Lisan deposits (Lisan Formation) along the Jordan-Arava valley.

In addition to well-preserved lacustrine deposits, the Lisan Formation contains sedimentary sequences that were deposited in the fan-deltas along the margins of the lake. These sequences are well exposed along the modern western escarpment of the Dead Sea (cf. Bowman, 1971; Sneh, 1979; Manspeizer, 1985). The mode of deposition and the morphology of the fan-deltas reflect: (1) the hydrography and physiography of the feeding valleys, and (2) the bathymetry and morphology of the lake margins. In the Dead Sea the bathymetry of the lake margins reflects a series of down-faulted blocks, which are overlain by stream and lake-sediments (Ben Avraham, 1997). The wide range of stream–lake relations results in a wide array of well-defined alluvial fans and fan-delta complexes. These complexes were initially deposited in association with the changing levels of Lake Lisan, each extending over an area of ~ 0.5–$5\,km^2$ adjacent to the escarpment (Bowman, 1997).

The availability of well-preserved exposures of sedimentary sequences deposited in various environments (main water body, fan-delta, and shores), which can be physically correlated (Kadan, 1997; Bartov, 1999) and the occurrence of lacustrine aragonite, which is used to obtain absolute ages and geochemical information (Kaufman, 1971; Katz et al., 1977; Katz and Kolodny, 1989; Kaufman et al., 1992; Machlus et al., 1997; Stein et al., 1997; Schramm et al., 2000) make the Lisan Formation an ideal target for establishing a lake-level curve.

Analysis of sedimentology and sequence stratigraphy has been previously applied for identifying depositional environments along shores of lakes and seas and for establishing sea-level curves (cf. Chappell, 1974; Link et al., 1985; Frostick and Reid 1986; Nemec and Steel, 1988; Colella and Prior, 1990; Postma, 1995). However, due to the scarcity of adequate exposures and sediments suitable for age control, few studies have hitherto combined sedimentology and stratigraphy of fan-deltas and associated landforms to establish water-level changes in continental basins and lakes (cf. Wells et al., 1989; Stine, 1990; Enzel and Wells, 1997; Adams and Wesnousky, 1998). The unique exposure of the Lisan Formation in the Perazim Valley (Fig. 1) allows correlation between shore and lacustrine environments to establish the lake-level curve.

2. Sedimentological analysis of the fan-delta deposits

A variety of sedimentary facies associated with the alluvial fan, shore, lagoon, and near-shore environments have been identified in the fan-deltas of the Lake Lisan Dead Sea system (LLDS) (cf. Bowman, 1971, 1990, 1997; Begin et al., 1974; Sneh, 1979; Manspeizer, 1985; Frostick and Reid, 1989; Kadan, 1997). Many of these facies are indicative of the lake level during their deposition, especially when they are compared with present-day deposits or with recently exposed Holocene sequences (Kadan, 1997). Each facies component dominates over a horizontal distance of a few hundred meters and interfingers downstream with the next one (Sneh, 1979). This configuration is most pronounced in a direction perpendicular to the escarpment.

The relationship between the fan-delta and lacustrine sediments during various lake stages is schematically illustrated in Fig. 2. The figure represents the case of an existing tectonic bench on top of which the fan-delta is deposited with relatively flat bedding. This is the most favorable setting for our study. The main depositional facies in the studied environment are summarized in Table 1: (a) on-land alluvial fan deposits, which are sorted at the fan-water contact and form a delta front. When covered by prograding beach sediments, the alluvial fan deposits can indicate the exact horizontal and vertical location of a paleo-shore; (b) shore deposits that are occasionally covered by aragonite crusts and may thus be indicative of the shoreline (similar crusts form at present on gravel exactly at the shoreline); (c) near-shore sand with symmetric ripple marks, which indicate the very shallow wave action zone in this basin and the transition into the deeper and farther lacustrine environment; (d) laminated lacustrine sediments, which are deposited in the main water body. These deposits interfinger and occur in on-lap/off-lap relations. For example, the sand layers wedge out lake-ward into a very thin bed, which transforms into a bounding surface within the laminated section. This facies change occurs within a vertical depth of a few meters in the gravel-rich zone of the fans and within a distance of 1–30 cm in the laminated zone.

Unconformities are common in the shore and near-shore deposits. These unconformities are useful tools in stratigraphic correlations in the Dead Sea area (cf. Kadan, 1997; Enzel et al., 2000) and provide information on transgressive or regressive modes of deposition (on-lap and off-lap modes of deposition). Cyclic changes between coarse off-lapping facies and limnic, fine-grained on-lapping sediments are typical and often abrupt. These frequent transitions between lake and shore facies in the LLDS are not consistent with known tectonic movements. Furthermore, the slip on syn-formational faults is typically in the order of less than a few meters in 10,000 years (Marco et al., 1996; Kadan, 1997). Hence, the abrupt facies transitions are indicative of hydrological fluctuations rather than vertical movements of the crust (Frostick and Reid, 1989).

3. Nahal Perazim sections

Nahal Perazim flows at the tow of the late Pleistocene fan-delta of Nahal Hemar (Fig. 1). The incision of its tributaries formed badlands and numerous long and deep exposures of the sediments. Several stratigraphic sections of the Lisan Formation (PZ-1, PZ-2 and PZ-2A)

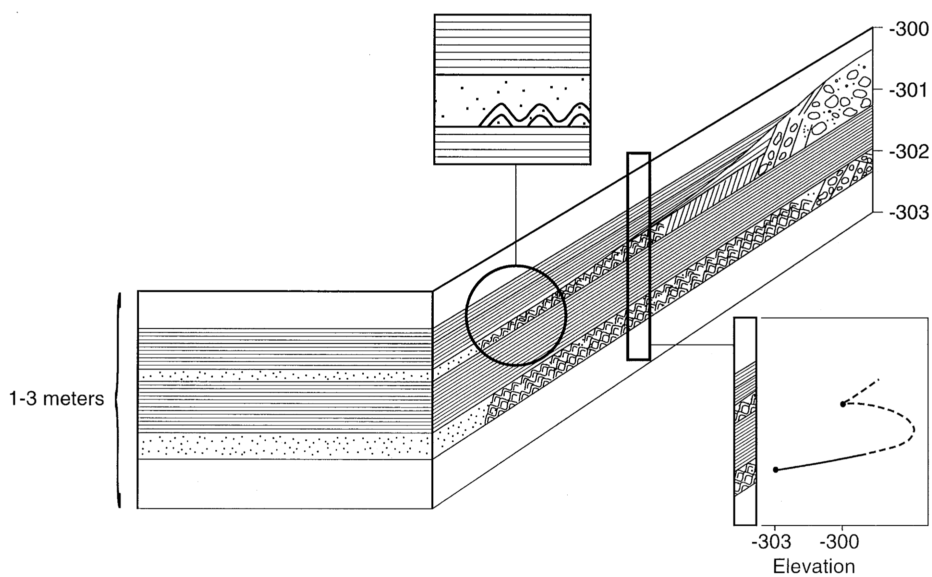

Fig. 2. Schematic illustration of facies change with distance from the canyon mouth of a fan-delta. In the inset — an example for a reconstructed lake-level curve. Flow from upper right to lower left.

Table 1
Description of facies and depth of deposition for sediments of the Lisan Formation (de-Raaf et al., 1977)

Facies	Description	Depositional environment and estimated lake depth
A	40–50 cm thick bed of partially platy, medium to very well sorted gravel forests and backsets at approx. 25°. Each set is $\sim$ 10 cm thick. Grain size in each set has a narrow range of either granules or pebbles. Aragonite crusts cover many pebbles	Prograding beach ridge alternating with thin delta front of alluvial fan at the lake's margins (0–1 m)
B	Either one of: (1) 10–30 cm bed of medium to poorly sorted grain supported pebbles to cobbles. Matrix is medium sorted coarse sand. Its basal contact with facies A is sometimes erosional aragonite crusts at top of gravel. (2) Poorly sorted, massive medium sand to 4-cm pebbles with aragonite crust. (3) Weakly bedded $\sim$ 10 cm thick bed, poorly sorted, medium sand with some granules or pebbles	Alluvial fan at or very near the lake shore. Lake level was just at or below these deposits
C	Contains clear lateral transitions between facies A and B. At the base of this facies there are eroded remains of facies A	A transition from the alluvial fan to the shoreline $\sim$ 0 m water depth
L	Either (1) 0.5 cm thick aragonite laminae that contains thin granules with aragonite crusts; or (2) a few cm thick, well-sorted sand, some with finer grain laminae that drapes over a set of facies A, B, or C. The length of this wedging out lens can reach up to 40 m	Lagoonal deposit on the shore side of a beach ridge. Contains wash-over sand. 0 m water depth, at the shoreline (Kadan, 1997)
W	Wavy lamination to distinct symmetrical ripple marks which match the criteria of de-Raaf et al. (1977, Fig. 8) and a mixture of broken aragonite and which is affected detrital laminae that grade into sand layers that bear ripple marks	High-energy environment affected by waves. Its lateral and elevational association with facies A, B, and C indicates that it was deposited no deeper than 5 m below lake level
Ln	Lenticular beds of fine sands in silt/clay. The lenses are either connected or disconnected. In places a wavy structure of fine sand as in Figs. 8.1–8.2 of de Raaf et al. (1977)	Low-energy environment (de Raaf et al., 1977) or transition between the turbulent environment affected by both waves and slack waters (Reineck and Singh, 1973). Deeper than 5 m
H+	1–2 cm thick halite layer that cements fine sand/silt with ripple marks, mud cracks or wavy laminations	Desiccating lagoon or shore environment. 0 m depth
MC	Silt and clay with polygonal mud cracks within facies D and AAD usually in distinctive bounding surfaces. Cracks form from top of fine-grained clastic layer down	Polygonal cracks indicate lake desiccation (e.g., Plummer and Gostin, 1981). $\sim$ 0 m water depth
R	Reddish crusts, usually in association with MC within AAD and D	In modern and Holocene deposits red crust is indicative of surface exposure to oxygenation due to low lake stand. $\sim$ 0 m of water depth or lake level lower than the cracks and crusts
S	Either a few meters thick massive very fine sand beds that coarsen upwards to medium sand; or $\sim$ 20 cm well-sorted massive coarse-medium sand beds	Near-shore environment. Exact water depth unknown. However, sediment associations indicate very shallow environment perhaps during lake-level rising. Not used as water level indicator
D	A few to 50 cm thick green clay layers sometimes with silt and very fine sand	Deposition is underwater. Depth unknown. Not used as water level indicator
AAD	Fine laminations of alternating aragonite and clay–silt detritus laminae. Laminae thickness 0.1–2 mm	Lacustrine environment. Not used as water level indicator

were described in this valley (Figs. 3 and 4). At this site, the Formation consists of three main lithologies: aragonite, gypsum and detritus. About 70% of the stratigraphic column consists of alternating, mostly mm thick aragonite and detritus laminae. The detritus is comprised of erosion products derived during the rainy seasons from the nearby Upper Cretaceous rocks in the Dead Sea drainage basin (dolomite, calcite and clay minerals) (Begin et al., 1974; Stein et al., 1997).

The PZ-1 section (Fig. 3) has been sampled for geochemical, paleomagnetic and paleoseismic studies (Marco et al., 1996, 1998; Machlus et al., 1997; Stein et al., 1997; Schramm et al., 2000). The section is divided into three members: the lowest member consists mainly of alternating aragonite and detritus laminae (the *aad* facies, Table 1) interbedded with three gypsum layers; the middle member contains abundant clastic beds (sand to silt and clay), which alternate with *aad* packages; the upper member again consists of mainly the *aad* facies with gypsum layers at the top (Fig. 3). The ages of aragonite in the PZ-1 section, based on U-series dating obtained by TIMS (Schramm et al., 2000), range from $\sim$ 67 to 19 kyr from the bottom to the top of the section. This time interval corresponds to isotopic stages 4, 3 and 2 in the global record. The lower and upper members with the *aad* facies (indicating relatively high-stand conditions) are correlated with colder conditions in the global record, while the clastic-dominated middle member (low-stand conditions), is correlated with warmer conditions in the global record (Stein, 1999; Schramm et al., 2000).

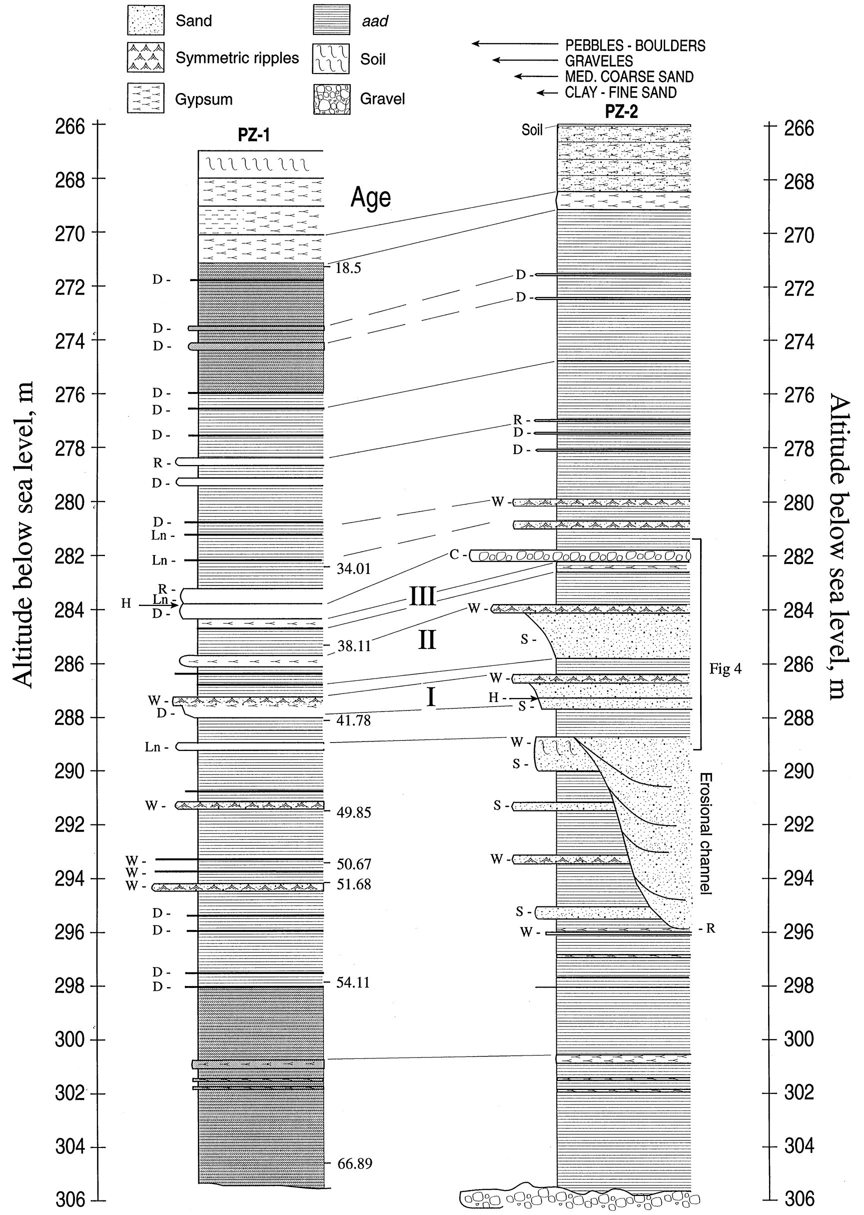

Fig. 3. Columnar sections at PZ-1 and PZ-2 sites (Nahal Perazim). Facies as defined in Table 1.

The shore deposits within the Nahal Hemar fan-delta are exposed at the PZ-2 and PZ-2A sections (Figs. 3 and 4). These sections contain mainly gravel, and rippled or massive sands. The sediments show different sedimentary structures; parts of them appear in well-sorted backsets and forests, and others in poorly sorted mixtures of sand and gravel. The recognition of these structures is instrumental in the identification of the depositional environment within the fan-delta complex and, eventually, in the determination of the exact elevation of the paleo-shoreline. Such interpretations are based on modern alluvial fan complexes in the Dead Sea area (Bowman, 1971, 1997; Kadan, 1997).

The excellent exposures of the fan-delta complex and lacustrine deposits in the Perazim valley sections allow for a precise physical correlation in the field. For example, it is possible to trace single aragonite and detritus couplets and transitions between main lithological units (aragonite/gypsum) for a distance of 1.5 km between the PZ-1 and PZ-2 sections. Precise topographic surveys provide the exact altitude of each unit in the three studied sections particularly the elevation of shore deposits, which mark the paleo-lake levels. The altitude of the PZ-1 section is between 306 and 266 m bsl, and the gradient between PZ-1 and PZ-2, as determined from several individual horizons, is less than 1‰. This

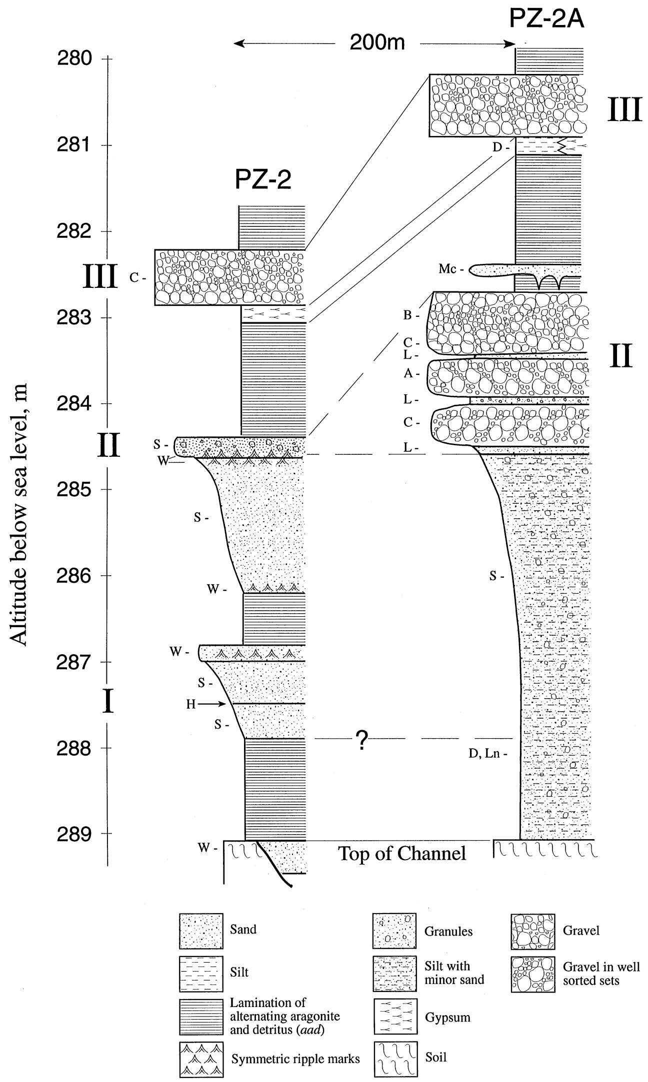

Fig. 4. Details of segments I–III in Fig. 3.

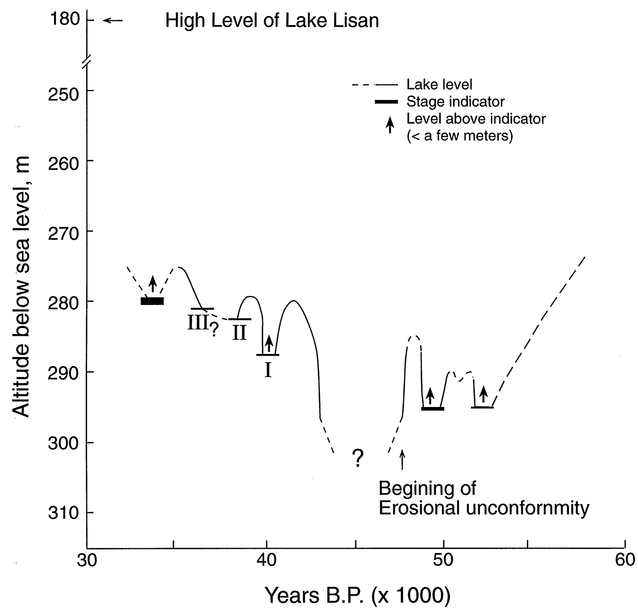

Fig. 5. Reconstructed Lake Lisan curve for the time interval 55–35 kyr.

facilitates the physical correlation between these two environments.

Fig. 4 illustrates a correlation for a beach complex within the fan-delta lacustrine sediments at elevation 283–284 m bsl. This beach complex is traced in the field and physically correlated with the sandy pebbles and sand with ripple marks at 284 m bsl of PZ-2 and a thin gypsum bed at 285 m bsl at PZ-1.

4. Reconstruction of low levels of Lake Lisan (55–35 kyr)

The reconstruction of the low-level stands at Lake Lisan is based on analysis of the middle member of the PZ-1 section, which consists of shallow water sediments, such as sand with ripple marks, sorted and unsorted gravel, gypsum and salt. The analysis of lacustrine and fan-delta sediments, their inter-correlation, and the application of U-series aragonite chronology allow us to draw a lake-level curve where episodes of low lake stand are precisely determined (Fig. 5). Between 55 and 50 kyr, thin sand layers of highly symmetric rippled sand (W in Table 1) punctuate the *aad* facies (Table 1), accompanied by thin gypsum layers, which indicate shallow water environment. In the Holocene and the modern Dead Sea, these sediments indicate a near-shore shallow environment (Kadan, 1997). During this time interval, lake-level stabilized at approximately 290 m bsl.

At 47 kyr, Lake Lisan dropped by more than 30–40 m. A major unconformity and the formation of an erosional channel at PZ-2 (Fig. 3) mark the sharp lake drop. The erosional channel incises the PZ-2 section at 288.5 m bsl (Fig. 3). The channel is ca. 6 m deep and sub-parallel to the present-day Perazim Valley. It can be traced for hundreds of meters between PZ-2 and PZ-1. The channel is filled with shallow lacustrine sediments, which consist mainly of sand alternating with thin beds of *aad*. The erosional channel can be physically correlated with a sand layer in PZ-1 (Fig. 3). U-series dating of aragonite in PZ-1 reveals a depositional hiatus between 47 and 43 kyr (Schramm et al., 2000), which is consistent with the appearance of the correlative erosional channel in the PZ-2 section.

The exact elevation of the lake stand during this episode cannot be well constrained at the Perazim valley. Based on correlations with the Lisan Formation sequence near the archaeological site of Massada, where a similar facies analysis was carried out (Bartov, 1999), this stand was as low as 330 m bsl. At the time of incision of the channel, a reddish soil developed over its base. This type of soil is expected to form on the exposed regression surface of receding lakes. Indeed, a similar soil covers the Amiaz plain, which represents the regression surface of the lake during its shrinkage at about 17 kyr.

At $\sim$ 42 kyr lake-level rose again to about 280 m bsl, leading to deposition of the *aad* facies. This rise was probably very short because it is limited between two low lake-level stands. Between 40 and 38 kyr, the sequence fluctuates between the *aad* facies and gypsum, while sand and gravel were deposited in PZ-2 (facies L, A, B, C, W and S, Fig. 4b, Table 1). This configuration suggests a slight lake-level change (in the order of a few meters).

Between 37 and 35 kyr (interval III in Fig. 3), lake-level dropped again to $<$ 283 m bsl. Gravel was deposited in PZ-2, while gypsum, clastics and halite were deposited in PZ-1. Well-exposed beach complexes in PZ-2 allow us to determine precisely the water level for this time interval. In the blow-up of the PZ-2A section, a fan-delta front (under water) is identified at 284 m bsl, and it is covered by a prograding beach (facies A, Table 1), which is covered by alluvial fan deposits (facies B). Laterally, these facies change to rippled sand and pebbly sand at PZ-2 and to gypsum at PZ-1. All these changes occur almost along the same elevation (-285 ± 0.5 m), suggesting very low water depth ($<$ 10 m) during this time interval at the Perazim region. It appears that between the times that the water level stood at 280 and 285 m bsl, a threshold was crossed in the Perazim valley, which lead to the formation of a lagoonal water body at PZ-1 and to the deposition of halite. Similar other sedimentary sequences appear in the middle member of the Lisan Formation. This sequence, or part of it, may serve as an indicator for very shallow water ($<$ 10 m) elsewhere.

The studied time interval (55–35 kyr) in the history of Lake Lisan corresponds to isotopic stage 3 in the global record. A correlation between the Lake Lisan sedimentary record and deep sea and ice core records reveals that during warm (interglacial) episodes in the North Atlantic, the Dead Sea-Jordan region was dry, and the level of Lake Lisan dropped (Stein, 1999; Schramm et al., 2000). This study suggests that for most of this time interval Lake Lisan level fluctuated between 280 and 290 m bsl (ca. 130 m above present day Dead Sea level), and was very shallow at the Nahal Perazim area (a few meters water depth). Sedimentation was very sensitive to small fluctuations in lake level, which caused fast transitions in the sedimentary record from clastics to gypsum to aragonite. The lower and upper members of Lisan Fm, which are dominated by the *aad* facies, were deposited during times of enhanced freshwater supply and higher lake stands (Stein et al., 1997; Bartov, 1999).

5. Summary

1. Lake-level elevations of the late Pleistocene Lake Lisan were determined by sedimentological analysis and sequence stratigraphy of fan-delta, shore and lacustrine sediments. Combined with high-resolution U-series dating of lacustrine aragonite, a lake-level curve was established for the time interval 55–35 kyr.
2. Lake Lisan was at a low stand during most of the studied time. The lake-level fluctuated between $\sim$ 280 and 290 m bsl and water depth at the Perazim valley was very shallow ($<$ 10 m). Between 47 and 43 kyr the lake reached a minimum stand of $\sim$ 330 m bsl. A depositional hiatus and the formation of an erosional channel mark this episode.

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