Ablupt aridities and salt deposition in the post-glacial Dead Sea and their North Atlantic connection

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A B S T R A C T

Ablupt arid events in the post-glacial (~17.4–10 kyr BP) Dead Sea Basin (DSB) were recorded by significant lake level declines in Lake Lisan and massive deposition of gypsum and salt. Between 17.4 and 16 kyr cal BP, the lake level dropped from its late MIS2 stand of ~260 m below mean sea level (m bmsl) to ~330 m bmsl, depositing a thick sequence of gypsum. Between ~16 and 15 kyr cal BP the lake level recovered but dropped abruptly again at ~14 kyr cal BP to below 465 m bmsl, probably the lowest late Pleistocene stand. Then, between 13 and 11 kyr cal BP (the Younger Dryas time interval) the lake rose above 400 m bmsl and declined at 11–10 kyr cal BP depositing a thick sequence of salt. The abrupt lake level drops and salt deposition coincided with times of ice and meltwater discharges into the North Atlantic (NA): Heinrich event (H1) and Meltwater Pulse ~ MWP1a. Similar coincidence between ice and meltwater discharges in the NA (e.g., H-events) and arid events at the Levant was recorded during the colder last glacial period, demonstrating a persistent effect of the North Atlantic hydrology and sea ice advances on the Levant climate. The climatically “turmoil” post-glacial period was accompanied by significant developments in human culture: the collapse of the Natufian culture during the Bølling-Allerød and the rise of the Pre-Pottery Neolithic cultures, PPN A and B around the 11–10 kyr cal BP salt deposition interval marking the initiation of the “Neolithic revolution” in the region.

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1. Introduction

The post-glacial period (~17.4–10 kyr BP) was characterized by abrupt changes in global climate: At ~17.4 kyr cal BP (all calibrated calendar ages in the manuscript are reported as cal BP) large-scale ice discharge into the North Atlantic resulted in the cooling of its surface water (Heinrich (H) event 1; e.g., Bard et al., 2000; Hemming, 2004; and references therein) that coincided with rapid rise in atmospheric CO2 (Monnin et al., 2001). Following a ~3 kyr period of dramatic and apparently conflicting global climate trends (termed the “Mystery interval”; Denton et al., 2006), a warm oscillation (“the early interstadial” ~14.7–12.9 kyr BP) was recorded in several locations in the northern hemisphere (the Bølling–Allerød (B/A) period defined by pollen studies in Poland, Laachar Zee and other sites; Litt et al., 2001). At ~12.9 kyr cal BP, colder, glacial-like conditions resumed in the northern Atlantic region and northern Europe marking the commencement of the Younger Dryas (YD) period that lasted until the beginning of the Preboreal (PB) at 11.5 kyr cal BP (Goslar et al., 1999; Litt et al., 2001). The short duration of these events, their internal structure, and their apparent association with non-linear climatic processes invoked broad interest in the paleo-climate community because of their relevance to rapid climate changes and the effect on modern human environment. Several studies pointed to the critical role that ice melt-freshwater discharges had on the Atlantic Thermohaline Circulation (THC) and the Meridional Overturning Circulation (MOC), which are strong modulators of global climate patterns (e.g., Broecker et al., 1989; Tarasov and Peltier, 2005).

A major open issue is the relation between the conditions in the North Atlantic and climatic patterns at lower latitudes. High-resolution lake records indicate abrupt changes in the patterns of the monsoonal wind system during the post-glacial period (e.g., Lake Tanganyika in east Africa; Tierny and Russel, 2007) calling for rapid inter-hemispheric climate signal transfer. In this context it is desirable to document the climatic response of mid-latitude regions, particularly those regions marginal to the arid belts, to the effects of meltwater discharges in the North Atlantic.

The Dead Sea Basin (DSB), accommodating the modern Dead Sea, which is the lowest water body on Earth (current water
elevation of 423 m bmsl), is located at the desert fringe between the subtropical Mediterranean climate zone and the Sahara-Arabia desert-belt (Fig. 1). During the Quaternary, the DSB was occupied by several hypersaline lakes characterized by their Ca-chloride composition. The salinities and water balances of these lakes were particularly sensitive to climatic shifts across the abovementioned climate zones (cf. Stein, 2001). Because tectonic movements had a relatively small effect on the measured lake level elevations (Bookman (Ken-Tor) et al., 2004; Bartov et al., 2007), the sharp and rapid fluctuations in the water levels (sometimes in the order of tens to hundreds of meters) are mainly attributed to major changes in the climatic–hydrological conditions in the lake’s drainage area (Neev and Emery, 1995; Stein, 2001; Bartov et al., 2003; Enzel et al., 2003; Bookman (Ken-Tor) et al., 2004; Migowski et al., 2006; Waldmann et al., 2007; Torfstein et al., 2008). For example, Enzel et al. (2003) established a qualitative linear relation between lake level changes and regional precipitation for the late Holocene period.

In this paper we focus on the climatic–hydrological history of the Dead Sea Basin during the post-glacial time interval (~17.4–10 kyr BP). Over this period Lake Lisan (the last glacial precursor of the Holocene-modern Dead Sea) declined from its last glacial high stand through several sharp lake level drops and significant changes in lake-configuration, demonstrating the extremely unstable nature of the post-glacial (termination) climate. The paper focuses on the magnitude and rate of these limnological changes and shows that they were significantly larger than the limnological changes that occurred before (last glacial) or after this period (Holocene). The paper begins with a short review of the relevant history of the last glacial (MIS2) Lake Lisan. Thereafter, we report new lithological and chronological data (radiocarbon dates obtained on terrestrial organic debris) from sediments deposited during the post-glacial period. The data were obtained from several boreholes drilled recently along the retreating shores of the Dead Sea. Finally, we discuss the correlation of the abrupt changes in the lake environment, which reflect the regional hydrology with global climate patterns, focusing on events of meltwater and sea ice discharges into the North Atlantic Ocean.

2. Lake Lisan and the regional hydrology of the Dead Sea basin

Lake Lisan occupied the tectonic depression of the Dead Sea basin (DSB) and the Jordan Valley during the last glacial period (~70–14 kyr BP; Kaufmann, 1971; Kaufman et al., 1992; Stein, 2001; Haase-Schramm et al., 2004; Fig. 1). The lake fluctuated between higher and lower levels reflecting the regional hydrological regime that shifted between wet and arid conditions, respectively (Bartov et al., 2003; Haase-Schramm et al., 2004). During high stands and positive freshwater input, the lake deposited sequences of primary aragonite and silty–detritus, mainly quartz and calcite grains of eolian origin. The deposition of the primary aragonite in the lake requires the supply of bi-carbonate by the inflowing freshwater and their limited mixing with the Ca-chloride brine (Stein et al., 1997). Thus, the intervals of deposition of primary aragonite imply significant supply of freshwater to the lake, which in turns indicates on enhanced precipitation in the drainage area of the lakes (Stein et al., 1997; Torfstein et al., 2008). The primary aragonite and silty–detritus form laminae that possibly reflect annual deposition (e.g. Begin et al., 1974). During low stands, the

Fig. 1. Location map. (A) and (B) Global and regional location maps. (C) The Dead Sea drainage area and location of drilling sites. The last Glacial Lake Lisan extended (during its highest stand) from the Sea of Galilee in the north to south of the present Dead Sea. The grey shadow north of the Dead Sea in panel B marks the location of Jericho, Gilgal and Fazael, which were settled during the PPN period.
lake deposited sequences of detrital calcites that reflect the contribution of seasonal floods and occasionally layers of gypsum, which were deposited during episodes of lake’s overturn (Stein et al., 1997; Waldmann et al., 2007; Torfstein et al., 2008).

The water levels of Lake Lisan (Fig. 2) were reconstructed by identifying sedimentary indicators of the shorelines, which were dated by radiocarbon or U–Th methods (Bartov et al., 2003, 2007). Lake Lisan reached its highest stands of 160–200 m bmsl during Marine Isotope Stage (MIS) 2. It thus appears that cold conditions in the northern latitudes were reflected by enhanced precipitation and a significant increase in available freshwater in the drainage area of Lake Lisan (see discussions by: Stein (2001), Haase-Schramm et al. (2004), Enzel et al. (2008)). Similar lake level rises were encountered in other closed basin lakes located in the poleward limits (<40°) of the drylands in both hemispheres (e.g., lakes Lahontan, Bonneville and Estancia; Quade and Broecker, 2009).

Lake Lisan began retreating in response to the global warming that generally imposed more arid conditions in the east Mediterranean–Levant region (e.g., Neev and Emery, 1995; Stein, 2001; Haase-Schramm et al., 2004). During the H1 time interval (17.4–16 kyr BP), the lake level dropped from ~260 m bmsl to ~330 m bmsl (Bartov et al., 2003) and massive deposition of primary gypsum took place (though in several cycles, see below), forming the “Upper Gypsum Unit” (Torfstein et al., 2005, 2008). Subsequently, at ~15 kyr cal BP the lake level rose to the elevation of ~260 m bmsl, depositing an aragonite–detritus bundle at the Perazim and Massada sites (at elevations of 270 and 330 m bmsl, respectively). This unit is capped by another gypsum layer, which is associated with the final retreat of Lake Lisan from the basin shoulders, dated to ~14.6 kyr cal BP (Haase-Schramm et al., 2004).

The water-level fluctuations during the time interval 14.6–10 kyr BP are reported in the following discussion. These fluctuations were characterized by two abrupt level changes, which reflect corresponding rapid shifts in the regional climate and paleohydrology. Later however, during the Holocene period, a relatively steady lake level was maintained at approximately ~400 ± 30 m bmsl (Bookman (Ken-Tor) et al., 2004; Bookman et al., 2006; Migowski et al., 2006).

Fig. 2. Lake level curve and correlation to regional and global climate records. (A) Lake levels during the last 50 kyr (Lake Lisan and the Holocene Dead Sea). The high and low levels reflect wet and arid regional hydrological conditions, respectively (Lake Lisan level curve modified after Bartov et al. (2003), Holocene Dead Sea level curve after Bookman (Ken-Tor) et al. (2004), Migowski et al. (2006)). Post-glacial dashed curve is the result of this study. (B) Soreq Cave speleothem δ¹⁸O record (Bar-Matthews et al., 2003). (C) East Mediterranean δ¹⁸O record (Almogi-Labin et al., 2009). (D) Western Mediterranean Sea Surface Temperature (SST; Cacho et al., 2001, 2000). (E) GISP2 δ¹⁸O record (Meese, et al., 1994; Grootes and Stuiver, 1997; Stuiver and Grootes, 2000). Note the correspondence between the trends of the different records during the Heinrich (H) events and the Younger Dryas (YD). See text for details.
The stratigraphy and chronology of post-glacial Lisan sedimentary sequence

The history of the post-glacial Lake Lisan is based on new chronological and sedimentological/lithological information recovered from sediment cores that were recently (except for the Ze’elim core) drilled along the retreating shores of the modern Dead Sea (Fig. 1 and see Yechieli et al., 2006). These drill-holes penetrated Holocene and pre-Holocene (Lisan) sections, recovering various sedimentary facies ranging from deepwater lake sediments to shore and fluvial sediments. A massive salt unit was reached at the base of the Holocene sequence, corresponding to previous reports by Yechieli et al. (1993) and Migowski et al. (2004).

The lithology of the cores used in this study is illustrated in Fig. 3 along with radiocarbon dates that were determined from terrestrial organic debris that were hand picked from the core sediment. The dated materials are leafs, seeds and tiny pieces of branches derived from trees growing on-land in the vicinity of the Dead Sea (see Ken-Tor et al. (2001) and Bookman (Ken-Tor) et al. (2004) for detailed description of these types of organic debris recovered from the Holocene section and used for radiocarbon dating). Radiocarbon dating was performed by AMS at the Poznan Radiocarbon laboratory (radiocarbon ages and laboratory numbers are listed in Table 1).

Detailed descriptions of the typical Holocene sections in the onshore and offshore (lacustrine) environments are given in Bookman (Ken-Tor) et al. (2004), Migowski et al. (2006) and Neumann et al. (2007). The main efforts in the new coring campaign described here were focused on the recovery, description and dating of the salt unit (Fig. 3).

3.1. The salt unit

The salt unit was encountered in several boreholes drilled along the margins and shores of the Dead Sea basin (Fig. 3 and Table 1). The unit reaches several meters in thickness at the marginal sites of the lake (e.g., the EG-7, EG-13 boreholes, near Nahal David and the DSIF drill at the Ze’elim terrace) and thickens toward the deeper lake environment (e.g., 10–15 meters at Maatz-1 and Mazor-1 sites, near En Gedi and 20–30 m at the southern sites of En Boqeq and Neve Zohar).

Holocene sediments that overlie the salt unit were recovered from the ML-2 borehole (at Mineral spa) and MZ-1 and the nearby DSEg boreholes at En Gedi spa (DSEg was reported by Migowski et al., 2004, 2006). Organic (terrestrial) debris recovered from these sediments yielded radiocarbon ages of ~9.9–9.5 kyr cal BP (Table 1; Fig. 3). These ages provide the uppermost limit of salt deposition. Organic debris collected from within the salt unit (e.g., at En Boqeq) yielded calibrated radiocarbon ages of ~10.5–9.9 kyr cal BP (Table 1), while those recovered from the bottom or immediately below the salt unit yielded ages of 11–10.5 kyr cal BP (e.g., at EG-7). These ages constrain the time of deposition of the salt unit in between 11 and 10 kyr cal BP.

3.2. The Lisan/salt unconformity

The sediments that lie up to a few meters below the salt unit yielded ages that spread over a large range: >44–20 kyr BP: 22–20 kyr BP at En Boqeq, EB-1; 41–31 kyr BP at En Gedi, EG-13; 30–20 kyr BP at Mineral spa, ML-2; >44 kyr BP at Mazor (En Gedi spa) MZ-1 and 45 kyr BP at HS-2-1 (Nahal Hever). Thus, the radiocarbon ages indicate that the salt unit overlies a significant unconformity that is documented at the various sites along the Dead Sea shores from Mineral spa to En Boqeq (Fig. 1). The chronological evidence for the pre-salt unconformity is supported by the absence of the upper Lisan lithological sequences, mainly the Upper Gypsum Unit (exposed in the marginal terraces, e.g. the Massada and Perazim sections) in the drilled sedimentary sequences beneath the salt unit. The deposition of the salt unit above a major unconformity is a key observation in our study that provides the basis for the
forthcoming discussion on the behaviour of the lake during the post-glacial period.

Additional key evidence for the post-glacial history of Lake Lisan comes from the borehole (DSIF) drilled in the Ze’elim terrace (north-east of the Archaeological site of Massada; Fig. 1; see core description in Yechieli et al. (1993)). The Ze’elim core (DSIF, Figs. 3 and 4) consists of sequences of fan delta deposits, marls and salt. The drilling recovered a 7 m-thick salt sequence which overlies and disseminated gypsum). These marly sediments unconformably overlie the laminated glacial Lisan aragonites, dated by U–Th age to 4.6 million years B.P. (base of salt unit at Maatz-1 and NZ-1 bores at 1967; Gavrieli et al., 1989). This lake level drop occurred sometime between 12.6 and 13.2 kyr cal BP (Fig. 4). The Ze’elim DSIF core located at the high margins of the lake provides a minimum lake level at the time of salt deposition. ~400–405 m bmsl (Figs. 3 and 4), similar to the elevation of the Dead Sea during modern episodes of salt deposition (e.g., Neve and Emery, 1967; Gavieli et al., 1989). Thus, during the time interval of 14.6–11 kyr cal BP Lake Lisan dropped from 260 to below 465 m bmsl (base of salt unit at Maatz-1 and NZ-1; Fig. 3) and rose back to above 400 m bmsl (before salt deposition). These are large and rapid changes. If for example the major drop in lake level had occurred between 14.6 and 13.5 kyr cal BP, the declining rate would reach a value of 0.2 m/yr, even more catastrophic as indicated by the erosional channels dissecting the floor of the Dead Sea at an elevation of ~600 m bmsl and below (Neve and Hall, 1979). Although some parts of these erosional channels could be submarine, present-day observations of the formation of deep gullies along the retreating shores of the Dead Sea suggest that the formation of deep erosional channels along the margins of the Dead Sea responds mainly to lake level decline (e.g., Bookman (Ken-Tor) et al., 2004). On the other hand, Yechieli et al. (1998) and Krumgalz et al. (2000) argued that the evaporation process of a hypersaline water body such as the Dead Sea is limited and cannot lead to full desiccation. In general, evaporation would continue as long as the lake-water activity is greater than the water activity in the air above the lake, the latter reflecting the relative air

4. Lake level fluctuations

Since Lake Lisan sediments are well recorded and dated until 14.6 kyr cal BP (top Lisan exposed section at PZ1 and Massada plain), their removal from the sedimentary sequences at the above-mentioned drilling sites (e.g., the absence of the Upper Gypsum Unit and the chronological hiatus) must have occurred after the retreat of the lake from the marginal terraces, namely after 14.6 kyr cal BP. This implies a lake level drop beneath the elevation of ~465 m bmsl (the elevation of the salt unit at Maatz-1 and NZ-1 bores, see, Fig. 3). This lake level drop occurred sometime between 14.6 and 11 kyr cal BP before the deposition of the salt unit. Moreover, relying on the Ze’elim wood sample, this significant lake level drop probably occurred between 11.5 kyr and ~12.3 kyr cal BP (Fig. 4). The Ze’elim DSIF core located at the high margins of the lake provides a minimum lake level at the time of salt deposition. ~400–405 m bmsl (Figs. 3 and 4), similar to the elevation of the Dead Sea during modern episodes of salt deposition (e.g., Neve and Emery, 1967; Gavieli et al., 1989). Thus, during the time interval of 14.6–11 kyr cal BP Lake Lisan dropped from 260 to below 465 m bmsl (base of salt unit at Maatz-1 and NZ-1; Fig. 3) and rose back to above 400 m bmsl (before salt deposition). These are large and rapid changes. If for example the major drop in lake level had occurred between 14.6 and 13.5 kyr cal BP, the declining rate would reach a value of 0.2 m/yr, ~20% of the current human-caused drop of the modern Dead Sea (which is currently (2009) more than 1 m/yr). Yet, the lake level drop during the Boiling–Alarmed time interval could be even more catastrophic as indicated by the erosional channels dissecting the floor of the Dead Sea at an elevation of ~600 m bmsl and below (Neve and Hall, 1979). Although some parts of these erosional channels could be submarine, present-day observations of the formation of deep gullies along the retreating shores of the Dead Sea suggest that the formation of deep erosional channels along the margins of the Dead Sea responds mainly to lake level decline (e.g., Bookman (Ken-Tor) et al., 2004). On the other hand, Yechieli et al. (1998) and Krumgalz et al. (2000) argued that the evaporation process of a hypersaline water body such as the Dead Sea is limited and cannot lead to full desiccation. In general, evaporation would continue as long as the lake-water activity is greater than the water activity in the air above the lake, the latter reflecting the relative air
humidity. Thus, as the lake level drops and the lake's volume decreases the salinity and density increase and evaporation rate decreases until it almost stops. In addition, water-level decline is accompanied by a decrease in surface area, further limiting the evaporation from the lake. The calculations indicate that under the current climate conditions (e.g., present-day relative air humidity), the Dead Sea brine would cease evaporating and stabilize at ~530–540 m bmsl. A more severe lake level drop could be reached only when extreme arid conditions prevailed in the region. Thus, if the lake indeed retreated to below 530 m bmsl, such extreme conditions should be considered for the Bolling–Allerød time interval at the Dead Sea region.

5. The Younger Dryas in the Levant: wet or dry period?

The evidence for an abrupt lake level drop between ~14.6 and 13.2 kyr cal BP and the requirement for a lake level rise prior to the deposition of the salt layer at ~11 kyr cal BP indicates that between 13.2 and 11 kyr cal BP lake level rose from below 465 m bmsl to above 415 m bmsl (highest elevation of the salt unit at the Ze’elim DSIF site). In fact, the lake level had to rise at least several meters above the Ze’elim (DSIF) salt before retreating and depositing several meters of salt. This scenario is illustrated in Fig. 4, where the ~4 m marly sequence (recovered in the Ze’elim DSIF borehole) represents the time interval of ~13.2–11 kyr cal BP - possibly encompassing the Younger Dryas (YD) at the Dead Sea basin. While the exact elevation of the lake during the YD is not known, mainly because no shoreline with YD ages has so far been identified along the Dead Sea margins, the key observation concerning the lake level history of the post-glacial Lake Lisan is the deposition of the salt unit (or the marly sequence of the YD age recovered in the DSIF borehole) on top of an erosional unconformity. This configuration requires that the lake first rose above the elevation of the unconformity and subsequently declined and deposited the salt unit. This scenario implies a relatively wetter Younger Dryas period at the Dead Sea drainage area followed by a dry spell associated with the salt deposition event (at 11–10 kyr cal BP). The occurrence of the ~13.2 kyr cal old wood debris within the marly section of the DSIF Ze’elim borehole complies with this scenario.

To a certain extent, our suggestion of a wetter YD in the drainage area of the Dead Sea basin stands in conflict with previous studies suggesting that the east Mediterranean region was arid during the YD (e.g., Rossignol-Strick, 1995). Assuming that the salt unit was deposited during the YD, Yechieli et al. (1993) concluded that arid conditions characterized the Dead Sea region during this time interval. Our new radiocarbon data clearly indicate that the salt unit was deposited on an unconformity and after the YD, between 11 and 10 kyr cal BP, implying a relatively wet YD. One of the arguments for an arid YD at the east Mediterranean region relies on the positive peak in the oxygen isotope composition in that period as recorded in Judea Mt. speleothems (Fig. 4). In general, Bar-Matthews et al. (1999) interpreted positive excursions in the $\delta^{18}$O of the cave as reflecting more arid conditions in the east Mediterranean region. However, Frumkin et al. (1999), Bar-Matthews et al. (2003) and particularly Kolodny et al. (2005) emphasized the importance of the source (the composition of the east Mediterranean seawater) on the $\delta^{18}$O in the speleothems. They showed a uniform residual $\delta^{18}$O value between the cave speleothem and east Mediterranean foraminifers that leaves limited room for other effects (e.g., rain amount). Indeed, east Mediterranean foraminifers and Judea Mt. speleothem that lived and were deposited at the time interval of 14–10 kyr cal BP yielded identical $\delta^{18}$O patterns and an uniform residual $\delta^{18}$O value (Fig. 4) that is consistent with a dominant source control on the $\delta^{18}$O values in the cave throughout the post-glacial and YD periods. The mechanism behind the rapid shift of the east Mediterranean water to heavier $\delta^{18}$O values during the YD is not clear and its interpretation stands beyond the scope of this paper.

Following the above reasoning it can be expected that the dramatic lake level decline at the Bolling–Allerød to below

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**Fig. 4.** Comparison between regional and global records during the post-glacial period (time interval of 20–10 kyr BP). (A) Lake Lisan level curve and lithology of the sedimentary section. The Upper Lisan section (20–17.5 kyr cal BP) is characterized by deposition of alternating laminae of primary aragonite and silty detritus ("Aad" in the figure); the section that contains the 13.2 kyr cal BP wood is composed of laminated marls; gypsum was deposited between 17.4 and 16 kyr cal BP, as well as at about 14.5 kyr cal BP; the salt unit was deposited between 11 and 10 kyr cal BP; (B) Soreq Cave speleothem $\delta^{18}O$ record (after Bar-Matthews et al., 2003); (C) East Mediterranean $\delta^{18}O$ record (after Almagri-Labin et al., 2009); (D) Sea level record (Peltier and Fairbanks, 2006). Note the occurrence of sharp sea level rises, defined as Meltwater pulse (MWP) 1a and 1b (Fairbanks, 1989). (E) GISP2 $\delta^{18}O$ record (GISP2 ages are based on the Almagri-Labin et al., 2009); (F) Sea level record (Peltier and Fairbanks, 2006). Note the occurrence of sharp sea level rises, defined as Meltwater pulse (MWP) 1a and 1b (Fairbanks, 1989). (E) GISP2 $\delta^{18}O$ record (GISP2 ages are based on the Almagri-Labin et al., 2009); (F) Sea level record (Peltier and Fairbanks, 2006).
465 m bmsl, must have resulted in unprecedented high salinity in the lake and thus, was possibly accompanied by salt precipitation. This salt could be eroded, dissolved and washed back to the lake upon the YD rise. We think that this dissolved salt was later to become the source for the salt precipitation during the subsequent 11 kyr BP lake decline. We also note that the top Lisan Fm. (e.g., at Massada plain) is covered by gypsum, which may represent the first stage of the evaporitic sequence during the 14.6–13.2 kyr cal BP lake decline. The modern Dead Sea provides evidence for salt deposition at the lake when water level declines below 400 m bmsl (Gavrieli et al., 1989). However, despite continuous halite deposition and the level decline of more than 15 m since the 1980s, no major halite layer has been identified along the Dead Sea shores. Salt that was deposited on the now exposed shorelines must have been dissolved within a year or two. This reworking of the modern salt provides an evidence of a mechanism for the absence of salt of older age (~14.6–12.2 kyr cal BP) in the section. The exposure of salt on the shorelines would result in its fast dissolution and transport into the lake. Alternatively it would have been washed by the freshwater runoff during the Younger Dryas or rising lake (with a relatively dilute mixolimnion). This scenario might have been repeated in the early Holocene time (~10–9 kyr cal BP) when lake level rose again but was limited to elevation above 415 m bmsl. Thus, the 11–10 kyr cal salt unit encountered in the boreholes probably remained submerged below the lake water and was not exposed to significant activity of freshwater runoff.

For the last two decades however, the salt unit at the base of the Holocene section has been vulnerable to subsurface dissolution caused by contact with freshwater groundwaters that flow in the subsurface toward the declining lake. This has resulted in the recent formation of sinkholes along the Dead Sea shores (Yechiel et al., 2006). The implication is that after the deposition of the early Holocene salt, at the interval of 10–9 kyr cal BP the lake and the adjacent subsurface groundwaters were sufficiently saline so as to inhibit salt dissolution.

6. The North Atlantic – Dead Sea climate–hydrology connection

The main observations outlined above are (a) abrupt lake level declines at 17.4 and after 14.6 kyr cal BP, (b) lake level rise and enhanced freshwater runoff during the Younger Dryas, and (c) lake level decline and deposition of salt in the early Holocene (11–10 kyr cal BP). While the overall retreat of Lake Lisan from its glacial high stands (MIS2) accompanied the general global warming trend of the post-glacial period (Fig. 2), the two major lake level drops appear to coincide in time with major freshwater and iceberg discharge events in the North Atlantic: H1 at ~17.4–16 kyr cal BP and MWP1a at 14.1 kyr cal BP (Fairbanks, 1989). Similar drops in lake level occurred during the last glacial period and appear to coincide with the timings of glacial Heinrich events in the North Atlantic (e.g. H5, 4, 3 and 2; see Bond et al. (1992) and Hemming (2004) for the chronology of the glacial H-events, and Fairbanks (1989) for the timing of MWP1a). The H-events had pronounced effects on northern hemisphere regional climates as well as some global impacts. For example, short SST cooling events, which respond to H-events were recorded in the west Mediterranean (Cacho et al., 1999, 2001), the Red Sea (Arz et al., 2003) and in the Indian Ocean (Kudrass et al., 2001). In the Dead Sea basin, Lake Lisan deposited the Upper Gypsum Unit (UGU) during the H1 time interval (17.4–16 kyr cal BP). The UGU consists of alternating sequences of primary aragonite (marking intervals of freshwater inputs to the lake) and gypsum (marking arid perturbations with possible lake level drops; Torfstein et al., 2008). Nine cycles of aragonite–gypsum sequences that appear in the UGU sequence may document rapid changes in the regional climate in an estimated frequency of ~200 ky, indicating a complex structure of the H1 stadial (as was already noted by Denton et al. (2006) for the “Mystery interval”).

The mechanism of shutting down the “rain engine” in the east Mediterranean during the H-events is not entirely clear. Typically, the eastward passage of cold fronts over the relatively warm Mediterranean causes cyclones (see Ziv et al., 2006 and references therein). Bartov et al. (2003) attributed the coincidence between the abrupt lake level drops and H-events to the addition of freshwater to the NA that inhibited the production of North Atlantic Deep Water. As a result, northward transport of heat from the tropics was inhibited too, resulting in the southern migration of low SST’s. Indeed, cool perturbations during H-events were recorded by Cacho et al. (1999, 2000) in the west Mediterranean Sea. Following Cacho et al. (2001) suggestion for the west Mediterranean Bartov et al. (2003) proposed that the rapid cooling of the East Mediterranean SST was controlled, at least in part, by atmospheric transfer.

The catastrophic lake (Lisan) level drop during the Bølling–Allerød coincides with the MWP1a event (at 14.1 kyr cal BP). We can only speculate that the changes in the hydrology of the Atlantic Ocean caused an amplification of the aridity trend in the Levant that commenced earlier ~17.4 kyr cal BP. This matter clearly requires more attention and climatic modelling.

What controlled the (Lisan) lake level rise during the YD? In most sites (mainly in the northern hemisphere) where YD “effects” were recognized the regional climate shows a short-term resumption of glacial climatic patterns (e.g., Broecker, 2006). In the case of the east Mediterranean/Dead Sea drainage area the implication is a return to colder conditions and an increase in the availability of freshwater in the drainage area of the Dead Sea Basin (similar to the conditions at MIS2). Furthermore, δ18O in the Mediterranean seawater displays a shift toward heavier (glacial) values. Thus, the climatic/hydrological patterns of the post-glacial Dead Sea drainage area appear to follow those of the glacial period with wetter periods prevailing during northern hemisphere glacial intervals (e.g. MIS4, 2 and YD) and drier periods during warm intervals (e.g. MIS3, Bølling–Allerød).

We conclude that the long-term warming trend in the post-glacial Levant was superimposed by abrupt arid events that coincided with, and was probably triggered by, the meltwater discharge events in the NA. Thus, the short-term climatic dry perturbations resulted in catastrophic lake level declines and massive salt deposition.

7. The climate–human development connection in the post-glacial Levant

The dramatic climatic–hydrological changes in the post-glacial Levant (as reflected in the Dead Sea Basin drainage area) were accompanied by significant developments in the prehistorical cultures in the region (Bar-Yosef, 1998) and references therein and see Fig. 4). These developments involved the decline of the Natufian culture during the extremely arid Bølling–Allerød period (when Lake Lisan declined to its minimum late Quaternary stand) and the rise of the Pre-Pottery Neolithic cultures (PPN A and B) upon the transition from the turbulent post-glacial period to the apparently less variable Holocene. Moreover, the chronological data that exist for the Pre-Pottery cultures suggest a significant break between the PPN A and B before and after the salt deposition (~10.8–10.2 kyr cal BP, Fig. 4). The available radiocarbon ages for the PPN A culture lie in the range of ~12 to ~10.7 kyr cal BP (e.g., Mithen et al., 2000 and references therein) coinciding with the time interval between the late YD and Preboreal. Dried figs from the PPN A sites of Gilgal, Jericho and Netiv Hagdol in the Jordan Valley yielded radiocarbon
ages in the range of 11.7–10.9 kyr cal BP (Kislev et al., 2006). These figs are considered to represent the last stages of human occupation of these sites, indicating the termination of the PPN A culture coincides precisely with the time of deposition of the salt unit, while the earliest ages of the PPN A sites extend into the late YD. The PPN B culture rose after the termination of the salt deposition event (at ~10.2 kyr cal BP) and the establishment of less variable climatic conditions in the region. This time window marks dramatic changes in the prehistory of the Levant with major developments in settlement size, animal domestication and tools industries (e.g., Belfer-Cohen and Bar-Yosef, 2000). While, the transition to milder climatic–hydrological conditions after salt deposition was possible in favour of the PPN cultures other geological/environmental factors could be influential, such as the accumulation of recycled (flood-washed) terra rossa soils (comprising the Fazael Formation) in the Jericho, Fazael and Gilgal basins (Jordan Valley) where the Neolithic settlements were established.

8. Conclusions

1. Exposed sedimentary sections and drill-core data combined with U–Th (on primary aragonite) and radiocarbon dating (of terrestrial organic debris) were used to construct a lake level curve for the post-glacial Lake Lisan (17.4–10 kyr time interval). Between 17.4 and 16 kyr cal BP (period known as the “Mystery interval”) the lake level dropped from its late MIS2 elevation of ~260 m bmsl to ~330 m bmsl, depositing a thick sequence of gypsum. Between 16 and 15 kyr cal BP the lake level sharply recovered but between 14.6 and 13.2 kyr cal BP it dropped abruptly to below 465 m bmsl (some lines of evidence even infer that the lake level declined below 530 m bmsl), possibly the lowest late Quaternary stand. Between ~13 and 11 kyr cal BP the lake level rose above 400 m bmsl and declined again at ~11–10 kyr cal BP depositing a thick sequence of salt.

2. The lake level drops at 17.4–16 and 14.6–13.2 kyr cal BP coincide with the time of H1 and MWP1a, respectively in the North Atlantic. This observation corroborates other observations from the last glacial period implying that major lake level drops in the Dead Sea Basin coincided with the H-events in the North Atlantic calling for a persistent linkage between North Atlantic NASA and Levant hydrology.

3. While the information on the Younger Dryas period in the Dead Sea basin is limited, the stratigraphic position of the 11–10 kyr cal BP salt unit above a significant unconformity in most drill cores requires a lake level rise before salt deposition during the YD period. This is consistent with the recovery of a lacustrine/marly sequence containing ~13 kyr cal BP organic (wood) debris at the Ze’elim drill-hole. Overall, the stratigraphic configuration recovered by the drill cores indicates relatively wet conditions in the Dead Sea Basin drainage area during the Younger Dryas.

4. Human culture development in the Levant appears to follow the major climatic events. The Natufian culture collapsed during the Bølling–Allerød catastrophic aridity of the region (14–13 kyr cal BP), while the Neolithic PPN A and B cultures (marking the initiation of the “Neolithic revolution” in the region) evolved upon the resumption of milder (less variable) climatic conditions in the region reflected by lake level rises before and after salt deposition. In particular, we note that the available radiocarbon dating of PPN A land organic debris (e.g., dried figs) spans the time from the YD to commencement of the salt deposition period (~12 to 10.9 kyr cal BP) supporting the interpretation of a pre-salt and post-Bølling–Allerød wet period in the region.

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References


