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The thermal structure of Israel and the Dead Sea Fault

Eyal Shalev [a,*], Vladimir Lyakhovsky [a], Yishai Weinstein [b], Zvi Ben-Avraham [c]

[a] Geological Survey of Israel, 30 Malkhe Israel, Jerusalem, 95501, Israel
[b] Department of Geography and Environment, Bar-Ilan University, Ramat-Gan, 52900, Israel
[c] Department of Geophysics and Planetary Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel

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ABSTRACT

In this paper we analyze temperature data from all the available oil and water wells in Israel and compare the results with seismicity depth and with heat flux estimation from xenoliths. We show that the average heat flux in Israel is 40–45 mW/m^2, consistent with measurements of the Arabian Shield. A heat flux anomaly exists in Northern Israel and Jordan. This could be attributed to groundwater flow or young magmatic activity (~100,000 years) that is common in this area. A higher heat flux exists in Southern Israel and Jordan, probably reflecting the opening of the Red Sea and the Gulf of Eilat (Gulf of Aqaba) and does not represent the average value present in the Arabian Shield.

The temperature gradient at the Dead Sea basin is relatively low, resulting in low heat flux (<40 mW/m^2) and a relatively deep seismicity extending to lower crustal depths, in agreement with earthquake depths (<25–30 km). Higher heat fluxes at the Sea of Galilee (70 mW/m^2) and at the Gulf of Eilat (65 mW/m^2) results with shallower seismicity (<10–12 km). The steep geothermal gradients yielded by xenoliths (>80 mW/m^2) could be the result of local heating by magmas or by lithospheric necking and shear heating.

1. Introduction

Heat flux is a major factor that affects the rheology of the lithosphere, magmatism, and groundwater flow (Ranalli and Rybach, 2005). Different assumptions about the heat flux in Israel have led to different tectonic and seismological models (Aldersons et al., 2003; Al-Zoubi and ten Brink, 2002; Sobolev et al., 2005). The heat flux controls the thickness of the lithosphere, the type of deformation (brittle versus ductile), and the depth of the seismogenic zone (Jaupart and Mareschal, 2011; Ranalli, 1995). Sobolev et al. (2005) and Petrunin and Sobolev (2006) presented results of a three-dimensional thermomechanical model of a pull-apart basin, formed at left stepping segments of an active continental transform fault such as the Dead Sea (see Fig. 1 for location). Adopting the classical scheme of a pull-apart basin formation, they demonstrated that the major parameter controlling the basin structure and deformation pattern beneath the basin is the thickness of the brittle layer. Significant ductile deformation of the lower crust and the upper mantle associated with basin growth due to a pull-apart mechanism requires normal or elevated heat flux. The closest fit to the Dead Sea structure has been obtained with the model corresponding to a surface heat flow above 60 mW/m^2. They also argued that a strong lower crust in a cold lithosphere with heat flow below 50 mW/m^2 could not allow the opening of a pull-apart such as the Dead Sea basin.

Förster et al. (2007) determined the heat flux in five, up to 900 m deep boreholes in southern Jordan to be 60.3 mW/m^2. Recently, Förster et al. (2010) analyzed a set of surface samples from the uppermost crust down to the lithospheric mantle underneath Jordan and assumed heat flux of 55–65 mW/m^2 to construct a thermal model. Thermobarometric calculations, based on lower crustal and lithospheric mantle xenoliths, suggest even steeper geothermal gradients (e.g. Al-Mishwat and Nasir, 2004; McGuire, 1988; McGuire and Bohannon, 1989; Nasir, 1992; Stein et al., 1993), thus higher heat flux (>80 mW/m^2). The above considerations contradict the general view of the Arabian Shield as an anomalously cold terrain characterized by heat flux values below ~45 mW/m^2 (Gettings and Showail, 1982). Davies and Davies (2010) showed that the heat flux along the Red Sea is very high (>150 mW/m^2), whereas the heat flux at the Arabian Shield is low (<55 mW/m^2). Measurements supporting low geothermal heat flux were published by Eckstein (1976), Eckstein and Simmons (1978), Levitte et al. (1984), and Eckstein and Maurath (1995) who measured thermal gradients and thermal conductivity in abandoned oil wells and unused water boreholes distributed over Israel. They calculated an average heat flux of 42 mW/m^2. The mean value of the corrected heat data for the northern part of the Dead Sea basin is 38 mW/m^2 (Ben-Avraham et al., 1978). Recent re-evaluation of the heat flow data for the Dead Sea basin (Shalev et al., 2007) confirmed these low values. Based on coal rank measurements, Bein and Feinstein (1988) showed that a low heat flux has prevailed in the Dead Sea area since the mid-Miocene period. Galanis et al. (1986) estimated a mean basal heat-flow value of 53 mW/m^2 in Jordan. Local elevated heat flux

* Corresponding author. Tel.: +972 50 6234890.
E-mail address: eyal@gsi.gov.il (E. Shalev).

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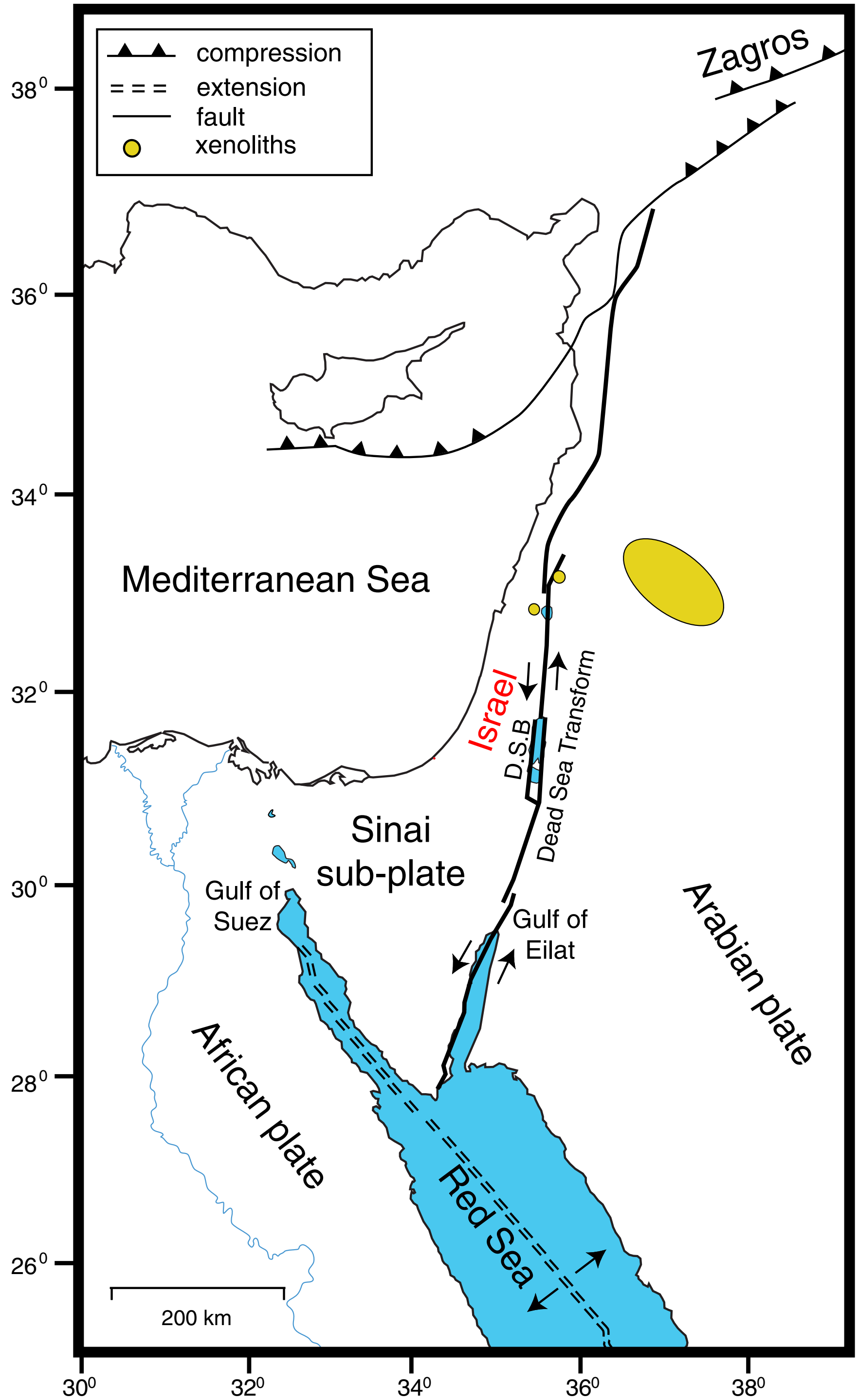

Fig. 1. Major tectonic features of the study area (Israel) and vicinity. The Dead Sea Basin (D.S.B.) is located at the center of the Dead Sea Transform.

values were shown to be associated with groundwater advection (Galanis et al., 1986; Gvirtzman et al., 1997; Kovach et al., 1990; Truesdell et al., 1983).

Another characteristic of the Dead Sea fault is the significant variations in the depth of the seismogenic zone. In the central part (the Dead Sea basin) the seismicity is anomalously deep extending almost to the mantle (Aldersons et al., 2003; Braeuer et al., 2010; Shamir, 2006). Sixty percent of well-constrained micro-earthquakes (ML≤3.2) in the Dead Sea basin during the period 1984–1997 were located at depths up to 25–30 km. The seismogenic zone becomes shallower to the south, toward the Gulf of Eilat, where most earthquakes are located at depths shallower than 10 km (the European-Mediterranean Seismological Centre catalog, 2011). Recent study of the seismicity in the northern part of the Dead Sea fault (Navon, 2011) shows that at the Sea of Galilee area, the seismogenic zone is also shallow (~12 km) and that it deepens northwards.

The two opposing opinions of high versus low heat flux suffer from some limitations. The analysis of Förster et al. (2007) is based on a very detailed study of just five closely located boreholes in southern Jordan, which they extrapolated on the entire region. On the