INTRODUCTION

Late Tertiary Exposure of the North Arabian Platform

The closure of the Neotethys Ocean in the late Eocene was accompanied by a significant change in the paleogeography of the northern Arabian Peninsula. Along with the collision in the Bitlis-Zagros thrust zone, an extensive area, previously submerged under water for tens of millions of years, rose above sea level. The exposure of this land mass, hundreds of kilometers to the south of the collisional plate boundary, created the continental region today occupied by Iraq, Syria, Jordan, Israel, and Lebanon and disconnected the Mediterranean basin from the Mesopotamian basin (Fig. 1). As a result, the contours of Arabia changed and shorelines that had previously extended from Egypt eastward toward the Persian Gulf changed their course northward toward Turkey along the present-day Mediterranean coasts (Adams et al., 1983; Buchbinder, 1996; Ziegler, 2001).

Reconstruction of the gradual land exposure and shoreline migration during that period is important not only for regional paleogeography, paleoceanography, and paleoclimatology (i.e., Allen and Armstrong, 2008; Boulton, 2009), but also for reconstruction of drainage systems that may have formed hydrocarbon reservoirs. In particular, this type of reconstruction provides important constraints for geodynamic processes that control vertical motions in continental interiors (e.g., Lithgow-Bertelloni and Silver, 1998; Gurnis, 2001; Daradich et al., 2003), such as the Levant–Middle East region, which is quite far from Arabia’s collision plate boundary in the north (Bitlis-Zagros) as well as from its divergent plate boundary in the south (Red Sea).

Israel as a Key Area for Tracing Late Tertiary Shifts of the Levant Shorelines

Israel is located in a key area between northern Egypt, where Late Tertiary shorelines extended in the E-W direction, as noted by facies zoning (Salem, 1976; Said, 1990), and Syria and...
Iraq, where, again, Late Tertiary facies strips are oriented in the E-W direction (Adams et al., 1983; Buchbinder, 1996; Ziegler, 2001). Shorelines that connected Egypt and Syria at that time through Israel are the focus of this study.

Along the western foothills of central Israel’s mountainous region (Judea and Samaria, Fig. 2), relicts of ancient abrasive and erosive surfaces, accompanied by morphological steps that were eventually shaped by ancient shorelines, can be traced in the field (Sneh and Buchbinder, 1984; Buchbinder et al., 1993; Buchbinder and Zilberman, 1997). These shorelines approximately follow the present-day topography and record the stages of uplift of the Judea mountainous plateau (Fig. 2). A recent study by Bar (2009) documented these surfaces and the sediments that cap them and distinguished three phases of uplift: late Eocene to early Oligocene, early Miocene, and Pliocene.

In northern Israel, on the other hand, it is harder to trace Oligocene–Miocene shorelines because rocks of that age are missing in much of the area. Michelson and Lipson-Benitah (1986) reported shallow-marine Oligocene to early Miocene sediments in the Golan Heights, east of the Dead Sea transform. After reconstructing the lateral offset of ~100 km by the Dead Sea transform since those times, we find that these outcrops were originally deposited opposite central Israel.

The purpose of the present study is to examine the trend of Late Tertiary shorelines from central Israel northward. Previous studies detected these paleoshorelines up to latitude 32°N (Fig. 2). Here, we examine whether they continue northward surrounding Mount Carmel from the west, as they currently do, or turn toward the northeast along an ancient sea that may have still covered northern Israel at that time. This question of shoreline directions is, thus, closely related to the question of when Mount Carmel began to rise. The topographic continuity from the Judea-Samaria Hills to Mount Carmel (Fig. 2), and the similarity of the exposed rock units along this course (Fig. 3), raise the possibility that the exposure history of these regions may be similar. However, evidence described in this study indicates that Mount Carmel may have been uplifted and exposed much later.

**Carmel Structure**

Mount Carmel is one of the most prominent topographical elements along the Levant continental margin, and aside from its influence on shoreline migration, its uplifting history is important for understanding the extension of northern Israel alongside the Africa-Arabia.
breakup. Mount Carmel branches off the mountainous backbone of central Israel (the Judea-Samaria Hills) and extends westward, narrowing the coastal plain to a few hundred meters (Fig. 2). Morphologically, its western border is a steep, 150-m-high cliff parallel and adjacent to the present-day coastline (Michelson, 1968), while structurally, it extends offshore to the shelf edge, where it is bounded by a 3 km drop in the continental slope, which is significantly steeper than the slope south of Mount Carmel.

To the northeast, the Carmel block is both structurally and morphologically defined by the NW-SE–trending Carmel fault (in some publications, named Yagur fault), which forms a steep, 300–500-m-high slope and has a total vertical displacement exceeding 1 km (Picard and Kasai, 1958; Achmon and Ben-Avraham, 1997; Fleischer and Gafsiou, 2003). This fault is part of an active seismogenic region that branches off the Dead Sea transform toward the Levant continental margin (Hofstetter et al., 1996; Shamir et al., 2000; Shamir, 2007) and contains a series of valleys (Harod-Yizreel-Qishon) that separate the Galilee from the Samaria Hills (Fig. 2).

The formation history of the Carmel fault and the valleys that dissect northern Israel provides important information regarding the tectonic regime prior, during and after the formation of the Dead Sea transform (Matmon et al., 2003). In particular, it provides information about motion partitioning between branches of the Dead Sea transform (i.e., Carmel and Roum faults) that help in interpreting the extent to which Arabia-Africa motion is transferred to the Levant continental margin (Schattner et al., 2006b).

Direct evidence of the beginning of faulting along the Carmel fault is hard to find. Based on ages of thick basalt flows filling the Yizre’el valley, Shaliv (1991) suggested that the Yizre’el-Qishon rift (Fig. 2) started to subside rapidly and accumulate sediments and volcanics during the middle to late Miocene. On the other hand, based on the identification of synrift sediments in the offshore Haifa Bay basin, Schattner et al., (2006a, 2006b) suggested that rifting started as early as the Oligocene as part of a continental rift that extended from Wadi Sirhan (eastern Jordan and northern Saudi Arabia), northwest through the Harod-Yizreel-Qishon valleys, offshore to Haifa Bay. This interpretation was based on the stratigraphic logs of the Qishon Yam-1 (offshore) and Canusa-9 (onshore) oil wells as published by petroleum companies (e.g., Derin, 2002). In the following sections, we revise the biostratigraphy of the Late Tertiary sections in those two wells and provide a different age constraint for the beginning of rifting.

Geological and Stratigraphic Background

The Levant continental margin was formed by repetitive phases of continental rifting in the Permian, Triassic, and Early Jurassic that thinned the continental crust and produced rapid differential subsidence (Freund et al., 1975; Bein and Gvirtzman, 1977; Garfunkel and Derin, 1984; Garfunkel, 1988, 1998).
Passive-margin conditions were established in the Late Liassic, and thermal subsidence persisted for the following ~100 m.y. (Garfunkel and Derin, 1984). Within that period, a phase of intracontinental tectonics associated with lithospheric heating, magmatism, and uplift strongly affected the inland area (Garfunkel, 1988; Gvirtzman and Garfunkel, 1997, 1998; Gvirtzman et al., 1998).

After the Turonian, along with the early stage of convergence between the African-Arabian plate and the Eurasian plate, the entire region was affected by a mild compressional stress regime that formed the Syrian Arc fold belt (Krenkel, 1929; Hensen, 1951; Freund et al., 1975). This series of folds and faults extends for 1000 km from the Palmyra Mountains in Syria, through Lebanon and Israel, to the Sinai Peninsula. The Comanian–Paleocene Mount Scopus Group, which was deposited during Syrian Arc folding, consists mainly of pelagic chalk and marl with some chert, phosphorite, and oil shale (Flexer, 1968; Garfunkel, 1988). The overlying Avedat Group was deposited in the early to middle Eocene when the sea had reached as far as Egypt and part of Arabia (Garfunkel, 1988).

The late Eocene–Paleocene Saqiye Group, which is the focus of this study, is mainly composed of greenish to gray shales and marls, differing from the more chalky facies of the Avedat and Mount Scopus Groups. Based on its appearance in boreholes and very few outcrops, the group was divided into the following formations (Fig. 4): Bet Guvrin (chalky marl), Lakhish (bioclastic limestone, partially contemporaneous with the Bet Guvrin Formation), Ziqlag (bioclastic and reeval limestone), Bet Nir (conglomerate), Ziqim (pelagic marl with tuff and basalt flows), Pattish (reef-limestone largely composed of portitid corals), Mavqim (anhydrite formed during the Messinian salinity crisis), and Yafo (pelagic shales) Formations. Among these, the Yafo Formation is the most homogeneous unit (Gvirtzman and Reiss, 1965; Buchbinder, 1969; Gvirtzman, 1970; Gvirtzman and Buchbinder, 1978; Buchbinder et al., 1986, 1993; Buchbinder and Zilberman, 1997; Gvirtzman, 1990).

The Saqiye Group represents several regressions and transgression cycles while deep canyons were incised across the continental slope. At some point during the Pliocene, the sediment supply from the Nile River was enough to completely fill the accommodation space, that is, to fill the canyons, to expand the continental shelf tens of kilometers to the west, and to form a relatively flat surface on which the sandy Pleistocene Kurkar Group was deposited.

The lithological boundary between the Saqiye and Kurkar Groups is clear and sharp. In contrast to the pelagic nature of the Yafo Formation, the Kurkar Group contains a variety of sediments: calcareous sandstones (some strongly cemented and some loose), reddish sandy soils (locally named “Hamra”), marine and continental clays, conglomerates, and sand dunes (Gvirtzman et al., 1984). The lowermost part of the Kurkar Group is composed of shallow-marine sandstone, which is, at least, partly equivalent to the pelagic Pliocene Yafo Formation. South of Mount Carmel, this sandstone was defined as the Pleshet Formation, whereas north of Mount Carmel, similar sandy calcarenites were defined as the Kordane Formation.

**RESEARCH APPROACH**

The lack of Oligocene–Miocene sediments on Mount Carmel makes it impossible to directly determine its Oligocene–Miocene history. Therefore, the relative vertical motions between the Carmel block and the nearby basins, both to the north and the south, were studied here, assuming that much of the uplift and truncation of the Carmel block are related to those differential vertical motions. In the Qishon graben, north of Mount Carmel, we revised the biostratigraphy of the Late Tertiary section in two oil wells (Fig. 2) and prepared a subsidence curve that shows the beginning of the accelerated subsidence that marks the onset of rifting, during which the Carmel horst began uplifting and the Qishon graben began subsiding. In the Hadera syncline (Fig. 2), south of Mount Carmel, we subdivided the monotonous 400-m-thick sequence of late Eocene to Miocene rocks (~30 m.y.) into six biostratigraphic units. This allows the examination of thickness variations of each subunit toward the Or Akiva fault, which defines the southern boundary of the Carmel block (Steinberg et al., 2010) and,
thus, constrains the onset of uplift of the southern side of the Carmel block.

Following constraints deduced from basins north and south of Mount Carmel, we studied the morphostratigraphy of the present-day landscape in the vicinity of Mount Carmel in order to identify relicts of ancient shorelines that can be correlated with shorelines that are already known farther south. Finally, we combined our results with additional data, and we discuss the gradual exposure history of Israel during the Late Tertiary.

**Qishon Graben Data**

Based on the stratigraphic log of the Qishon Yam-1 oil well, Schattner et al. (2006a) determined the age of the synrift sediments in the Qishon graben as Oligocene to mid-Miocene. However, the presence of anhydrite layers within that section entails episodes of evaporitic deposition prior to the Messinian salinity crisis, which is not known anywhere in the entire Levant area (Schattner et al., 2006a). The question examined here: Is the 1200–1600 m depth interval that includes anhydrite with middle Oligocene to early middle Miocene fauna (Derin, 2002) autochthonous? If not, the indication for Oligocene rifting should be reconsidered.

In the nearby Canusa-1 well, a 200-m-thick reefal limestone body, which is defined in the national oil well catalog (Fleischer and Varshavsky, 2002) as the middle Miocene Ziqlag Formation, apparently indicates accelerated subsidence during the middle Miocene. However, this stratigraphic interpretation relies on the 1970s nomenclature of Miocene reefs in Israel (e.g., Gvirtzman and Buchbinder, 1978) that did not distinguish between the middle Miocene Ziqlag Formation, with its platform and reef limestones, and the late Miocene Patish Formation (Fig. 4), with its poritid reefs, which are typical of late Miocene reefs in the Mediterranean region (Esteban, 1996). The biostratigraphic revision conducted here is aimed at examining the coral population of the thick limestone reef in the Qishon graben according to the criteria described in Buchbinder et al. (1993) and, thus, determining the exact age of rifting.

**Hadera Syncline Data**

The subsurface structure across the southern border of the Carmel block is best demonstrated by the structural map of the top of the Judea Group (top Turonian; Fig. 5; Fleischer and Gafsou, 2003). This map shows that the boreholes studied in this region are located within the NNE-trending Hadera syncline, which is sharply cut by the Or Akiva fault. Biostratigraphic analysis of the Hadera syncline is aimed at determining if and when layers deposited in the syncline were influenced by the Or Akiva fault, which marks a substantial episode of the Carmel uplift.

**Shoreline Reconstruction**

The western flanks of the Judea and Samaria Hills (south of latitude 32°N, Figs. 2–3) are accompanied by two distinct, relatively flat surfaces: the higher and the lower foothill regions ("Lower Shefela" and "Higher Shefela," respectively, in the local terminology; Fig. 2). These surfaces are relicts of shallow-marine shelves and coastal plains formed by abrasive and erosive processes during early stages of land exposure due to land uplift and shoreline migration westward. A comprehensive description of these surfaces can be found in Bar (2009) and references therein.

The upper foothill region was shaped by a middle Miocene transgression, when the advancing sea first flattened the topography and then deposited a thin cover of shallow-marine limestone of the Ziqlag Formation over the abrasive surface (Sneh and Buchbinder, 1984; Buchbinder et al., 1993). Similarly, the lower foothill region was first shaped by the late Miocene transgression that deposited the shallow-marine limestone of the Patish Formation (Buchbinder and Zilberman, 1997), and again by a Pliocene transgression, which deposited...
the shallow-marine sandstone of the Pleshet Formation (Buchbinder, 1969; Gvirtzman and Buchbinder, 1969; Buchbinder and Zilberman, 1997). Outcrops of the middle Miocene Ziqlag Formation at the upper foothill region and of the Pliocene Pleshet Formation at the lower foothill region are marked in Figure 2.

To examine whether the same distinction between the lower and upper foothill regions can be recognized north of latitude 32°N toward Mount Carmel, a morphostratigraphic analysis was performed along 18 topographic profiles running along local watersheds west of the Samaria-Carmel area (Fig. 2).

MATERIALS AND METHODS

Biostratigraphy

The biostratigraphy of the lithologically monotonous 400-m-thick sequence of the late Eocene to Miocene in the Hadera syncline was established based on foraminifera that were examined in more than 110 cutting samples from six water boreholes. Eight samples were examined from the Givat Ada borehole, 11 from Menashe-t3, 48 from Pardes Hanna-1, 19 from Gan Shemuel, 14 from Menashe-t1, and 12 from Bet Eliezer borehole (for location, see Fig. 5).

In the Qishon Yam-1 borehole, 68 cutting samples were examined between 520 m (Pleistocene) and 1742 m (Maastrichtian). In the Canusa-9 borehole, foraminifera were examined in 36 samples between 400 m (Messinian) and 860 m (late Eocene) with a special emphasis on the coral population in the depth range of 400 m to 600 m.


Morphostratigraphy

Using a geographic information system (GIS)–based digital terrain model of Israel (Hall, 1993), 18 topographic profiles were prepared along secondary, mostly E-W–oriented, water divides descending from Israel’s regional water divide in the east to the coastal plain in the west. These local water divides are the least eroded topographic elements that best preserve the ancient landscape. Subhorizontal segments of the topographic profiles that may represent relicts of regional abrasive surfaces were defined as targets for a field survey.

The purpose of the field work was to find remnants of shallow-marine and coastal sediments of the middle Miocene Ziqlag Formation on the higher surface and remnants of the Pliocene Pleshet Formation on the lower surface. Surfaces that were detected in the topographic profiles, and were capped by marine sediments, were finally used as a database for reconstruction of ancient shorelines. The exact location of shorelines was marked at the easternmost (landward) part of each surface along the foothills of the adjacent higher surface.

RESULTS

Qishon Graben

Qishon Yam-1 Borehole

Detailed reexamination of the foraminiferal biostratigraphy of Qishon Yam-1 borehole shows Pleistocene ages up to a depth of ~1110 m and a late Pliocene age up to ~1180 m. Deeper than that, within the depth range of 1190–1640 m, early Pliocene foraminifera were found to be mixed with rare Miocene and Oligocene species. This suggests that the 1190–1640 m depth interval is composed of allochthonous, mass-transported, Oligocene to early Pliocene sediments, which had migrated to their present location in the early Pliocene (Fig. 6A). In other words, this lens does not indicate synrift deposition; neither does it represent Oligocene evaporites. Rather, it indicates an early Pliocene mass transport event, which is quite typical for the Levant continental slope.

Canusa-9 Borehole

In the Canusa-9 borehole (Fig. 6A), poritid corals were found to be dominant in the reefal limestone body occupying a depth range between 400 and 600 m. The similarity of this 200-m-thick limestone body to other late Miocene reefs in the Mediterranean region (Esteban, 1996) implies that it should be defined as the late Miocene Pattish Formation and not as the middle Miocene Ziqlag Formation, as currently documented in the national oil well catalog (Fleischer and Varshavsky, 2002). In addition, the interbedded bioclastic and marly beds found just below that reef, which were previously included in the Oligocene Lakshih Formation (Fleischer and Varshavsky, 2002), are most probably of Miocene age (Fig. 6A).

Burial Curve for the Qishon Graben

Based on these results, the burial curve of the revised Canusa-9 borehole (Fig. 6B) demonstrates that the Oligocene subsidence continues the Middle Late Cretaceous and Early Tertiary trend and that the younger pulse of rapid subsidence began only in the late Miocene (Fig. 6B). Considering the shallow-marine reeval environment of the late Miocene Pattish Formation, the enhanced sedimentation rate expresses tectonic subsidence and not the filling of a preexisting deep basin. The burial curve of the revised Qishon Yam-1 borehole, which contains a long hiatus from the Paleocene to the Pliocene, only shows rapid deposition during the late Pliocene, but it does not reveal when this rapid subsidence began.

Hadera Syncline and Or Akiva Fault

The biostratigraphic division of the Late Tertiary sequences in six water boreholes in the Hadera syncline is presented in Figure 7, together with additional data from the Hadera-1 oil borehole and the Bet Rosh outcrop taken from Martinotti (1981b) and Buchbinder et al. (2005), respectively. Based on this biostratigraphic division, we prepared geological cross sections for the Hadera syncline and its vicinity and examined the geometric relations between Oligocene–Miocene strata and the Or Akiva fault (Figs. 8–10). In section 5 (Fig. 8), running northeastward along the syncline’s axis, the Oligocene–Miocene section gradually thins toward the Givat Ada borehole, located at the NE corner of the syncline. Eighteen kilometers farther to the northeast, the Bet Rosh outcrop (Buchbinder et al., 2005) is even more condensed (Figs. 5 and 7). This indicates a regional trend of landward thinning (and shallowing) combined with local thinning at the syncline’s margin.

In contrast, in the north-trending section 3 (Fig. 9), the same Oligocene–Miocene units show no thickness variations toward the Or Akiva fault, indicating that faulting and uplifting of the Carmel block postdated the middle (and maybe even late) Miocene. This conclusion is consistent with seismic mapping offshore that shows similar geometric relations between Miocene strata and the marine part of the Or Akiva fault (Steinberg et al., 2010).

Section 4 (Fig. 9) further shows two buried erosion channels. One developed along the Or Akiva fault and then filled with Pliocene sediments. A second and much larger channel, 18 km to the south, was incised and filled in the early Miocene and again in the late Miocene, indicating more than one pulse of inland uplift. The east (inland)–trending cross sections of Figure 10 further demonstrate a pre-Pliocene truncation that cuts deeper into older rocks in the east.

To constrain the end of faulting along the Or Akiva fault, we further analyzed the base Pliocene subsurface map obtained by stripping
Figure 6. (A) Revised bio- and lithostratigraphic division of Canusa-9 and Qishon Yam-1 oil wells. (B) Composite burial curve for the Qishon graben showing that the Late Tertiary enhanced subsidence began in the late Miocene. Early Mesozoic data were taken from Haifa Bay1 and Foxtrot1 wells (Fleischer and Varshavsky, 2002), indicating that prior to Miocene rifting, the Carmel (Foxtrot1) and the Qishon (Haifa Bay1) blocks had similar subsidence histories.
Figure 7. Biostratigraphic correlation of the water boreholes and outcrops from the southern Carmel block and Hadera syncline (for location, see Fig. 5). The thickest sequences occur at the central part of Hadera syncline, thinning out toward the margins. Base Pliocene is used as datum. Plus signs (+) mark location of samples (vertical bar marks the depth interval, whereas horizontal bar marks the mean depth). In places where age determination is uncertain (upper part of Menashe-t3 well), interpretation is supported by lithological variations. Biostratigraphic division of the Bet Rosh outcrop and the Hadera-1 borehole is after Buchbinder et al. (2005) and Martinotti (1981b), respectively.

Figure 8. Geological cross section 5 along the syncline axis showing condensation of the section toward its northeastern border (for location, see Fig. 5). Red dots along boreholes mark biostratigraphic boundaries.
Retreating Late Tertiary shorelines in Israel

Figure 9. Geological and seismic cross sections showing the Or Akiva fault, the Caesarea structural high, and the Netanya fluvial channel (see location in Fig. 5). Red dots along boreholes mark biostratigraphic boundaries. Note that no thickness variations in Oligocene–Miocene units are observed in section 3 (A) toward the Or Akiva fault, indicating that faulting along the southern boundary of the Carmel block postdated the middle (and maybe even late) Miocene. The Pliocene fill in the erosional channel that developed along the Or Akiva fault (section 4 [B]) hints at Pliocene cessation of faulting. The much larger erosion channel 18 km to the south (section 4) indicates that the Samaria region was already exposed in the early Miocene. TWT—two-way traveltime.
Figure 10. Geological (A and C) and seismic (B) cross sections across the Hadera syncline (location in Fig. 5). Red dots along boreholes mark biostratigraphic boundaries. Note the base Pliocene unconformity in both sections that expresses accumulating inland uplift. Figure 11C shows that the amount of truncation increases toward the south-east. TWT—two-way traveltime.
off the Kurkar Group (Fig. 11A) and the Yafo Formation (Fig. 11B). The resulting map (Fig. 11C) shows that the base Pliocene unconformity surface cuts the Or Akiva fault, which does not reach the surface as seen in the present geological map (Fig. 11A). The subsurface map also shows that the base Pliocene unconformity truncates deeper into the Bet Guvrin Formation and older units toward the SE. Thus, we postulate that prior to truncation, the Samaria Hills SE of the study area were uplifted and eroded. In contrast, the present-day dip of this unconformity surface (structural contours in Fig. 11C) indicates younger, southwest tilting of the entire region.

In conclusion, the Samaria region (southeast of Mount Carmel) has been exposed at least since the early Miocene times, while the Hadera syncline (south of Mount Carmel) was submerged at least until the end of the middle Miocene. The absence of thickness variations within the Oligocene–Miocene section in the syncline toward the Or Akiva fault suggests that faulting and differential uplift of the Carmel block did not start before the late Miocene. In addition, the base Pliocene unconformity suggests that in Pliocene times, faulting had already ceased, and the entire region was tilted southwestward.

This conclusion is consistent with results obtained from the region north of Mount Carmel, and both indicate that the differential motion, which had uplifted the Carmel structure, began in (mid-)late Miocene times. In the following sections, we independently examine this conclusion by reconstructing shoreline trends.

Traces of Shorelines along Central Israel’s Foothills Region

Figure 12 shows 4 out of 18 morphostratigraphic profiles that were analyzed and comparisons with a previously known profile crossing the area south of latitude 32°N (see location in Figs. 2–3). The newly prepared profiles show two relatively flat surfaces east of the coastal plain. The lower surface continues the lower foothill surface known from south, as evident by outcrops of Pliocene marine sandstones and conglomerates (Pleshet and Ahuzam Formations) marked on the maps of Figures 2–3. Accordingly, the upper surface is the continuation of the middle Miocene upper foothill surface known from south. On this upper surface, only one single outcrop of the Ziqlag Formation...
This analysis shows that the Pliocene shoreline bounding the lower foothill surface can be traced all the way up to northern Mount Carmel; the middle Miocene shoreline only reaches southern Carmel or northern Samaria (Figs. 2 and 3); and the Oligocene shoreline is traced only to the western Judea-Samaria mountain plateau (Figs. 2, 3, and 12A). It is, therefore, suggested that the Oligocene shoreline turned northeastward at northern Samaria (as also indicated by marine sediments of that age in the Golan Heights, as discussed later herein); the middle Miocene shoreline turned northeastward somewhere between Samaria and Mount Carmel; and only in Pliocene times did the shoreline surround the Carmel block from west and continue along the present-day Mediterranean coast (Fig. 2).

**DISCUSSION AND SYNTHESIS**

Information about land exposure is commonly obtained from rocks containing terrigenous material transported into nearby basins. The age of sediments filling submarine channels that were incised in the Levant continental slope during the Late Tertiary has been studied by numerous researchers over several decades (e.g., Neev, 1960; Gvirtzman, 1970; Gvirtzman and Buchbinder, 1978; Druckman et al., 1995; Buchbinder et al., 2005; Gardosh et al., 2008; Steinberg et al., 2010, 2011). A recent revision of all the available data shows that the very first sediment to fill the Ashdod canyon (offshore central Israel) indicates that land exposure and canyon incision had already begun in the late Eocene (Bar, 2009).

This was accompanied by the formation of a regional erosional surface extending over large areas of the Arabian platform, including the Judea uplands and southern Israel (Picard, 1951; Garfunkel and Horowitz, 1966). Zilberman (1992) and Avni (1989) showed that in southern Israel, truncation postdates the late Eocene and predates the early Miocene. However, according to Bar (2009), the Judean mountain plateau was exposed and truncated earlier (late Eocene to early Oligocene).

Earliest evidence for a fluvial system transporting clastic material from the Samaria region into the Mediterranean basin is obtained from an early Miocene channel fill at the Netanya-2 borehole (Fig. 2; Fig. 9, section 4). This channel indicates that Samaria was already exposed in early Miocene times (possibly earlier). The base Pliocene truncation trend found in the Hadera region, which cuts deeper into older units toward Samaria (Fig. 11), further supports this conclusion.

In contrast, northwest of Samaria, pelagic sedimentation continued until the end of the middle Miocene, as indicated by the section preserved in the Hadera syncline. Gradual thinning and shallowing of that section are noticed at the syncline’s northeast margin (Givat Ada borehole, Figs. 8 and 7; location in Fig. 5) and farther landward (Bet Rosh outcrop), but no facies or thickness variations are observed toward the Or Akiva fault in the Pardes Hanna-1 and Menashe t3 boreholes (Fig. 7, section 3). Thus, we infer that differential vertical motions across the Or Akiva fault did not occur until after the middle Miocene. Then, in the late Miocene, faulting uplifted the Carmel block relative to the downfaulted southern side (coastal plain and offshore) and Oligocene–Miocene rocks were eroded from the Carmel region. A late Miocene slump complex (Afiq Formation) distributed along the late Miocene continental slope offshore Mount Carmel that contains fragments of Neogene rocks further supports this conclusion (Steinberg et al., 2010). This differential motion was relatively short, as indicated by the base Pliocene unconformity surface that cuts the Or Akiva fault at the present coastal plain. The present dip of that unconformity surface further implies Pliocene–Pleistocene tilting toward the

![Figure 12. Morphostratigraphy. (A) Topographic profiles of this study (location in Fig. 2) along the Samaria-Carmel foothills showing remnants of two surfaces continuing the lower and upper foothills surfaces west of the Judea mountain stage. (B) Distinction between the lower and upper foothills surfaces west of the Judea region and south of latitude 32°N from Bar (2009) and references therein.](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/3/2/95/3038910/95.pdf)
southwest and uplifting of the Carmel-Samaria regions (more details about the marine part of the Or Akiva fault and age constraints on the uplift of the Carmel block are in Steinberg et al., 2010).

Consistent with the conclusion derived from south of Mount Carmel, analysis of the Oligocene–Miocene section in the Qishon graben (Fig. 6) indicates that the differential subsidence of the Qishon graben also began in the late Miocene. Thus, it is suggested that prior to the late Miocene, the Carmel block was covered by Oligocene–Miocene sediments of pelagic origin in the Menashe syncline (Figs. 2 and 5) and shallow-marine sediments over the neighboring anticlines. The Bet Rosh outcrop at the flanks of the Menashe syncline and an additional relict of the Bet Guvrin Formation just north of the Or Akiva fault (geological map of Fig. 11A) support this suggestion. The Bet Rosh outcrop indicates condensed but almost continuous Eocene to middle Miocene sedimentation along the southern Carmel region.

On the other hand, a single report by Picard and Kashai (1958) about a small outcrop found on the higher northern part of Mount Carmel near the village of Usfiye (exact coordinates were not specified) apparently indicates that uplift and erosion of the Carmel block may have begun before the late Miocene. Picard and Kashai (1958) described a small outcrop of the Ziqlag Formation unconformably covering the Judea Group. This indicates that a few hundred meters of Cretaceous, Paleogene, and possibly Neogene rocks were removed from the northern Carmel by middle Miocene times. On the other hand, considering our interpretation that faulting and differential uplift of the Carmel structure only began in the late Miocene, we note that the distinction between the middle Miocene Ziqlag Formation and late Miocene Pattish Formation was established only in 1993 (Buchbinder et al., 1993). Thus, the small Miocene outcrop on the northern Carmel defined in 1958 may very well be a part of the late Miocene Pattish Formation. A similar example was obtained for the Canusa-9 well, where a limestone layer that was previously defined as Ziqlag Formation was reexamined and redefined as Pattish Formation (Fig. 6A). Unfortunately, the exact location of the outcrop in northern Carmel is unknown and cannot be rediscovered and reexamined due to the urbanization of that location.

Our interpretation about continuous marine conditions over the Carmel block until the late Miocene is further supported by the morphostratigraphic analysis showing that the Carmel block was abraded in the middle Miocene by the advancing shoreline, the easternmost boundary (morphological step) of which cannot be found in northern Carmel (Figs. 2 and 12A).

We postulate that this shoreline probably crossed the area somewhere between Mount Carmel and eastern Galilee, where continental deposits of the early to middle Miocene Hordos Formation (Shaliv, 1991) are found (Fig. 13B). This reconstruction is also consistent with the marine Miocene outcrops in the Golan Heights studied by Buchbinder et al. (2005), which indicate a pelagic environment during the Oligocene (Fig. 13A), shallow-marine environment in the early Miocene, and the beginning of continental conditions only in the middle Miocene (Fig. 13B).

In a wider perspective, the uplift of the Carmel block relative to its surroundings in the late Miocene (this work; Steinberg et al., 2010) occurred coeval with significant faulting and differential vertical motions that occurred in northern Israel (Ron and Eyal, 1985; Matmon et al., 2003). At that time, the Yizre’el Valley, to the southeast of the Qishon graben (Fig. 2), subsided and accumulated shallow-marine deposits of the Bira Formation (Shaliv, 1991). According to Shaliv (1991), this marine invasion extended into the Jordan valley and deposited evaporites of the Sedom Formation in the Dead Sea region as shown in Figure 13C. Important to note is that according to Sneh et al. (1998), the marine invasion into the Sedom region occurred only in Pliocene times.

Along the Mediterranean coast, Pliocene transgressions reflooded the late Miocene shelf and invaded far eastward into the Be’er Sheva valley south of the Judea Hills (Fig. 13D; Gvirtzman and Buchbinder, 1969; Gvirtzman, 1970; Buchbinder and Zilberman, 1997). This invasion deposited the shallow-marine Pleshet Formation over the abraded surface along the western margins of Judea and Samaria and into the Menashe syncline (Fig. 12A), surrounding the northern Carmel “island” from south (Fig. 13D).

Altogether, our reconstruction of shorelines in Israel and its vicinity shows a transition from the middle Eocene eastern-trending shoreline (Fig. 1) to gradual land exposure (Fig. 13). This transition began with the formation of an Oligocene erosional surface, which truncated large parts of southern and central Israel (Picard, 1951; Garfunkel and Horowitz, 1966; Zilberman, 1992; Avni, 1989; Bar, 2009) and descended toward northern Israel, which was still submerged (Fig. 13A). It continued into Miocene and Pliocene times by the formation of a wide continental shelf along the present-day foothills region (Figs. 13B–13D). Finally, it ended with seaward progradation of the shelf to its present location tens of kilometers offshore (Fig. 13E).

Within this gradual process of land exposure, the most significant change occurred in the early Miocene. In the Oligocene, northern Israel was still submerged under deep waters (Fig. 13A), whereas in the middle Miocene N-S-oriented facies strips were already developed, and eastern Israel was completely exposed (Fig. 13B). It is suggested that this change reflects a major phase of regional inland uplift.

SUMMARY AND CONCLUSIONS

Despite the topographic continuity among Judea, Samaria, and Mount Carmel and the similarity in their exposed rock units, their exposure history differs, with Mount Carmel being exposed much later.

A revised biostratigraphy of the Qishon Yam-1 and Canusa-9 oil wells in the Qishon graben just north of Mount Carmel indicates that accelerated subsidence of the Qishon graben began only at the late Miocene.

A detailed biostratigraphic analysis of an Oligocene–Miocene sequence preserved south of Mount Carmel indicates that pelagic deposition continued at least until the end of the middle Miocene. The absence of any facies and thickness variations further suggests that faulting and the differential uplift of the Carmel block did not start before the late Miocene.

Based on the observations from both sides of the Carmel structure, it is suggested that prior to the late Miocene, the entire region north of the Samaria Hills was probably submerged below water.

A morphostratigraphic analysis of ancient abrasive and erosive surfaces along the Carmel-Samaria foothills suggests that unlike Pliocene shorelines, which surround Mount Carmel from the west, Oligocene to middle Miocene shorelines most probably did not reach that region and extended from the Judea foothills northeastward.

In spite of the present-day similarities among the Carmel, Galilee, and Judea-Samaria regions, northern Israel was exposed much later than central Israel.

Oligocene to early Miocene marine outcrops in the Golan Heights indicate that seawater at that time reached areas east of the Dead Sea transform. The possibility that Galilee was exposed at that time cannot be excluded, but the similarity between Carmel and Galilee, in the sense that in both places faulting and differential vertical motions began only in the late Miocene, makes this possibility very unlikely.

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Figure 13. Synthesis of the gradual land exposure of Israel and its vicinity (SE Levant) since the Oligocene. For middle Eocene times, when the entire region was submerged under deep waters, see Figure 1. Location of outcrops was taken from the geological map of Sneh et al. (1998). Ages of Oligocene to early Miocene Susita Formation are after Michelson and Lipson-Benitah (1986) and Buchbinder et al. (2005). Ages of early to late Miocene Hor dos and Hazeva Formations are after Shaliv (1991), Garfunkel and Horowitz (1966), and Zilberman (1992). Ages of other formations are as in Figure 4. Offset along the Dead Sea transform was restored for each time frame according to an average rate of 5 km/m.y.


