Thermal anomalies associated with forced and free ground-water convection in the Dead Sea rift valley

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ABSTRACT
The Dead Sea rift valley is a left-lateral transform, along which several rhomb-shaped grabens were formed. At the Sea of Galilee, which is one of these rhomb-shaped grabens, ambiguous heat fluxes were measured: 70–80 mW/m² at the central part of the lake, 36 mW/m² at the lake’s southern coast (10 km apart), and most surprising, about 135 mW/m² at the southern Golan Heights, 6–8 km east of the graben margin. A detailed geologic cross section, traversing the entire sedimentary basin, was constructed. The hydrodynamics in this cross section were analyzed quantitatively using a two-dimensional finite element code that solves the coupled variable-density ground-water flow and conductive-convective heat transfer equations. On the basis of numerical simulations, different mechanisms of basin-scale ground-water convection are suggested for the two sides of the rift that could influence the transport of heat: (1) forced convection (gravity-driven flow) of hot brines from deeper aquifers to the land surface at the western side; and (2) large-scale free convection (buoyancy-driven flow) of deep ground water at the eastern side. The different heat fluxes within the rift valley are attributed to the different lithologies and to the locations of specific conduits through which the hot ground waters ascend from deeper horizons. These simulations also explain the different salinities of the hot springs on the two sides of the rift.

INTRODUCTION
Deep ground-water flow plays a major role in many geologic processes (Bredehoeft and Norton, 1990). Hydrothermal ore deposits, petroleum migration and entrapment, diagenesis of sediments, and geothermal anomalies provide excellent examples of the dynamic coupling of large-scale hydrologic systems and the evolution of the Earth’s crust (Bethke and Marshall, 1990; Garven et al., 1993). Sedimentary basins are subject to several forces known to cause large-scale ground-water migration, each characterized by a typical flow rate, as reviewed by Garven (1995). Gravity-driven flow resulting from a slope in the ground-water table is the most familiar mechanism and is characterized by flow rates on the order of 10 m/yr. Buoyancy-driven flow associated with temperature and salinity gradients creates free convection with flow rates of 1 m/yr at most. The above two mechanisms may be stable over a relatively long period of time, thus, steady-state flow conditions may persist. Compaction-driven and tectonically driven flows associated with abnormal overpressure, which dissipates quickly when stress relaxes induce flow rates of 0.1–0.01 m/yr.

Geothermal anomalies induced by ground-water flow involve either forced convection through open systems (gravity- or pressure-driven flow), or free convection within closed systems (buoyancy-driven flow), and in some places, both convective systems may coexist. Forced ground-water convection is a well-known phenomenon, observed at large and small basins throughout the world. It was identified either directly, on the basis of hydraulic head distribution (e.g., Toth, 1978; Habermehl, 1980), or indirectly, using geochemical (e.g., Musgrove and Banner, 1993; Bentley et al., 1986) or geothermal observations (e.g., Deming et al., 1992). Quantitative analysis of such flow systems has been applied at several basins using hydrogeological modeling (reviewed by Person et al., 1996). On the other hand, relatively less evidence exists for natural free ground-water convection. Such convection may result from several different causes: (1) thermal perturbations within the upper Earth’s crust induced by intrusive igneous bodies (Norton and Knight, 1977); (2) temperature variations at mid-ocean ridges inducing sea-water circulation (Anderson et al., 1979); and (3) salinity variations of formation water in sedimentary basins at the vicinity of salt diapirs (Hanor, 1987; Evans and Nunn, 1989). In principle, when permeable, fluid-saturated, sedimentary layers are subjected to normal geo-thermal gradients (about 25 °C/km), convection cells will spontaneously arise and persist (Wood and Hewett, 1982). However, quantitative documentation of this phenomenon is rare. This paper analyzes quantitatively a unique relationship at a continental rift between both forced and free ground-water convections associated with geothermal anomalies.

The study was carried out at the Sea of Galilee region, located within the Dead Sea rift valley (Fig. 1), which includes the lowest land-surface elevations on Earth. The Dead Sea rift is a left-lateral strike-slip transform, separating the Sinai-Levant subplate from the Arabian plate. Along this transform, several en echelon rhomb-shaped grabens were formed, including the Hula basin, the Sea of Galilee, and the Dead Sea (Garfinkel, 1981). The lateral shift along this transform is estimated to be 105 km. This deep base level serves as a discharge area for a gravity-driven ground-water flow system at the western side of the graben. We suggest that large-scale free convection cells of deep ground water persist on the eastern side of the graben.
HEAT-FLUX DATA

Through an extensive study at 70 locations in Israel (Fig. 2), a mean heat flux of 50 mW/m² with a standard deviation of 24 mW/m² was calculated (Eckstein, 1976; Eckstein and Simmons, 1978). The heat flux equals the product of thermal conductivity and temperature gradient. The thermal conductivities were determined using core samples, and temperature gradients were measured in a series of deep oil and water wells at depths of several hundreds of meters using a thermistor probe. Other workers have subsequently measured temperature gradients in additional deep wells (Levitte and Olshina, 1985; Kashai and Croker, 1987). All these studies have shown that gradients of 15–25 °C/km are common along the Dead Sea rift valley. Similarly, a U.S. Geological Survey team has measured the heat fluxes in 18 boreholes at depths of several hundreds of meters at the State of Jordan (Galanis et al., 1986). They have reported that the average heat flux is 53 mW/m², and it ranges between 42 and 65 mW/m² (Fig. 2).

The common heat fluxes at these two neighboring states, Israel and Jordan, are slightly higher than those measured at the Mediterranean Sea, and slightly lower than those at the Red Sea. Erickson et al. (1977) reported that the average heat flux at the eastern Mediterranean Sea is 31 mW/m² with a standard deviation of 13 mW/m², whereas heat fluxes in the range of 60–340 mW/m² were detected at the Red Sea (Erickson and Simmons, 1969) at the vicinity of a relatively young mid-ocean ridge. It seems, however, that the Dead Sea rift valley is not definitely different from its surrounding mountain chains (Ben-Avraham et al., 1978; Kashai and Croker, 1987); only at some specific spots are higher geothermal fluxes found (Eckstein and Maurath, 1995). This normal heat flux is surprising because continental rifting is thought to accompany stretching and thinning of the lithosphere, resulting in an elevated geothermal gradient (McKenzie, 1978). However, no thinning of the lithosphere is evident along the Dead Sea Transform (Folkman, 1980), and, therefore, a heat flux anomaly is not necessarily expected.

It is surprising that ambiguous heat fluxes were detected at the Sea of Galilee, within the Dead Sea rift valley (Fig. 2b). Ben-Avraham et al. (1978) measured a relatively high mean heat flow of 74 mW/m² (range between 70 and 80 mW/m²) in the Sea of Galilee using an outboard heat flow probe. Temperature gradient and thermal conductivity measurements were taken using the standard needle probe with a string of four tensiometers emplaced in the sediments over a depth interval of 3.0–4.8 m below the lake bottom. They reported difficulties with penetration of the probe through the bottom layers, which contained a hard gypsum crust. They also reported on thermal instabilities of the bottom layer. Therefore, of a total of 25 heat flow measurements made in the lake, only 5 were considered valid.

On the other hand, Levitte et al. (1984) measured a much lower heat flux at a distance of 10 km, at the southern coast of the Sea of Galilee. They determined an average heat flow of 36.5 mW/m², with a range of 34.0 to 39.3 mW/m², over a depth interval of 2250–3470 m in a 4.2-km-deep borehole (Zemah-1). Thermal conductivity measurements were taken on both core samples and drill cuttings. The downhole temperature survey was conducted several months after completion of drilling operation, using a thermistor probe to obtain a continuous temperature log.

Most surprising are the significantly elevated geothermal anomalies detected outside the graben, at its shoulders (Fig. 2b). At the graben’s western margin, at the Kinneret-6 well, a geothermal gradient of 48 °C/km was measured.
The hot springs of Tiberias, Fulya, and Tabha, which have water temperatures of as much as 64 °C, emerge at the lake’s western coast (Mazor et al., 1980). On the other side of the graben, in the 3 wells of Mezar, located 6–8 km east of the graben margin, geothermal gradients of 46 °C/km were measured (Fig. 3). It is evident that the geothermal gradient at these wells is about two to three times higher than that measured in Zemah-1 and other surrounding wells, some of which are shown in Figure 3 (Levitte and Olshina, 1985). The thermal conductivities of formations found in the Mezar wells were estimated by Mercado (1981) to be 2.9 W/m°C. Thus, the heat flux is estimated to be 135 mW/m².

Eckstein and Maurath (1995) argued that at aquifer recharge zones, at higher elevations along the mountain backbone in Israel, where cool meteoric waters percolate downward, lower heat-flow values of 33 mW/m² (with standard deviation of 13 mW/m²) are found, whereas in discharge zones along the Dead Sea rift, where hot waters ascend from deep aquifers, a heat-flow value of 75 mW/m² (with a standard deviation of 23 mW/m²) was calculated. Similarly, in several other studies it was suggested that the thermal anomaly detected at the lake’s western margin results from the ascent of hot brines from deep aquifers (Goldshmidt et al., 1967; Mazor, 1968; Gvirtzman et al., 1996). The most tangible expressions of the rift’s convective hydrothermal systems are the warm to hot springs emerging along the margins of the rift (Table 1, Fig. 2).

In any case, this hypothesis can only explain the heat anomalies detected at locations where local conduits allow upward ground-water flow, such as the faults near the Tiberias, Fulya, and Tabha springs; however, it cannot explain the heat anomaly detected at the Mezar wells and Hammat Gader springs, because they are located some 6–8 km east of the rift fault system. Furthermore, hot waters ascending from deep aquifers in this area are highly saline (Table 1) due to mixing with deep-seated brines. However, the waters of Mezar wells and Hammat Gader springs are fresh, emerging from shallow aquifers (Starinsky et al., 1979; Arad and Bein, 1986). We believe that the thermal anomaly observed at the eastern side of the Sea of Galilee may be explained by large-scale free convection cells of deep ground water.

**HYDROGEOLOGIC SETTING**

An east-west detailed geologic cross section, 5 km deep by 70 km long, was prepared (Fig. 4) that traverses through the Galilee Mountains, Sea of Galilee, and the Golan Heights (A–A’ in Fig. 1). A list of lithostratigraphic units is appended (Table 2) that range in age from Triassic to Quaternary. The cross section was prepared using subsurface data collected from 20 deep boreholes and from several hundred kilometers of seismic lines carried out during oil exploration in northern Israel. A map of the top Judea Group (Klang and Gvirtzman, 1987; and Oil Exploration Investments Ltd. unpublished reports) served as a reference structural surface, and isopach maps of various pre-Judea stratigraphic intervals were used to construct the cross section. Lateral facies changes were included, such as the transition within the Kurkub Group (units Klw and Kle), and wedgeouts, such as the Asher Volcanics (unit Jlav) and Rosh Pina Formation (unit Jmr). The asymmetry of the stratigraphic sequence on the eastern and western sides of the rift valley is related to the 105 km shift along the left-lateral transform (Garfunkel, 1981). The stratigraphy within the rift valley was based on data from Zemah-1 borehole (Marcus and Slager, 1985). We empha-
size that the integrated stratigraphic sequence is grouped and divided into various hydrostrati-
graphic units (Table 2; Fig. 4) according to their estimated hydraulic properties.

Mesozoic to Tertiary sedimentary rocks crop out in the highlands on both sides of the rift val-
ley and constitute the main recharged area for the major aquifers. Ground-water discharge to the
rift is from three regional aquifers: (1) the 600-
m-thick, Cretaceous Judea Group (unit Km2j), of
predominantly platform carbonates; (2) the
400-m-thick, Lower Cretaceous Kurnub Group
(units Klw and Kle), of mainly continental san-
dstones; and (3) the 2500-m-thick, Jurassic
Arad Group (units Jln, Jms, and Juzh), of
mainly platform carbonates.

The subsiding rift valley is capped by a
Miocene–Quaternary sequence that is at least 4
km thick (Fig. 4) and that consists of evaporites,
aluvial deposits, basalt, and a few intrusions of
gabbro (Marcus and Slager, 1985); these rocks
are mainly aquitards. The ground-water systems
on both sides of the rift became separated due
to juxtaposition of aquifers on the flanks with
aquitards across the faults in the rift valley.
Ground-water systems at the two sides of the
graben behave differently (Arad and Bein,
1986). On the western margin of the graben,
some downfaulted blocks expose the Judea
aquifer (unit Km2; not seen in Fig. 4) along the
margins of the Sea of Galilee, channeling the
main discharge of the system. Because continuity
between aquifer units exists through down-
faulted blocks (units Kle, Km2j and Pb; Fig. 4),
ground water from deep aquifers flows upward
and emerges as springs. On the other hand, on
the eastern margin of the graben, the low-per-
meability chalk, salt, and marl sediments (units
KuE, Ps, Pds, Mt, and Qds; Fig. 4) prohibit
significant discharge from the regional deep con-
fined aquifers to the outlets.

HYDROGEOLOGIC MODELING

Large-scale hydrogeologic models provide a
useful approach for studying the nature of fluid
migration in sedimentary basins, especially
where the complexities of heterogeneity, struc-
ture, and coupled thermal and chemical
processes preclude analytical solutions (Gar-
ven, 1995). Assuming a continuum approach
under steady-state conditions, conservation of
fluid mass is defined by

$$\nabla \cdot (\rho_f q) = 0 \quad (1)$$

where \( \rho_f \) is the fluid density, and \( q \) is the
specific flux, which is defined by Darcy’s law,

$$q = (k \rho_f g / \mu) (\nabla h + \rho_f \nabla z), \quad (2)$$

where \( k \) is the intrinsic permeability tensor, \( \rho_f \)
is a reference fluid density, \( \mu \) is the dynamic
viscosity, \( g \) is the equivalent fresh-water hydraulic head,
and \( z \) is elevation above datum. This equation
defines the two driving forces: the hydraulic
head gradient and a buoyancy term. The relative
fluid density, \( \rho_r \), is defined by

$$\rho_r = (\rho_f - \rho_w) / \rho_w. \quad (3)$$

Conservation of thermal energy, including both
conduction and convection processes, under
steady-state conditions is defined by

$$\nabla \cdot (\lambda \nabla T) - \rho_c c_f \dot{q} \cdot \nabla T = 0, \quad (4)$$

where \( \lambda \) is the effective thermal conduction-
dispersion tensor of the porous medium, \( T \) is
temperature, and \( c_f \) is the specific heat capacity
of the fluid. Steady-state regional flow of vari-
able-density ground water is best simulated
using the stream function \( \Psi(x, z) \) representation
of flow lines and equivalent fresh-water head
(Bear, 1972).

The numerical code used here is OILGEN
(Garven, 1989), which has been successfully
applied previously to several sedimentary
basins around the world (e.g., Person and Gar-
ven, 1992; Garven et al., 1993; Haszeldine and
McKeown, 1995). This two-dimensional code
uses the finite-element method to solve the
steady-state fluid and heat flow. Computations
were conducted on a Silicon Graphics Personal
IRIS 4D/35 workstation.

A two-dimensional finite element grid (21
rows by 44 columns in Fig. 5a) was developed by
digitizing the geologic cross section (Fig. 4)
to describe the geometry of the hydrostrati-
graphic units. Formation properties such as per-
meability, porosity, thermal conductivity, and
fluid salinity were assigned for each element
(Fig. 5b and Table 3). Next, boundary condi-
tions were defined for ground-water flow and
heat transport. Many of these parameters and
boundary conditions were based on necessity
on generalized assumptions and simplifications;
however, the sensitivity to changes in assigned
values of some of these parameters were
analyzed and are described below.

Boundary conditions for the region of flow
(Fig. 5, a and b) were defined as follows. The
water-table surface, which is routinely moni-
tored at tens of wells (Israel Hydrological Sur-
vey, 1996), forms the upper boundary to the reg-
ion of flow. In the Galilee, the water table
reaches elevations of 40 m above mean sea level
at the water divide. Westward and eastward
water-table gradients are different, because the
base level at the west is the Mediterranean Sea,
and at the east is the Sea of Galilee, where sur-
face elevation is –210 m (below sea level). At

![Figure 3. Temperature vs. depth (MSL—mean sea level) in deep wells around the Sea of Galilee, exhibiting the spatial variability of geothermal gradients. Number in parentheses, next to borehole names, indicate geothermal gradients calculated by linear regression. Because temperature at Kinneret-6 borehole was only measured at two depths, its significance is limited.](image)
the southern Golan Heights the regional water table is at about −40 m. For the steady-state modeling, we have assumed a constant water table position; i.e., the rate of ground-water flow delivered to the water table from the surface is just the rate sufficient to maintain the water table in its equilibrium position. The lower boundary is located at 4–5 km depth, along the base of the sedimentary sequence studied, mostly at the base of the Jurassic layer. This surface is assumed to be impermeable to fluid flow. The two lateral boundaries are considered impermeable to fluid flow because they are assumed to occur where no horizontal hydraulic gradient exists. This assumption is reasonable because the western lateral boundary is located beneath the Mediterranean Sea shore, and the eastern one is located beneath the horizontal water table at the Golan Heights.

Thermal boundary conditions were defined as follows. A constant temperature of 20 °C, which is the mean annual air temperature, was assumed for the top surface. The lower boundary conditions, at 4–5 km depth, reflect the upward undisturbed heat flux, before it is redistributed by ground-water circulation. Therefore, steady geothermal fluxes of 60 mW/m² beneath the Galilee Mountains and of 72 mW/m² beneath the Dead Sea rift valley (eastern 30 km of the cross section) were assumed. Insulated boundaries have been assumed at both sides of the cross section. The components of fluid flow and heat flow normal to the cross section are assumed to be negligible, thereby justifying the two-dimensional representation of the basin.

At the initial stage of the simulation, the steady-state hydraulic head distribution was computed by assuming there are no salinity or temperature gradients. Darcy velocities were then computed for each element in the mesh. The steady-state heat equation was solved next to find the temperature pattern. With the new values of pressure and temperature, and the specified salinity distribution, fluid densities and viscosities were calculated from the equations of state. These four steps were repeated until the iterations converge to a stable temperature solution.

**SIMULATION RESULTS**

Results include equivalent fresh-water hydraulic head distribution, fluid velocity field, stream function, and temperature distribution throughout the cross section (Figs. 5, c, d, e and f, respectively). The hydraulic head distribution within the rift valley (Fig. 5c) demonstrates an artesian ground-water system. Through the upper 500 m of sediments beneath the lake’s floor, the hydraulic head increases considerably with depth, forming a steep gradient toward the lake. The actual ground-water leak through these sediments, however, is relatively small due to the low permeability of the sediments (mainly marls). The springs through which this system is partially discharged are located only where specific conduits, such as faults, permit relatively easy pathways. In general, regions with dense isohydraulic-head lines are actually aquicludes (and aquitards) and those with lower density of lines are aquifers. The distribution of ground-water velocity across the two-dimensional section (Fig. 5d) is directly related to the head distribution and the permeabilities of the various units (Darcy law). It exhibits higher velocities in aquifers, especially in the Judea and Kurnub ones, and slower velocities in aquitards. In the Galilee, the highest velocities are found at the uppermost horizons of the Judea aquifer, discharging waters to both sides, eastward into the rift valley and westward toward the Mediterranean Sea. The velocity distribution also exhibits the typical slow rates in deep aquifers, such as the Arad one. The stream function (Fig. 5e) is an alternative way to demonstrate the flow field by tracing actual flow lines. These lines are plotted so that a constant amount of 10 m³/yr per meter width of cross section is discharged between each pair. Consequently, dense flow lines are found in aquifers with relatively high discharge rates, such as the Judea and Kurnub ones. Where no flow lines are plotted, such as at depths of 3–5 km beneath the western and eastern edges of the Galilee Mountains, negligible discharges are found. These flow lines best present the free convection cells, one in the Kurnub and upper Arad aquifers, and a second

### TABLE 1. HOT SPRINGS ALONG THE DEAD SEA RIFT VALLEY

<table>
<thead>
<tr>
<th>Location</th>
<th>Name</th>
<th>West or east</th>
<th>temp. (°C)</th>
<th>Chloride (mg/L)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabha</td>
<td>Hassartan</td>
<td>West</td>
<td>28</td>
<td>2800</td>
<td>Arad and Bein (1986), Mazor et al. (1980)</td>
</tr>
<tr>
<td>Tabha</td>
<td>Nur</td>
<td>West</td>
<td>29</td>
<td>1900</td>
<td>Arad and Bein (1986), Mazor et al. (1980)</td>
</tr>
<tr>
<td>Tabha</td>
<td>Druzi</td>
<td>West</td>
<td>26</td>
<td>1400</td>
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<tr>
<td>Fulya</td>
<td>Russian Garden</td>
<td>West</td>
<td>27</td>
<td>800</td>
<td>Mazor et al. (1980)</td>
</tr>
<tr>
<td>Tiberias</td>
<td>Roman Spring</td>
<td>West</td>
<td>64</td>
<td>18000</td>
<td>Arad and Bein (1986), Mazor et al. (1980)</td>
</tr>
<tr>
<td>Gofra</td>
<td>Gofra Spring</td>
<td>East</td>
<td>31</td>
<td>2900</td>
<td>Arad and Bein (1986), Mazor et al. (1980)</td>
</tr>
<tr>
<td>Hammat Gader</td>
<td>Makie Spring</td>
<td>East</td>
<td>50</td>
<td>480</td>
<td>Arad and Bein (1986), Mazor et al. (1980)</td>
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<tr>
<td>Hammat Gader</td>
<td>Balsam Spring</td>
<td>East</td>
<td>42</td>
<td>330</td>
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<td>Reah Spring</td>
<td>East</td>
<td>37</td>
<td>240</td>
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<td>Hammat Gader</td>
<td>Sahina Spring</td>
<td>East</td>
<td>29</td>
<td>75</td>
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<tr>
<td>Malih</td>
<td>Malih Spring</td>
<td>West</td>
<td>39</td>
<td>1200</td>
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<td>Zukim</td>
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<td>26</td>
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<td>27</td>
<td>7200</td>
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<td>Zukim</td>
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<td>27</td>
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<td>Zerka-Main</td>
<td>#6</td>
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<td>53</td>
<td>650</td>
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<td>East</td>
<td>62</td>
<td>670</td>
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<td>East</td>
<td>58</td>
<td>760</td>
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<td>Zerka-Main</td>
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<td>47</td>
<td>770</td>
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<td>Zara</td>
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<td>East</td>
<td>55</td>
<td>360</td>
<td>Rimawi and Salameh (1988)</td>
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<tr>
<td>Zara</td>
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<td>East</td>
<td>54</td>
<td>315</td>
<td>Rimawi and Salameh (1988)</td>
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<tr>
<td>Zara</td>
<td>#30</td>
<td>East</td>
<td>43</td>
<td>300</td>
<td>Rimawi and Salameh (1988)</td>
</tr>
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<td>#41</td>
<td>East</td>
<td>63</td>
<td>305</td>
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<td>Kedem</td>
<td>Kedem Spring</td>
<td>West</td>
<td>43</td>
<td>125000</td>
<td>Starinsky (1996, personal commun.)</td>
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<td>Yesha</td>
<td>Yesha Spring</td>
<td>West</td>
<td>41</td>
<td>96300</td>
<td>Mazor et al. (1980)</td>
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<td>Zruya</td>
<td>Zruya Spring</td>
<td>West</td>
<td>41</td>
<td>95000</td>
<td>Starinsky (1996, personal commun.)</td>
</tr>
<tr>
<td>Zohar</td>
<td>Zohar Spring</td>
<td>East</td>
<td>30</td>
<td>49500</td>
<td>Mazor et al. (1980)</td>
</tr>
</tbody>
</table>

*Note: Symbols correspond to those used in Figure 4.*

### TABLE 2. LITHOSTRATIGRAPHIC UNITS

<table>
<thead>
<tr>
<th>Age</th>
<th>Symbol</th>
<th>Group</th>
<th>Formations</th>
<th>Lithology</th>
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<tbody>
<tr>
<td>Quaternary</td>
<td>Oqs</td>
<td>Dead Sea</td>
<td>Lisan, &quot;fill&quot;</td>
<td>Marl</td>
</tr>
<tr>
<td>Pliocene</td>
<td>Pb</td>
<td>Dead Sea</td>
<td>Upper basalt</td>
<td>Basalt</td>
</tr>
<tr>
<td>Pliocene</td>
<td>Pds</td>
<td>Dead Sea</td>
<td>Unnamed</td>
<td>Marl</td>
</tr>
<tr>
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<td>Psy</td>
<td>Saqye</td>
<td>Yafo</td>
<td>Marl</td>
</tr>
<tr>
<td>Pliocene</td>
<td>Ps</td>
<td>Dead Sea</td>
<td>Sedom</td>
<td>Salt, gabbro</td>
</tr>
<tr>
<td>Miocene</td>
<td>Mt</td>
<td>Tiberias</td>
<td>Herods, Lower basalt</td>
<td>Marl, sand, basalt</td>
</tr>
<tr>
<td>Upper Cretaceous–Eocene</td>
<td>KuE</td>
<td>Shefela</td>
<td>Mount Scopus, Adulam, Maresha</td>
<td>Chalk, marl</td>
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<tr>
<td>Albian–Turonian</td>
<td>Krij</td>
<td>Judea</td>
<td>Kamon, Dir Hana, Sakhnin, Bina</td>
<td>Dolomite, limestone, marl</td>
</tr>
<tr>
<td>Albian</td>
<td>Kaj</td>
<td>Judea</td>
<td>Zalmon, Yahini, Hidra, Asfuri, Rama</td>
<td>Marl, limestone</td>
</tr>
<tr>
<td>Lower Cretaceous</td>
<td>Kie</td>
<td>Kurnub</td>
<td>Hatira, Nebi Said, En En Assad</td>
<td>Sand, limestone, marl</td>
</tr>
<tr>
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<td>Kkw</td>
<td>Kurnub</td>
<td>Helez, Telaimim, Yavne</td>
<td>Limestone, sand</td>
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<tr>
<td>Lower Cretaceous</td>
<td>Kft</td>
<td>Kurnub</td>
<td>Tayassir Volcanics</td>
<td>Basalt, pyroclastics</td>
</tr>
<tr>
<td>Upper Jurassic</td>
<td>Juzh</td>
<td>Arad</td>
<td>Zohar, Halutza</td>
<td>Limestone</td>
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<tr>
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<td>Jms</td>
<td>Arad</td>
<td>Sederot</td>
<td>Limestone, dolomite</td>
</tr>
<tr>
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<td>Jmr</td>
<td>Arad</td>
<td>Rosh Pina</td>
<td>Marl</td>
</tr>
<tr>
<td>Lower Jurassic</td>
<td>Jin</td>
<td>Arad</td>
<td>Nimrim</td>
<td>Dolomite, limestone</td>
</tr>
<tr>
<td>Lower Jurassic</td>
<td>Jiv</td>
<td>Arad</td>
<td>Asher Volcanics</td>
<td>Basalt, pyroclastics</td>
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</tbody>
</table>

*Note: Symbols correspond to those used in Figure 4.*

in the lower Arad aquifer (which are partially separated from each other by a thin aquitard). The distribution of temperatures (Fig. 5f) is directly related to the convective ground-water systems, as is explained in the following.

On the basis of these results, two types of basin-scale ground-water convection, and therefore of heat transfer, are suggested on both sides of the rift valley. The first is a simple forced convection which takes place at the western side of the valley (Fig. 5, d and e). Rainwater recharges at the Galilee Mountains, flows vertically to the shallow Judea aquifer and partially to the deep Kurnub and Arad aquifers (2–3 km deep) where it is heated, and discharges at the lake’s western margin, creating the hot springs (Fig. 5f). The springs are actually a mixture of fresh and salty sources emerging from these aquifers (Goldshmidt et al., 1967). The fresh component drains laterally from the shallow Judea aquifer, and much of the saline component emerges as hot brines from the deeper Kurnub and Arad aquifers. The model predicts that average linear ground-water velocities at the Judea, Kurnub, and Arad aquifers approach 40, 5, and 0.8 m/yr, respectively (Fig. 5d), depending on the elevation of the ground-water table at the Galilee Mountains, and the hydraulic parameters of each of the hydrostratigraphic units (especially permeability and anisotropy). The total amounts of discharges per meter width of cross section are 750, 150, and 20 m³/yr for the Judea, Kurnub, and Arad aquifers, respectively (Fig. 5e). A detailed discussion on the effect of changes in water table elevation on discharge rates was given by Gvirtzman et al. (1996).

A second ground-water flow mechanism exists at the eastern side of the valley; it is free convection, driven by buoyancy forces. Two thermally driven convection cells, 6–10 km in size, that flow counterclockwise (on the east-west section) are proposed for the confined, 3-km-thick, Cretaceous–Jurassic aquifers beneath the southern Golan Heights (Fig. 5e). The increasing temperature with depth creates physically unstable conditions, in which cold, high-density ground water lies above hot, low-density ground water. The model calculates that because the aquifer is thick enough and permeable enough (Fig. 5b), the common heat flux induces buoyancy forces to overturn the density inversion. Flow rates in these convection cells approach 1.0 m/yr in the Kurnub aquifer and 0.1 m/yr in the Arad aquifer (Fig. 5d), depending on the thickness of the aquifer, ground-water salinity gradient, permeability values, and anisotropy. This value fits with the common range of flow rate estimated for deep ground-water convection cells in hydrothermal systems (Evans and Nunn, 1989). The total amounts of heated-water vertical discharge per meter width of cross section are 40 and 20 m³/yr for the Kurnub and Arad aquifers, respectively (Fig. 5e), resulting in a double regional geothermal gradient (Fig. 5f).

The counterclockwise flow direction within the free convection cells is explained as follows. The subsiding rift valley is filled by high-thermal-conductive evaporites. The lateral thermal conductivity difference between the evaporite beds in the rift \( (\lambda = 4 \text{ W}/\text{°C}/\text{m}) \) and the surrounding carbonate rocks \( (\lambda = 3 \text{ W}/\text{°C}/\text{m}) \) results in heat refraction, so that a larger amount of heat reaches the surface at the graben. Moreover, different vertical geothermal gradients are created at the sides of the graben’s eastern fault. Therefore, at a given depth, a lateral temperature gradient is created toward the salt beds in the surrounding carbonate sediments, resulting in ground-water sinking adjacent to the salt and upwelling away from it; i.e., a counterclockwise motion (Fig. 5e). The model results are consistent with field observations (Starinsky et al., 1979; Bein and Feinstein, 1988): an elevated heat anomaly at Mezor wells and at the Hammat Gader springs, 6–8 km east of the graben margin. Note that a reversed flow circulation, with an upwelling along the salt flank, has sometimes been reported near salt diapirs (Jenssenius and Munksgaard, 1989; Hanor, 1987). This pattern may exist under other conditions, such as higher contrast thermal conductivities, additional salinity gradients, or under isothermal conditions at the lower boundary (Evans and Nunn, 1989).

The influence of the right side boundary condition on the simulation results was tested by

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**Figure 4.** A geologic cross section through the Galilee Mountains, Sea of Galilee, and the Golan Heights (A–A’, Fig. 1). Symbols are listed in Table 2. Formations were grouped into hydrological units on the basis of their lithology and relative permeability. The thick line beneath the Sea of Galilee is the strike-slip transform and the nearby arrows give a sense of motion. Gabbro intrusions are drawn within the graben.
Figure 5. Results of the coupled variable-density ground-water flow and heat transfer model, carried out along the geologic cross section (Fig. 4), using the OILGEN (Garven, 1989) code and estimated rock properties (Table 3). Results include (a) finite element mesh; (b) hydrostratigraphic cross section, where units A–F are defined in Table 3; (c) equivalent fresh-water hydraulic head distribution; and (d) computed ground-water velocities (m/yr), where the vector length is linearly proportional to the flow rate. Note that high velocities are found in the two upper aquifers (unit A) emerging as springs at the Sea of Galilee western coast (Fulya Springs). (e) Stream function exhibiting the deep, buoyancy-driven, free convection cell beneath the Golan Heights, and the shallow, gravity-driven, convection beneath the Galilee Mountains. (f) Temperature distribution (degrees Celsius). Note that the heat anomaly at the Fulya Springs results from rising of deep hot ground water, and that beneath the Golan Heights (Mezar wells) results from the free convection cell.
moving it 20 km out. Results indicated that the counterclockwise-flow free convection cells remain, but new convection cells with a clockwise flow direction are located eastward of the previous ones. The total effect of these convection-cell pairs is an upwelling of deep ground water at the center, and downwelling on both sides. This results in a similar geothermal anomaly beneath the Mezar wells and Hammat Gader springs, as was predicted previously.

Because precise values for many of the hydrological parameters are unknown, especially at a large-basin scale, the sensitivity of the modeling results was checked against variations in assigned parameters. Through these analyses, it was found that flow rates are particularly sensitive to uncertainties of regional permeability, but the flow patterns persist throughout the tested hydraulic conductivity range (10–500 m/yr for the Judea and Kurnub aquifers). However, in other cases a change in an assigned permeability has caused a significant change in flow pattern. For example, a reduction in hydraulic conductivity of the Arad aquifer to below a certain value (KH = 1 m/yr, where KH/KV = 100; see Table 3) stops fluid circulation in the free convection cell, and no heat anomaly is formed, which is inconsistent with field observations (Fig. 2b).

The results shown in Figure 5 are derived from many simulations in which parameters were modified until the comparison between calculated and the actual measured recharge, discharge, and geothermal gradients seemed favorable (Table 3). The simulations estimate an average recharge of 100 mm/yr at the Galilee Mountains, a discharge of about 900 m/yr per meter width slice at the Fulya springs, and geothermal gradients of 20 and 45 °C/km at the Galilee and Golan Heights, respectively. All these calculated values are in good agreement with measured ones.

Table 3 provides a list of most favored values of properties for groups of hydrostratigraphic units. The assigned thermal conductivity values are in very good agreement with those reported in the literature (Eckstein and Simmons, 1978; Ben-Avraham et al., 1978), which range between 0.76 and 3.6 W/Cm², depending on the specific lithology. Similarly, the assigned permeability values fit those reported in the literature (Mercado and Mero, 1984; Michelson, 1975; Nativ, 1987; Nativ and Menashe, 1991). The estimated hydraulic conductivity of the Judea-Kurnub aquifer, KH = 200 m/yr, is slightly higher than previously reported. Through a detailed study, Bein (1967) reported permeabilities of 1.0–0.01 mD using core permeability measurements, and hydraulic conductivity of 1 m/day using aquifer pump tests. Using drill stem tests in these formations, Nativ and Menashe (1991) reported permeabilities of 1–20 mD. However, the hydraulic conductivity of carbonate and sandstone aquifers at the basin-scale is commonly almost two orders of magnitude higher than the permeability measured in the laboratory on core plugs, or about one order of magnitude higher than permeability measured by a pumping test at the field (Garven, 1995). Garven argued that the hydraulic conductivity measured in the laboratory reflects primary porosity; when measured at a borehole it reflects the macroscale fracture sets; however, at the basin scale it should reflect karst systems and regional fracture networks.

**DISCUSSION**

In principle, variations in heat flow may result from several different reasons. Variations in the concentration of radioactive heat-producing elements can lead to some differences in heat flow, but no evidence exists at the Dead Sea rift valley to support this hypothesis. Moreover, this is not a likely explanation because there is no way that it would result in the observed variations in heat fluxes (at least 40 mW/m²) near the Sea of Galilee. On the other hand, the subsiding Dead Sea rift valley is characterized by a rapid sedimentation rate, which results in a lower heat flow. In addition, the various rock types in the rift (salt, gabbro, and marl) have different thermal conductivity values. Consequently, appreciable heat refraction into more conductive rocks can cause slight lateral variations. These hypotheses can explain the slight variations observed within the Dead Sea rift valley. It seems unlikely, however, that these mechanisms could be of sufficient magnitude to explain the high heat anomalies at the western margin of the Sea of Galilee, and especially, those at the Mezar wells at the east. We argue that ground-water convection is the major mechanism that causes redistribution of the heat within the rift valley, as follows.

The hydrological systems on the sides of the Sea of Galilee exhibit two types of ground-water convection: (1) a forced convection due to gravity forces at the western side; and (2) a free convection induced by buoyancy forces at the eastern side. These ground-water convections profoundly redistribute heat throughout the rift valley basin. At the western side, cold rainwater percolates at the high elevations of the Galilee Mountains, and is diverted vertically and laterally to the east. As water percolates downward, its temperature increases as it absorbs heat that would otherwise warm the sediments, thereby decreasing the thermal gradient (Fig. 5f). Ground water preferentially follows the path of least resistance, mostly through the Judea, and partially through the Kurnub and Arad aquifers. The upward flow of heated water at the western margin of the rift valley leads to elevated temperatures of the surrounding rocks, thereby increasing the thermal gradient. Eventual discharge occurs mostly as saline hot springs at high-permeable conduits, and also underneath parts of the lake’s floor where relatively permeable filling material exists. At the eastern side of the graben, ground water in the deep Kurnub and Arad aquifers has neither inputs nor outputs; it is a closed hydrological system where free convection cells take place. At the upwelling zone, heat is transferred vertically by both mechanisms, conduction and convection, heating the surrounding rocks. Rising warm ground water at one location and sinking cold ground water at another location, increase and decrease the temperature gradients, respectively (Fig. 5f). The aquitard unit covering the Kurnub aquifer simply serves as a heat conductor layer between the deep convecting cell and the shallow Judea aquifer. The waters emerging from the hot springs at Hammat Gader originate from the shallow Judea aquifer; those at the western side emerge from deeper aquifers.

These two different mechanisms are actually a direct result of the specific geologic configurations developed through continental rifting. On the western side, the aquifer is phreatic at some portions and downfaulted blocks form a continuum between several aquifer units, discharging waters from shallow and deep aquifers and creating an open system (Fig. 5f). On the
SUMMARY AND CONCLUSIONS

Ambiguous geothermal fluxes were measured at the vicinity of the Sea of Galilee, located within the Dead Sea rift valley: 70–80 mW/m² at the central part of the lake, 36 mW/m² at the lake’s southern coast (10 km apart), and about 135 mW/m² at the southern Golan Heights, 6–8 km east of graben margin. This study argues that these geothermal anomalies directly result from ground-water convection systems, which redistribute the heat. Using a detailed geologic cross section that traverses the entire sedimentary basin and applying the OILGEN numerical code for solving the coupled variable-density ground-water flow and conductive-convective heat transfer equations, the observed temperature gradients along the entire cross section were reproduced. On the basis of the numerical simulations, two different mechanisms of basin-scale ground-water convection are suggested for the two sides of the rift that could influence the transport of heat: (1) forced convection (gravity-driven flow) of hot brines from deeper aquifers to the land surface at the western side; and (2) large-scale free convection (buoyancy-driven flow) of deep ground water at the eastern side. The different heat fluxes within the rift valley are attributed to the different lithology and to the locations of specific conduits through which the hot ground waters ascend from deeper horizons. This study demonstrates the value of using hydrogeological modeling as a basic tool for understanding hydrogeological and hydrothermal systems. The existence of free convection cells of deep ground water beneath the southern Golan Heights, which has never been suggested previously, is hypothesized on the basis of such modeling. Moreover, through this study we have gained insights into (1) the mechanisms that generate the significantly different geothermal gradients near the Sea of Galilee and (2) the processes that create hot springs with extremely different salinities on the eastern and western sides of the rift.

Absolute flow magnitudes cannot be proven, verified, or validated by such models (Konikow and Bredehoeft, 1992; Oreskes et al., 1994). This study is based on a few generalized assumptions and simplifications because there are only poorly constrained hydrologic data for this region. There is much uncertainty regarding the exact location of faults beneath the lake, thickness of formations, properties of various lithostratigraphic units, and the three-dimensional temperature distribution. Nevertheless, this study is the first attempt to construct a comprehensive regional model of ground-water flow and heat transport across the Dead Sea rift valley, and we argue that a better understanding of the ground-water system behavior has been already achieved through this regional modeling. In any case, further hydrological, geophysical and geochemical investigations are required in order to understand the behavior of the entire hydrogeological system.

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