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

Discussion

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In a most interesting and excellent study, Gvirtzman et al. (1997) used modeling as a basic tool for understanding hydrogeologic and hydrothermal systems in the Dead Sea rift valley in the Sea of Galilee region. They say that, "The existence of free convection cells of deep ground water...which has never been suggested previously, is hypothesized on the basis of...modeling" (Gvirtzman et al., 1997, p. 1175). They demonstrated that geothermal anomalies result from ground-water convection systems, which distribute the heat. They believe that through their study they have gained insights into the processes that create hot springs. Gvirtzman et al. (1997) presented a most convincing argument.

In their paper they refer to an alternative interpretation for a regional heat anomaly attributed to the extensive Miocene–mid-Pleistocene volcanism and intrusions (Arad and Bein, 1986). They feel that this explanation may be less relevant because the heat anomaly is observed only locally, and any intrusions probably have cooled since the last eruption took place 0.7 Ma (Mor and Steinitz, 1984).

In my study of the sediment in this same area, I have used a different approach that seems to support the influence of volcanism and that supplements and complements the data of Gvirtzman et al. (Friedman, 1995). My interest was the origin of dolomite in the sediment of the Tiberias Hot Springs along the shores of the Sea of Galilee (Friedman, 1995). The Sea of Galilee region is located within the Dead Sea transform, which joins the Red Sea transform via the Gulf of Aqaba. These plate boundaries host hydrothermal exhalations that raise the question of fluid processes at these boundaries. As an example, the circulation of seawater through the still-hot oceanic crust within the Red Sea axial zone has produced hot brine pools (Degens and Ross, 1969; Backer and Schoell, 1972; Amann et al., 1973; Backer, 1975; Coleman, 1993). In the Red Sea, at least 18 hot brine pools have been discovered and new ones continue to be reported as more detailed oceanic studies are carried out. The composition of the brine has been compared with hydrothermal fluids emanating from active "black smokers" of the East Pacific Rise and Juan de Fuca Ridge. The similarity of these fluids is striking in that they are all saturated with NaCl and are enriched in Na, K, Rb, and Ca when compared to seawater (Coleman, 1993). These brines are thought to have been derived from deep circulation of hydrothermal fluids within the underlying basalts at high temperature.

Along the Dead Sea strike-slip basin, brines form carbonate and evaporite

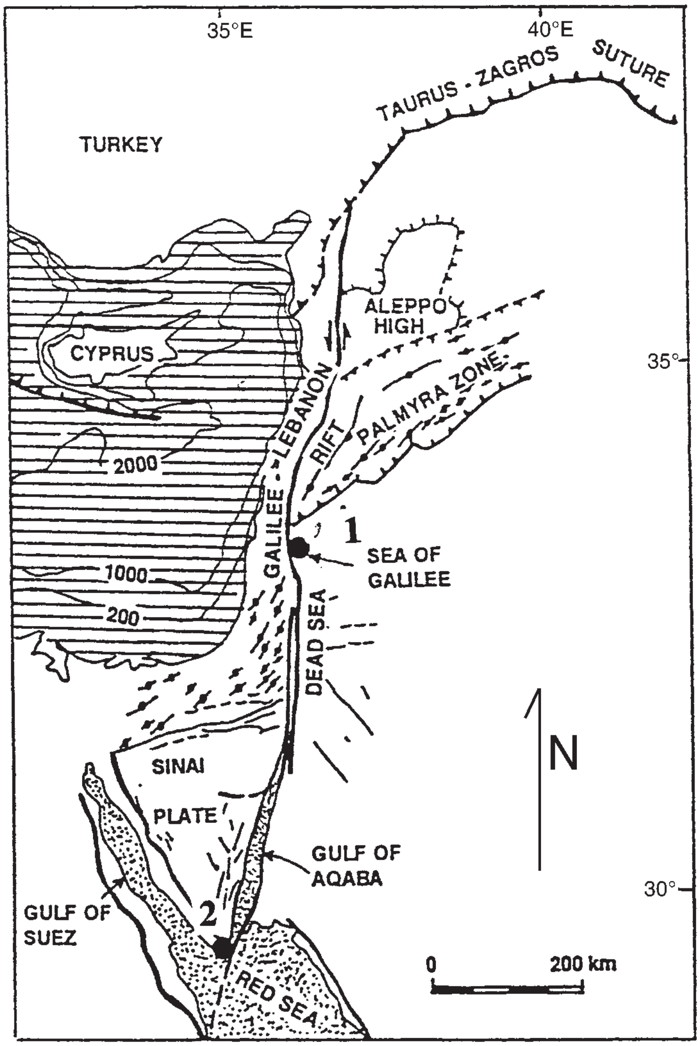

Figure 1. Map of Dead Sea–Gulf of Aqaba–Red Sea rift valley fault system showing (1) location of Tiberias Hot Springs along the shores of the Sea of Galilee and (2) the Ras Muhammad hypersaline pool at the southernmost tip of the Sinai Peninsula (Sinai plate) (after Walley, 1988).

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GSA Bulletin; July 1999; v. 111; no. 7; p. 1098–1102; 3 figures; 2 tables.

TABLE 1A. MINERALOGY

Location	Quartz	Plagioclase feldspar	K-feldspar	Calcite	Dolomite	Gypsum	Pyrite	Halite	Illite/ chlorite
Tiberias Hot Springs I	3	1	1	83	11	0	1	0	0
Tiberias Hot Springs II	1	0	0	12	5	82	0	0	0
Tiberias Hot Springs III	3	0	0	92	3	0	0	0	0
Tiberias Hot Spring IV	23	1	1	92	0	0	0	0	3
Hamat Gader near Tiberias	4	1	0	92	0	0	0	3	0
Hamat Gader near Tiberias	1	0	0	18	0	0	81	0	0

TABLE 1B. ISOTOPES

Location	Mineral	$\delta^{13}C$ (‰)	$\delta^{18}O_{SMOW}$ (‰)	$\delta^{18}O_{PDB}$	$^{87}Sr/^{86}Sr$ (±2 S.D.)*	Age
Tiberias Hot Springs I	Calcite	–2.4	+22.6	–7.5	Not analyzed	Not analyzed
	Dolomite	+0.3	+28.7	–1.6	0.7450(02)	>40770 ^{14}C yr B.P. (^{13}C corrected)
Tiberias Hot Springs II	Calcite	–6.4	+24.6	–5.6	Not analyzed	Not analyzed
	Dolomite	+2.4	+30.7	+0.3	Not analyzed	Not analyzed

Note: Krueger Enterprises determined stable isotopes and the age of the Tiberias dolomite. Mineralogy, Inc. performed the X-ray work. SMOW—standard mean ocean water; PDB—Pee Dee belemnite; S.D.—standard deviation.

*The Sr analyses are normalized to $^{86}Sr/^{88}Sr$ + 0.1194. Analyses of NBS 987 averaged 0.71023 (02) during the period of these analyses. Errors on $^{87}Sr/^{86}Sr$ are better than ±0.00002 (95%) internal (within run) precision; replicate analyses indicate external precision is better than ±0.00008 (95%).

deposits in the area of the Sea of Galilee (Fig. 1) at Tiberias Hot Springs, where the trapped water becomes heated and is brought to the surface. Along the Gulf of Suez, the Hammam–El-Farum Hot Springs are almost identical in composition to the Tiberias Hot Springs (Mazor, 1968). Dolomite and calcite precipitated from these hot springs (Magaritz and Issar, 1973). The waters of the Tiberias Hot Springs were discussed by Goldschmidt et al. (1967), Gat et al. (1969), Mazor and Mero (1969), Horowitz (1970), Kafri and Arad (1979), Issar (1983), and Arad and Bein (1986).

Tiberias Hot Springs is located 200 m below sea level. Table 1 shows the mineralogy and isotopic composition of carbonate and evaporites from Tiberias Hot Springs and from another nearby site, known as Hammat Geder. Table 2 gives the water chemistry of two separate springs from which samples were taken.

The sediment from the hot springs is composed of authigenic carbonate and/or gypsum with sporadic detrital particles (Table 1). The carbonate minerals present are low-magnesian calcite and dolomite; calcite is more abundant than dolomite. Although I have measured water temperatures ranging from 51 to 59 °C, the temperature of the springs is usually 60 °C. The stable isotopic composition of the calcite reflects the effect of fresh water (Table 1), hence fresh water is involved in generating the brines that precipitate calcite. The stable isotopic composition of dolomite falls in the field of Cretaceous bedrock (Fig. 2). The apparent age of sampled dolomite exceeds 40 770 ^{14}C yr (^{13}C corrected) (analyzed by accelerator mass spectrometry). However, the dolomite has not been recycled from Cretaceous bedrock. Its strontium isotopic signature (Fig. 2; Table 1) shows that it formed from waters that contain strontium derived from the mantle (Faure, 1991). The source in the subsurface that provides heat and saline fluids to form the brines generated the dolomite. The dated carbon of the dolomite is inherited and much older than the dolomite, which currently forms where the springs extrude and which has inherited a strontium signature of basaltic ground water (Friedman, 1995; Raab et al., 1997). The saline ground water in the area formed by mixing fossil brines (of Neogene age) with meteoric water. Such solutions, and their precipitates, are not expected to result in a modern radiocarbon age.

TABLE 2. TIBERIAS HOT SPRINGS WATER ANALYSIS

	I	II
K	340	340
Ca	3450	3320
Na	7300	6600
Mg	340	660
Cl	18265	18298
SO_4	728	728
HCO_3	155	151
Br	232	236
Total	31140	30333

Note: All measurements in mg/L. Analysis by Geological Survey of Israel.

This dolomite is quite different from most other dolomites in its origin. It is epigenetic and hydrothermal in origin and compares with dolomites that have formed in the geologic past, where faults or fractures acted as passageways for basinal brines (Friedman and Sanders, 1967, p. 330–331; Friedman, 1992).

It is of interest to compare the strontium isotopic composition of the carbonate sampled at the Ras Muhammed Pool at the southernmost end of the Gulf of Aqaba (Fig. 1). Figure 2 is a plot of $^{87}Sr/^{86}Sr$ age taken from Burke et al. (1982) on which strontium isotopic values from this study have been superimposed. On this plot, the strontium isotopic composition of the Ras Muhammad carbonate sample, of which dolomite is only a minor constituent and aragonite is a major component, shows disequilibrium with respect to the water. The carbonates precipitated from a less-radiogenic fluid than modern seawater. The low strontium number may relate to hydrothermal brines at depth. Using the Burke et al. (1982) $^{87}Sr/^{86}Sr$ ratio of marine carbonate ages, the carbonate sediment yields an early Miocene strontium isotope age, yet radiocarbon dates range between 26 and 1050 yr B.P. The strontium isotopic composition confirms that in this rift zone the samples precipitated from (or exchanged with) fluids closer in isotopic composition to extant waters or hydrothermal fluids, probably basaltic ground water.

As Gvirtzman et al. (1997, p. 1167) pointed out, "the different heat fluxes within the rift valley are attributed to the different lithofacies and to the locations of specific conduits through which the hot ground waters ascend from deeper horizons." In this perspective, identification of fluids from the mantle, and more specifically basaltic ground water, provides one possible answer to the origin of the thermal anomaly in the Dead Sea rift valley. The brines at the Sea of Galilee, those found at the Gulf of Suez and Gulf of Aqaba, and those detected at the mid-ocean ridge of the Red Sea are not comparable; however, the observation of primitive strontium ratios in the hot spring carbonate deposits of the Tiberias Hot Springs and at Ras Muhammed at the southernmost tip of the Gulf of Aqaba does suggest interaction with rift basalt, or basalt pyroclastic material in the sedimentary section.

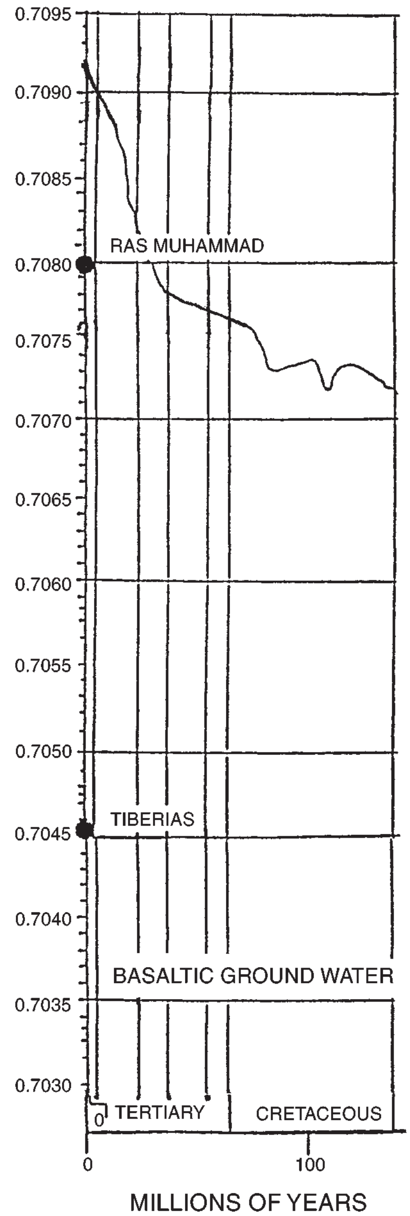

Figure 2. Plot of $^{87}Sr/^{86}Sr$ ratio of marine carbonate stages (curved line) taken from Burke et al. (1982) on which strontium isotopic values of basaltic ground water and carbonates from Tiberias and Ras Muhammed have been superimposed.

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Manuscript Received by the Society February 17, 1998
Manuscript Accepted September 14, 1998

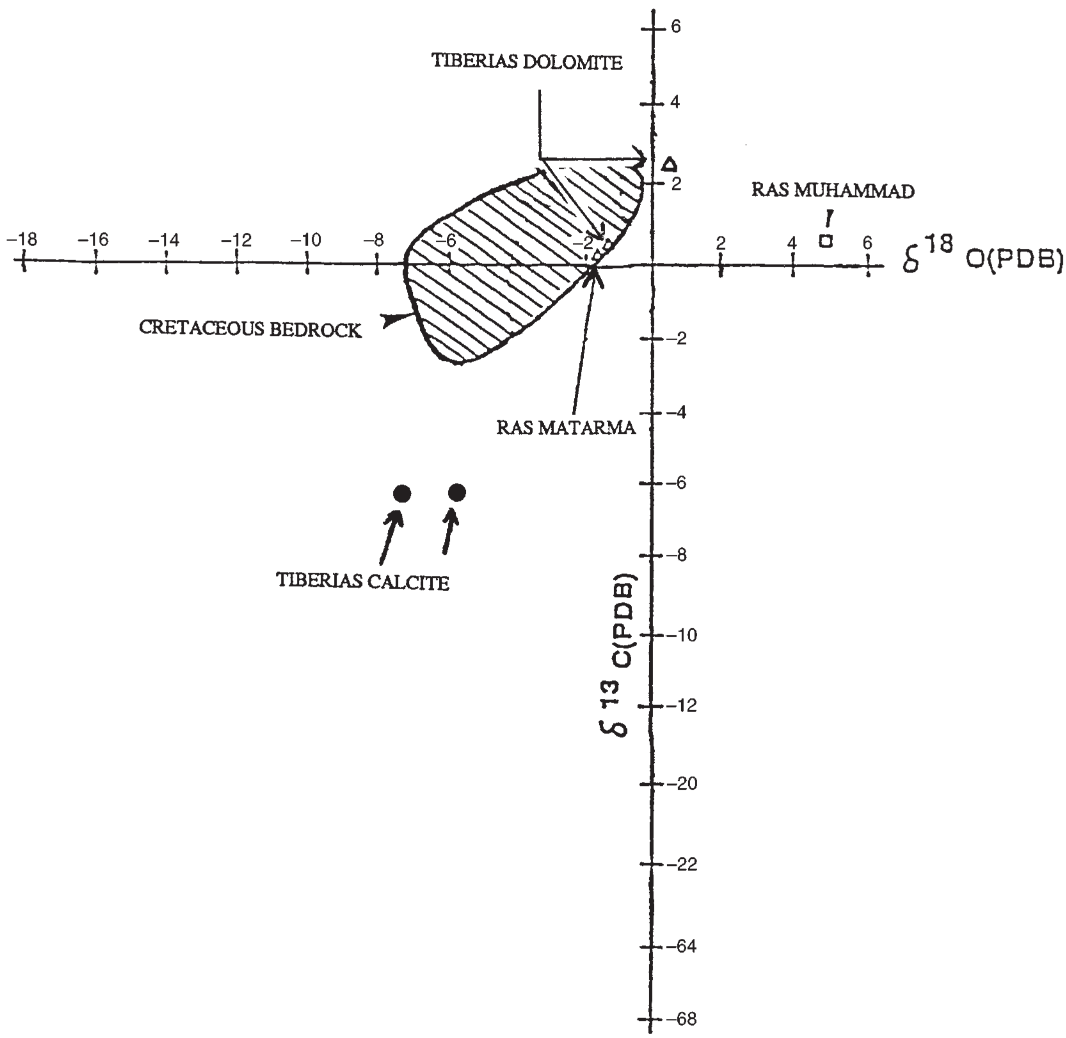

Figure 3. Stable isotope composition of carbonates in Levant rift valley. The location of the sampling sites is shown in Figure 1 and includes Tiberias Hot Springs along the shores of the Sea of Galilee, Ras Muhammad, Ras Matarma samples (open triangles) from Luz et al. (1984), and Cretaceous bedrock from Magaritz et al. (1983). PDB—Pee Dee belemnite.

Reply

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We welcome the discussion by Friedman on our recent paper in the *Bulletin* (Gvirtzman et al., 1997a) and hope that it will stimulate more research on the unclear coupled hydrogeology and geochemistry processes that took place during the formation of the Dead Sea rift.

In his stimulating discussion, Friedman presents some new geochemical data that suggest that ground waters in the Dead Sea rift have interacted with igneous rocks, and has provided other published references supporting this hypothesis. The data include chemical composition, mineralogy, temperature, carbon dating, as well as strontium and oxygen and carbon isotopic compositions. We appreciated learning about these findings and their interpretation. Moreover, Friedrichsen and Hammerschmidt (1997) have detected mantle-related helium in the rift ground waters. We feel that water-rock interaction with basalt should not be a surprise given the geologic history of the rift, but it is worth highlighting the geochemical evidence.

The notion of deep fluid circulation in the Dead Sea rift was discussed in our last two papers (Gvirtzman et al., 1997a, 1997b). Our modeled groundwater flow systems are big enough to enhance water-rock interactions to depths of several kilometers, including interactions with magmatic intru-

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sions within the rift. We simply showed that both forced and free ground-water convections are operative in the Sea of Galilee vicinity. Topography-driven convection of fresh ground water as well as density-driven convection of deep brines are integral parts of many rift systems throughout the world. As Friedman states, his data supplement and complement our interpretation, and we welcome his added discussion.

What is the source of the present-day heat anomaly? We (Gvirtzman et al., 1997a) argued that the major heating mechanism is large-scale ground-water convection. We still believe that the extensive Miocene–mid-Pleistocene volcanism and intrusions seem likely to have cooled since the last eruption. The coalification profile from the Notera-3 deep well in the Hula basin (Gvirtzman et al., 1997a, Figs. 1 and 2) indicated a relatively high thermal gradient averaging 40 ^{o}C/km throughout Neogene time (Bein and Feinstein, 1988); however, in the Notera-1 well, 0.6 km away, the recent thermal gradient is 13 ^{o}C/km (calculated from data of Levitte and Olshina, 1985). This temporal difference is obviously the result of the cooling process that took place after the Miocene–mid-Pleistocene volcanism and intrusions. In other words, magmatic intrusions were a major source of heating, albeit transient, in the past along the Dead Sea rift.

In this perspective, it should be noted that geochemical evolution and geothermal anomaly may begin together, but may not persist together. A volcanic heat anomaly may cool while its geochemical fingerprint may persist much longer. Therefore, there is no contradiction between the two approaches. Using the geochemical approach, a signature of mantle-related geochemical tracers in ground water was detected, probably associated with the already-cooled hydrothermal exhalations. However, on the basis of our hydrogeological calculations, the current geothermal anomaly is attributed to another heat-transport mechanism, i.e., convection in a ground-water flow system.

In summary, the discussion offered by Friedman highlights research topics that deserve more study. These include (1) geochemical evolution of ground water and brines; (2) rift paleohydrology and the evolution of transients; and (3) quantitative coupling between the geochemical and hydrogeological systems. Friedman's data may provide further constraints on future studies.

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Manuscript Received by the Society May 13, 1998
Manuscript Accepted September 14, 1998

Printed in U.S.A.