

Geophysical (time domain electromagnetic model) delineation of a shallow brine beneath a freshwater lake, the Sea of Galilee, Israel

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Abstract. The Sea of Galilee is a freshwater lake, into which saline water emerges through onshore and offshore springs and through flux from the lake's sediments. The novel surface marine modification of the time domain electromagnetic method was used to map the spatial distribution of brines in the sediments below the lake. Results indicate that electrical resistivities of 1.0 and 0.5 ohm-m are detected at depths of ~ 10 m below the lake bottom in most of the lake area, which are equivalent to $\sim 11,000$ and $22,000$ mgCl/L, respectively. Relatively fresh groundwater was detected beneath most of the shoreline. Faulting controls the vertical interfaces between saline and fresh groundwaters. It is hypothesized that salt transport is dominated by molecular diffusion in the central part of the lake and by advection from regional aquifers in the margins.

1. Introduction

The Sea of Galilee has the lowest elevation of any freshwater lake on Earth. It is located within a deep pull-apart basin in the northern part of the Dead-Sea Transform [Ben-Avraham *et al.*, 1996], (Figure 1). The surface area of the lake is ~ 170 km², with maximum water depth of 46 m [Ben-Avraham *et al.*, 1990]. Average water level is 210 m below mean sea level. The average salinity of the lake (expressed in chloride concentration) is 220 mgCl/L, an order of magnitude higher than the concentration in the Jordan River and other streams entering the lake. This order of magnitude difference is a result of salt fluxes from two major sources: (1) onshore and offshore springs (Figure 1) with chloride concentrations ranging between 300 and 18,000 mg/L, depending on location and season [Gvirtzman *et al.*, 1997; Bergelson *et al.*, 1999; Rimmer *et al.*, 1999] and (2) seepage from sediments beneath the lake [Braudo *et al.*, 1970; Stiller *et al.*, 1975; Stiller, 1994].

The average annual contribution of all sources is estimated to be 146,000 tons of chloride [Simon and Mero, 1992], out of which 80,000–100,000 tons are contributed annually from beneath the lake [Smith *et al.*, 1989; Nishri *et al.*, 1999; Kolodny *et al.*, 1999]. The relatively high salinity of the lake poses a major problem for the Israeli water system because the lake supplies $\sim 25\%$ of the national water consumption.

A gradual increase in chloride concentration with depth was observed in three 5.0-m cores and nineteen 0.5-m cores drilled to sediments within the lake basin (Figure 1). At the water-sediment interface chloride concentrations are 220 mg/L, increasing to 350–600 mg/L, at a depth of 0.5 m below lake's

bottom, and to 2000–3500 mg/L at 5 m depth [Stiller, 1994]. On the basis of tritium data, upward water velocities were estimated to be 4×10^{-2} m/yr [Stiller *et al.*, 1975]. An extrapolation based on the observed gradients and transport rates in these cores suggests an annual contribution of 9000 tons of chloride from the lake sediments to the lake, mainly by diffusion [Stiller, 1994]. In a few locations close to the western shore, Nishri *et al.*, [1997] measured seepage rates of 0.2–1.2 m/yr from the lake bottom. The chloride concentration in these waters varied between a few hundred to $\sim 14,000$ mgCl/L near Tiberias springs. However, the information obtained from these studies is very limited in both depth and area, so that no spatial patterns of brine distribution or transport process can be deduced. The large difference between the chloride flux calculated by Stiller [1994] and the actual amount of chloride deduced from mass balance requires either that there are areas where the salinity gradients must be greater than those measured or that salt transport via advection is a dominant process.

In this study, the time domain electromagnetic (TDEM) geophysical method and its novel surface marine modification [Goldman *et al.*, 1996] was applied to detect the spatial distribution of brines in the sediments below and adjacent to the lake. The TDEM method is very useful for detecting conductors and saline groundwater has very low resistivity compared to the surrounding host rock or fresh-water [Goldman and Neubauer, 1994]. Three-dimensional mapping of salinity distribution allows areas with different mechanisms of groundwater discharge and solute transport into the lake to be distinguished. In addition, results clearly indicate that in the geological past, most, if not all of the area underlying the lake was covered with a saline water body, which had percolated into the sediments.

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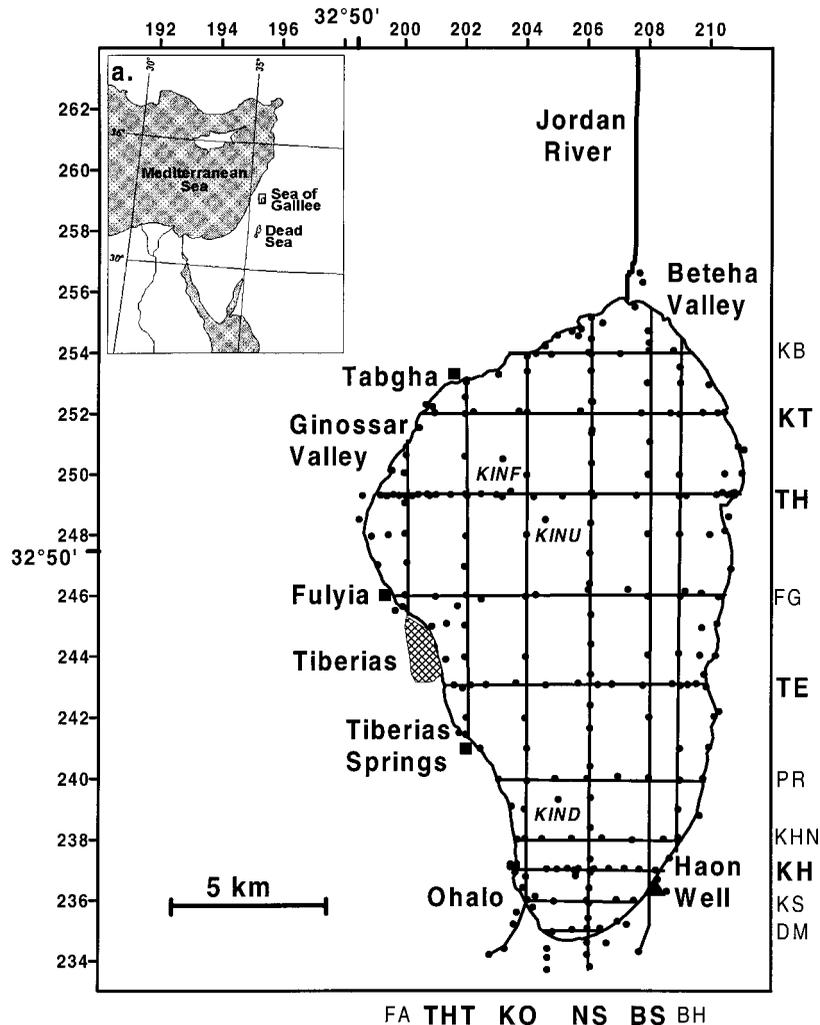


Figure 1. (a) Location maps of the study area and (b) of time domain electromagnetic model (TDEM) sounding sites and profiles. Map coordinates are of the Israeli grid. Labels on bottom and right side of the map are profile names; those in bold are presented in Plate 1. KIND, KINU and KINF are cores obtained by *Stiller* [1994].

2. Methods

The conventional onshore TDEM system is well known and widely described in the geophysical literature [e.g., *Fitterman and Stewart*, 1986; *Goldman et al.*, 1991]. In this study, a square transmitter loop of insulated wire with sizes ranging between $50\text{ m} \times 50\text{ m}$ to $200\text{ m} \times 200\text{ m}$ was used. A multi-turn air coil (about 1 m in diameter) was placed in the center of the loop (central loop array), and served as the receiver antenna. The current waveform driven through the transmitter loop consists of equal periods of time on and time off. The receiver coil measures the signal during the transmitter "time-off" period, providing the measurements of a purely secondary response caused by the currents induced in the ground. To the best of our knowledge, all previous marine TDEM surveys have been carried out using a seafloor located transmitter and/or receiver antenna [*Cairns et al.*, 1994]. Taking advantage of the fact that the water in the Sea of Galilee has low salinity (and therefore low conductivity), *Goldman et al.*, [1996] have presented a new effective surface marine TDEM system (Figure 2). This system was operated for the first time in the Sea of Galilee. The array consists of a 25-m-diameter circular transmitter loop with the

receiver antenna located in the center. The system floats on the water surface and is towed by a motor boat. Navigation was carried out with a highly accurate differential Global Positioning System.

Thirty-three onshore soundings and 269 offshore soundings have been carried out within the lake and its surroundings (Figure 1b). The density of the soundings was determined by the observed areal variations of the apparent resistivity during measurement. The data collected at both onshore and offshore locations were processed and interpreted using the well-known TEMIX-XL software [*Interpex*, 1996]. Two different inversion algorithms were used for data interpretation at each station. The first algorithm allows gradual resistivity change with increasing depth (smooth model), and the second algorithm is for sharp resistivity contrasts between layers (layered model). It should be noted that although the two interpretation methods are completely independent, they show very similar results for resistivities lower than $\sim 2.5\text{ ohm-m}$ and usually show only minor differences at higher resistivities (Figure 3), thereby increasing the confidence of interpretation. Only results of the smooth inversion method are presented in this paper.



Figure 2. A photo of the Marine TDEM system. The system consists of a 25-m transmitter loop, towed by a boat. The receiver antenna is located at the center.

2.1. Geoelectric Results

All offshore soundings were acquired along profiles, some of which continue onshore for distances of up to 1 km from the shoreline (Figure 1b). Results are presented as 2-D resistivity cross sections at selected profiles (Plate 1) and as resistivity maps at four different depths below the lake's floor (Plate 2). The maps were prepared with the krigging method, whereas the cross sections were plotted using the linear triangulation with a vertical/horizontal anisotropy ratio of 0.1. The latter procedure was selected to minimize horizontal effects caused by the much larger horizontal distance between stations compared to the vertical distance between different resistivity values.

Generally, resistivity values may be divided into two major units, each having a distinct spatial distribution. The first, the high-resistivity unit (HRU) is plotted in blue and light blue colors and has values greater than 2.5 ohm-m, and the second, the low-resistivity unit (LRU) is plotted in red and pink colors and has resistivities lower than 2.5 ohm-m. The HRU principally corresponds to the following three zones (Plate 1): 1) lake-water, 2) the upper few meters of the sediments in the internal part of the lake, and 3) the major part of the explored section along the margin of the lake.

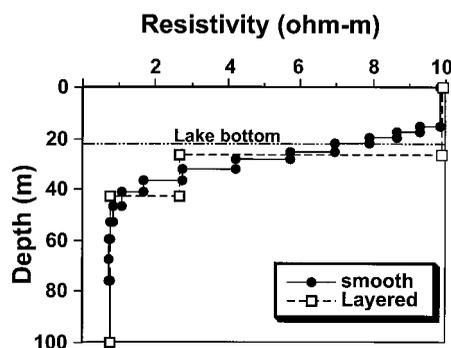


Figure 3. Resistivity-depth profiles at sounding site KIND obtained by the smooth inversion (dashed line) and the layered inversion (solid line) methods. The resistivity gradient detected within the lake's water body itself using the smooth inversion is obviously a model artifact.

Lake-water has typical resistivity values of 7 to 12 ohm-m, usually closer to 10 ohm-m, in agreement with independent direct measurements of lake-water resistivity (A. Katz, personal communication, 1999). Along the northeastern and northwestern margins of the lake, the HRU was detected down to the entire explored depth (~ 100 m), whereas along the northern and eastern margins of the lake, it includes only the upper 70–90 m of the profile. In the southeast part of the lake, the HRU was not detected below the lake bottom (Plate 1d). In most locations, the contact between the HRU and LRU is vertical or subvertical to depths of 100 m (Plate 1).

A prominent feature of all 2-D cross sections, apart from the southern one (Plate 1h), is the top of the LRU is relatively parallel to the lake bottom within the central part of the lake. In the 5-m resistivity map (Plate 2a), the HRU covers almost the entire area of the lake. The exceptions are small areas located near the Tiberias springs and in the southeast part of the lake, opposite Ha'on (Figure 1b). Several other locations within the lake basin have resistivities of 2–2.5 ohm-m as indicated by the pink colors. In the 10-m resistivity map, nearly half of the area under the lake is covered with red and pink colors, indicating resistivities < 2.5 ohm-m (Plate 2b). In the 15 and 20 m maps, areas on the center of the lake with resistivities lower than 1.5 ohm-m occupy $\sim 70\%$ of the total lake area (Plate 2c and 2d). A noticeable feature is that except for the southern and southwestern parts of the lake, the HRU is located along the entire perimeter of the lake to a distance of ~ 2 km from the shore. The LRU continues onshore in the southeastern and southern parts of the lake. North of the lake, in the Beteha valley, the LRU appears as an isolated area (Plate 2).

Eleven values of resistivity lower than 0.2 ohm-m have been detected throughout the lake. Eight are located in the southern part of the lake at depths < 20 m below the lake bottom. In contrast, the < 0.2 ohm-m resistivity values in the northern part of the lake are at depths of 50–100 m below the lake bottom.

2.2. Resistivity-Salinity Calibration

Calibration of bulk electrical resistivity into the groundwater salinity is required for analyzing the spatial distribution of saline groundwater. Previous studies have suggested that a resistivity value of 1 ohm-m corresponds to a total dissolved

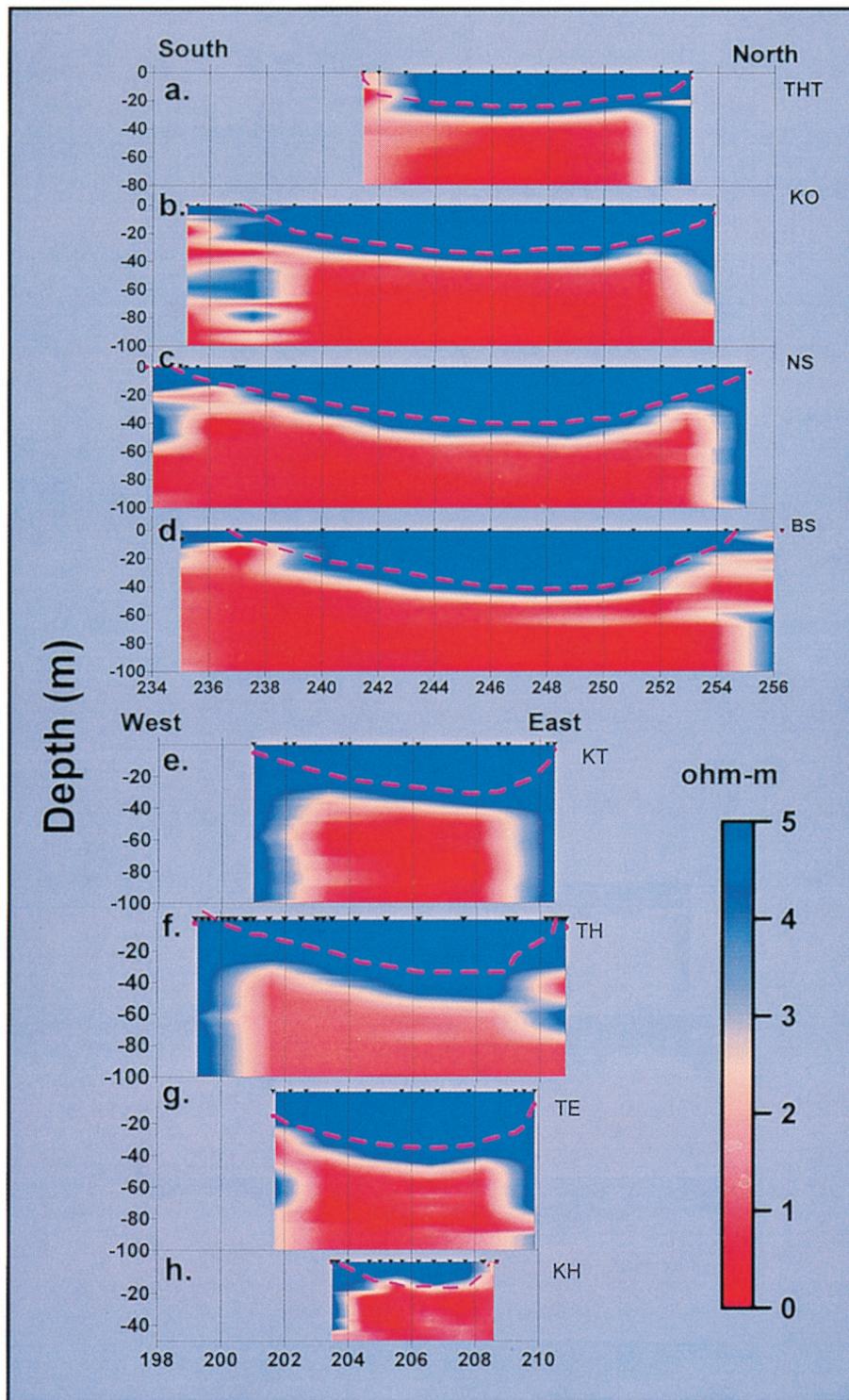


Plate 1. Selected north-south and east-west resistivity cross sections. The labels on the right side of the profiles are their names and the labels on the bottom are map coordinates as in Figure 1b. The dashed purple line on each of the profiles is the lake bottom, and the black triangles on the top of each profile are locations of TDEM soundings. In profile KH, data were not obtained from depths greater than 40 m, probably because of the very low resistivity.

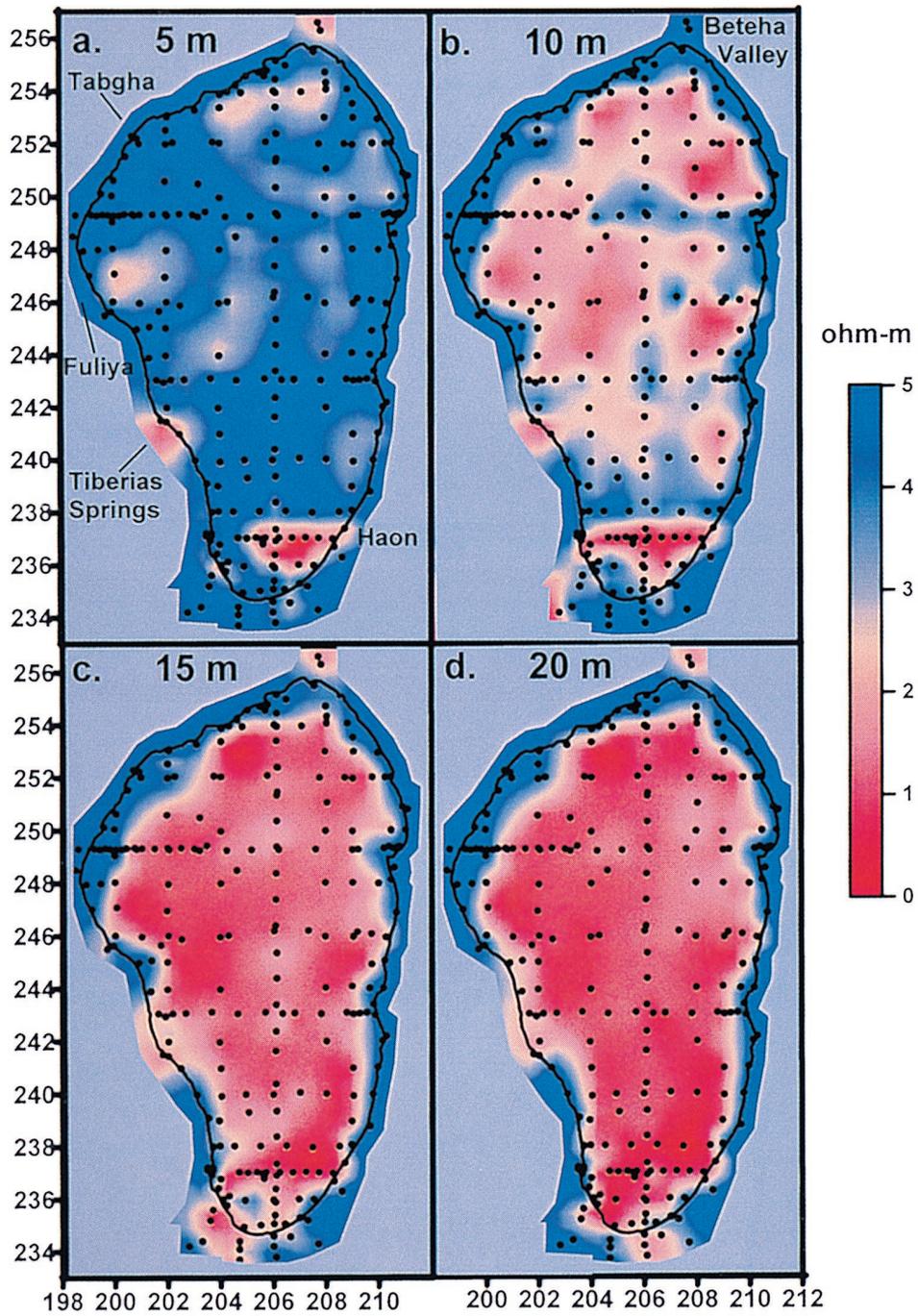


Plate 2. Maps of resistivity distribution at four depths beneath the lake’s bottom, illustrating the existence of brine at a shallow depth.

Table 1. Calibration Data Obtained From Chloride Concentration Profiles in Cores, Groundwater from Haon Well and Time Domain Electromagnetic Soundings

Core/Well Location*	$\partial C/\partial Z, \dagger$ mgCl/l m ⁻¹	Depth, m	Resistivity, ohm-m	$c(z), \S$ mgCl/L
KIND	390	24.5	1.07	9,500
KIND	390	30.6	0.85	11,900
KIND	390	37.5	0.75	14,600
KIND	390	45.3	0.70	17,700
KINF	620	16.2	1.20	10,000
KINF	620	21.4	0.91	13,300
KINU	550	15.5	1.09	8,600
KINU	550	22.3	0.85	12,300
KINU	550	30.0	0.66	16,500
KINU	550	38.6	0.46	21,200
KINU	550	48.4	0.45	26,700
Haon	...	10	0.63	16,700

*Locations of cores and Haon well are shown in Figure 1b.

\dagger Chloride concentration gradient at the lower part of the core [Stiller, 1994].

\S Calculated chloride concentration at top of the conductive layer, based on the concentration gradient (except for the value at Haon well).

solid (TDS) concentration of $\sim 20,000$ mg/L [Goldman and Neubauer, 1994]. Although resistivity values are related to the TDS content, only chloride concentration data were available for calibration in the Sea of Galilee. The proportion of chloride out of the TDS as measured in onshore springs around the lake ranges between 33 and 48% [Mazor and Mero, 1969 Bergelson et al., 1999].

Resistivity values in the subsurface of the Sea of Galilee lower than 1.5 ohm-m may be attributed only to saline water because no lithology in the vicinity can have such a low resistivity unless saturated with saline water [Goldman and Neubauer, 1994]. Resistivity values >1.5 ohm-m can be caused by varying combinations of pore water salinity and lithology. Thus resistivity alone can not be used to distinguish between the brackish groundwater and some lithologies (e.g., clays which have typical values of 2.5–5 ohm-m). Therefore the calibration correlated only resistivity values lower than 1.5 ohm-m with the appropriate salinity concentrations. Two types of calibration were performed (Table 1 and Figure 4): (1) linear extrapolation of the vertical chloride concentration gradient of each of the three 5-m deep cores [Stiller, 1994] down to a depth where resistivity values are lower than 1.5 ohm-m, and (2) comparison of chloride concentration in water sample taken from a depth of ~ 10 m in Ha'on-2 well (Figure 1b), with the resistivity profile measured at the well.

The calculated fit ($R^2 = 0.92$) implies that resistivity (R , ohm-m) is related to chloride concentration (C , mg/L) by the following empirical expression (Figure 4):

$$\log C = -0.96 \log R + 4.02; 0.4 < R < 1.5.$$

On the basis of the above relationship, values of 1.5, 1, and 0.5 ohm-m correspond to $\sim 7,000$, 11,000 and 22,000 mgCl/L, respectively.

A few assumptions were applied in these calibrations: (1) the proportion of chloride of the TDS content is a constant; (2) the concentration gradient at the bottom part of the cores continues linearly down to the conductive layer; and (3) only saline water has affected the interpreted resistivities.

3. Discussion

Previous geological studies have suggested that between 70,000 and 18,000 years ago, Lake Lisan covered a large area in the Dead Sea rift valley [Kaufman et al., 1992; Schramm et al., 1999]. This former lake extended from the Sea of Galilee in the north to the Dead Sea in the south [Begin et al., 1974]. The salinity of the lake varied between 100,000 and 300,000 mg/L TDS throughout most of its history [Katz et al., 1977; Stein et al., 1997]. After the retreat of the lake, two residual lakes remain; the flow-through, freshwater Sea of Galilee in the north and the terminal hypersaline Dead Sea in the south. It has been proposed that the saline groundwater detected in the low-permeability sediments beneath the Sea of Galilee is a relic of this former lake [Stiller, 1994; Stiller and Nissenbaum, 1996]. Since the Sea of Galilee formed, $\sim 18,000$ years ago [Horowitz, 1979, p. 145], freshwater has covered the sediment-hosted saline groundwater. Consequently, diffusion of salts from the sediment into the lake has been initiated. It has been postulated that Lake Lisan covered only the southern part of the area covered by the Sea of Galilee [Begin et al., 1974]. However, the areal extent and the depth of the brine clearly indicate that a saline lake, probably Lake Lisan, has covered the entire area covered by the Sea of Galilee and the Beteha Valley (Plate 2).

The resistivity values measured within the present lake basin show the present horizontal and vertical distribution of the interstitial saline groundwater, which is probably different from its original spatial distribution. The most significant changes, both in brine concentration and in depth distribution, are concentrated at a distance of 1–2 km from the shore, where the LRU is either absent or located at depths of a few tens to a few hundreds of meters. In the central part of the lake basin only, the resistivity pattern is quite homogeneous and the top of the LRU has been depressed to depths of 10 to 15 m (Plate 2).

It is proposed that the sharp lateral contrasts between the LRU and HRU at some sites along the margins of the lake reflect the plumbing system of groundwater into the lake. Sedimentation in the lake and subsidence of the basin have led to the emplacement of clastic low-permeability units in the central part of the basin, adjacent to higher permeability limestone-dolostone units in the margins of the basin. The vertical boundary between the LRU and the HRU, which is an interface between fresh and saline groundwaters, is probably a

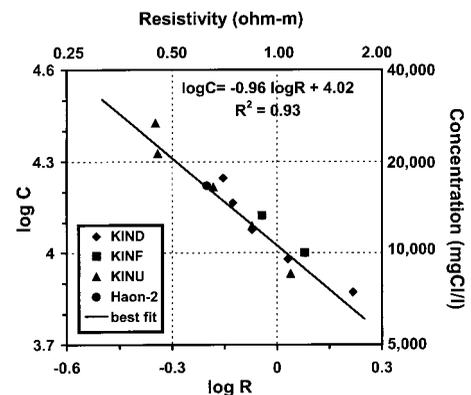


Figure 4. Calibration of the resistivity values to chloride concentrations. KIND, KINU, and KINF are cores obtained by Stiller [1994]. Haon is a shallow well on the eastern shore (Fig. 1b).

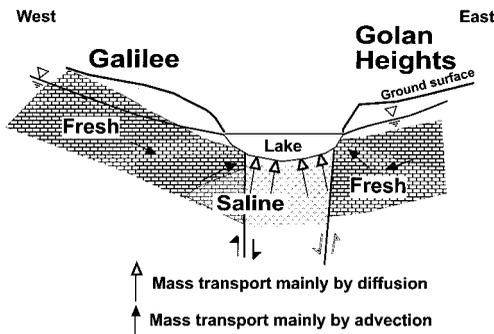


Figure 5. A schematic cross section illustrating the two salt transport mechanisms beneath the lake: advection of diluted groundwater at the margins and diffusion in the internal part of the lake. The vertical interfaces between fresh and saline groundwater are fault controlled, due to the emplacement of low-permeability units opposite aquifer units.

fault-controlled boundary between the clastic and carbonate units (Figure 5). Indeed, along the eastern shore, the interface coincides with a major transform fault [Ben-Gai and Reznikov, 1997]. In the northern and northwestern parts of the lake, it is suspected that faults do control the interface configuration although the faults have not been mapped.

It is hypothesized that groundwater advection from the regional aquifers is the dominant transport mechanism along the lake's margins. Location of the HRU at the marginal part of the lake indicates that if highly concentrated brines were originally located there, they have been leached. The different transport mechanisms are also confirmed by flow measurements. In the central part of the lake, measured upward fluxes are 2 orders of magnitude lower than those measured off the western coast [Stiller et al., 1975; Nishri et al., 1997].

The very similar geometries of the top of the LRU and the floor of the lake in the central part of the basin (Plates 1a–1g) suggest that salt transport from the sediments to the lake is diffusion controlled. Advection induced by sediment compaction is orders of magnitude slower than diffusion. On the other hand, advection induced by hydraulic head gradients may push the diffused concentration profile upwards. South of latitude 238, the HRU is shallower, located at depths of only a few meters and, thus, concentration gradients are steeper (Plates 1g and 2a). This difference may be attributed to southward expansion of the freshwater lake at a later stage. This caused a shorter period for freshening of pore water in the southern part of the basin compared with the central part of the basin.

4. Summary and Conclusions

The subsurface electrical resistivity distribution beneath the Sea of Galilee suggests that at the margins of the lake, groundwater is much less saline than beneath the central part of the lake. We suggest that this is a result of different mass transport mechanisms. In the margins, advection of diluted saline groundwater by regional flow discharging into the lake basin is the major transport mechanism; whereas in the central part of the lake, salt flux into the lake is mainly by diffusion. In the southern part of the lake, resistivity measurements suggest that the saline unit is located at shallower depths and is probably more concentrated. The subsurface vertical interfaces between fresh and saline groundwaters near the lake margin are prob-

ably fault controlled, placing high resistivity, permeable carbonate units in contact with low resistivity, low-permeability sediments. Results also indicate that a saline water body, Lake Lisan, has covered most if not all of the area underlying the present lake.

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