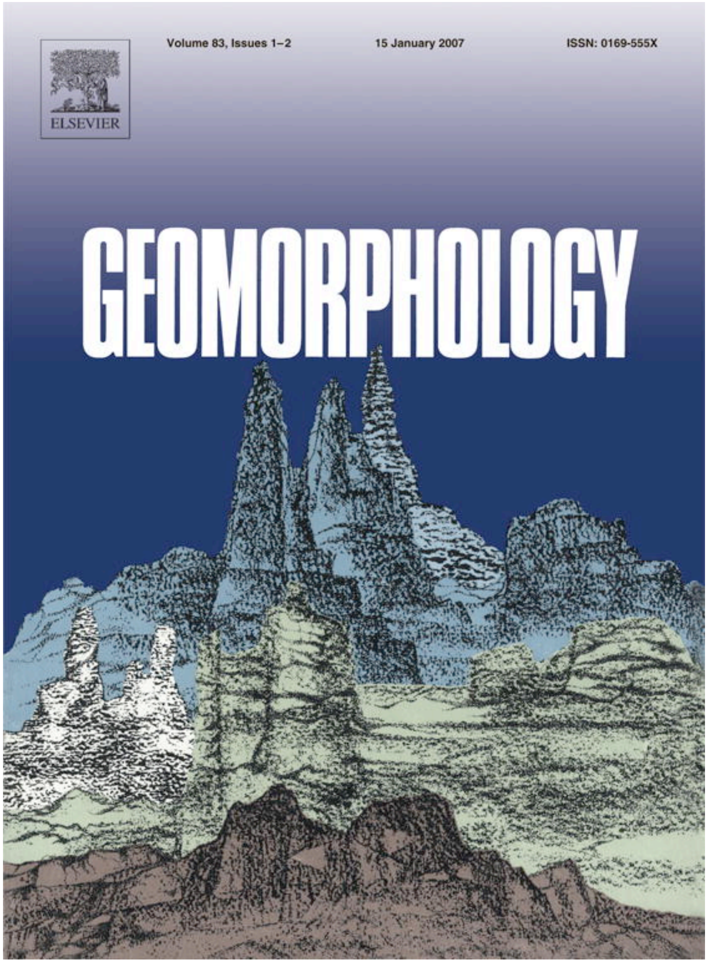
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The use of acoustic imaging to reveal fossil fluvial systems—a case study from the southwestern Sea of Galilee

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Abstract

The analysis of reflected, high-resolution seismic data shows a distinct separation of regions with good and poor seismic penetration. Additional analysis of core data revealed good correlation between grain size and seismic penetration.

As a case study, a shallow geophysical survey using a Chirp profiler was conducted in the southwestern part of the Sea of Galilee. By correlating the seismic and core data we found that areas with good seismic penetration represent coarse clastics, while poor seismic penetration is related to fine clays. New detailed bathymetric mapping and bottom morphology images combined with the penetration characteristics of the Chirp signal reveal a large alluvial fan consisting mainly of coarse material (sand to pebbles). A fine-grained band of mostly clay-size material, associated with an asymmetric bathymetric channel, continues the trend of the old entrance of the Yavniel Creek into the Sea of Galilee. We interpret the fine-clay stripe to be a low energy streambed of the Yavniel Creek.

The clear relations between the reflected Chirp signal and the grain size of the water-bottom sediments suggests that this type of survey can be used to characterize depositional environments.

Keywords: Seismic reflection; Sea of Galilee; Alluvial systems; Granulometry

1. Introduction

Seismic data, when properly calibrated, can be used for remote determination of the subsurface lithology. Extraction of rock properties from seismic data usually requires multi-channel data acquisition and special procedures for data processing like AVO (Amplitude Versus Offset) analysis (Yilmaz, 2001). Multi-channel seismic data are not always available, especially in shallow water, and subsurface geological studies occasionally rely on single-channel data. Single channel survey is relatively inexpensive, requires minimal operational overhead and in the aquatic environment can be conducted from a small boat. Whereas single channel data, known as zero-offset (source and receiver are positioned at the same location) seismic section, can be used to study structural elements of the subsurface geology, it cannot serve as a lithology indicator. In general, lithological studies using single-channel seismic data are possible only if calibrated with additional in-situ information. However, when true-amplitude seismic processing can be applied to the single-channel data, some information on the lithology can be extracted from the strength of the reflectors on the seismic records.

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The investigation and analysis of ancient fluvial systems requires the knowledge of the old structural and lithological setting (Velegrakis et al., 1999). When the study area is under water, seismic survey is required to map the shallow subsurface. In this study we mapped a fossil alluvial system in the southwestern Sea of Galilee (Kinneret in Hebrew) using single channel seismic data. The seismic data were calibrated with sediment cores, direct observations and samples collected by scuba diving.The Sea of Galilee (Kinneret) is a flow-through lake, which occupies a graben within the Dead Sea Fault (DSF, Fig. 1). The types of sediments that accumulated in the Kinneret Basin vary as a result of the changes in the erosion and the tectonic processes. The surface of the Kinneret, the last of a series of lakes to have occupied the basins of the DSF through the ages, is at about 210 m below mean sea level (bmsl). The region is in a transition zone between wet and arid climates. It is therefore sensitive to changes in the climate and resultant environment. Information on such changes can be recovered from the lake sediments. The pre-Kinneret Lake Lisan left a series of laminated deposits dated to the last glacial period. Uranium series ages in the Dead Sea Basin (about 400 m bmsl) range from 70 ka to 15 ka (Schramm et al., 2000). Lake Lisan reached the Kinneret only during high stands. The highest level of Lake Lisan, about 165 m bmsl (Begin et al., 1974), lasted only briefly from 26 until 24 ka (Hazan et al., 2005).

There is no deep drill hole in the Kinneret, therefore the detailed lithology of the Pleistocene sedimentary fill in the basin is poorly known. Outcrops of the Late Pleistocene Lisan Formation on the southern shores of the lake have been radiocarbon-dated to ∼20 ka at the surface (Nadel et al., 1995, 2001). Evidence from the 23 ka Paleolithic camp at Ohalo attest to lake levels below 213 m bmsl (Belitzky and Nadel, 2002). Hence the River Jordan, which enters the lake from the north and exits southward (Fig. 1), could have started flowing southward only when the water level dropped below the elevation of the sill on the south margin of the Kinneret.

Several outcrops of fluvial deposits, mostly conglomerates, indicate that the Yavniel Creek flowed into the lake from the southwest (Fig. 1). However, the present course of the Yavniel Creek is different; it joins the Jordan about 5 km south of the lake. The outflow of the Jordan also changed its location. Historical records and archaeological evidence show that until the 12th century AD the River Jordan outlet was north of Tel Bet Yerah, an elongated hill capped with monumental Bronze age structures (Ben-Arieh, 1965). Exploratory trenches revealed alluvial pebble units below lacustrine beds in the old outlet (Hazan et al., 2005). An outflowing river could not have transported pebbles from the lake bottom, so we interpret this observation as a fossil inward-flowing streambed. The Yavniel Creek is the only significant candidate for an in-flowing stream. Its drainage basin is enclosed between two tilted blocks with only a narrow canyon draining it eastward.

To test the hypothesis that the incision of the canyon contributed the alluvium that was encountered in the trenches at the former outlet of the Jordan, we conducted

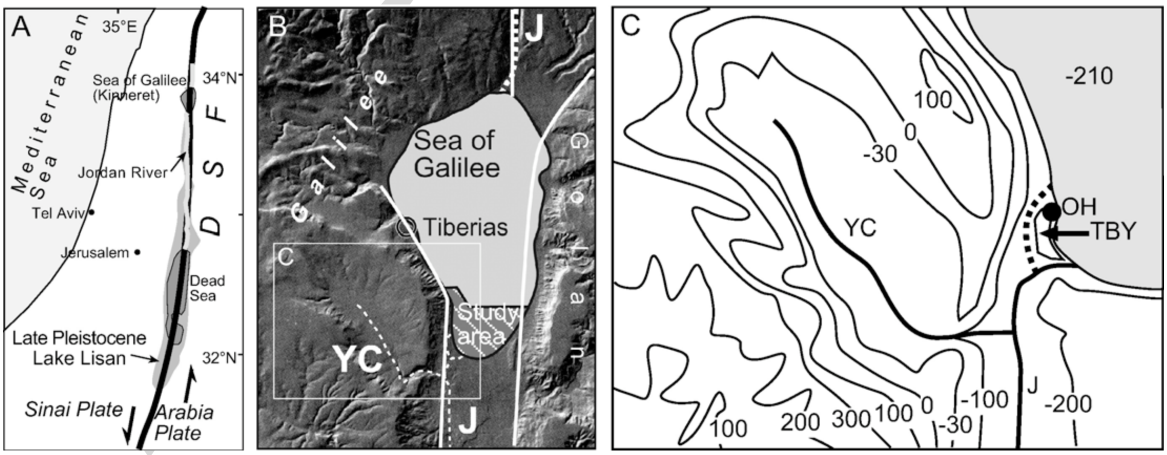

Fig. 1. Location maps. A: Map showing the Dead Sea Fault (DSF), which separates the Sinai plate and the Arabia plate, and the extent of Lake Lisan at its highest stand of 165 m below mean sea level. B: Shaded relief map of the Sea of Galilee (Kinneret) area. YC is Yavniel Creek, which joins the River Jordan (J) south of the Kinneret. White solid lines mark the main DST faults around the lake (after Hall, 1994). C: Elevation contours (m above mean sea level) of the southwestern Kinneret basin. Dashed line shows the post-Lisan channel of Yavniel Creek, which later became the early outlet of the River Jordan out of the lake. Since the 13th century AD the River Jordan exits the lake south of Tel Bet Yerach (TBY) archaeological hill whereas the old (dashed) channel is dry. The Paleolithic site of Ohalo (marked OH) is at −213 m, where 23 ka remains of fisherman's brush huts were discovered, constraining the level of the ancient lake (Nadel et al., 2001, 1995).

a single-channel, high-resolution Chirp survey in the southwestern part of the Kinneret. The interpreted results show a fossil alluvial fan, which is compatible with flow of the Yavniel Creek into the early Lake Kinneret. This interpretation is based on bottom morphology and the penetration strength of the acoustic waves into the shallow sediments. The acoustic reflectivity of the shallow sedimentary section of Lake Kinneret was previously studied using a 3.5 kHz seismic system by Ben-Avraham et al. (1986). They reported good seismic penetration in the southwestern part of the lake. Since only sparse seismic data were used in that study, the authors were inconclusive about the relation between the seismic reflectivity and the characteristics of the lake bottom sediments. In the present study we show how the complementary laboratory analyses of the sampled bottom sediments can be used to provide a reliable correlation between seismic reflectivity and lithology of the bottom sediments in the investigated area.

2. Methods

The southwestern part of the Kinneret was surveyed where the water depth ranges from 4 to 20 m. At the time of acquisition (Summer 2003), the lake level was 210.7 m bmsl (Fig. 2). Detailed mapping of the bottom morphology and bathymetry was achieved with Marimatech E-Sea Scan 800 side scan sonar (325 kHz) and ODOM Echotrack dual frequency (24 kHz and 200 kHz) echo sounder. For processing and assembling of a mosaic image of the side scan sonar data we used Caris software.

The shallow sub-bottom structure (up to 13 m deep) was mapped with acoustic single-channel data acquired by a Datasonics dual-frequency (2–7 kHz and 10–20 kHz) sub-bottom CAP 6600 Chirp II profiler. The seismic data totaled approximately 60 km with a source interval of about 2.5 m.

The overall quality of the seismic data was fair. No significant reflections have been observed in the higher frequency record (10–20 kHz), which we eliminated before the processing stage. In order to maintain the relative amplitude characteristics of the reflected data, minor processing was applied to the data prior to interpretation. The processing consisted of trace editing, geometry assignment, zero-phase deconvolution, filtering and water-bottom top mute. The deconvolution process widens the frequency band of the data (Yilmaz, 2001) making the seismic signals sharper in the time domain (where interpretation is carried out). We shaped the output signal to be a zero-phase in order to ensure the consistency of the picking process during the interpretation. For a final filter we used a simple band-pass

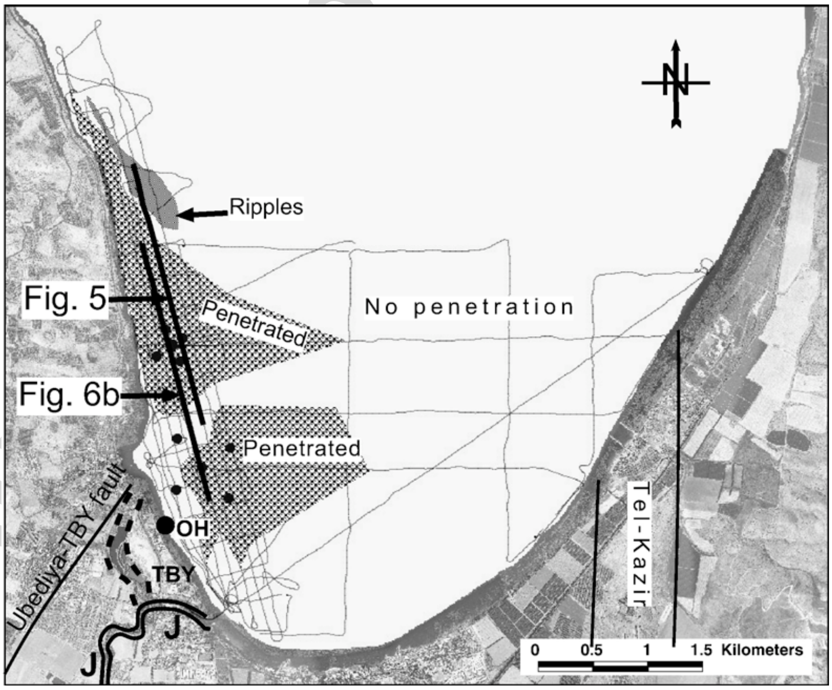

Fig. 2. Airphoto and Chirp survey course map showing the extent of the penetrated area (large dots). In the area marked by the tiny dots, we observed ripple marks, evidence for water currents. Large black circles mark the bottom sampling location. Faults are marked with solid black lines. TBY is Tel Bet Yerach archeological hill. It is surrounded by the lake on the east, the present channel of the River Jordan (marked “J”), and an elongate depression on the west, which was the River Jordan channel until the 13th century AD (dashed line). OH is the Paleolithic 23-ka site.

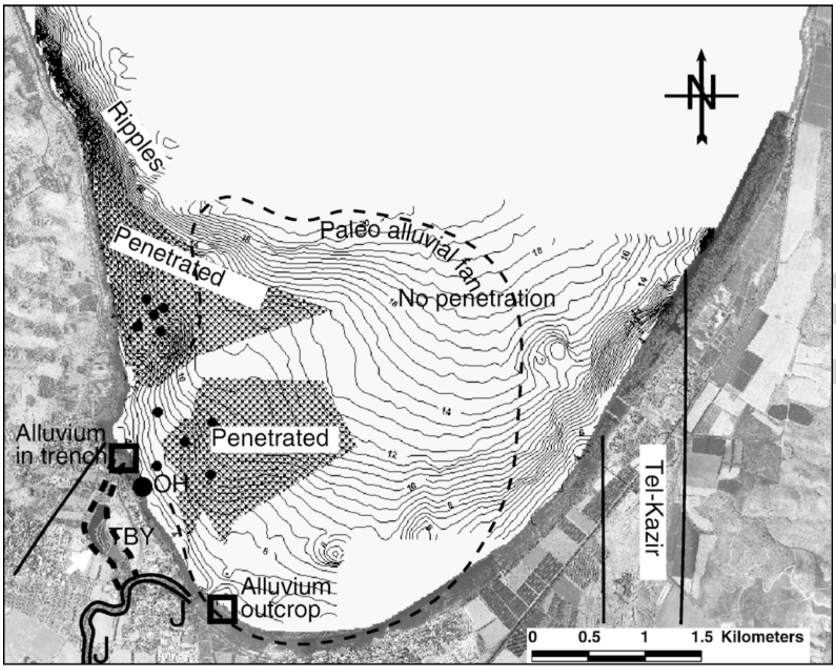

Fig. 3. Bathymetric chart of the southwestern Kinneret compiled from the Chirp data. Steep bathymetric gradients appear along the projected trace of the faults that bound the Tel Kazir hill (Garfunkel et al., 1981). Abbreviations are the same as in Fig. 2. An elongate inactive stream channel (dashed) is interpreted to have been the channel of the Yavniel Creek and later the outlet of the River Jordan from the lake until the 13th century. The present outlet is marked "J".

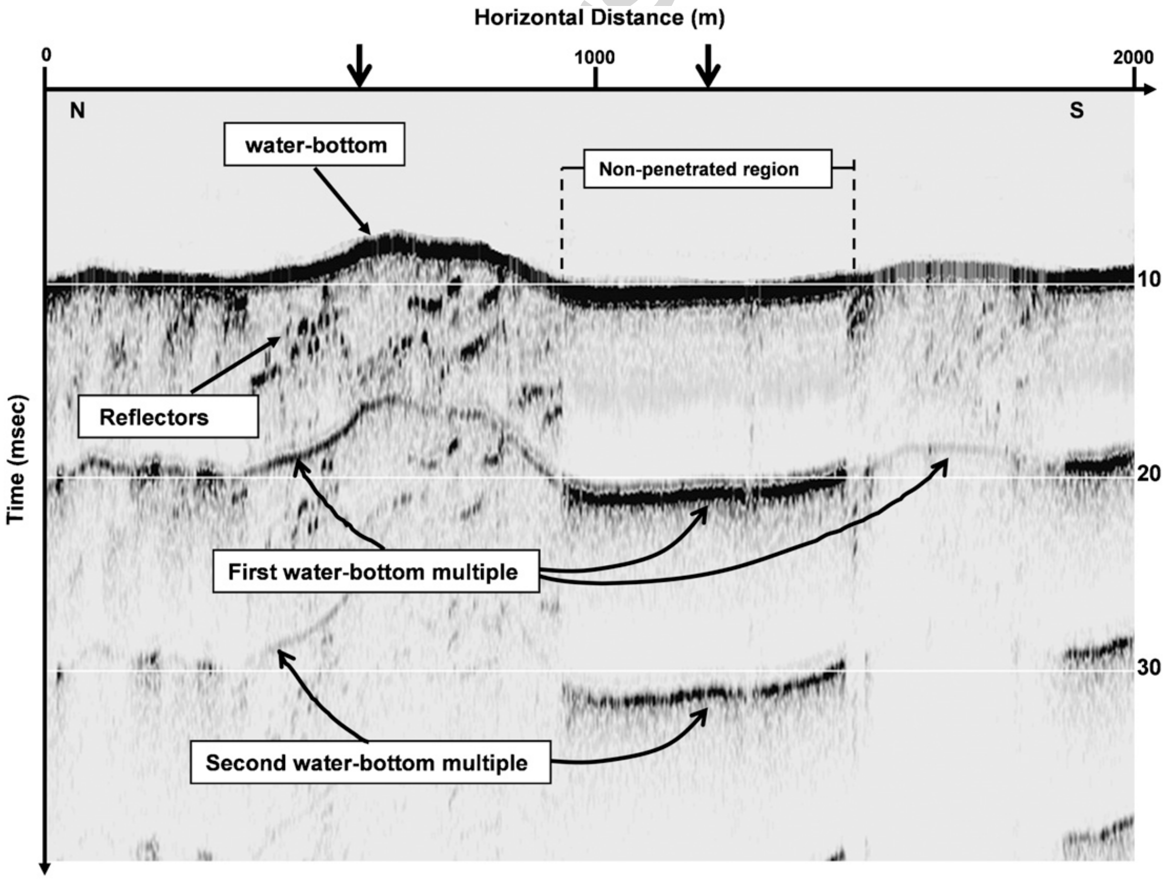

Fig. 4. Example of a Chirp section showing acoustic properties and location of sediment sampling (vertical arrows). The water-bottom multiples are stronger under the non-penetrated regions. The few reflectors which can be observed on the left are weak and not coherent.

filter with an open frequency band from 150–1000 Hz. True amplitudes were maintained through the entire processing sequence. Although the dominant reflector in the data was the water-bottom, the acquisition method (single-channel) prevented efficient application of multiple-suppression. The processed data were finally loaded into an interpretation workstation, on which it was analyzed using commercial interpretation software (SeisWorks from Landmark Graphics Co.). A single-channel dataset is a zero-offset time section which we interpreted without application of a seismic migration. Since the target event (which in many locations was the only one seen in the section) was the water-bottom, time to depth conversion became trivial, using the constant water velocity. The interpretation was carried out along each of the sail lines and resulted in a definition of strong and weak reflections from the water bottom. In areas where the seismic signal penetrated the water bottom, structural elements (faults, dipping reflectors) were picked, down to a maximum depth of 13 m. We found most of the data collected over very shallow (<5–6 m) water unusable for interpretation due to their poor quality related to short water-bottom multiples and boat manoeuvering.

To calibrate the Chirp and side-scan sonar records, we collected sediment samples in several locations using a 20-cm-long box corer in soft sediments and a grab in harder surfaces. We also observed and sampled the bottom sediment by scuba diving. The analysis of the sediments included grain size distribution with a Sedigraph particle size analyzer.

3. Results

3.1. Sediments

Penetration of the seismic energy varies in the studied area (Figs. 2 and 3). A typical seismic section is shown in Fig. 4. The strong reflectivity of the non-penetrated water-bottom segment causes a significant appearance of multiples in the seismic section. The multiples are much weaker under the areas which are characterized by a smaller reflection coefficient. The interpretation of sub-bottom reflections is limited to the arrival time of the first water-bottom multiple. Most of the densely surveyed region shows good penetration of the seismic energy into the sediments, in agreement with a previous 3.5-kHz reflection survey (Ben-Avraham et al., 1986). A SW–NE narrow band of un-penetrated sediments was mapped in the central part of the area. Our direct observation of the bottom sediments during scuba dives, as well as inspection of dredged samples

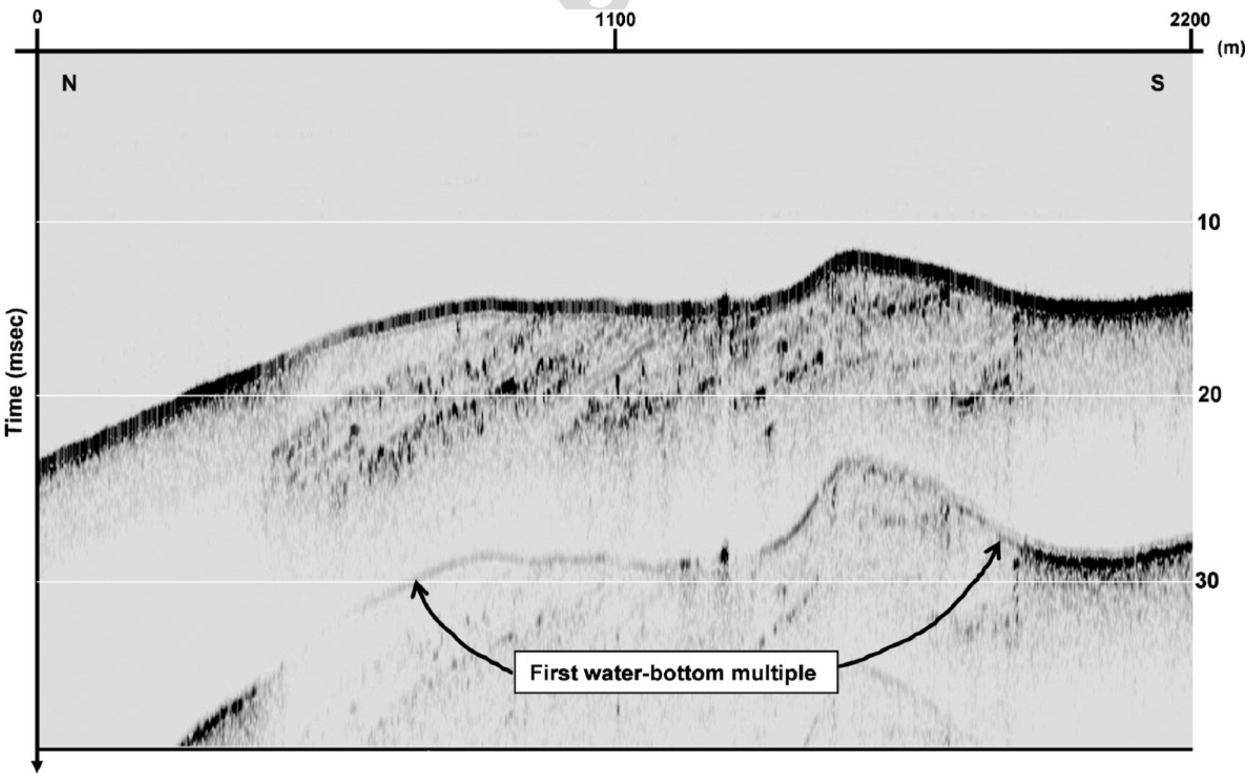

Fig. 5. Example of Chirp section showing dipping reflectors, interpreted to be alluvial fan deposits (see location in Fig. 2). Note that the coherency of the shallow reflections is poor, but clear enough to indicate the northward dipping trend.

(locations marked in Fig. 2), reveal that penetration in the surveyed area is associated with coarse sediments, whereas very fine clays are found where the seismic data show almost no penetration below the lake water bottom. Since we did not find any indication for the presence of gas in the clays, we attribute the acoustic penetration (or the water-bottom reflectivity) to the grain size and the porosity of the sea-bottom sediments.

Based on our direct observations and on granulometric analyses done in the northwestern part of the lake (Goldstein, 2004) we attribute the different acoustic behavior of the sediments to their different grain size distributions. The same grains are present in both the penetrated and the "opaque" area, but the fraction of large grains of about 48 μm is significantly higher in the penetrated area, reaching 5–6% (Goldstein, 2004). The increased presence of small grains of 0.23–22.5 μm inhibits the acoustic wave penetration whereas increased proportion of larger grains allows some energy in. The transition between penetrated and non-penetrated regions is quite sharp (Fig. 4). It is, therefore, easy to map the areas which contain coarser or finer grain sizes.

In several places we see inclined reflectors, which we interpret as the foresets of the alluvial fan of the Yavniel Creek (Fig. 5). The extent of the alluvial fan indicates a low water level. A period of low level that post-dates the high stand of Lake Lisan is known from the Dead Sea (Neev and Hall, 1979). In the absence of direct dating we can only constrain the age of Yavniel Creek fan stratigraphically. It post-dates the lowering of Lake Lisan, which reached its peak level at 26 ka (Hazan et al., 2004). The level of about 215 m bmsl was reached about 23 ka, based on a paleolithic campsite excavated during extreme low stands of the Kinneret (Nadel et al., 1995, 2001). The upper bound is not constrained. Historical data show that the River Jordan outflow from the lake was north of Tel Ohalo until the early 13th century AD (Ben-Arieh, 1965). However, the timing of the Yavniel Creek capturing by the Jordan and the transition to the current configuration of the flow is as yet unknown.

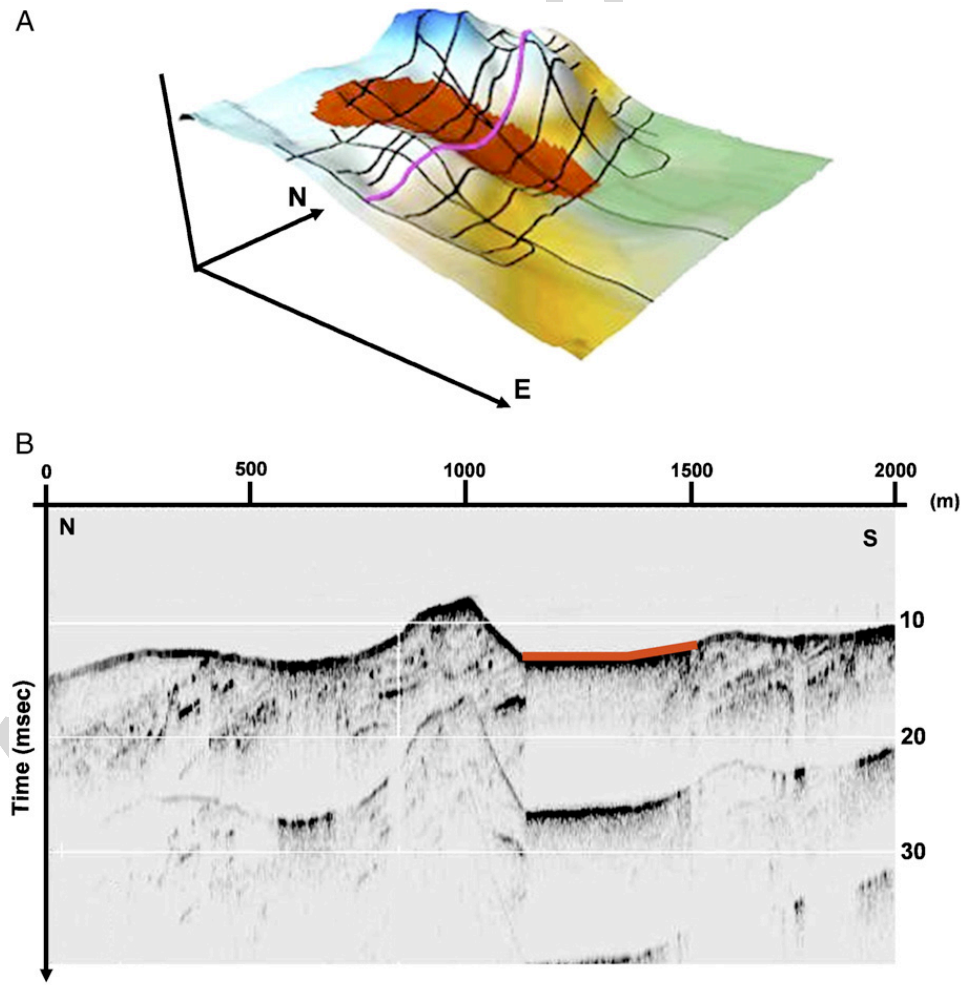

Fig. 6. A: Three-dimensional view of the fossil channel of the Yavniel Creek. B: A seismic section through the fossil channel (see location in Fig. 2).

The thickness of the post-Lisan sediments may be estimated using sedimentation rates. Measurements using sediment traps show values ranging from 2 g/m^2/day in the southern part of the lake and up to 36.3 g/m^2/day near the entrance of the River Jordan in the north (Koren and Klein, 2000). The mean sedimentation rate measured in the trap closest to our study area in 1995–1996 was about 6–8 g/m^2/day. In order to translate this value to thickness per year we need to assume sediment density and compaction. An accumulation rate of about 0.9 mm/year was determined by ^{14}C dating of 5-m-long sediment cores recovered ~2 km east of our survey area. The porosity in the core (=water content) went down from 87% at the top to about 65% at the bottom of the core (Thompson et al., 1985). Hence, we assume an accumulation of less than 10 m after the retreat of Lake Lisan, and even less than that after the build-up of the Yavniel Creek fan, which may have taken several thousands of years.

We conclude that the map of the penetrated versus "opaque" bottom sediments shows the fabric of the alluvial fan of the Yavniel Creek. The parts with coarser grains were deposited in the early phase of the Yavniel Creek incision in which its deep gorge formed. Subsequent low-energy flow, which is manifested in the stripe of fine clay, is interpreted to indicate moderate slope similar to the current relief. The conspicuous break in the slope in the northern part of our survey area, which is clearly manifested in the bathymetry (Ben-Avraham et al., 1990), is probably the margin of the Yavniel Creek alluvial fan. The modification of the stream flow is a reflection of climate change, namely a transition from high stand during the last glacial period to low stand at present.

3.2. Structure

We interpret tilted reflectors in the penetrated area as evidence for a tilted block (Fig. 5). Tilted blocks dominate the area west of the Kinarot and Kinneret valleys. The sediments that are juxtaposed against the block are confined to a channel, which does not receive sediment supply in the current configuration of the lake. Fig. 3 shows that the penetrated region terminates abruptly to the north. The end-of-penetration line follows the bathymetric contours from the NW corner of the survey to the NE. On the eastern side, the change in water-bottom reflectivity follows a bathymetric step (Fig. 3), which was observed in the previous survey (Ben-Avraham et al., 1986).

Dense bathymetric measurements show a NE trending, 250–300-m-wide, 2–4-m-high ridge in the central part of the survey (Fig. 3). A few hundred meters to the south, parallel to this ridge, another smaller ridge was mapped. A three-dimensional view of these two bathymetric irregularities is shown in Fig. 6. North–South profiles collected across the ridges (Fig. 6B) show that the area between them is characterized by a very strong water-bottom reflectivity, which inhibits acoustic

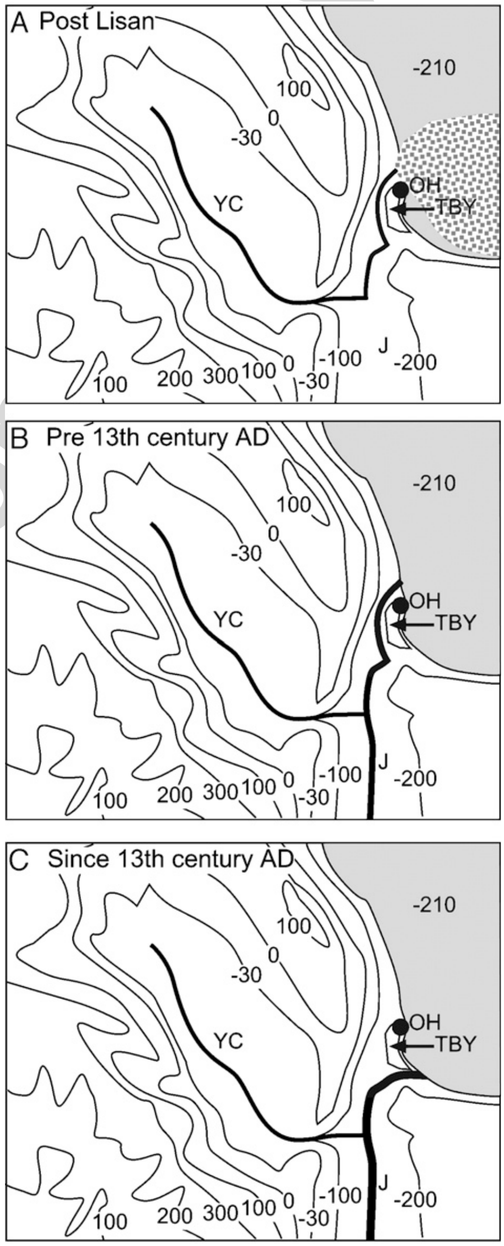

Fig. 7. History of the River Jordan (J) and Yavniel Creek (YC) after Lake Lisan level dropped from its highest stand at 165 m bmsl at 26 ka (Hazan et al., 2005, 2004) to below 200 m bmsl. A: After the retreat of Lake Lisan Yavniel Creek flows to the incipient Lake Kinneret, forming an alluvial fan in the southwestern part of the lake (stippled area). B: The River Jordan captures the lower channel of Yavniel Creek. The former inlet of Yavniel Creek becomes the outlet for the River Jordan. C: In the 13th century AD the course of the River Jordan changed to the present outlet.

penetration. We interpret this low relief canyon as the old inlet of the Yavniel Creek. This channel is surrounded by the alluvial fan, which we attribute to the Yavniel Creek based on its section that overlies the Lisan Formation (Hazan et al., 2005).

The ridges appear to be tilted fault-bounded blocks, the same features that characterize the tectonic province west of the study area. Geophysical data, in particular gravity and magnetism, indicate that this province of extends eastward approximately one-third of the present lake (Ben-Avraham et al., 1996; Eppelbaum et al., 2004).

The young age of the bottom sediments in the lake is regarded as evidence for recent faulting activity. We recognize a NE-striking continuation of the Ubediya–Bet Yerah fault for about 4 km from the shore. The orientation of this fault is compatible with reverse faulting but other kinds of data are needed to test this hypothesis. Intense post-Lisan deformation is conspicuous in folded layers of the Lisan Formation exposed along the shore around the Ohalo paleolithic site (Belitzky and Nadel, 2002) and older strata that exhibit compressional features in the form of folds are observed in seismic sections south of Bet Yerah (Rotstein et al., 1992).

A normal fault is interpreted parallel to the south-western lakeshore. We regard this strand as part of the western boundary fault of the Kinneret, primarily showing normal component associated with the ongoing subsidence of the basin.

Steep west-facing bathymetric slopes appear to extend into the lake as continuations of the two N-striking faults that bound the Tel Kazir hill on the east and west (Fig. 3). The shape of the subaqueous scarps is compatible with left-lateral motion, but since the Chirp did not penetrate into the sediments it is impossible to confirm the faulting.

4. Conclusions

Our study demonstrates the use of the seismic reflection method to resolve the fabric and near-surface structure of a shallow lake. The reflectivity of the lake's water-bottom is very sensitive to the grain-size of the sediments in the upper few centimeters of the section. Based on the Chirp data and geological observations on land we conclude that the initial exit of the River Jordan from Lake Kinneret was a channel, which was first incised by the flow of the Yavniel Creek into the lake. This channel was later abandoned and the River Jordan has been using its current exit channel since the 12th century AD (Fig. 7). Using Chirp survey and sediment analyses we show that the old alluvial fan of Yavniel Creek occupies the southwestern part of the lake. It is comprised mainly of coarse material except for a stripe of fine clay, which extends northeastward from the fossil Yavniel Creek entrance to the lake. The correlation of seismic reflection properties and grain size of the bottom sediment proves essential to the process of detecting and mapping subaqueous features.

Truncated reflectors and unusually-steep bathymetric gradients, which are interpreted as faults, indicate active subsidence of the basin. We hypothesize that a north-east-trending fault within the basin is associated with previously-reported compressional features observed in the southwest shores of the Kinneret in outcrops and in seismic sections. Left-lateral motion on the east is compatible with a N-striking, west-facing steep sub-aqueous escarpment.

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