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First Paleomagnetic Map of the Easternmost Mediterranean Derived from Combined Geophysical-Geological Analysis

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he easternmost Mediterranean is a tectonically complex region evolving in the long term and located in the midst of the progressive Afro-Eurasian collision (e.g., Ben-Avraham, 1978; Khain, 1984). Both rift-oceanic systems and terrane belts are known to have been formed in this collision zone (Stampfli et al., 2013). Despite years of investigation, the geological-geophysical structure of the easternmost Mediterranean is not completely known. The formation of its modern complex structure is associated with the evolution of the Neotethys Ocean and its margins (e.g., Ben-Avraham and Ginzburg, 1990; Robertson et al., 1991; Ben-Avraham et al., 2002). The easternmost Mediterranean was formed during the initial phase of the Neotethys in the Early and Late Permian (Golonka and Ford, 2000; Stampfli et al., 2013). At present this block of the ocean crust situated in the northern part of the Sinai plate (Ben-Avraham, 1978; Eppelbaum et al., 2012, 2014) is object of our investigation.

The easternmost Mediterranean region has attracted increasing attention in connection with the recent discoveries of significant hydrocarbon deposits in this region (e.g., Montadert et al., 2010; Schenk et al., 2010; Eppelbaum et al., 2012). For example, Schenk et al. (2010) consider that more than 4 trillion m^3 of recoverable gas is available in the Levant Basin (which located in the central part of the easternmost Mediterranean).

Currently seismic prospecting is the main tool used in hydrocarbon deposit discovery. However, even sophisticated seismic data analysis (e.g., Hall et al., 2005; Roberts and Peace, 2007; Gardosh et al., 2010; Marlow et al., 2011; Lazar et al., 2012), fails to identify the full complex structural-tectonic mosaic of this region, and more importantly, is unable to clarify its baffling complex tectonic evolution. This highlights the need for combined analysis of geophysical data associated with the paleomagnetic and paleobiogeographic conditions that can yield deep paleotectonic criteria for oil and gas discovery in this region.

Extensive geological-geophysical investigations have been carried out in this region, and a significant number of deep boreholes have been drilled. However integrated estimation of the deep structure of the hydrocarbon host deposits and their space-time evolution in terms of the modern geodynamics (first of all, plate tectonics: Ben-Avraham and Ginzburg, 1990; Robertson, 1998; Ben-Avraham et al., 2002, 2006; Jimenez-Munt et al., 2003; Le Pichon and Kreemer, 2010), are comparatively recent (Eppelbaum and Katz, 2011, 2012a; Eppelbaum et al., 2012, 2014).

We elucidate this geodynamic relationship by examining the structural floors within the following tectonic-geophysical zones: (1) regions of development of continental crust of the Nubian, Arabian and Sinai plates, (2) remaining oceanic crust of the eastern Mediterranean, and (3) the thinned continental crust of the terrane belt. A series of new gravity and magnetic maps developed by employing satellite and airborne data (as well their transformations) accompanied by tectonic schemes were constructed (Eppelbaum and Katz, 2011; Eppelbaum et al., 2012a, 2012b, 2014). These new maps are crucial to a better understanding of the dynamics of hydrocarbon basin formation within the continental and shelf depressions, as well as the deep depressions of the easternmost Mediterranean where gas deposits in zones of oceanic crust evolution have only recently (April 2013) begun to be exploited.

Careful attention should be paid to the blocks of oceanic (basaltic) crust with reverse magnetization that were discovered (Ben-Avraham et al., 2002; Eppelbaum, 2006). This issue was very briefly (Eppelbaum and Katz, 2012a) explained as paleomagnetic Kiama zone of inverse polarity and demands separate consideration. An integrated magnetic-gravity-seismic analysis conducted along three interpretation profiles unambiguously indicates the presence of blocks of the Earth's crust with reverse magnetization (Ben-Avraham et al., 2002). The results of 3D magnetic field modeling (advanced GSFC program was applied) along three profiles, enabled to detect a boundary between continental and oceanic crust. A reconstruction of the position of a reverse magnetized block of Earth crust enabled to obtain a magnetization zone with a S – N orientation and width reaching 70 km and length – about 200 km. Such a large, thick (about 10 km) zone of inverse magnetization must correspond to the significant and prolonged effect of inverse polarity in the Earth's magnetic field history. We suggest that this is the Kiama zone of inverse polarity that was first detected in the Late Carboniferous and Permian in Australia (Irving, 1966). Subsequent investigations (e.g., Khramov et al., 1974) have shown that the Kiama hyperzone underlies and is covered by zones of alternating polarity; i.e., Donetzk and Illawarra, respectively. According to zircon chronology the Kiama hyperzone extends over a period of 312–265 Ma (Khramov and Iosifidi, 2012), and according to K-Ar, ^{40}Ar/^{39}Ar and various historical planetology methods this period extends of 293-242 Ma (Lapkin and Katz, 1990).

Delineation and mapping of the Kiama reverse paleomagnetic zone on the basis of 3D combined modeling of magnetic and gravity fields creates a necessity for attraction of wide spectrum of other geophysical-geological data for substantiation of space-tectonic position of this zone. Practically this is a first real evidence of delineation such an ancient oceanic crust of the Late Paleozoic. On the basis of investigation of Mediterranean ophiolites of the Alpine belt, the most ancient crust of the eastern Mediterranean corresponds to Late Triassic – Jurassic (Robertson et al., 1991).

According to the latest paleogeodynamic reconstructions (Stampfli et al., 2013), the Alpine belt is a complex structure and includes structures associated with Neotethys and Paleotethys oceans and with more ancient oceans. It is considered that the northern part of the Neotethys has been developed as active zone of the arc island tectonics, and southern part is bounded with Gondwana, belonged to the passive tectonic conjunction. Usually forming of the initial rift of the Neotethys Ocean in the east was presented as a common basin formed in the Early Permian, and in the west – as a collection of small rift basins which began to form after breakdown of the Hercynian fold belt. However, the easternmost Mediterranean does not correspond to any of these schemes. Earlier was considered that the oceanic crust was formed here as a result of movement to north a continental Tauride-Anatolian block. However, these constructions did not take into account earlier published paleomagnetic data (Robertson et al., 1991; Scotese, 1991). The modern paleogeodynamic reconstructions testify to position of the Tauride-Anatolian block in other place – in the northern side of the Paleotethys (Stampfli et al., 2013).

The performed integrated geological-geophysical analysis (Katz and Eppelbaum, 1999; Eppelbaum, 2006; Eppelbaum and Katz, 2011, 2012a, 2012b; Eppelbaum et al., 2012, 2014) have shown that the southern side of the Neotethys Ocean, developed in the easternmost Mediterranean, does correspond to the model of passive continental-ocean conjunction. Here are developed both a belt of the Early Mesozoic terranes and remains of the oceanic crust as Triassic-Jurassic mélange and accretional prisms of subducted Permian-Triassic oceanic crust. These data have a direct relation to the substantiation of location of the Kiama paleomagnetic zone of inverse magnetization in the easternmost Mediterranean. We can also suggest that the Kiama zone and the oceanic crust adjacent to it from the east may represent a part of small oceanic basin. It is necessary to note that such tectonic structures were earlier revealed in the eastern Mediterranean (e.g., Ben-Avraham, 1978; Robertson, 1998).

It was noted earlier (Katz and Eppelbaum, 1999) the terrane belt contains Jurassic fauna of the Ethiopian zoogeographical province that indicates to the drift of this belt from the east along the zone of transform faults. Analysis of dyke complexes and age of postaccretional traps shows that at the boundary of Jurassic and Cretaceous the terranes have been moved from east on the distance up to 500 km (and more) during 20–30 mln years. The Kiama zone was situated near the continental crust zone and initially sub-latitude oriented, had been clockwise rotating, at that time arc of the terrane belt has been moved in the counterclockwise direction.

The paleomagnetic reconstructions with attraction of radiometric data of ophiolitic complexes in the zone of transition of continental zone to oceanic one and with consideration of age of tectono-thermal activations (Katz and Eppelbaum, 1999; Eppelbaum and Katz, 2011, 2012a, 2012b; Eppelbaum et al., 2014), were utilized to construct a first paleomagnetic map of the ocean crust in the easternmost Mediterranean (Table 1). To the west of the Kiama zone is located an oceanic crust block with a direct magnetization (Table 1). We propose that it has Middle-Cretaceous (Aptian-Cenomanian) postaccretional age and is associated with the northern drift of the Eratosthenes terrane. Taking into account the aforementioned considerations, the considered block corresponds to Jalal hyperzone (Table 1). We propose that it has Middle-Cretaceous (Aptian-Cenomanian) postaccretional age and is associated with the northern drift of the Eratosthenes terrane. Taking into account the aforementioned considerations, the considered block corresponds to Jalal hyperzone (Table 1). This proposition is supported by development of mainly directly magnetized Aptian abd Albian traps of Makhtesh Ramon (Gvirtzman et al., 1996). These traps are also developed to south of the proposed Halal hyperzone within the Gulf of Suez (Eppelbaum and Katz, 2012b) that confirm active displacement of the oceanic crust to west of the Kiama hyperzone in the Middle Cretaceous. To the east of Kiama zone oceanic crust has mainly direct magnetization and corresponds to Illawarra, Omolon and Gissar hyperzones (Table 1). These constructions are based on the analysis of the radiometric age of Triassic-Jurassic spilites, keratophyres, olivine basalts and gabbroids developed in ophiolitic plates of the Carmel Mt., which were displaced within the Galilee-Lebanon terrane on 120 km during the Levantine tectonic phase (Katz and Eppelbaum, 1999).

Table 1. Geological-geophysical aspects confirming development of the paleomagnetic map

Paleomagnetic hyperzones	Geophysical-geological signatures					
	Magnetic	Gravity	Seismic	Radiometric	Petrological	Facial
Kiama	⊕ (**A**)	⊕ (**A**)	⊕ (**A**)	Early-Late Permian traps: 288–257 m.y. (**C**)	alkaline traps (**C**)	
Illawarra	⊎ (**A**)	⊙ (**A**)	⊙ (**A**)	upper Carmel ophiolites 222.4 m.y.(**B**) Hameishar basalts 231-250 m.y. (**D**) ophiolites Saharonim 205–207 m.y.(**B**)	olivine-basaltic melange (**B**) brecciated basalts (**D**) Saharonim basalts (**B**)	first Neotethian bentic carbonates (**C**)
Omolon	⊎ (**A**)	⊙ (**A**)	⊙ (**A**)	lower basaltic melange 196–189 m.y. (**B**) spilite-ophiolites 190.9–189.9 m.y. (**B**)	olivine-basaltic melange (**B**) spilite-melange (**B**)	Mt. Carmel allochtonic neritic carbonates (**B**)
Gissar	⊎ (**A**)	⊙ (**A**)	⊙ (**A**)	lower Carmel ophiolites 172.1–147.8 m.y. (**B**)	spilite-keratophyre melange (**B**)	Mt. Carmel allochtonic neritic carbonates (**B**)
Jalal	⊕ (**A**)	⊙ (**A**)	⊎ (**A**)	upper traps Tayasir (**B**) 125–108 m.y.	basaltic alcalic complexes (**B**)	
Tuarkyr	⊙ (**A**)	⊙ (**A**)	⊙ (**A**)	Troodos ophiolite complex (**B**): 90 m.y. 83–75 m.y. 75 m.y.	Troodos ophiolite complex (**B**): plagiogranites sheeted dike complex extrusives	

⊕ positive evidence, ⊎ indirect evidence, ⊙ does not contradict

(**A**) ocean crust, (**B**) ophiolites, (**C**) surrounding terranes, (**D**) obduction complexes.
Analysis of gravity, magnetic and seismic data was carried out mainly by the data of Ben-Avraham et al. (2002), Eppelbaum (2006), Gardosh et al. (2010), Eppelbaum et al. (2012), Lazar et al. (2012), and Eppelbaum et al. (2014).
Radiometric data for Israel were obtained from Garfunkel (1989), Lang and Steinitz (1989), Segev (2005), and for Cyprus — from Borradaile et al. (2010).
Petrological data: Dvorkin and Kohn (1989), Garfunkel (1989), Gvirtzman et al. (1996), Segev (2005, 2009), Borradaile et al. (2010).
Facial data after: Hirsch and Picard (1988), Katz and Eppelbaum (1999), Eppelbaum and Katz (2011).
Paleomagnetic scale after Irving (1966), Molostovskii et al. (1976), Khramov et al. (1974).

The obtained data have important theoretical and practical significance for paleogeodynamic reconstructions, tectonic zonation, and prognosis and searching hydrocarbon deposits in this region. In particular we can suppose just now that the oceanic basin with Permian crust may be overlaid by sedimentary deposits of depression salt and reef carbonate associations of Triassic. An important fact is that directly over the revealed Kiama zone a large gas deposit Leviathan-1 is situated. Here a superdeep borehole drilling for oil searching to the depth of about 9 km is suggested.

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