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Focus paper

Mud volcano origin of the Mottled Zone, South Levant

Igor Novikov [a], Yevgeny Vapnik [b], Inna Safonova [a,*]

[a] Institute of Geology and Mineralogy SB RAS, Koptuyga Ave. 3, Novosibirsk 630090, Russia
[b] Department of Geological and Environmental Sciences, Ben-Gurion University of the Negev, P.O.B. 653, Beer-Sheva 84105, Israel

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ABSTRACT

The Mottled Zone (MZ) or Hatrurim Formation, which occurs near the Levantine Transform in the South Levant, has been studied during the last 150 years but its origin remains debatable. Mottled Zone Complex/Complexes (MZC/MZCs) consist of brecciated carbonate and low-temperature calcium-hydrosilicate rocks, which include unusual high- and ultra-high-temperature low-pressure (HT-LP) metamorphic mineral assemblages. The MZ has been regarded as a product of combustion of bituminous chalks of the Ghareb Fm. of Cretaceous (Maastrichtian) age. In this paper we present detailed geographic, geomorphologic, structural and geological data from the MZCs of the South Levant, which show that the MZCs cannot be stratigraphically correlated with the Ghareb Fm., because MZC late Oligocene–late Pleistocene deposits occur within or unconformably, i.e., with stratigraphic hiatus, overlap both the late Cretaceous and, in places, Neogene stratigraphic units. We propose an alternative model for the formation of MZCs by tectonically induced mud volcanism during late Oligocene–late Pleistocene time. This model explains (i) the presence of dikes and tube-like bodies, which consist of brecciated exotic clastic material derived from stratigraphically and hypsometrically lower horizons; (ii) mineral assemblages of sanidinite facies metamorphism; (iii) multi-stage character of HT-LP pyrometamorphism; and (iv) multi-stage low-temperature hydrothermal alteration. High temperatures (up to 1500 °C) mineral assemblages resulted from combustion of hydrocarbon gases of mud volcanoes. Mud volcanism was spatially and structurally related to neotectonic folds and deformation zones formed in response to opening of the Red Sea rift and propagation of the Levantine Transform Fault. Our model may significantly change the prospects for oil-and-gas deposits in the region.

1. Introduction

The Mottled Zone (MZ) or the Hatrurim Formation (Fm.) in South Levant, which includes of Jordan, Israel and Palestine, consists of sixteen complexes of high-temperature (high-T) low-pressure (low-P) metamorphic rocks associated with low-temperature (low-T) hydrothermally altered and/or brecciated rocks (Fig. 1). Picard (1931) termed these rock complexes "the Mottled Zone". This term accurately describes the diversity of rocks and their irregular distribution. Several dozens of rock types have been identified by Gross (1977) including 127 mineral species. MZ is a type locality of 11 unique minerals and totally includes about 200 mineral species (Vapnik et al., 2006). The MZ occurs as a cover with well-defined margins. During early geological surveys these complexes were regarded as magmatic (Tristram, 1865; Hull, 1886). Later, when the absence of magmatism became obvious, the Mottled Zone rocks were attributed to hydrothermal activity (Blanckenhorn, 1912; Gilat, 1998), diagenesis (Picard, 1931; Avnimelech, 1964), or to the burning of dispersed organic matter in the Maastrichtian Ghareb Fm. (Lees, 1928; Bentor and Vroman, 1960) (Fig. 2). Each of the above origins only partially described the observed features of the MZ rocks. Since 1963 the hypothesis of burned organic matter, combustion of bituminous chalk in our case, has become more popular (Bentor et al., 1963a,b; Gross et al., 1967; Gross, 1977; Burg et al., 1991, 1999; Gur et al., 1995).

However, there are several inconsistencies in the hypothesis of bituminous chalk combustion, which require the origin of the MZ rocks to be re-addressed: (1) bituminous chalk of the Ghareb Fm.

* Corresponding author. Tel.:+7 383 330 84 03.
E-mail address: inna@igm.nsc.ru (I. Safonova).

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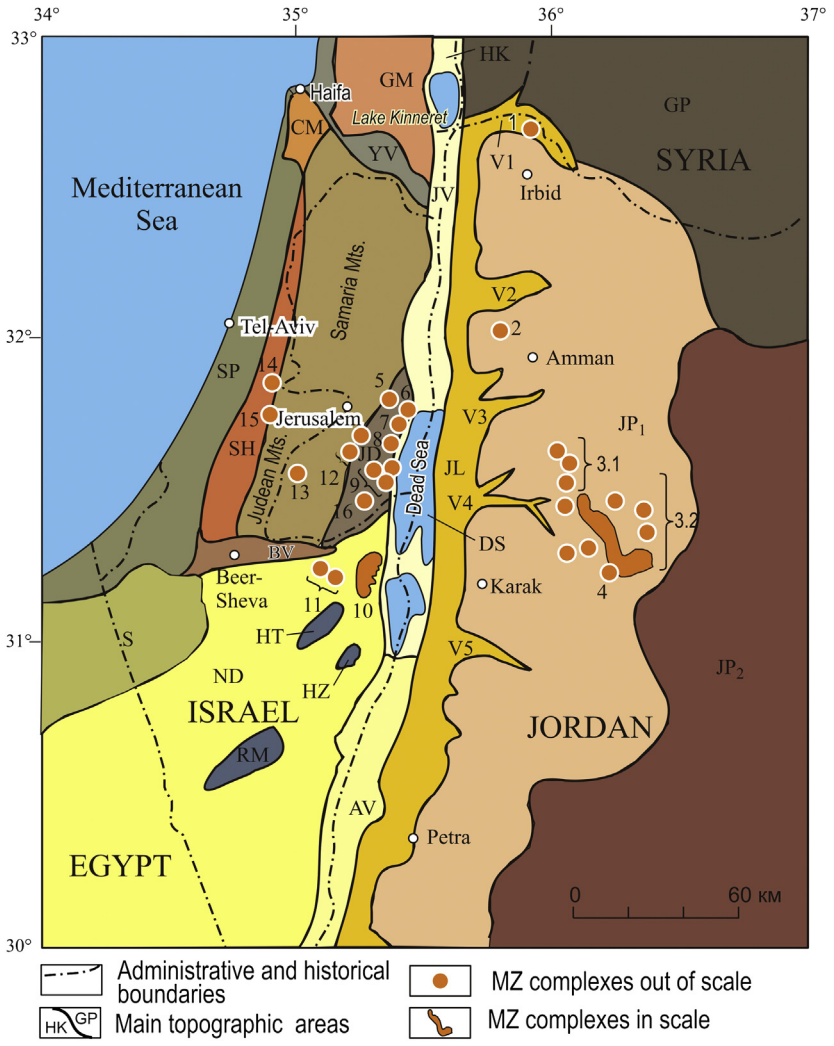

Figure 1. Tectonic scheme of the South Levant including fields of the Mottled Zone Complex (based on Barijous, 1985; Qudairah, 1994; Hammour, 1998; Sneh et al., 1998; Burg et al., 1999). The segments of the Levantine Transform: AV = Arava Valley, BV = Beer-Sheva Valley, DS = Dead Sea, HK = Hula and Kinneret lakes, JV = Jordan Valley, YV = Yizreel Valley. Main topographic areas east of the Levantine Transform: JL = Jordanian Ledge, river valleys: V1 = Yarmuk, V2 = Zarqa, V3 = Kafrein, V4 = Heidan and Mujib, V5 = Hasa. Main topographic areas west of the Levantine Transform: CM = Mount Carmel, ND = Negev Desert, SH = Shefela hills, SP = coastal plane. The Negev Desert: S = sand fields; erosional windows - HT = Hatira, HZ = Hazera, RM = Ramon. Transjordanian Plateau: JP_1 = denudated part, JP_2 = denudated and accumulated part. Mottled Zone Complexes (MZCs): 1 – Maqarin, 2 – Suweilih, 3.1 – Daba, 3.2 – Siwaqa, 4 – Matruk, 5 – Ma'ale Adummim, 6 – Nabi Musa, 7 – Jebel Harmun, 8 – Hyrcania, 9 – Nahal Darga, 10 Hatrurim, 11 – Malhata, 12 – Beit Sahur, 13 – Tarqumiya, 14 – Nahal Ayalon, 15 – Kefar Uriyya, 16 – Hatzatzon. Other abbreviations: GM = Galilee Mountains, GP = Golan Plateau, JD = Judean Desert, MZ – Mottled Zone.

has low porosity, so that spontaneous combustion is impossible; (2) the stratigraphic position of MZ rocks is different from that of the Ghareb Fm., e.g., they may occur above, below and/or in place of the Ghareb Fm. (see Sections 4, 5); (3) the rocks of the MZ are, in places, strongly brecciated, thermally metamorphosed and hydrothermally altered (Gross, 1977); (4) the dikes and pipe-like bodies of pyrometamorphic and brecciated rocks, fragments of sedimentary rocks from the sedimentary sequence below the observed hypsometric levels, crosscut the MZ (Vapnik and Sokol, 2006); (5) combustion was accompanied by melting at 1100–1500 °C to form paralavas, i.e., quenched glass-bearing rocks forming the walls of mud volcano feeder channels (Sharygin et al., 2006; Vapnik et al., 2007; Sokol et al., 2010, 2012). Such high temperatures cannot be reached during combustion of low-calorific fuel, e.g., bituminous chalk (common C_{org} is below 15 wt.%; Burg et al., 1991). Moreover, the heat source and composition of protolith postulated by Bentor et al. (1963a,b) do not match the mineral assemblages and bulk compositions of the MZ rocks.

The new mud volcano model for the origin of the MZ was proposed by (Vapnik et al., 2006, 2007; Sokol et al., 2007, 2008) and is based on revised (Gross, 1977) and new (Sokol et al., 2010) mineralogical and petrologic data, and on negative gravitation anomalies located beneath the MZ, which suggest mud volcano diapirism (Vapnik et al., 2008a,b; Khesin et al., 2010a,b). Mud volcanism is typical of marginal parts of Mesozoic and Cenozoic oil-bearing sedimentary basins (Kholodov, 2002a,b), and is closely associated with neotectonic deformation, which typically results in redistribution of sediments in host rocks of hydrocarbon reservoirs under abnormally high seam pressures. This process is accompanied by surface eruption of disintegrated rock, water, hydrocarbon gases and, in some cases, oil, to form a cone or plateau-like feature depending upon the viscosity of the erupted material (Lilienberg, 1955). Mud volcanoes may generate flows up to 300–400 m thick and extend for more than 1 km^3 (Lichagin, 1952). Rocks occurring close to the site of combustion commonly experience heating to temperatures >1000 °C resulting in the formation of sanidinite