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The late Quaternary limnological history of Lake Kinneret (Sea of Galilee), Israel

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Abstract

The freshwater Lake Kinneret (Sea of Galilee) and the hypersaline Dead Sea are remnant lakes, evolved from ancient water bodies that filled the tectonic depressions along the Dead Sea Transform (DST) during the Neogene–Quartenary periods. We reconstructed the limnological history (level and composition) of Lake Kinneret during the past ~40,000 years and compared it with the history of the contemporaneous Lake Lisan from the aspect of the regional and global climate history. The lake level reconstruction was achieved through a chronological and sedimentological investigation of exposed sedimentary sections in the Kinnarot basin trenches and cores drilled at the Ohalo II archeological site. Shoreline chronology was established by radiocarbon dating of organic remains and of Melanopsis shells.

The major changes in Lake Kinneret level were synchronous with those of the southern Lake Lisan. Both lakes dropped significantly ~42,000, ~30,000, 23,800, and 13,000 yr ago and rose ~39,000, 26,000, 5000, and 1600 yr ago. Between 26,000 and 24,000 yr ago, the lakes merged into a unified water body and lake level achieved its maximum stand of ~170 m below mean sea level (m bsl). Nevertheless, the fresh and saline water properties of Lake Kinneret and Lake Lisan, respectively, have been preserved throughout the 40,000 years studied. Calcium carbonate was always deposited as calcite in Lake Kinneret and as aragonite in Lake Lisan–Dead Sea, indicating that the Dead Sea brine (which supports aragonite production) never reached or affected Lake Kinneret, even during the period of lake high stand and convergence. The synchronous level fluctuation of lakes Kinneret, Lisan, and the Holocene Dead Sea is consistent with the dominance of the Atlantic–Mediterranean rain system on the catchment of the basin and the regional hydrology. The major drops in Lake Kinneret–Lisan levels coincide with the timing of cold spells in the North Atlantic that caused a shut down of rains in the East Mediterranean and the lakes drainage area.

Keywords: Lake Kinneret; Lake Lisan; Dead Sea; Quaternary; Geo-archeology

Introduction

The present Sea of Galilee (Lake Kinneret) is a remnant lake that evolved from the ancient water bodies filling the Kinnarot basin (northern part of the Jordan Valley (Fig. 1)) during the Pleistocene–Holocene periods. The Kinneret is one of several lakes that occupied the tectonic depression along the Dead Sea Transform, e.g., the Pleistocene Lake Amora (Samra), the Last Glacial Lake Lisan, and the Holocene Dead Sea (Neev and Emery, 1967; Stein, 2001). The salt dissolved in the lakes originated from the ancient Sedom brine, and freshwater mixed with the brine reflects

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the hydrological–climatic conditions in the region that changed from wet to arid during the Quaternary (Stein, 2001). The various lakes along the Dead Sea–Jordan rift were characterized by distinct salinities. Lake Kinneret, a flow-through water body, was fresher than the southern terminal lakes occupying the Dead Sea basin. This difference is manifested by the abundance of fauna in mid-late Holocene Lake Kinneret; e.g., diatoms, ostracods, and molluscs (cf. Ehrlich, 1985; Pollinger et al., 1986). Prior to the present study, however, no information was available on the mineralogy, chemistry, and fauna abundance in the late Pleistocene–early Holocene Kinneret. The configuration of contemporaneous fresh (flow-through) and saline (terminal) lakes that converged during high lake stand into a unified water body makes the Kinneret–Lisan (Dead Sea) system a unique case of limnological and geochemical evolution. Here, for the first time, we reconstruct the sedimentological and level history of Lake Kinneret during the past ~40,000 yr. Lake-level reconstruction is based on sedimentological identification of shorelines and their dating by radiocarbon. The level and sedimentological history of Lake Kinneret is compared with the independently derived history of Lake Lisan–Dead Sea, based on data from the Dead Sea basin (Bartov et al., 2002, 2003; Bookman (Ken-Tor) et al., 2004). The implications of level history of the lakes for the regional hydrology and climate conditions are discussed.

Geological background

The Quaternary water bodies that filled the tectonic depressions along the Jordan–Dead Sea Rift Valley developed from ancient (Miocene) brines, related to the ingression of the Seldom lagoon into the valley (Starinsky, 1974; Zak, 1967). The modern Dead Sea and the Sea of Galilee both occupy pull-apart basins that were formed by the left-lateral slip on the major faults (Garfunkel, 1981). In the past, during times of high stands, the water bodies overflowed the tectonic depressions, expanding past their shallower margins. Their lateral extent and elevation were determined by the amount of input water, by evaporation, and by topographic effects. The topographic sill at Wadi Malih (Fig. 1) separated the southern Lake Lisan (occupying mainly the Dead Sea basin) from the northern Lake Kinneret (occupying the Kinnarot and Bet Shean basins) during most of the past 70,000 yr (Bartov et al., 2002; Begin et al., 1974). The Quaternary sediments filling the depressions to the south of the Wadi Malih sill (at ~280 m bsl) form the Samra, Amora, Lisan, and Ze' elim formations (Stein, 2001 and references therein), and the late Pleistocene–Holocene sediments deposited north of the Wadi Malih sill form the Kinneret Formation (Fig. 2; Hazan, 2003).

The Lisan Fm. consists mainly of authigenic aragonite and gypsum and clastic material transported by floods. The aragonite appears in thin (~0.5–1-mm thick) laminae alternating with detrital laminae of similar thickness. The detrital laminae consist mainly of quartz and calcite grains, probably of wind-blown origin, and dolomite, calcite, and clay minerals derived from the surrounding basin shoulders. The aragonite precipitated directly from the surface water (requiring supply of alkalinity to the lake) and is preserved in its primary state due to the dry climate in the Dead Sea basin and the high Mg/Ca ratio of interstitial soluble salts that precipitated from the formation pore water (Katz and Kolodny, 1989; Stein et al., 1997). Lake Lisan began its retreat ~17,000–15,000 yr ago (Bartov et al., 2002, 2003; Begin et al., 1985; Neev and Emery, 1995), and reached its minimum stand ~13,000–12,000 yr ago (Stein, 2002). During most of the Holocene the Dead Sea level fluctuated around 400 m below sea level (bsl), reaching a minimum stand of <420 m bsl ~3900–3400 yr ago (Bookman (Ken-Tor) et al., 2004; Frumkin et al., 1991; Kadan, 1997; Neev and Emery, 1995). The sediments deposited in the Holocene Dead Sea are essentially similar to those deposited in Lake Lisan, alternating sequences of aragonite and detritus laminae (~1–2-mm thick), gypsum and clastic units (Bookman (Ken-Tor) et al., 2004; Migowski et al., 2004).

Environments of deposition

The sediments deposited at Lake Kinneret and its surroundings represent several depositional environments: the offshore lacustrine (deep water) environment, the onshore fluvial environment, and the fan deltas and shore environments. Similar configuration was described in detail for the southern Lake Lisan and the Dead Sea (Bartov et al., 2002; Bookman (Ken-Tor) et al., 2004; Machlus et al., 2000 and references therein). The sediments representing each of those sedimentary environments are classified to several sedimentary facies representing the variations in water depth, energy, and the limnological configuration of the lake. Examples of these sedimentary facies are illustrated in Figure 3.

Onshore sedimentary environments include stream fan deltas, mud plains, and buried soils. At the shorelines, breaking waves wash away finer sediments and produce beach ridges consisting of pebbles or coarse sand. Typical examples of beach ridges are exposed at Tel Bet Yerach and Ha'on (Figs. 1 and 3). As the depositional environment shifts from the shoreline into deeper water, the influence of surface waves is reduced and the sediments become finer. In water depths of tens of centimeters to several meters, sediments with grain sizes varying from sand to silt are deposited. The sediments also exhibit ripple marks and cross bedding (e.g., the Tel Qazir outcrop, Appendix B). Clay to silt-size laminated sediments are deposited under water depths of more than a few meters. The lamination probably indicates deposition during time of layered lake configuration, similar to that in Lake Lisan. In

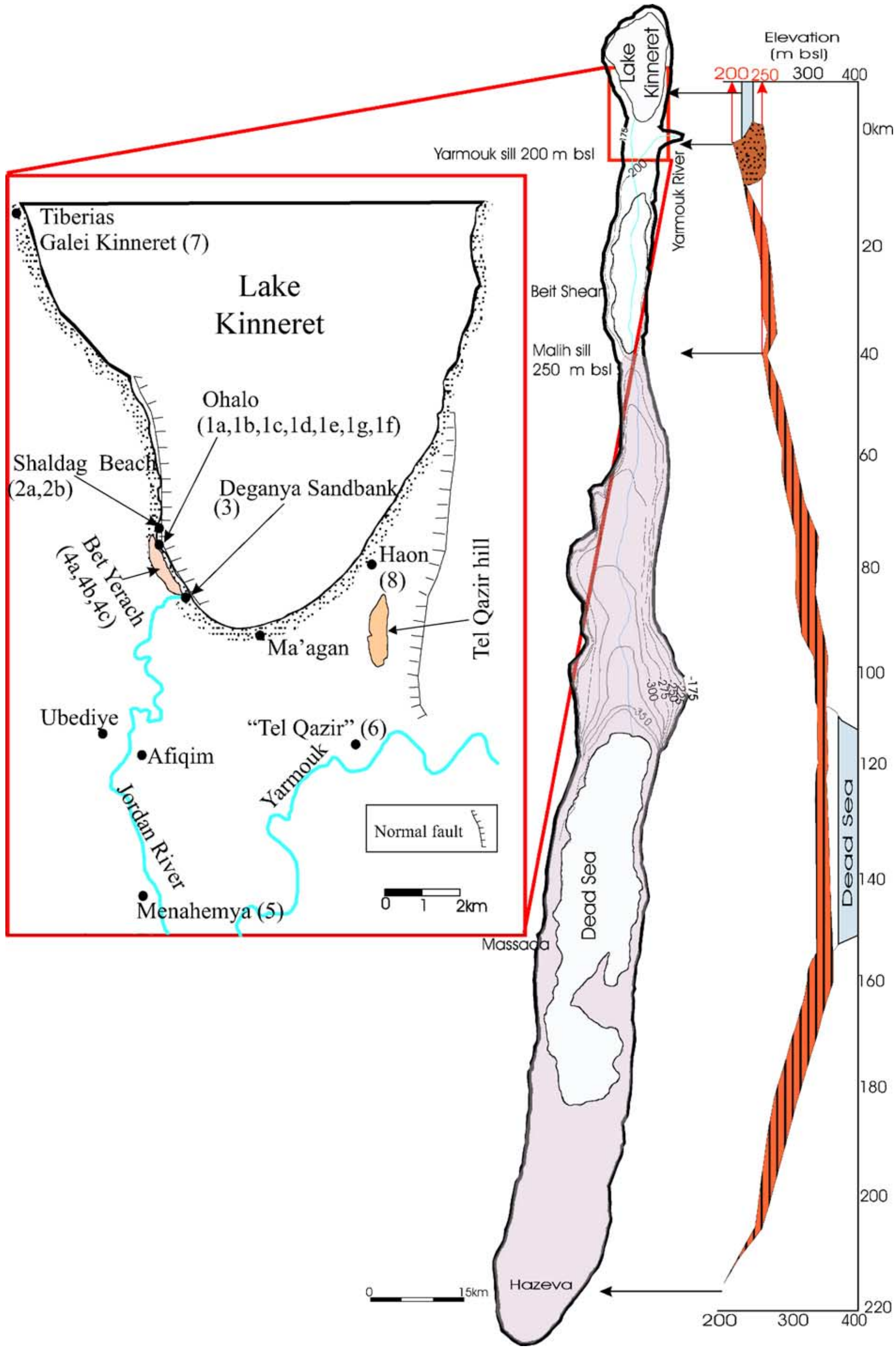

Figure 1. Location map: (a) Sampling sites in the Kinnarot basin are marked with numbers #1 to #8. The numbers match those in the lake-level curve (Fig. 4) and the site numbers in the text. Faults are marked after Rothstein et al. (1992). (b) Topographic map of the Jordan Valley from the Hazeva area to the north of Lake Kinneret (after Belitzky, 1996). The 175 m bsl elevation contour describes the high stand of the lake. (c) Cross section along the Jordan Valley showing the Yarmouk and Wadi el Malih thresholds (after Begin et al., 1974).

this respect, it should be noted that the late Holocene sedimentary sections of Lake Kinneret are mainly calcitic marls but rarely show lamination. This probably reflects annual overturn of the modern lake (occurring in summers), daily seiches, and boring-organism activity, preventing the preservation of lamination.

Aragonite, which is the major mineralogical component of the lacustrine–sedimentary sections of the Lake Lisan and Dead Sea, was absent in the Kinneret sections. The northernmost site where aragonite was found is the Menahemya section, in the southern Kinnarot basin (Fig. 1 and Appendix A). The lack of aragonite represents a fundamental difference in the limnological and geochemical conditions as compared to the southern Lake Lisan. It suggests insignificant contribution of the Ca–Cl brine into Lake Kinneret, since the production of Lisan-type aragonite

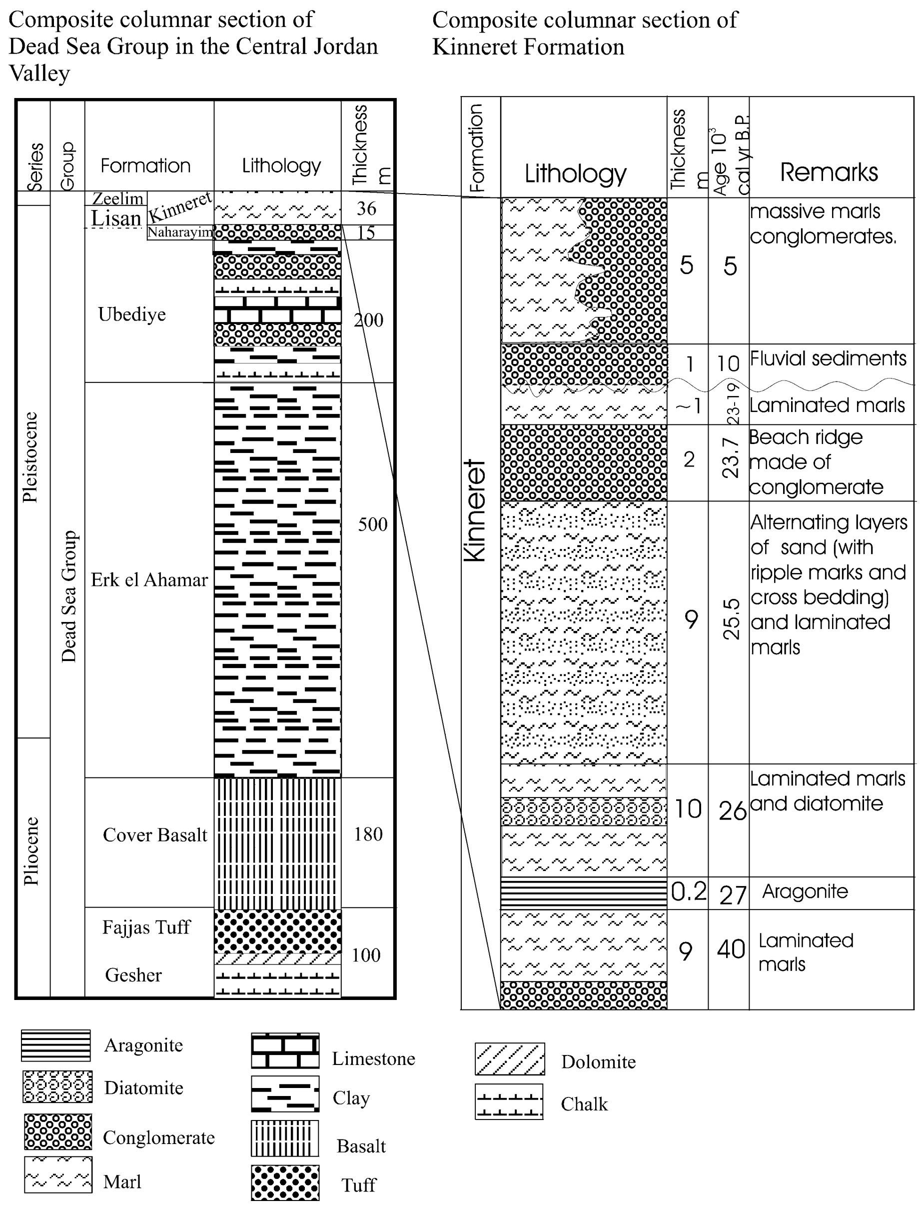

Figure 2. A composite stratigraphic section of the Dead Sea Group in the Central Jordan Valley (after Braun, 1992; Heimann and Braun, 2000). The detail (left) displays a composite columnar section of the Kinneret Formation in the studied area.

requires significant Mg input from the Dead Sea brine causing sufficiently high Mg/Ca ratio (>2) in the aragonite precipitating surface layer (Stein et al., 1997).

Radiocarbon chronology of the Kinneret sedimentary sections

The chronology of the Kinneret sedimentary sections was established by radiocarbon dating of mainly organic debris (e.g., seeds and woods) and in some cases Melanopsis shells. Numerous wood and organic remains were found at Ohalo II archeological site (Nadel, 1995), buried in the sediments south of this site (Nadel et al., 2001), buried in the shoals off Degania beach (Figs. 1 and 3), and along Ha'on beach. Most of these woods and other organic debris are embedded within beach sediments. The ^{14}C analyses were done in the AMS facilities at the University of Aarhus, and at Tucson, Arizona. The ^{14}C data are listed in Table 1.

Melanopsis shells are significant target for radiocarbon dating in Lake Kinneret as well as in freshwater springs and streams all over Israel (e.g., Lev et al., 2004). The Melanopsis shell is secreted as aragonite, and if well preserved, it can be used as a paleolimnological tracer (e.g., Rosenthal and Katz, 1989). However, the use of Melanopsis shell for radiocarbon dating requires knowledge on the reservoir age of the specific water body. We dealt with this problem in the following ways: (1) ^{14}C content was determined in living Melanopsis specimens

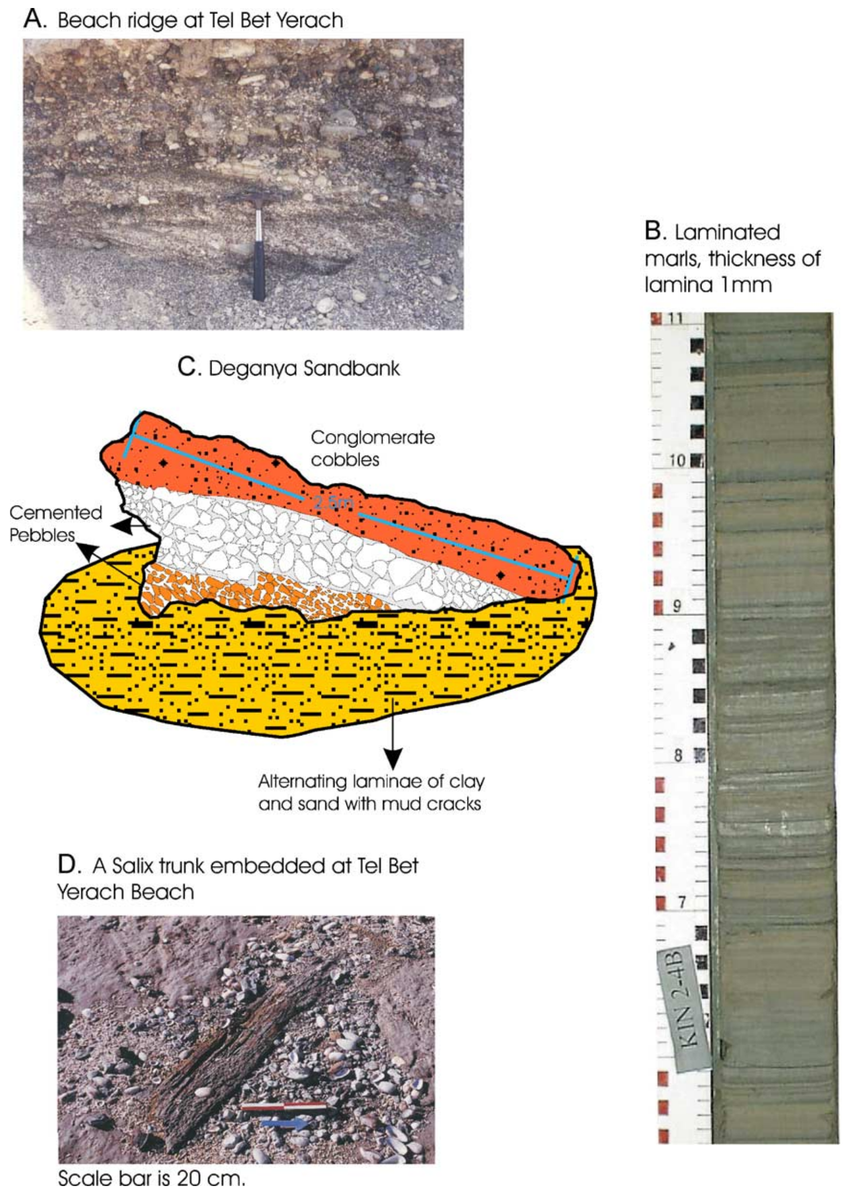

Figure 3. Illustration of deposits in various studied depositional environment around Lake Kinneret. (a) Beach ridge from the eastern side of Tel Bet Yerach (TBY). The beach ridge deposits is 160-cm thick and comprises coarse sand to pebbles. The bottom of the beach ridge was dated to 22,200 cal yr B.P. (b) A segment of a core drilled in the Ohalo II beach (next to archeological site). The photograph shows the fine lamination (~1 mm) of the late Pleistocene lacustrine marl sediments. (c) Schematic illustrations of the shoals at Deganya beach. The shoals are composed of pebbles and boulders of limestone, marls and basalts, and overlie laminated marly sediments with mud cracks. A tree trunk found beneath the shoal was dated to 21,000 cal yr B.P. (d) A Salix trunk embedded in late Pleistocene sediments at the Tel bet Yerach southern beach. This trunk is one of a group of eight trunks, which were found in an area of 100 m^2. The trunks were dated to 19,100 cal yr B.P. Scale bar is 20 cm.

from the Kinneret (Table 1 and new data reported by Lev et al., 2004). They yielded ~85 pMc similar to the content of modern Kinneret water (reported by Stiller et al., 2001), suggesting equilibrium with lake water. (2) ^{14}C ages were determined for Melanopside shells and organic debris (e.g., wood remains) from the same stratigraphic horizons. The Ohalo II Melanopsis yielded ^{14}C ages that are older by ~800 yr than the organic debris and charcoal from the same stratigraphic layer. This result is consistent with the living specimen/Lake Kinneret water relation, suggesting an approximately uniform reservoir age correction over the past 20,000 yr. Yet, Melanopsis shells from the Tel Qazir exposure, which were deposited at the same time as the Ohalo II ones yielded ^{14}C ages higher by ~3000 yr than the adjacent organic debris. The sediments in both sites were deposited during the period of highest lake level (24,000–25,000 yr ago). This difference is attributed to the living environment of the Melanopsis shells. The Ohalo II site was located in the deep-water environment, while the Tel Qazir exposure represents offshore environment (see below). The latter was probably affected by freshwater spring or stream

Table 1
Calendar and ^{14}C age data for samples and level markers

Sample	Location	Type	Height (m bsl)	Age (^{14}C yr B.P.)	Error	Calendar age (yr B.P.)	Mineralogy	# in Figure 4
BY 4-1	Bet Yerach	Shells	206.5	6265	60	6105		4a
BY 1-1	Bet Yerach	Melanopsis	204.9	20,500	180	22,500	aragonite	C
BY 1-2	Bet Yerach	Melanopsis	203.3	19,830	180	22,300	aragonite	C
BY 1-5	Bet Yerach	Melanopsis	200.3	5560	60	5230	aragonite	4b
BY 1 O-5	Bet Yerach	Melanopsis	200.3	20,360	190	22,500		C
On 3	Ha'on	Melanopsis	208.1	4805	60	4250	arag ≫ cc	
NHl	Kinneret	Live Melanopsis		835	60	785		
Mg 6	Ma'agan	Melanopsis	208.3	24,400	300	26,000		
Kin 5A-2B-3	Ohalo cores	Coal chunks	215.7	33,020	510	35,000		1b
Kin 2-6B	Ohalo cores	Melanopsis	222	40,510	1280	41,500		1a
Kin 2-3A-2	Ohalo cores	Melanopsis	214.5	21,420	160	23,000		3
Oh 70	Ohalo trench	Coal chunk	212.2	19,520	160	22,000		1c
Oh 175	Ohalo trench	Coal chunk	213.3	21,150	150	24,000		1c
Oh 185	Ohalo trench	Coal chunk	213.4	21,790	210	24,500		1c
Oh 212	Ohalo trench	Coal chunk	213.7	20,640	200	23,500		1c
Oh 310	Ohalo trench	Melanopsis	214.6	21,130	180	23,000	aragonite	2a
Oh 400	Ohalo trench	Wood	215.5	21,120	190	23,000		1a
Jr 8-1	Shaldag beach	Melanopsis	212.1	9520	90	9540	arag ≫ cc	2b
Jr 3-6	Shaldag beach	Melanopsis	214.1	20,830	200	23,000	aragonite	1d
TQ 1-1	Tel Qazir	Coal chunk	178.4	22,070	200	25,500		6
TQ 1-2	Tel Qazir	Coal chunk	177.8	21,470	180	24,500		6
TQ 1-3	Tel Qazir	Melanopsis	177.5	26,700	300	27,000	arag ≫ cc	
TQ 1-4	Tel Qazir	Melanopsis	176.6	30,550	550	33,000		
TQ 2-1	Tel Qazir	Melanopsis	176.8	25,200	250	26,500		6
TQ 2-2	Tel Qazir	Melanopsis	180.7	21,900	250	23,800		6
SH 1	Sheik Hosean	Melanopsis	240.7	36,060	800	39,000		
SH 2	Sheik Hosean	Melanopsis	235.5	39,100	1300	40,500		
DgW	Degania	Wood trunk	214	21,000		23,500		1e
	Ohalo	Wood trunks	213	19,430	770	22,500		1f
	Ohalo II	Wood	212.5	12,830	80	15,200		1g
	Ohalo II	Wood	212.5	15,430	110	18,500		1g
	Galei Kinneret	Roman stadium	212			2000		7

activity (e.g., the Yarmouk River) with enhanced radiocarbon "hard water" effect. Thus, the use of Melanopsis shells for ^{14}C dating requires information on their depositional environment (Lev et al., 2004). Here, we assume that the Melanopsis shells from the deep lake habitat require a reservoir age correction of ~1000 yr. After correcting for the reservoir age, the ^{14}C dates were calibrated by OxCal program (Bronk Ramsey, 2000). Ages older than 23,000 ^{14}C yr B.P. were transformed to "calendar" ages by the calibration scheme of Lisan aragonites (Schramm et al., 2000).

Reconstruction of Lake Kinneret level curve

The reconstruction of Kinneret level curve is based on identification of shorelines, surveying elevations, and radiocarbon dating. The identification of paleo-shorelines of Lake Kinneret is based on sedimentary information collected from several exposed sections along the southern shores of the lake, at Tel Bet Yerach and in the Jordan and Yarmouk creeks (marked in Fig. 1). Moreover, the recent (2001–2002) low stand of Lake Kinneret exposed small islands of lacustrine marls and fluvial sediments (e.g., off Ma'agan and Deganya beaches, Fig. 1). In addition, we dug several trenches at the Ohalo II archeological site, and at the adjacent Shaldag beach. For this project, we drilled a nine-meter deep borehole at the Ohalo II site. This is the longest borehole drilled to date in Lake Kinneret.

The level curve of Lake Kinneret for the past 40,000 yr is illustrated in Figure 4. In the following, we describe the sedimentary sections from which the lake level data are derived. The sites are annotated #1 to #8 in the location map (Fig. 1). The same numbers are used in the level curve (Fig. 4) and in Table 1.

The Ohalo II archeological site (#1 in Fig. 4)

The Ohalo II prehistoric site is located on the southwest shoreline of Lake Kinneret at the elevation of 212–213 m bsl. The site was first discovered during the low lake stand of fall 1989. Excavations revealed the remains of six in situ brush hut floors, hearths, and a grave. All floors and hearths contained large numbers of animal bones (including freshwater fish) as well as a wealth of plant remains (Nadel, 2002). *The Ohalo II borehole* was drilled at the shoreline of

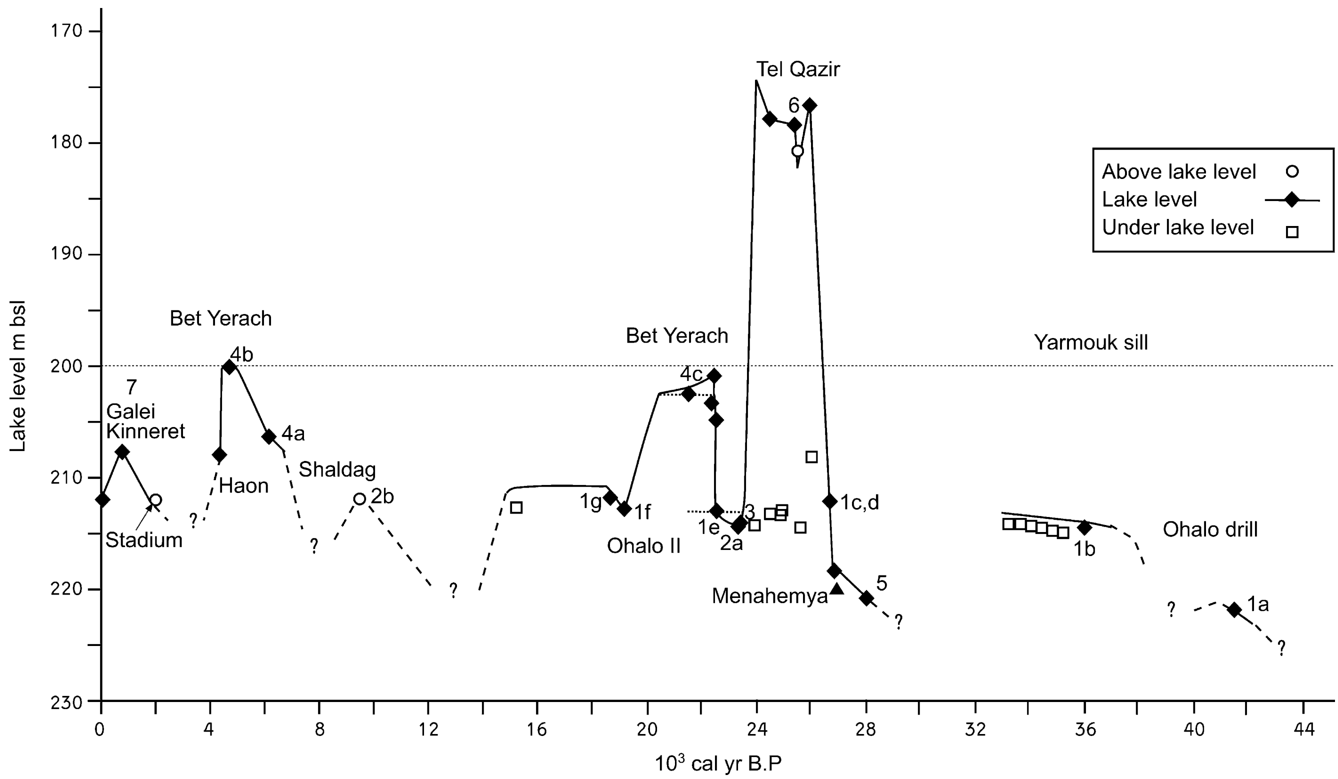

Figure 4. Reconstruction of the Lake Kinneret level curve during the past 40,000 yr. Filled diamonds mark lake level. They were determined by identification of beach sediments and ^{14}C dating (see text). Open squares mark below-lake levels that were evaluated by the location and ages of lacustrine marls. Open circles mark above-lake levels. These points were determined by the occurrence of fluvial sediments and by archeological sites. The numbers on the diagram match those on the location map (Fig. 1) and the description of lake-level reconstruction in the text. During most of the last 40,000 yr, Lake Kinneret level was around 212 m bsl, with some prominent high-stand and low-stand excursions. The two prominent high stands are: (1) at 26,000–24,000 cal yr B.P., lake level reached its highest stand of >174 m bsl and the Kinneret converged with the Southern Lake Lisan. (2) At 5200 cal yr B.P., lake level exceeded the altitude of 200 m bsl. The stands are reflected by several gaps in the curve. Major dropped occurred: (1) Before 41,000 cal yr B.P.; (2) between 40,000 and 36,000 cal yr B.P.; (3) between 33,000 and 27,000 cal yr B.P.; and (4) between 14,000 and 10,000 cal yr B.P. The beach sediments from these low-stand periods are probably buried in the lake under younger sediments.

the Ohalo II site (surface elevation of 213 m bsl). The drill provided the oldest sediments found to date in the vicinity of Lake Kinneret. At the depth of 9 m (222 m bsl, #1a in Fig. 4), a layer of pebbles was reached, and warm, saline waters were leaking. The pebbles may indicate the existence of an ancient shoreline or a riverbed. A Melanopsis shell found in the core a few centimeters above the pebbles yielded a ^{14}C age of 40,500 ^{14}C yr B.P. Considering a possibly large reservoir or hard-water age correction of up to ~3000 yr (similar to the value derived from the Tel Qazir Melanopsis, Table 1) and the uncertainty in the ^{14}C calibration at this time interval, we estimate the calendar age to lie in the range of ~40,000–43,000 cal yr B.P. In the modern Lake Kinneret, the association of pebbles and Melanopsis shells mark the shoreline facies. Thus, it appears that ~40,000–43,000 cal yr B.P. the shoreline was 9–10 m below the level of the Ohalo II site. Since no evidence exist for differential tectonic movement between the archeological site and the adjacent borehole, the depth difference should reflect a lake level change.

At a depth of 2.4 m in the core (215.7 m bsl), a charcoal sample was found and dated to 35,000 cal yr B.P. (in Table 1, marked as #1b in Fig. 4). A few centimeters above the 1b horizon in a nearby trench several samples of organic debris (marked as #1d in Fig. 4) yielded ages of 24,000–25,000 cal yr B.P. The last two groups of samples (#1c and #1d) were deposited during the rise of the lake to its highest stand of 170 m bsl (as deduced from the Tel Qazir exposure, described below). The chronology and stratigraphy of the core indicate a significant depositional hiatus between ~35,000 and ~28,000 cal yr B.P. Lake level at the time interval was below 216 m bsl.

Forty-five plant remains, both charred and not charred, from the Ohalo II archeological site and the surrounding lacustrine layers, were dated by radiocarbon (Nadel, 2002; Nadel et al., 2001) to 22,500 ± 1000 cal yr B.P. (#1e in Fig. 4, represented as dotted line). The relatively good state of preservation of the archeological remains suggests rapid burial of the Ohalo II site by sediments, implying a rise in the lake level or tectonic sinking of the shore (Belitzky and Nadel, 2002). Radiocarbon dating of organic remains found above the site yielded significantly younger ages. South to the Ohalo II site, below Tel Bet Yerach (1f in Fig. 1), several tree trunks were found at the elevation of 213 m bsl (#1g,f in Fig. 4), and were dated to 19,500 ± 500 cal yr B.P. (Nadel et al., 2001). Thus, it appears that the lake receded to ~214 m bsl after 24,000 cal yr B.P. and rose again above the archaeological site at ~19,500 yr cal B.P. The Kinneret drop at 23,000–24,000 cal yr B.P. coincides with a significant drop in Lake Lisan (Fig. 8), which was correlated to Heinrich event H2 by Bartov et al. (2003). This coincidence between the lake falls and the global H events is elaborated on below.

Shaldag beach (#2 in Fig. 1)

Several trenches were dug at the Shaldag beach (500 m north of the Ohalo II site); the old outlet of the Jordan river was located here (Belitzky and Nadel, 2002) (Fig. 5). An organic-rich layer was found in some of the trenches at elevation 213–212 m bsl. This organic-rich layer is a remnant of the shore vegetation, overgrown during low lake stand and submerged when the lake level rose. A Melanopsis shell found just below the organic layer within marly sediments yielded a radiocarbon age of 20,800 cal yr B.P. The organic-rich layer containing the shell was correlated with the *Ohalo II layers* (Fig. 5). The calendar age of the Melanopsis shell is 23,500 cal yr B.P. (#2a in Fig. 4), implying a reservoir age correction of ~1000 yr similar to the value derived from the modern and late Holocene specimens. Another Melanopsis shell was found within fluvial sediments (pebbles of chert and basalt) above the organic layer at 212 m bsl. It yielded a

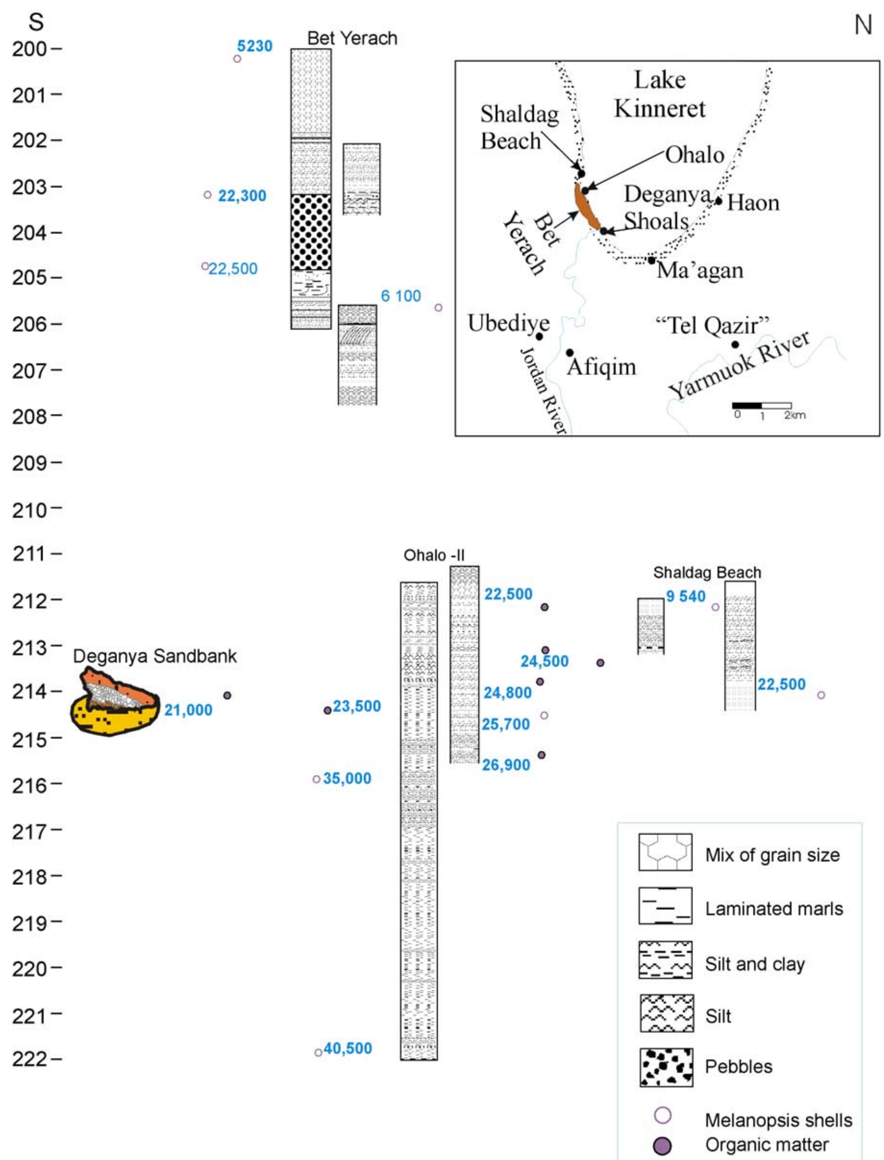

Figure 5. Stratigraphic correlation between the sedimentary sections at Shaldag Beach, Ohallo II, Bet Yerach, and the Degania sandbank (marked from north to south). The numbers next to the columnar sections are calibrated ^{14}C ages (cal yr B.P.).

significantly younger age of ~8000–9000 cal yr B.P. (# 2b in Fig. 4).

The pebbly sediments must have been deposited by an in-flowing stream. The only stream in the vicinity is the Yavniel creek. The inlet subsequently reversed its flow direction and became an outlet of the Jordan River.

Deganya shoals (#3 in Fig. 1 and see illustration in Fig. 3)

The low stand of Lake Kinneret during the years 2001–2002 exposed several small islands and shoals in the southern part of the lake. We examined the shoals exposed at the Kibbutz Deganya beach. They comprise a conglomerate consisting of chert, limestone, and basalt pebbles overlying laminated marls at the elevation of 214 m bsl. The marls exhibit desiccation cracks, indicating past exposure of this surface. Similar clastic sediments were found at the same elevation on the small island that emerged opposite Kibbutz Ma'agan (Fig. 1). A large tree trunk was found in the marls just beneath the Deganya shoals and was dated to ~23,500 cal yr B.P. (Fig. 4, #3 that converges with point 2a). This age marks the time of a significant lake drop and formation of the exposed surface and fluvial deposits in the southern part of the lake.

Summarizing the findings in the Ohalo–Shaldag–Deganya–Ma'agan sites, similar sequences of coarse clastic material appear at the same elevation of 214–213 m bsl (Fig. 5). Apparently, at ~23,500 yr cal B.P., a large fluvial plain covered the southern flat basin of the Kinneret. The pebbles are mainly limestone, chert, and basalt. The only feasible sources for such pebbles are the Yavniel Creek on the west and the Yarmouk river on the east. The former possibility would imply that the lake outlet to the Jordan River migrated westward to its present location subsequent to the erosion forming the fluvial plain. We note that after the lake drop and during the formation of the large south-Kinneret fluvial plain, the paleolith humans settled in the *Ohallo II* and other sites around the retreating lake.

Tel Bet Yerach (TBY, #4 in Figs. 1 and 6)

TBY is one of the most significant prehistoric sites in the Levant (Vinogradov, 1992, and references therein) (Fig. 6). It also provides indispensable information on the late Pleistocene and early Holocene geological–limnological history of Lake Kinneret. The lower part of TBY comprises sedimentary sequences of the late Pleistocene Kinneret while the upper part consists of archeological layers that are overlain by sediments of mid-Holocene lake transgression.

TBY was inhabited from the Early Bronze Age (5300–4300 yr ago). Then, the Tel was conquered and destroyed by the EB IV people, who resettled it until 4200 yr ago, and was then abandoned. By that time, most of the rural settlements of the Middle East including TBY were deserted. This is the "Intermediate Bronze Age" cultural break (Gophna, 1992, and see summary in Neev and Emery, 1995 and references therein). Subsequently, TBY was not resettled until the Hellenistic time, about 2600 yr ago, and later, during the Arabic Period (1360–900 yr ago). The settlement history of TBY was to a large extent dictated by the climatic-lake level changes.

TBY is bounded to the east by the Kinneret and to the south and west by the modern and ancient channels of Jordan River (Fig. 7). The location of the sill that acts as a natural spillway of Lake Kinneret is seemingly controlled by the delta of the Yarmouk River, demarcated at present by the 200 m bsl contour. Deposition of lacustrine sediments on

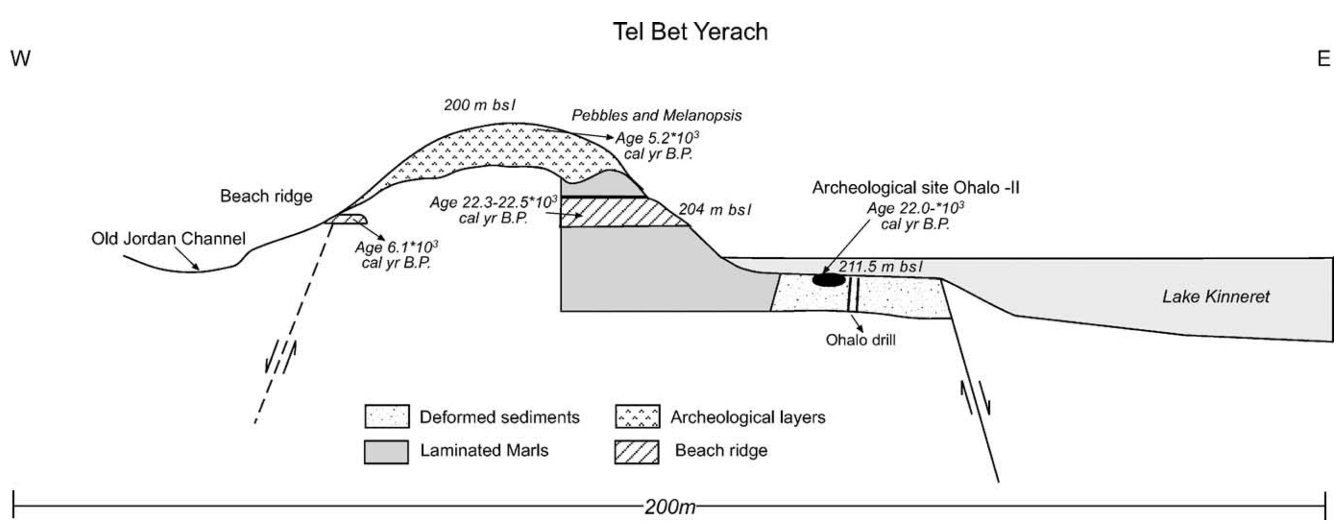

Figure 6. Schematic E–W section of Tel Bet Yerach (TBY). The Tel consists of two main layers: the lower layer comprises late Pleistocene to mid-Holocene sediments. The upper layer comprises archeological remains. The prehistory site of Ohalo II was exposed on the eastern shore of the Tel during the Kinneret low stands of the mid-1990 (now submerged). Also marked is the drilling site of the Ohalo II borehole.

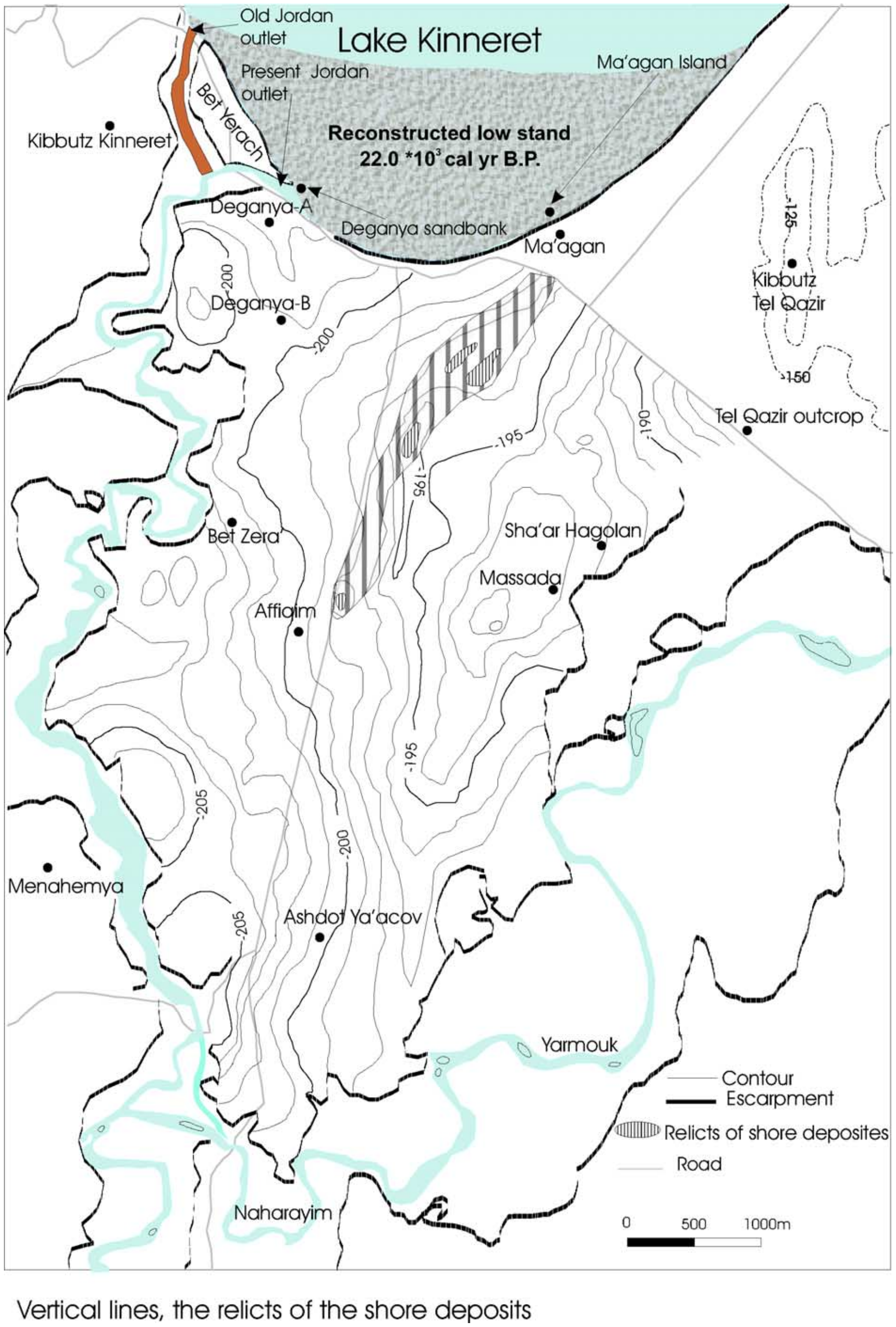

Figure 7. Topographic map of the Kinnarot basin. The stippled areas are relicts of ancient shoreline (~200 m bsl), which were probably deposited at the high stand of 5200 cal yr B.P. The textured area in the southern Lake Kinneret marks the reconstructed alluvial surface at ~23,800–23,000 cal yr B.P.

TBY requires one of two conditions: either the entire Dead Sea–Jordan basin is flooded above the Yarmouk delta (acting as a topographical sill), or the elevation of the sill changes due to changes in the balance between erosion and sedimentation (tectonic effects are likely smaller as discussed below).

At the bottom of TBY, at an elevation of 206.5 m bsl, a coarse sand layer contains numerous Melanopsis shells. The shells were dated 6000 cal yr B.P. (#4a in Fig. 4). Flooding of TBY is indicated by the presence of post Early Bronze IV shallow (20–50 cm) wide (2–4 m) drainage channels entrenched across the upper surface of the Early–Bronze settlement (Bar-Adon, 1966). These channels were filled by poorly sorted, cross-bedded sand to small pebbles, lenses, mixed with pottery shreds of Early Bronze age, as well as scattered shells of freshwater Melanopsis and *Unis* shells. A ^{14}C age of 5400 $\pm$ 180 ^{14}C yr B.P. was determined for a *Unis* shell, found within the same layer was dated to 5200 cal yr B.P., which is the same error as the age of the Unis shell (#4b in Fig. 4).

We do not overlook a slight possibility that the molluscs lived above the level of the lake, at man-made channels draining a small and now extinct man-made reservoir. In any event, the coincidence of the age of both molluscs and their absence in other period suggests that the lake level reached a maximum at 5200 cal yr B.P. The ~5200 yr lake rise can possibly be linked with a shoreline feature identified in old aerial photographs extending southwards from the southern section of Kibbutz Ma'agan running parallel to the Naharayim–Zemah railway at the elevation of 197 m bsl (Ben-Arieh, 1964) (see Fig. 7).

The late Pleistocene sedimentary section of the Kinneret Formation is exposed on the eastern face of TBY. The section comprises alternating sequences of laminated marls and clastic units. The latter exhibit shallow water sedimentary structures, namely ripple marks and cross bedding. One of the outcrops at the site contains a beach ridge at the elevation of 203.3–204.9 m bsl. A Melanopsis shell from the base of the beach ridge was dated to 22,500 yr cal B.P., while the top was dated by another Melanopsis shell to 19,800 and 22,300 cal yr B.P. (#4c marked as dotted line Fig. 4). Within the beach ridge, lithoclasts of lacustrine sediments are visible that must have been removed intact from a preexisting and topographically higher sedimentary section, consistent with the assertion that the ridge formed during a period of falling lake level. Within uncertainty of the reservoir age correction, this beach ridge yielded a similar age to that of the Ohalo II samples that are located at a lower elevation. The stratigraphical configuration could imply a fast lake rise or vertical displacement of some 7 m between the Ohalo II site and TBY over the past 24,000 yr. Evidence for tectonic movements along the western shore of the Kinneret was recently reported: Marco et al. (2003) documented ~40 cm vertical displacement of the Galei Kinneret fault (western shore of the lake) that was associated with A.D. 749 historically documented earthquake. Although these findings indicate some tectonic displacement along the lake's shore, the major fluctuations in lake level were significantly larger. In Figure 4, we favor the interpretation of a fast rise between 23,000 and 22,000 yr ago. This is supported by the rapid cover of the Ohalo II site (Nadel et al., 2001) and by the agreement with the lake level pattern of Lake Lisan during this time interval (Fig. 8).

The elevation of long-term spillway at the Yarmouk still reflects a balance between sedimentation and erosion, with a possible tectonic overprint. The observation that the level curve is relatively steady in the last 20,000 yr suggests a buffer close to 214 m msl. Two exceptions to the above rule include the high stand at 5200 cal yr B.P. and seemingly a hiatus between ~13,000 and ~9000 cal yr B.P. Understanding the nature of the low stand requires drill-hole data in the deep basin, yet to be recovered. The ~5200 cal yr B.P. high stand (~200 m bsl) exceeds the present level of the Yarmouk delta "sill". This requires an ephemeral rise of the sill. Barring a significant tectonic effect, such a rise can be achieved by a rate of sedimentation higher than the rate of erosion.

The Menahemya outcrop (#5 in Figs. 1 and 4)

The Menahemya outcrop comprises shore deposits, laminated marls, and laminated aragonite (Appendix A). A massive marl layer is exposed at the base section, overlain by shore ridge deposits (at elevation 223 m bsl). Above the shore deposits, a sequence of laminated marls appears with lenses of broken laminae of aragonite in its upper part. This is overlain by a sequence of alternating aragonite and detrital laminae. The aragonite was dated by the $^{230}Th–^{234}U$ method to 27,000 ± 1000 yr ago (Haase-schramm et al., 2004; Schramm et al., 2000). Marls with aragonite crust and cross-bedded and rippled sands overlie this sequence. The appearance of the aragonite crust is typical to the near-shore environment of the Dead Sea lacustrine system (Bookman (Ken-Tor) et al., 2004). The upper part of the Menahemya section consists of laminated marls of the Kinneret lacustrine facies.

The sequence of alternating laminae of aragonite and detritus at the Menahemya outcrop represents the northernmost appearance of the Lisan-type lacustrine facies in the Jordan Valley. Laminae of a similar type were deposited from Lake Lisan and the Holocene Dead Sea, representing a mixture between incoming freshwater rich in bicarbonate and the Ca–Cl brine (Stein et al., 1997). Thus, it appears that the deposition of aragonite at the Menahemya site indicates migration of brine from the Dead Sea basin over the Wadi Malih sill into the Kinnarot basin (Fig. 1). No aragonite was found north of Menahemya, suggesting that the Dead Sea brine did not cross the Yarmouk threshold. The Menahemya aragonite shows an $^{87}Sr/^{86}Sr$ ratio of 0.70804, which is indistinguishable from ratios exhibited by Lake Lisan aragonites (Stein et al., 1997), but is significantly different from Lake Kinneret water or aragonitic Melanopsis shells $^{87}Sr/^{86}Sr = 0.70745$; Hazaan, 2003).

About 27,000 yr ago, Lake Lisan rose and approached the Kinnarot Valley, but its heavy brine could probably not cross the Yarmouk threshold. The evidence for the highest lake level at 26,000–24,000 yr ago was found at the Tel Qazir outcrop described below. This rise is expressed in the Menahemya exposure by the deposition of the laminated marls above the beach pebbly deposits.

The Tel Qazir section (#6 in Figs. 1 and 4)

The top of the Kinneret–Lisan Formation in the Kinneret basin is exposed near Kibbutz Tel Qazir on a flank of the Yarmouk River fan delta at an elevation of 174 m bsl. The Tel Qazir samples represent the highest stand of Lake Kinneret, when it merged with Lake Lisan (see discussion below). The outcrop comprises cross-bedded and rippled sandy layers alternating with laminated marly units (Appendix B). The sandy layers are typical of a shallow

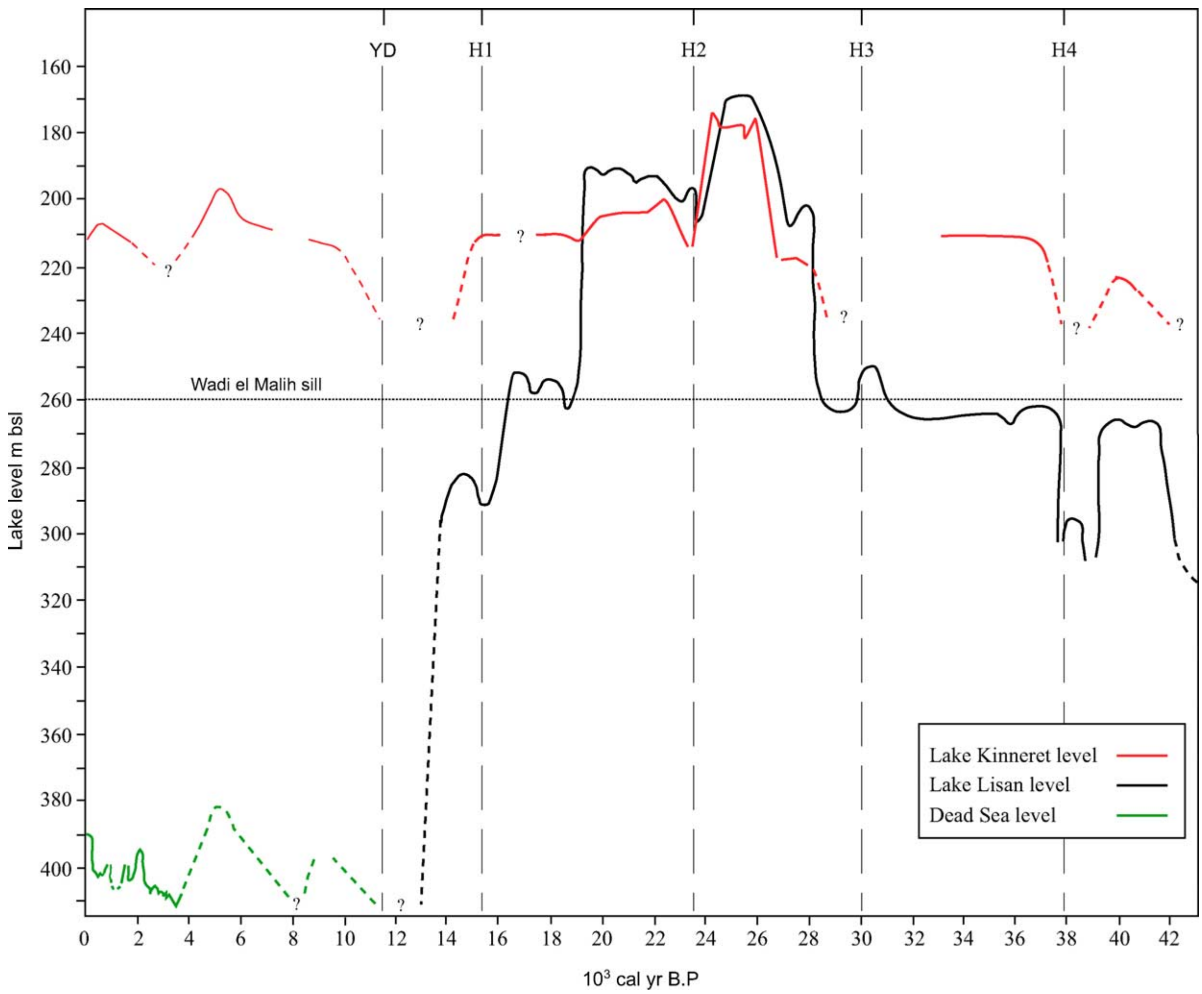

Figure 8. Comparison between Lisan (black), Dead Sea (green), and Kinneret (red) level curves. Note the good agreement between the Lisan and Kinneret curves at periods of high or significantly low stands. Low stands are expressed as hiatuses in the Kinneret curve, and they coincide with the timing of H events in the North Atlantic. The difference between the amplitudes of lake level is significantly larger in the late Pleistocene period (Lisan and Kinneret diagrams) as compared to the Holocene period (Kinneret and Dead Sea diagrams). The Lisan diagram is after Bartov et al. (2003), the Dead sea diagram is after Bookman (Ken-Tor) et al., 2004 and Migowski et al. (2004).

water near-shore depositional environment, while the marly units suggest deposition in deeper water. Radiocarbon ages were obtained from Melanopsis shells and charcoal found at elevations of 176.8–180.7 m bsl. The calibrated ages range between 26,000 and 25,000 cal yr B.P., (Table 1). Beach sediments and a small unconformity separate the age samples dated to 26,000 and 25,500 cal yr B.P., suggesting erosion at the shore environment. The exposure provides the best documented and dated high-stand shoreline of the converged water body. It is significant that both the dating and the elevation of the high-stand inferred in Tel Qazir agree so well with those of Lake Lisan highest stand determined by Bartov et al. (2001) (Fig. 8).

Galei Kinneret site (#7 in Figs. 1 and 4)

The mid-Holocene represents the last high stand of Lake Kinneret. The construction of the city of Tiberias by King Herod at A.D. 17 indicates that the shoreline was at ~211 m bsl. New archaeological excavations at the Galei Kinneret site in Tiberias exposed sedimentary alluvium and lacustrine sediments, which bury the lower parts of the site, suggesting a rapid rise of lake level during the Early Arabic period (Marco et al., 2003). The rise is constrained by the archaeological findings to between the late 7th and 8th century. The sudden high stand, accompanied by increased high-energy boulder-bearing sediment flux, can explain the abandonment and subsequent deterioration of over a dozen Roman and Byzantine piers and jetties around the lake.

Gaps in the level curve

The reconstructed level curve of Lake Kinneret displays several gaps that probably indicate significant level falls and lack of deposition or erosion at the sampling area. No deep cores are available thus far from the deepest part of the lake (~40 m). The main gaps appear between 40,000 and 36,000; 32,000 and 28,000; 14,000 and 9000; and 4000 and 2000 yr ago. Most of these gaps can be correlated with low stands in the independently derived curves of Lake Lisan and the Holocene Dead Sea (Fig. 8).

Lake Kinneret–Lake Lisan relation and global climate connection

The lakes along the Jordan–Dead Sea basin (Fig. 1) currently comprise a chained limnological system where the northern Lake Kinneret is a fresh flow-through water body while the southern Dead Sea is a terminal hypersaline water body. The reconstruction of the lake-level curves (Figs. 4 and 8) suggests that this chained configuration prevailed during most of the past ~40,000 yr. The northern Lake Kinneret stabilized for long periods of time at the elevation of ~212 m bsl, while the southern late Pleistocene Lake Lisan and the Holocene–Dead Sea stabilized for long periods at 280 ± 10 and 400 ± 10 m bsl, respectively (cf. Bartov et al., 2003; Bookman (Ken-Tor) et al., 2004). This pattern was punctuated by shorter episodes of sharp rises or falls in lake level that exceeded several tens of meters (e.g., the sharp rise of Lake Lisan and Lake Kinneret by ~120 and ~40 m, respectively between 26,000 and 24,000 cal yr B.P.). The information on the lowest stands of Lake Kinneret is incomplete. Nevertheless, sharp declines in Lake Lisan, such as the ~70 m drop at 46,000–43,000 cal yr B.P., coincide with more than 10–15 m drops in Lake Kinneret (Fig. 8). We speculate that the significant drop at Lake Kinneret coincided with the strongest drop of Lake Lisan (by more than 200 m) 13,000–12,000 cal yr B.P. (Stein, 2002). This drop could have potentially transformed the Kinneret into a terminal water body. The hypothesis should be tested by future drilling at the deepest part of the present lake.

Salinity changes in the Kinneret–Lisan system

The Kinneret and Lisan lakes were characterized by distinct salinities and chemical composition. The Ca–Cl brine dictated the precipitation of aragonite and gypsum in Lake Lisan (see Stein et al., 1997). In the freshwater Lake Kinneret, calcite has been the dominant carbonate phase, indicating insignificant contribution of Mg-rich brine to the water. Calcite was deposited in Lake Kinneret, while aragonite precipitated in Lake Lisan during the time of the lakes' convergence (26,000–24,000 cal yr B.P.). The northernmost appearance of the Lisan-type aragonite is in the Menahemya exposure (Fig. 1), where a few layers of aragonite were found. The Menahemya aragonite yielded a U–Th age of 27,000 ± 1000 yr, when Lake Lisan commenced its rise to the maximum stand of 174 m bsl. This could infer that the Dead Sea brine was invading the upper Jordan Valley, yet we could not trace the Menahemya aragonite for a long distance, and so far we have no indication that the Menahemya aragonite represents a continuous unit throughout the Jordan Valley. Above the Menahemya aragonite, laminated "Kinneret-type" calcitic marls were deposited (see Appendix A), marking the high-stand period (~26,000–24,000 cal yr B.P.). Thus, during the time interval of high stand, the Dead Sea brine was limited to south of the Wadi Malih sill (Fig. 1). We suggest that Lake Kinneret behaved as a big estuary during that time, pushing large amounts freshwater over the Yarmouk sill southward. Overall, the combined high-stand lake displays a significant salinity gradient, which is also reflected by the existence of freshwater fauna and diatomite in the northern Jordan valley. The upper layer of this long and narrow lake had a prominent salinity maximum near the archeological site of Massada (Begin et al., 2004).

Lake levels and global climate

The simultaneous changes in the level of the Kinneret–Lisan–Dead Sea suggest simultaneous modulation of the hydrological–lacustratine system by the regional climatic conditions in the drainage area (e.g., a different configuration could reflect an enhanced contribution of southern rain and floods to Lake Lisan and the Dead Sea). This is consistent with the estimation based on $^{87}Sr/^{86}Sr$ and Sr concentrations in the various waters from the Lisan drainage area and the Lisan aragonite that ~50% of the freshwater were contributed to Lake Lisan from the northern paleo-Jordan, whereas the rest were mainly runoff water (Stein et al., 1997). The coincidence in the timing of lake drops emphasized the role of the northern sources of freshwater and their coupling with the runoff sources. This coincidence is consistent with the dominance of North-Atlantic-Westerly climate system as the main source of rainstorms in the drainage area of the lake (Bartov et al., 2003; Enzel et al., 2003 and references therein).

Previous studies on Lake Lisan inferred that cold periods in the northern latitudes are correlated with fluvial periods and higher stands in the lakes (e.g., MIS 2 and 4) and warmer periods are correlated with dryness and low stands in the lakes (e.g., MIS3 or the Holocene, Hasse-Schramm et al., 2004; Stein, 2001). Yet the sharp drops in Lake Lisan–Lake Kinneret levels (e.g., at 38,000 and 23,800 cal yr B.P.) appear to coincide with the catastrophic ice rafting Heinrich (H) events in the northern Atlantic. Bartov et al. (2003) proposed that during the ice rafting events, cold water entered the Eastern Mediterranean and stopped the uptake of water vapor shutting down the rains.

The sharp rise of Lake Kinneret level at 27,000–24,000 cal yr B.P. and the subsequent drop at ~23,500 cal yr B.P. deserve particular attention. Comparing the Kinneret–Lisan curve to the North Atlantic ice-core record, Figure 8 shows that the lake rise coincides with a sharp decline in ice-core temperature and the lake drop coincides with the ice-rafting event H2 (noted for Lake Lisan by Bartov et al., 2003; Haase-schramm et al., 2004). After the 23,800 cal yr B.P. drop, Lake Lisan stabilized in the high stand of ~200 m bsl until 18,000 cal yr B.P. (Fig. 8). Lake Kinneret dropped at 23,800 cal yr B.P. to 208 m bsl (the Ohallo II site) and then rose by several meters and covered the prehistoric site (at 19,500 cal yr B.P.). Thus, the LGM is marked by high lake stands although the maximum level was reached already at 26,000 cal yr B.P. This may imply that maximum pluvial conditions prevailed in the East Mediterranean region earlier than the presently inferred LGM (at ~19,000–20,000 cal yr B.P.). The question of the configuration of the LGM and its relation to the hydrology of the East Mediterranean and level history of the lakes certainly deserves more attention. Nevertheless, the synchronous level fluctuation of Lake Kinneret, Lake Lisan, and the Holocene Dead Sea, is consistent with predominance of Atlantic–Mediterranean rain system in the regional hydrology (Bartov et al., 2003; Enzel et al., 2003; Prasad et al., 2004, and references therein). This system feeds the Jordan sources as well as the runoff from the rift shoulders, and its modulation by global climate controls the filling or drying of the lakes.

Summary

1. Lake Kinneret (Sea of Galilee), Lake Lisan, and the Dead Sea occupied the tectonic depressions along the Dead Sea–Jordan Valley during the late Pleistocene–Holocene time. We reconstructed, for the first time, the sedimentological and level history of Lake Kinneret during the past ~40,000 years, and compared this history to that of the last Glacial Lake Lisan and the Holocene Dead Sea. The level curve is based on identification of shorelines, determination of their elevation, and establishment of their chronology by ^{14}C dating organic debris and Melanopsis shells.
2. During most of the studied period, the northern and southern lakes were disconnected forming a chained lacustrine system. They converged only during the high stand of ~170 m bsl at 26,000–24,000 cal yr B.P., and then at ~23,800 cal yr B.P. separated again. Lake Kinneret underwent several rises and falls that exceed several tens of meters (compared with hundred of meters changes in the terminal Lake Lisan). Significant drops in Lake Kinneret occurred at ~42,000, 38,000, 23,800, 13,000, and 8000 cal yr B.P., contemporaneously with significant drops in Lake Lisan and the Holocene Dead Sea.
3. The lake fall at ~23,800 cal yr B.P. exposed the southern part of the Kinneret to fluvial activity of the Yarmouk and Yavniel rivers. During this period, the prehistoric settlement of Ohalo II was established. The settlement was subsequently covered under a veneer of laminated marls by the rising lake.
4. The synchronous level fluctuation of Lake Kinneret, Lake Lisan, and the Holocene Dead Sea, is consistent with the dominance of Atlantic–Mediterranean rain system on the regional hydrology. The main freshwater suppliers to the lakes are the paleo-Jordan and runoff from the valley shoulders. The sharp drops in the lakes coincide with the timing of H-events in the northern Atlantic, suggesting a rapid modulation of the Kinneret–Lisan–Dead Sea hydrological system by the north Atlantic climate.
5. The Dead Sea Ca–Cl brine, which played a major role in the geochemistry and limnology of Lake Lisan and the Dead Sea, did not cross for most of the past 40,000yr Malih sill and its influence was limited to the southern and central Dead Sea–Jordan basin. The water body north of the sill was fresh, reflected by precipitation of calcite as the carbonate phase.

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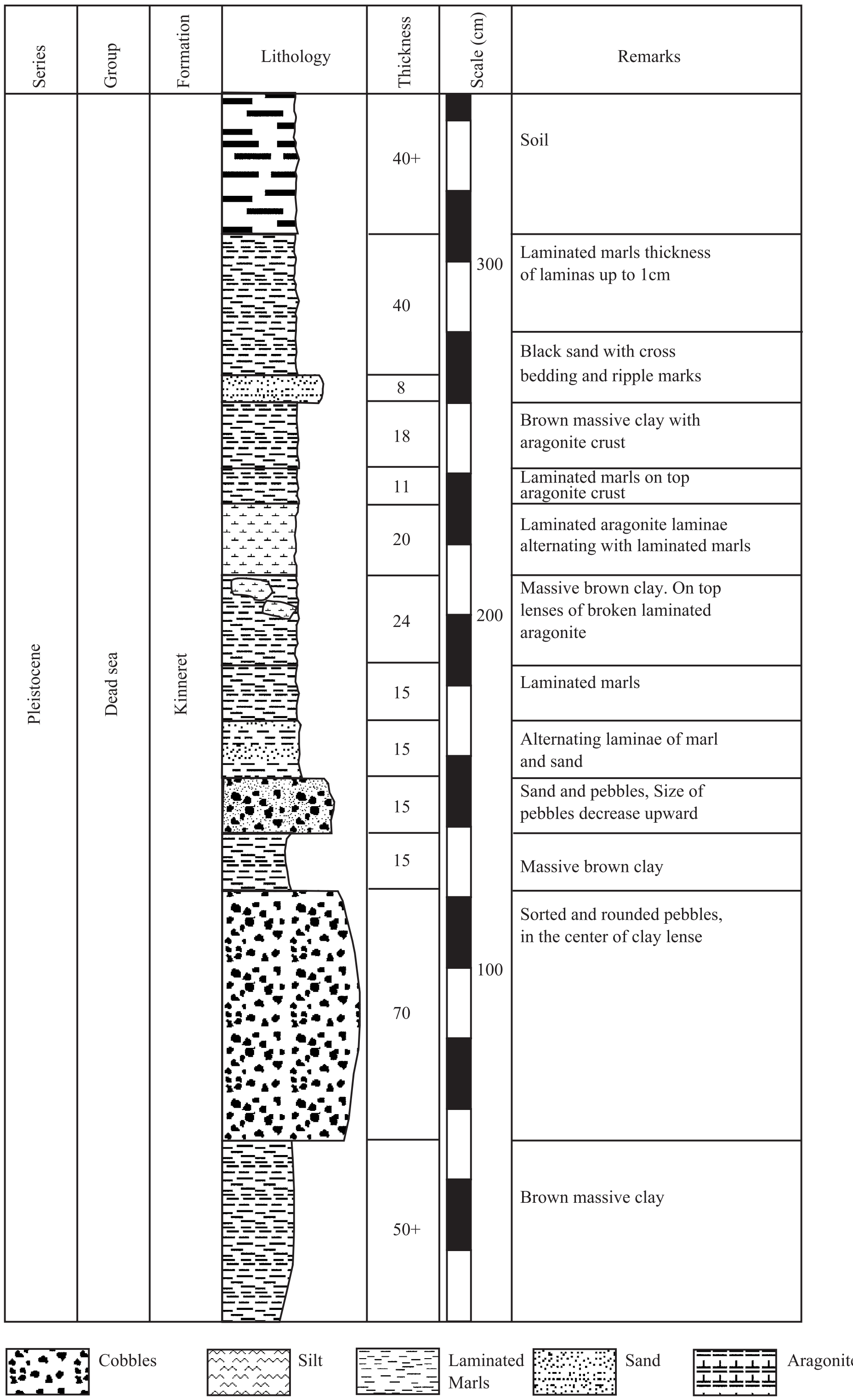
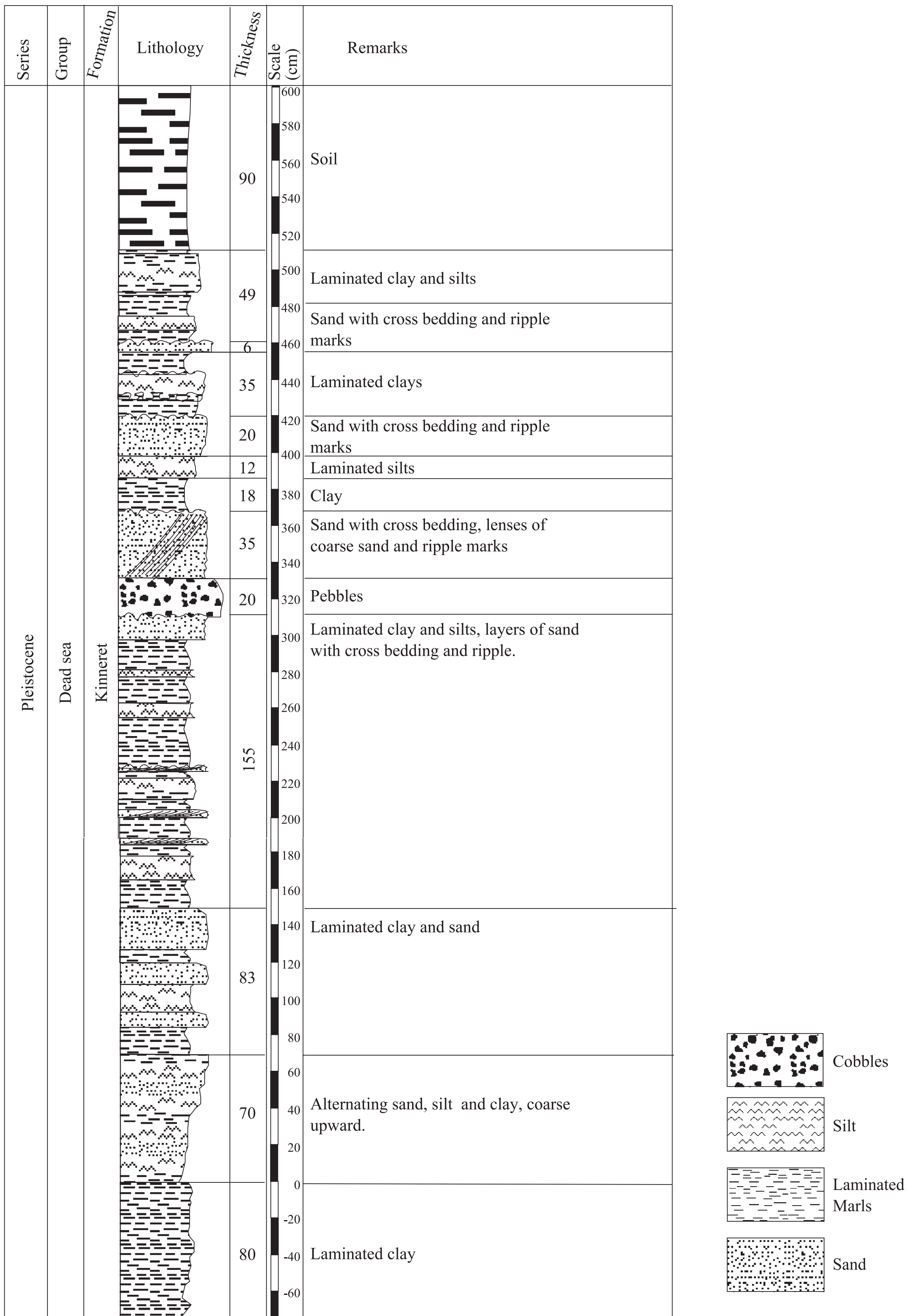
Appendix A. Menahemya section

The section is composed of clastic sediments (pebbles, sand, and marl), excluding one layer of laminated aragonite that resembles the aragonite laminae of the Lisan Formation in the Dead Sea area. This outcrop marks the beginning of the rise in the Lisan and Kinneret lake level at 27,000 ± 1000 cal yr B.P. and the migration of the Dead Sea brine to the central Jordan Valley.



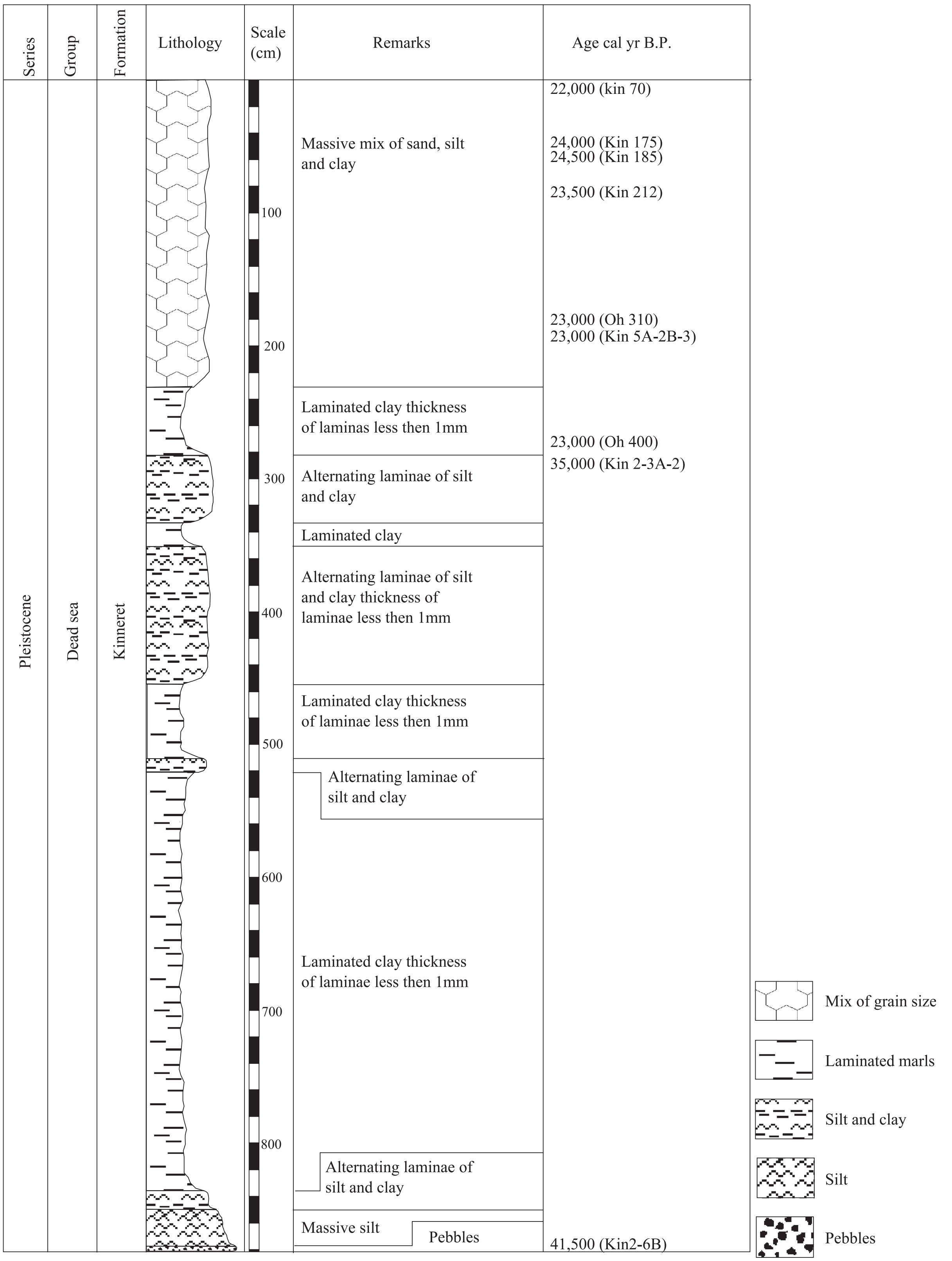
Appendix B. Tel Qazir section

The section is composed of clastic sediments: marls, silt, sand, and pebbles. It is located at elevations 181–174 m bsl and was dated to 26,000–24,000 cal yr B.P. The Tel Qazir ourcrop marks the period of high stand of the Lisan and Kinneret lakes, when they merged into one unified water body.



Appendix C. Composite section of Ohalo II cores

A composite section of the cores recovered in the Ohalo II bore hole. The top of the core was located at 211 m bsl (currently under Kinneret water).



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