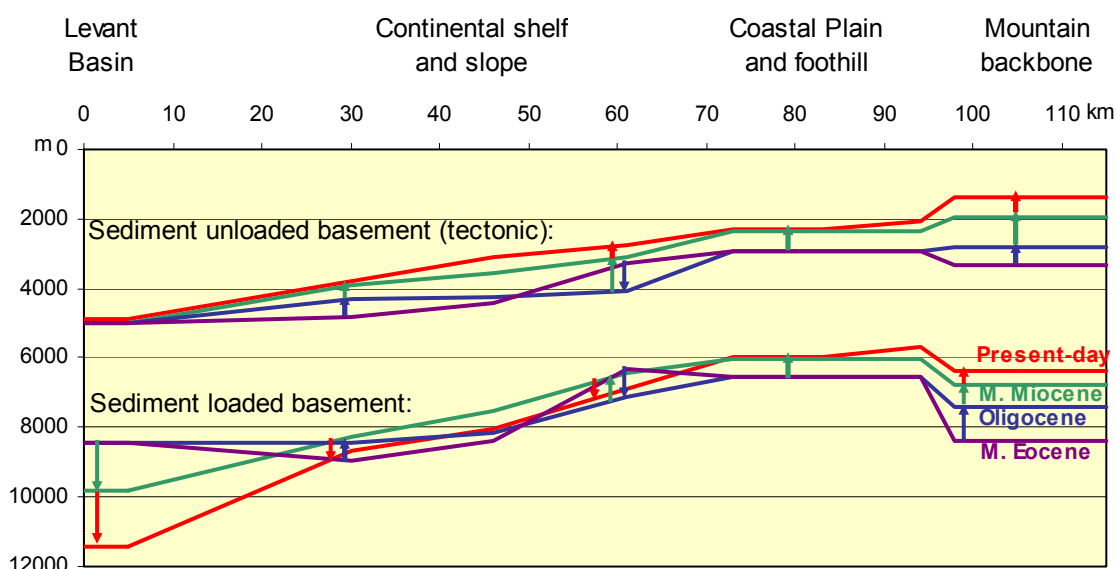




THE MINISTRY OF NATIONAL INFRASTRUCTURES
GEOLOGICAL SURVEY OF ISRAEL

Late Tertiary subsidence of the Levant margin: Distinction between sedimentary load and tectonics

Oded Bar, Zohar Gvirtzman, Shimon Feinstein, Ezra Zilberman



Fundamental studies for promoting hydrocarbon exploration in Israel
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Table of Contents:

ABSTRACT	1
1. INTRODUCTION	2
1.1. Late Tertiary reactivation of the Levant passive continental margin	2
1.2. Geological setting	6
2. METHODS	8
2.1. Backstripping	8
2.2. Isostatic calculation of paleobathymetry	8
2.3. Morphological reconstruction of paleobathymetry and paleotopography	10
3. RESULT	11
3.1. Paleobathymetry and paleotopography reconstruction	11
3.2. Backstripping	14
4. DISCUSSION	22
4.1. Interpretation of the backstripping results	22
4.2. 1D versus 2D analysis	24
4.3. Possible mechanisms for uplift	25
5. SUMMARY AND CONCLUSIONS	26
ACKNOWLEDGEMENTS	27
REFERENCES	28

ABSTRACT

Since the Middle Eocene the northwest Arabian Platform has been emerging out of the water whereas the adjacent Levant Basin subsided and accumulated a thick sedimentary section. This study investigates these opposing vertical motions by distinguishing their tectonic component from isostatic adjustments to sedimentary loading and erosional unloading. To reduce large uncertainties involved with such an analysis, due to uncertainties in paleo-water-depths, which in pelagic environments may vary from hundreds to thousands of meters, we employed a non-routine two-stage approach. We estimated water depth in the Levant basin before the beginning of the late Tertiary tectonism by assuming thermal equilibrium and isostatic balance with the adjacent inland crustal column. For later periods, we reconstructed paleo-bathymetry-topography profiles based on analyses of morpho-structural elements such as incised canyons and abrasion surfaces. The reconstructed bathymetry indicates that in the Middle Eocene the Levant Basin was 2-3.5 km deep. Accordingly, the enhanced subsidence of the Levant Basin and its continental margin during the Late Tertiary could be driven by isostatic response to sedimentary loading and filling of a pre-existing deep-water basin with no involvement of a downward tectonic force. On the contrary, the tectonic force in most of the study area was upward and counteracted sedimentary loading. We conclude that the tectonic processes that uplifted and exposed the Arabian platform in the Late Tertiary extended far westward beyond the inland region. Such processes may express long wavelength arching of the Arabian Platform during its collision with Eurasia, and/or heating and thinning of the lithosphere.

1. INTRODUCTION

1.1 Late Tertiary Reactivation of the Levant Passive Continental Margin

Following the Middle Eocene, at *ca.* 37 Ma, the paleo-geography of the Middle East region (Fig. 1B) underwent significant changes. Huge areas in northwest Arabia, previously covered by seawater, emerged above sea level and eroded and shorelines retreated hundreds of kilometers towards present day Mediterranean coasts [e.g. Ziegler, 2001]. Contemporaneously, the Levant continental margin accumulated a thick succession of fine clasts, reaching a thickness of 2.5 km along the Israeli continental shelf. In the Levant Basin, at the southeast corner of the Mediterranean Sea, more than 5 km of fine clasts were accumulated [Gvirtzman et al., 2008; Gardosh et al., 2008; Steinberg et al., 2011] (Fig 2). This study aimed to find out the causes for these young opposite vertical movements of an inland uplift and basin subsidence, by analyzing the relationships between tectonic forces, sedimentation and erosion.

Among the crucial parameters for understanding geodynamic mechanisms controlling the vertical motions that shaped the southeastern Mediterranean are the relative roles of tectonically driven motions vs. motion due to isostatic response to sediment loading and unloading. To distinguish between the two effects we used the well-known backstripping method [Watts and Ryan, 1976; Steckler and Watts, 1978], in which the sedimentary column is gradually unroofed backward in time and the crustal motion due to isostatic response and tectonic force is calculated at each stage.

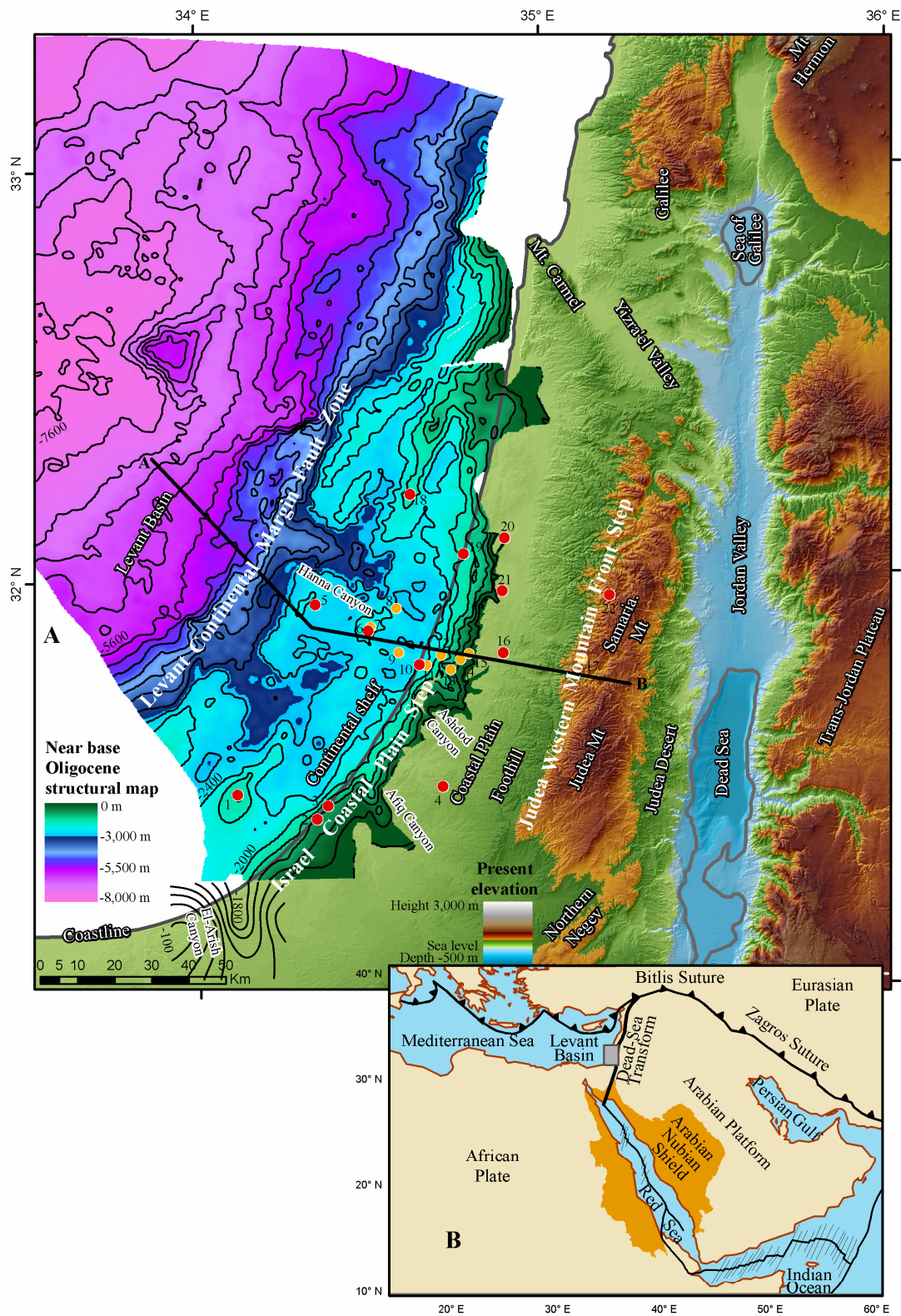


Figure 1: A. A map of the study area that combines the present topography in the east with a subsurface structural map of the base Saqiye Group in the west. We used this structural map, which nearly describes the Base Oligocene surface, as a proxy for the Early Oligocene relief showing morpho-structural steps and incised canyons (discussed in text). The structural map is taken from Steinberg (2011) with minor modifications in its eastern part from Fleischer and Gafsoy (2003). Outlines of the El-Arish Canyon are modified after Gvirtzman et al. (2008). Solid dots show location of wells studied (Figs. 2, 4-7, 9). Backstriped wells are marked in red. Numbers refer to well names as follows: 1= Til 1; 2= Kefar-Darom 1; 3= Nezarim 1; 4= Pleshet 1; 5= Yam-West 1; 6= Yam 2; 7= Yam 1; 8= Joshua 1; 9= Echo 1; 10= Hof-Ashdod 1; 11= Ashdod 1; 12= Bene-Darom 1; 13= Gan-Yavne 5; 14= Mivtah 1; 15= Geder 1; 16= Hulda 1; 17= Motza 1; 18= Yam-Yafo 1; 19= Jaffa 1; 20= Petah-Tiqva 2; 21= David 1; 22= Ramallah 1. Solid black line outlines the course of the geological cross section of Figure 2. B. A map of the regional tectonic setting of the Middle East and Eastern Mediterranean. The gray rectangle outlines the study area.

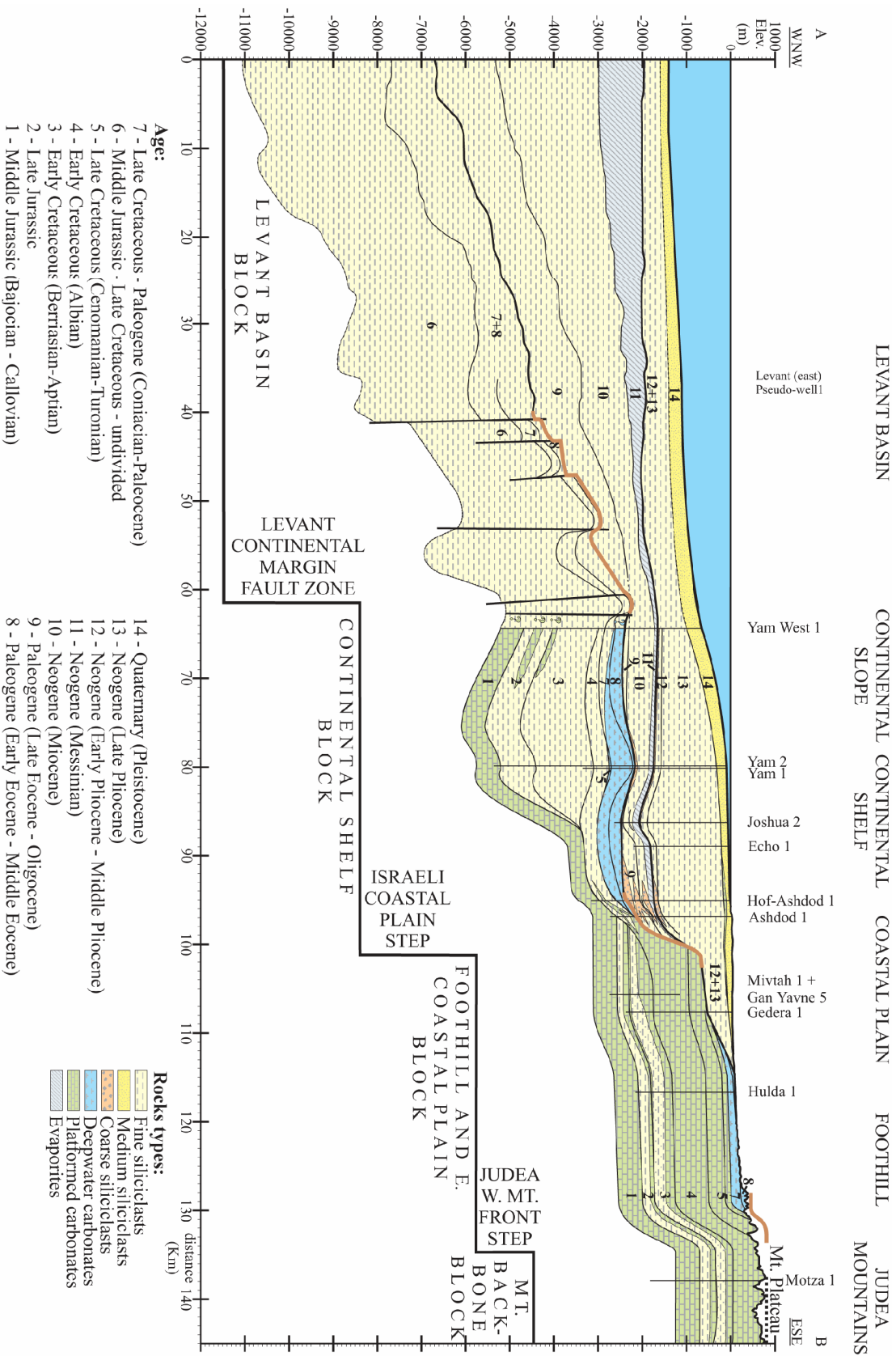


Figure 2: Geological cross-section through the Levant continental margin from the Judea mountain plateau to the southeast Levant Basin (location in Fig. 1). The stepped structure of the continental margin includes four blocks separated by three morpho-structural steps (schematically illustrated at the bottom). Brown thick lines emphasize Early Oligocene relief of the morpho-structural steps. Information west of the Yam-West-1 well is based on seismic data from Gardosh et al. (2008), Gvirtzman et al. (2008), and Steinberg et al. (2011).

Distinction of the tectonic component from the total basin subsidence requires knowledge of three factors at each point in time: sediment load (thickness and density of the sedimentary column), paleo-water-depth, and paleo-sea-level. Sediment thickness and density at each stage were deduced from wells data corrected for compaction at later burial stages. Paleo-sea-level was taken from global eustatic curves such as Haq et al. [1987] or Miller et al. [2005]. A first estimation of paleo-water-depth is commonly deduced from sedimentological and paleontological data, particularly in shallow marine environments, where the possible range of water depths is small. However, in pelagic environments, where water depth may vary from hundreds to thousands of meters, there is a large uncertainty and different environmental estimations may lead to completely different tectonic interpretations.

A difference in estimates of paleo-water-depth in the beginning of the Pliocene is probably the reason for the diverse interpretation of a ~2 km thick Plio-Pleistocene sedimentary section offshore central Israel. Tibor et al. [1992] suggested that the accumulation of this section was linked with tectonic subsidence, while Gvirtzman et al. [2008] argued that it expresses sedimentary filling of a pre-Pliocene deep-water basin and isostatic adjustment to that loading. In this study we attempted to establish when deep-water conditions were established along the eastern Mediterranean continental margin and in the deeper Levant Basin. Foraminifera assemblages and benthic to planktonic ratios from three oil wells located along the continental shelf [e.g. Buchbinder et al., 2000; Almogi-Labin et al., 2001] indicate that the region, which is only a few tens of meters deep today, was 500-1000 m deep in the Early Pliocene. This partial information supports the sediment infilling approach. However, similar studies for the Oligocene and Miocene section in the continental shelf and deeper Levant Basin are not available, and therefore paleo-water-depths are mostly unknown.

To compensate for the relatively limited paleontological data available, Tibor and Ben-Avraham [2005] used the backstripping method in a reverse manner. That is, to compute Late Tertiary paleo-water-depths, they removed estimated tectonic subsidence from the unloaded basin results. However, their estimation of the tectonic subsidence only considered the minor thermal effect resulting from the early Mesozoic rifting and did not take into account late Tertiary tectonic processes, which are the focus of this study.

In this study we developed and employed a non-routine geologic approach for paleo-water-depth estimation, which is applicable to areas of dramatic morphology and large depths, where paleontological methods fail to provide the needed paleobathymetric data. Our approach is based on two independent methods. For the Middle Eocene period, just before renewal of tectonism, we assumed thermal equilibrium and calculated the water depth in the Levant basin by balancing its crustal column with the crustal column of the inland region. For later periods, we reconstructed a paleo-bathymetry and paleo-topography profile extending from the Levant Basin to the Judea Mt.

plateau. We based this reconstruction on geological data, such as height differences across morpho-structural steps and relicts of ancient abrasive and erosive surfaces, which were originally close to sea level. Using this approach for reconstructing paleo-bathymetry and paleo-topography, we identified the key elements in the regional geodynamic processes that controlled the NW Arabian Platform and the Levant continental margin during the time in which Arabia rifted from Africa and collided with Eurasia.

1.2 Geological Setting

The southern Levant continental margin was formed by a series of rifting phases that extended over a few tens of millions of years from the Permian to Middle Jurassic. The northward shift of the rifted continental blocks resulted in the formation of the Levant Basin, which is a part of the eastern Mediterranean Sea, a relict of the ancient Neo-Tethys ocean [e.g. Robertson and Dixon, 1984; Garfunkel, 1998, 2004].

Early Mesozoic rifting was followed by prolonged thermal relaxation during which passive margin conditions were established [Garfunkel and Derin, 1984; Gardosh, 2002]. Along with the tectonic driven subsidence, a series of transgressions and regressions affected the rate and nature of deposition. Sea invasion and inland sedimentation reached a climax in the Senonian – Middle Eocene period when pelagic sedimentation reached as far as Sinai, Jordan, and parts of Saudi Arabia [Beydoun, 1991; Ziegler, 2001]. Contemporaneously, the closure of the Neo-Tethys in the Late Cretaceous [e.g. Robertson and Dixon, 1984; Garfunkel, 1998, 2004, Robertson et al., 2006] resulted in a horizontal compression and formation of the Syrian Arc folds belt along the NW margin of the Arabian Platform [e.g. Krenkel, 1924; Walley, 1998]. During the Early to Middle Eocene, these folds were mostly submerged under deep waters [Buchbinder et al., 1988].

In the Late Eocene (*ca.* 37 Ma), inland emergence, enhanced basin sedimentation and structural deformation interrupted the regional prolonged tectonic subsidence and slow rate sedimentation. Three morpho-structural steps reshaped the moderate, gradually, westward descending seafloor. These steps, which are evident in the tectonic setting map of the eastern Mediterranean (Fig. 1A), combines the present topography in the east with a subsurface structures in the west. We used the near base Oligocene structural map (Fig. 1) as a proxy for the Early Oligocene relief, which was controlled by the newly formed steps. The eastern step, which accentuated an old Syrian Arc structure [Bar, 2009] forms the present day Judea Western Mountain Front (WMFS). The central step, now buried under Neogene sediments below the present day coastal plain of Israel (CPS), accentuated the Cretaceous continental slope [Gvirtzman, 1970; Gvirtzman et al., 2008; Bar, 2009]. The western step, bounding the Levant Basin from east approximately below the present day

continental slope, vertically accentuated a Senonian-Eocene, 10 km wide fault zone. This step was termed by Gvirtzman et al. [2008] as the Levant Continental Margin Fault Zone (CMFZ).

The formation of steep morphological steps at the bottom of the sea rapidly caused prominent incision by sub-marine canyons. The Ashdod, Afiq, El-Arish and Hanna Canyons (Fig. 1A), which are 1,200 - 2,000 m deep each [Druckman et al., 1995; Buchbinder et al., 2005; Bar, 2009] approximately indicate the heights of the morphostructural steps (further discussed below).

In the following Oligocene-Miocene times, massive sedimentation in the deeper Levant Basin diminished the morphological expression of the CMFZ [Steinberg et al., 2011], while the CPS continued to dominate sea floor morphology for much longer [Bar, 2009]. During the Messinian Salinity Crisis [e.g., Hsü et al., 1973] sea level within the Mediterranean Sea drastically dropped and deep canyons were incised again across the continental margin. However, the Messinian incision was not as deep as the former Late Eocene – Early Oligocene incision and did not reach the canyons bottom, as evident by thick Oligo-Miocene sections preserved in the canyons [e.g. Druckman et al., 1995]. Finally, during the Pliocene Nile derived sediments buried the coastal plain step. These sediments extended the continental shelf westwards and built the present-day continental slope.

The present day terraced structure of the eastern Mediterranean continental margin is composed of four relatively undeformed blocks separated by the three morpho-structural steps described above (Fig. 1A, 2). The four blocks are: (1) The Judea Mt. plateau block, (2) the foothill and eastern coastal plain block, (3) the continental shelf block, and (4) the Levant Basin block. Two later tectonic phases, at the late Early Miocene and during the Middle to Late Pliocene, caused a longer wavelength regional uplift without a reactivation of the morpho-structural steps and, therefore, maintained the terraced structure of the continental margin [Bar, 2009].

The transition from the truncated, nearly 1000 m high, Judea Mt. plateau to the 1500 m deep Levant Basin, with its >5 km thick Late Tertiary sediments (Fig. 2), raises questions such as what caused the contemporaneous inland emergence and basin subsidence and what were the contributions of tectonic mechanisms, sedimentation, and erosion to this process. To answer these questions we used a backstripping analysis. This analysis depended greatly on constraining paleo-water-depth from the Middle Eocene, before a period of tectonic deformation, and during that period, between the Early Oligocene to Middle Miocene.

2. METHODS

2.1 Backstripping

Thirteen columnar sections based on data from wells (some composed of two adjacent wells), were backstripped (for locations see Fig.1). One well from the Judea Mt. block (Ramallah-1 well), three wells along the Coastal Plain block (David-1 & Petah Tiqva-2, Hulda-1, Pleshet-1), three wells along the present day coastline at the foot of the CPS (Jaffa-1, Hof Ashdod-1, Netzarim-1 & Kefar Darom-1), and four wells in the continental shelf block (Yam Yafo-1, Yam-2, Yam West-1, Till-1). Two more columnar sections were based on seismic data from pseudo-wells in the Levant Basin as interpreted by Ben-Avraham et al. [2002], Netzeband et al. [2006], Gardosh et al. [2008] and Steinberg et al. [2011].

For the post Middle Eocene section, which is the focus of this study, high-resolution time intervals were used based on the revised biostratigraphic division of Bar [2009]. For wells that did not penetrate the base of the sedimentary section missing information was completed from nearest wells that penetrated the basement (Besor 1, David 1, Gevim 1) or from seismic data.

A decompaction correction (thickness correction for compaction effect) followed the procedure described by Sclater and Christie [1980], using their parameters and those of Royden and Keen [1980]. Gradual unloading of the sedimentary column, considering paleo-water-depth and paleo-sea-level corrections, was applied according to equation 1 [Steckler and Watts, 1978].

$$(1) \quad Y = S^*(\rho_m - \rho_s^*/\rho_m - \rho_w) + W_d - \Delta_{SL}(\rho_m/\rho_m - \rho_w)$$

where Y is the depth of a water loaded basin (relative to the present-day sea-level and positive downward), S* is the thickness of the decompacted sedimentary column, W_d is the paleo-water-depth, Δ_{SL} is the paleo-sea-level (relative to the present sea level and positive upward), and ρ_m, ρ_s, ρ_w are the densities of the mantle, sedimentary column, and water, respectively.

For periods of exposure, topography was considered instead of bathymetry as is seen in equation 2.

$$(2) \quad Y = S^*(\rho_m - \rho_s/\rho_m - \rho_w) - H(\rho_m/\rho_m - \rho_w) - \Delta_{SL}(\rho_m/\rho_m - \rho_w)$$

where H is paleo-topographic elevation (positive upward).

Paleo-water-depth, which is especially important in this study, was reconstructed utilizing geological data as explained below. Paleo-sea-level fluctuations [e.g. Miller et al., 2005], which are 1-2 orders of magnitude smaller than the paleo-water-depth correction in this study, were neglected.

2.2 Isostatic calculation of paleo-bathymetry

The Middle Eocene period, just before the reactivation of the Levant continental margin, is a special time in the history of the Levant region, presenting relative tectonic quiescence. Approximately 120 m.y. after the Early Mesozoic rifting and approximately 80 m.y. after the Early Cretaceous magmatism, we may assume that the Levant passive margin was approaching thermal equilibrium.

This implies that by then lateral density variations in the mantle lithosphere were approximately negligible and therefore regional isostatic compensation was practically achieved at the base of the crust. This enabled us to balance the crustal column of the Levant basin, with its unknown overlying water depth, with the crustal column of southern Israel, where water depth can be estimated from sedimentological data:

$$(3) \quad W_{d(LB)}\rho_w + S^*_{(LB)}\rho_{S^* (LB)} + C_{(LB)}\rho_{C(LB)} = W_{d(SI)}\rho_w + S^*_{(SI)}\rho_{S^* (SI)} + C_{(SI)}\rho_{C (SI)}$$

where C and ρ_c are the thickness and the density of the crust, respectively, and the subscripts LB and SI refer to Levant Basin and Southern Israel, respectively.

Using appropriate values of crustal and sediment thicknesses and densities, the relations in Eq. 3 are used to constrain the water depth of the Levant basin in the Middle Eocene. Thicknesses of the crystalline crust are inferred from seismic refraction studies. Densities of the crystalline crust are calculated from seismic velocities using the empiric relations of Christensen and Mooney [1995]. Thicknesses and densities of the Middle Eocene sedimentary column, corrected for decompaction, are calculated using the procedure described above for backstripping. Water depth in southern Israel is estimated from sedimentological data.

Table 1: Parameters for calculating paleo-water-depth in the southeastern Levant Basin (LB) during Middle Eocene by balancing its crustal column with that of Eilat, southern Israel (SI). This calculation is based on the assumption of thermal equilibrium in the Middle Eocene as explained in text (Equation 3). The two datasets in the Table represent two possible end member values for the required parameters that were combined selectively to constrain minimum and maximum paleo-water-depths of the Levant Basin. The results of ~2 km and ~3.5 km, respectively, are marked in bold.

			Southern Israel (SI)		Levant Basin (LB)	
			Minimal estimation of bathymetry			
Parameter			Value	Reference	Value	Reference
Water	Water-depth (m)	W_d	500	This study	2090	Calculated (Equation 3)
	Density (kg/m^3)	ρ_w	1030		1030	
Sediment	Thickness (m)	S^*	1100	Gvirtzman (1997)	7890	Ben-Avraham et al. (2002)
	Density (kg/m^3)	ρ_s	1950	Gvirtzman (1997)	2400	This work
Crust	Thickness (m)	C	32900	Hofstetter and Bock (2004) Al-Damegh et al. (2005)	9000	Netzeband et al. (2006, Profile 1)
	Density (kg/m^3)	ρ_c	2870	Seismic velocity - Weber et al. (2004)	2840	Seismic velocity - Netzeband et al. (2006, Profile 1)
			Maximal estimation of bathymetry			
Water	Water-depth (m)	W_d	100	This study	3570	Calculated (Equation 3)
	Density (kg/m^3)	ρ_w	1030		1030	
Sediment	Thickness (m)	S^*	1100	Gvirtzman (1997)	5630	Netzeband et al. (2006)
	Density (kg/m^3)	ρ_s	1950	Gvirtzman (1997)	2400	This work
Crust	Thickness (m)	C	34900	Hofstetter and Bock (2004) Al-Damegh et al. (2005)	9300	Ben-Avraham et al. (2002)
	Density (kg/m^3)	ρ_c	2840	Seismic velocity - El-Isa et al. (1987)	2900	Seismic velocity - Ben-Avraham et al. (2002)

In order to evaluate the dependence of the backstripping tectonic analysis on the paleo-water-depth correction, we selected for the model parameters two sets of values that provide constrains on minimum and maximum paleo-water-depths.

2.3 Morphological reconstruction of Paleobathymetry and Paleotopography

For the period postdating the renewed tectonism, isostatic balancing cannot be used for paleobathymetric estimations. On the other hand, wealth of other geological data enables the reconstruction of a relatively detailed bathymetric-topographic profile from the Judea Mt. plateau all the way to the Levant Basin. First, we used relicts of flat morphological surfaces formed by abrasive and erosive processes as proxies for approximate paleo-sea-levels (zero elevation) during their formation. Next, we used known height differences across morpho-structural steps to reconstruct either paleo-topography or paleo-bathymetry landward and seaward to the zero-elevation surfaces, respectively (Fig. 3A). For example, a buried canyon provides a minimum height estimation for the paleo step through which it incised (Fig. 3C). In a case of block tilting, the reconstruction brought into consideration the possibility of some vertical overlap between steps (Fig. 3B). These principles are applied below to reconstruct paleo-profiles from the Judea Mt. plateau to the Levant basin for the Early Oligocene and Middle Miocene.

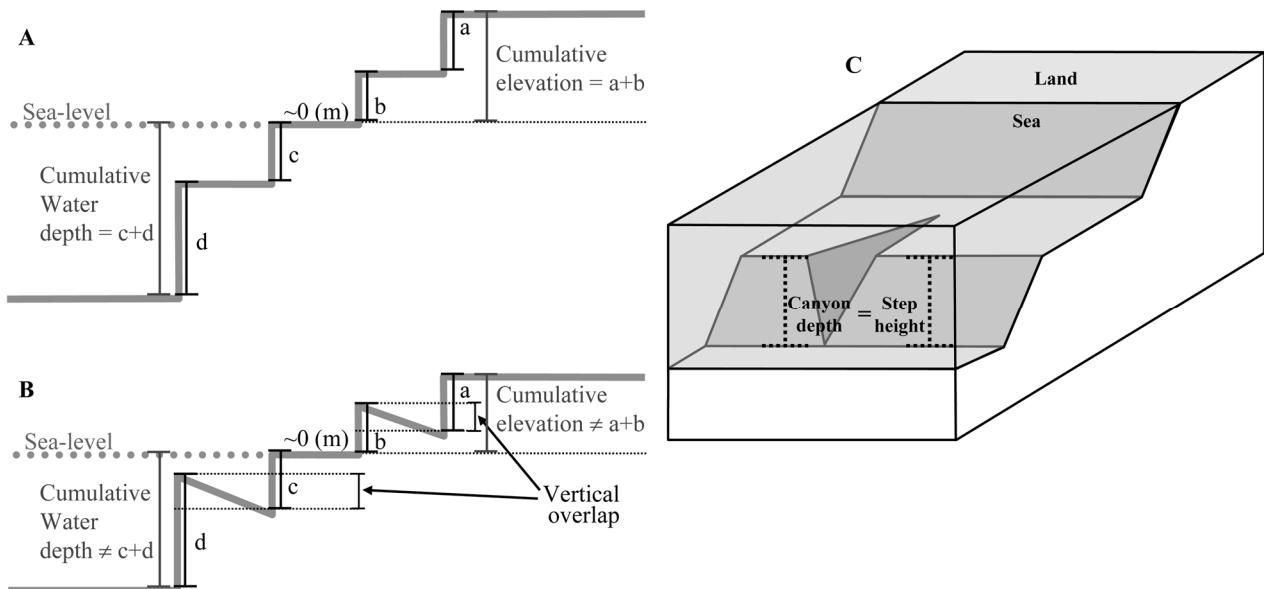


Figure 3: Principles for the reconstruction of paleo-bathymetry-topography profiles based on height differences across morpho-structural steps and on relicts of ancient abrasive and erosive surfaces, which were originally close to sea level. A. Estimation of paleo-relief assuming a sub-horizontal state of structural blocks. In this case, water depth in the deep part of the basin is the sum of all submarine steps and similarly topographic elevation accumulates landwards. The depth and/or elevation are calculated with respect to a certain surface inferred to had been at sea level at a certain time and are representative for that time. B. Estimation of paleo relief considering the possibility of tilted blocks with a partial overlap of vertical differences across the steps. C. Schematic figure illustrating how a canyon cross cutting a morpho-structural step is used to constrain the step's height.

There is some controversy surrounding the magnitude of sea-level drop during the Messinian Salinity Crisis. Estimates range between hardly any sea level lowering [e.g. Lu, 2006; Krijgsman and Meijer, 2008] to a major drop down of more than 1,000 m, and almost complete desiccation [e.g. Hsü et al., 1973; Rouchy and Caruso, 2006]. Considering the isostatic response of the lithosphere to water unloading, if the Mediterranean basin did dry out, the paleogeography of its rims must have changed significantly at that time [e.g., Govers et al., 2009]. However, since this dramatic event was very short (less than 1 my) and was caused by far field processes (closure of Atlantic-Mediterranean gateways) not related to local tectonism, we simply ignore it. We assume that this transient effect did not exert major influence on the long-term geodynamic processes, which are the scope of this study.

3. RESULTS

3.1 Paleobathymetry and Paleotopography Reconstruction

Figure 4 presents paleo-bathymetric-topographic profiles for the Middle Eocene (A), Early Oligocene (B), and Middle Miocene (C), reconstructed based on the method described above. To define the range of uncertainty each profile presents minimal and maximal estimations. For comparison, the present day profile is also presented (D). In addition, all profiles are underlain by an independently prepared cross section of the decompacted sedimentary column (based on Figure 2), showing how unit thicknesses decreased with time until reaching their present day thickness. Note, however, that these composite geological cross-sections are entirely based on geological data of paleo-sediment thickness and paleo-water-depth rather than calculated by sedimentary unloading (for one-dimensional backstripping see section 3.2 below).

Middle Eocene

Sedimentological analysis of pelagic Early to Middle Eocene rocks in Israel indicates that a carbonate ramp gradually descended at that time from the region that eventually became inland Israel westward into the Levant Basin [Buchbinder et al., 1988]. In the Judea Mt. plateau, Eocene rocks are mostly missing, but one single Early Eocene outcrop preserved near the city of Jerusalem [Lewy et al., 1995] indicates that, at least in the Early Eocene, sea water covered that region. The existence of Middle Eocene submarine slumps west of the Judea Mt. [Buchbinder et al., 1988] further indicates marine conditions over the Judea region. The angle of the unconformity between Senonian and underlying strata west of Jerusalem indicates that during the main phase of Syrian Arc folding only one third of the observed WMFS existed [Bar, 2009]. This means that sea floor relief in the Middle Eocene was mild (Fig. 4A). The exact water depth in the inland region is hard to estimate. However, given the mild sea floor relief and given that at least the Ramon anticline

crest in southern Israel was within the photic zone, as indicated by rich nummulitic fauna [Benjamini, 1979; Buchbinder et al., 1988; Sneh, 1988], we estimate that in general, water depth in the inland region was between 100-500 meters (Fig. 5a).

To constrain the possible range of water depths in the Levant Basin at that time utilizing Equation 3, we used crustal and sediment thicknesses and densities as listed in Table 1. The two datasets in Table 1 present two possible end member values for the required parameters that were combined selectively to constrain minimum and maximum paleo-water-depths of the Levant Basin. The results are 2 km and 3.5 km, respectively (Fig. 4A).

Early Oligocene

The Early Oligocene reconstruction of Fig. 4B is based on the following observations, which are described from east to west:

1. The Judea Mt. Plateau [Bar, 2009] described here is part of an extensive erosion surface previously known from Jordan and southern Israel [e.g. Picard, 1943; Quennell, 1958; Garfunkel and Horowitz, 1966; Zilberman, 1992]. During the Early Oligocene this erosion surface had leveled the entire region to nearly sea level.
2. The sub-horizontal unfolded geometry of the Early Oligocene erosion surface, which truncates the steeply folded layers of the WMFS, indicates that folding ended before the Oligocene. This constrains the duration of the main (2/3) folding phase between Late Eocene and Early Oligocene, so that by then the WMFS already reached its present height.
3. Pelagic Oligocene sedimentation in the western foothill of the Judea Mt. [Buchbinder et al., 2005] indicates that a deep-water environment existed at the foot of the WMFS, contemporaneous with truncation on the Judea Mountains Plateau.
4. Information about the CPS is obtained from the size of submarine canyons that had crossed it and from the thickness of the younger filling sediments. By the Early Oligocene, a 1100 m deep canyon was incised by the Afik channel [Druckman et al., 1995] and an up to 2000 m deep canyon was incised by the Ashdod channel [Buchbinder et al., 2005]. Thus, the CPS at that time was ≥ 1100 -2000 m high.
5. Thickness variations in Senonian to Middle Eocene sections across the CMFZ indicate that faulting along this zone started along side with Syrian Arc deformation, prior to the time interval discussed in this study [Gvirtzman et al., 2008]. However, canyon incision across a 1500-2000 m high step occurred only in the Oligocene as indicated by the canyon fill penetrated by the Hanna-1 oil well and from seismic mapping [Gardosh et al., 2008, 2009]. We therefore suggest that differential vertical motions and the formation of a bathymetric step occurred during the Oligocene.

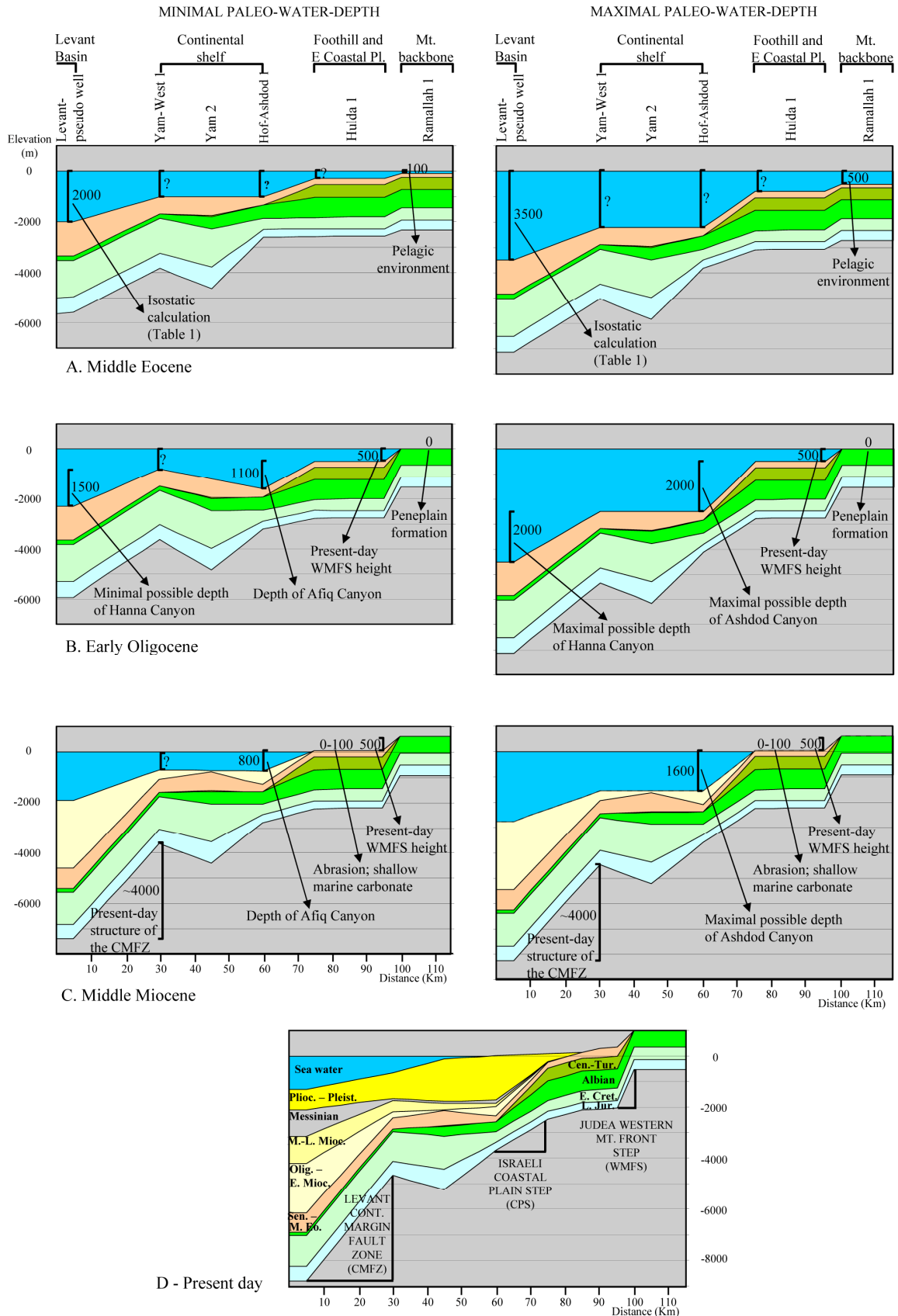


Figure 4: Reconstructions of variation with time of the paleo-bathymetry-topography along a simplified geological cross section running from the Judea Mt. plateau to the Levant Basin (location in Fig. 1): A. Middle Eocene, B. Early Oligocene, and C. Middle Miocene. D is a simplification of Fig. 2, which represents the present day situation. For each period, minimal and maximal relief estimations are presented on the left and right hand sides, respectively. Geological constraints are marked on the figures and explained in the text (values in meters). Unit thicknesses are decompacted as explained in text. Note that the difference between A and B is only related to tectonic deformation with no sedimentation, i.e., the thin and non-continuous Late Eocene section is ignored.

Altogether, these observations indicate that in the Early Oligocene, the Mountain plateau was at nearly sea level and the WMFS had already reached its maximum height of 500 m. From this we inferred that the foothills and eastern coastal plain block must have been 500 m below sea level. The base of the CPS was 2500-1600 m below sea level as evident by the size of ancient canyons. However, unlike the mountain plateau and the foothill blocks that were sub-horizontal during their formation, the ancient dip of the continental shelf block is poorly constrained, so the depth of the eastern edge of that block at the top of the CMFZ is uncertain. Therefore, the height of the CMFZ step inferred from the canyon that crossed it, is not enough to constrain the absolute depth of the Levant Basin below it.

Middle Miocene

The Middle Miocene reconstruction of Fig. 4C is based on the following observations, described once more from east to west:

1. Shallow water, Middle Miocene, carbonates capping flat abrasive surfaces west of the Judea Mt. plateau indicate that by the Middle Miocene the foothill block was raised to nearly sea level [Buchbinder et al., 1993].
2. Lack of deformation along the Afiq canyon axis indicates that structurally, the CPS was not reactivated after the early Oligocene. However, by Middle Miocene times deposition of 300-400 m at the foot of the CPS [Bar, 2009] decreased the bathymetric step to a depth of 1600-800 m.
3. Cessation of faulting along the CMFZ is harder to constrain. The exact age of the uppermost strata, which are faulted, is not clear. They could be from the Oligocene or maybe even Early Miocene [Gvirtzman et al., 2008]. In any case, by the Middle Miocene the CMFZ step had already reached most of its present day structural height. Therefore, for the Middle Miocene reconstruction, we take the present day height of the CMFZ step (~4 km) as marked in Fig. 4C and fill it with the sedimentary section that existed in the Middle Miocene [Gardosh et al., 2008]. This reduces the bathymetric expression of the CMFZ step to a depth of ~1200 m.

Altogether, these observations indicate that when the western foothill region was raised to nearly sea level, the mountain plateau must have reached an elevation of 500 m above sea level. The continental shelf and Levant basin blocks were 700-1550 m and 1,900-2,750 m below sea level, respectively.

3.2 Backstripping

Figure 5 presents four curves of basement subsidence through time for each of the thirteen backstripped sections:

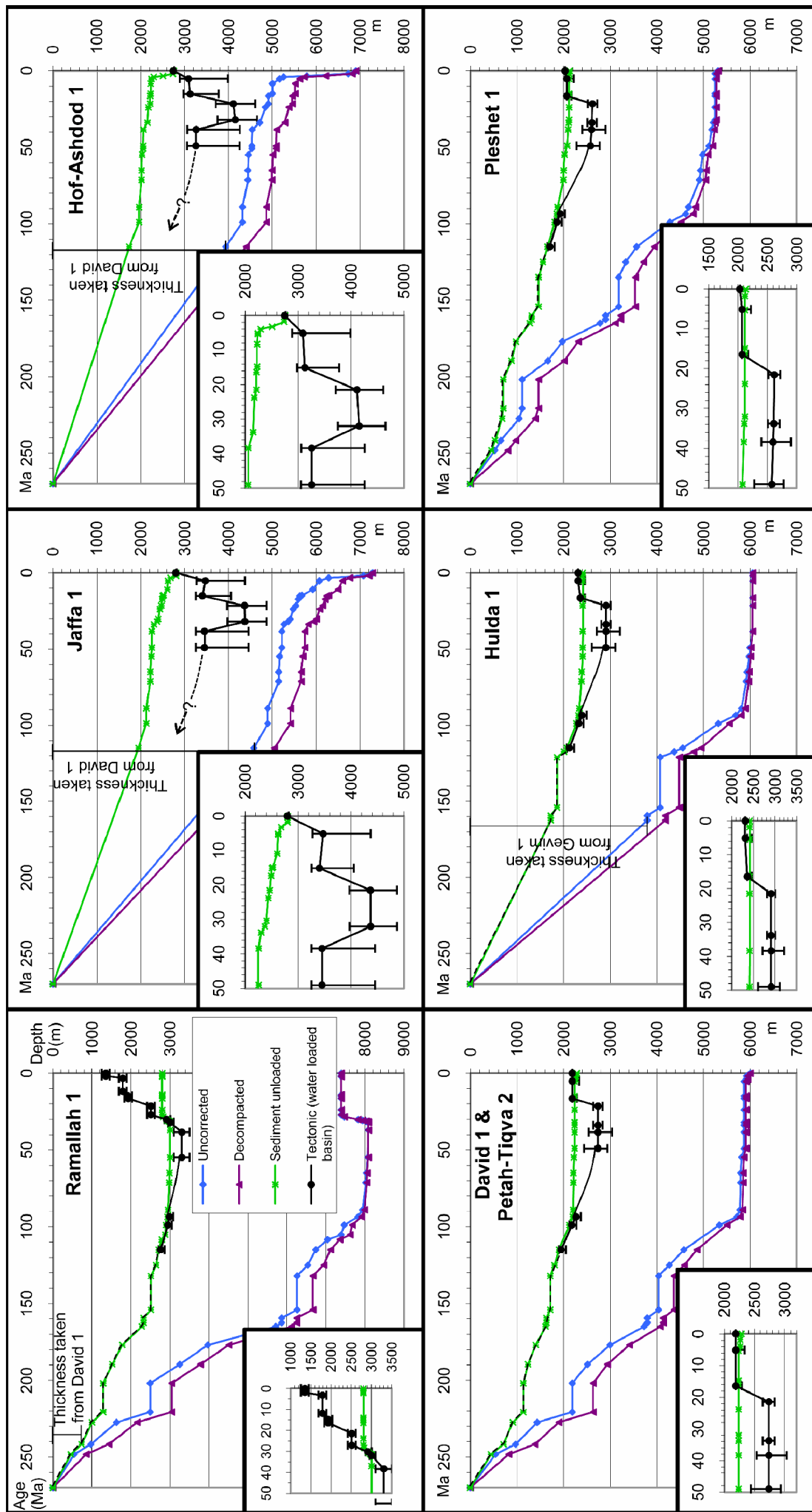


Figure 5: Subsidence curves reconstructed for 13 oil wells across the study area (location in Fig. 1). For each well four curves are presented. (1) Basement subsidence curve obtained by the cumulative thickness of the sedimentary column as measured in wells with no decompaction correction (labeled "uncorrected"). (2) Basement subsidence curve as in curve 1, corrected for compaction during burial (labeled "decompacted"). (3) Basement subsidence curve of a water filled basin as in curve 2, after gradual sedimentary layers unloading, with no water depth correction (labeled "sediment unloaded"). (4) Tectonically driven basement subsidence curve as in curve 3, with a correction for paleo-water-depth (labeled "tectonic"). Uncertainties in water depths are shown by error bars. During periods of shallow marine deposits the tectonic curve approximately coincides with the sediment unloaded curve (dashed black line).

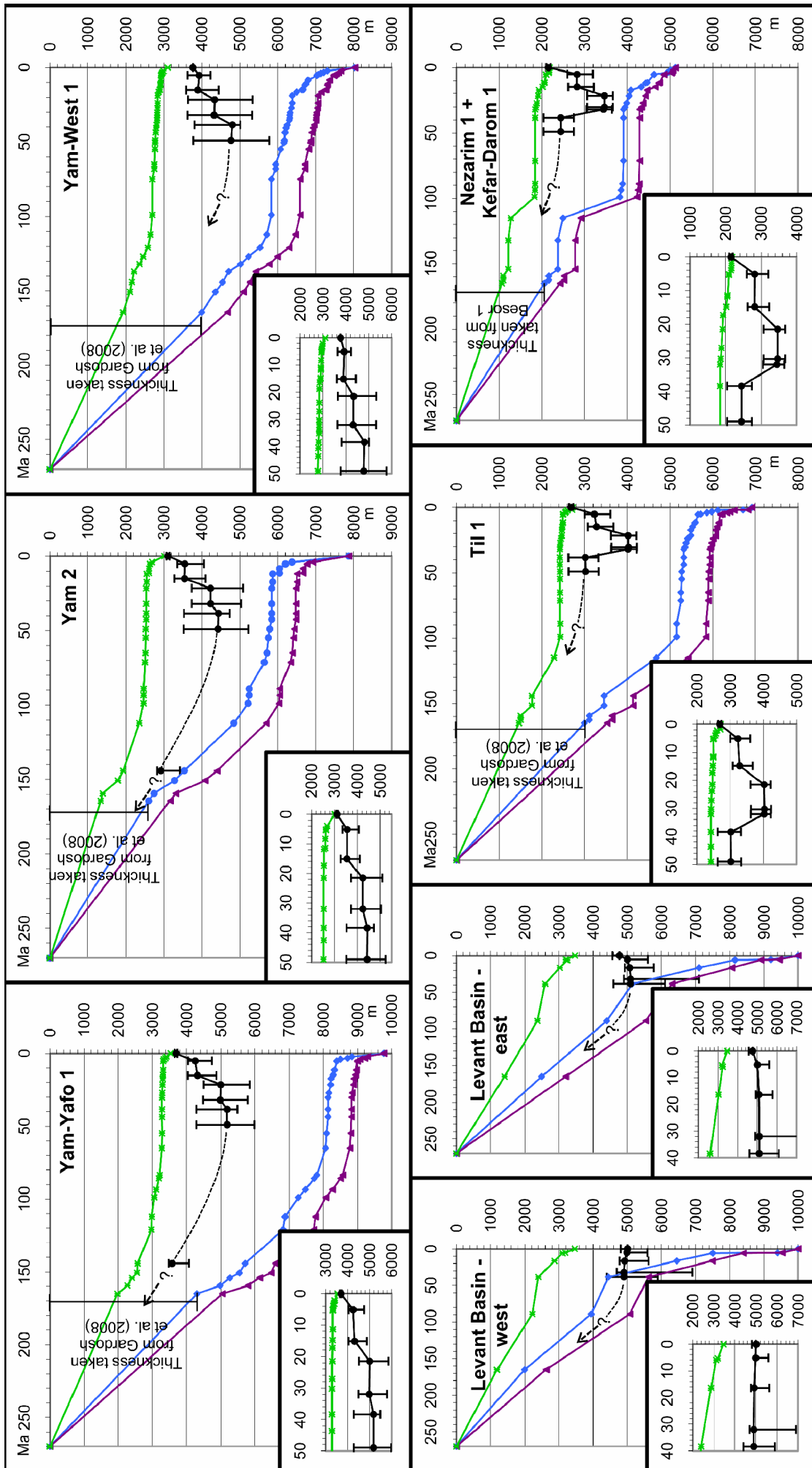


Figure 5 (continued)

1. Basement subsidence curve, calculated from the cumulative thickness of the sedimentary column as measured in wells, with no decompaction correction (this curve is labeled "uncorrected").
2. Basement subsidence curve as in curve 1, corrected for compaction during burial (labeled "decompacted").
3. Basement subsidence curve as in curve 2, after gradual sedimentary layers unloading, with no water depth correction (labeled "sediment unloaded").
4. Tectonically driven basement subsidence curve as in curve 3, with a correction for paleo-water-depth (uncertainty is shown by error bars). This final curve shows what would have been the subsidence of the basin, if tectonic forces operated without sedimentation and erosion and the basin was filled only with seawater. Note that for wells in the Judea Mt. and Coastal Plain blocks (Ramalla-1, David-1 & Petah-Tiqva-2, Hulda-1, and Pleshet-1), where shallow water sediments were continuously deposited from the Permian until the Turonian (270-89 Ma), the tectonic curves approximately coincide with the sediment unloaded curves. For the rest of the wells, where a pelagic environment prevailed most of the time and water-depth is unknown, a broken line annotated by question marks schematically shows the tectonic curves.

Gathering the decompacted curves of all wells in one figure emphasizes the main regional events (Fig. 6A). The two rapid pulses of subsidence during the Permian-Triassic (270-220 Ma) and the Jurassic (200-150 Ma) are the result of two rifting phases that stretched the continental crust and formed the Levant Basin and its continental margin [e.g. Garfunkel and Derin, 1984]. These pulses were followed by thermal subsidence (post rifting lithospheric cooling) that was temporarily interrupted in the Early Cretaceous while a pulse of magmatism affected the inland region [Gvirtzman and Garfunkel, 1998; Gvirtzman et al., 1998]. Between 100 and 90 Ma a noticeable decrease in subsidence rates was felt in all regions. At *ca.* 37 Ma a series of processes began as further discussed below.

A comparison of decompacted subsidence curves for four wells representing the four main regional blocks (mountain plateau, coastal plain, continental shelf, and Levant basin) (Fig. 6B) with their tectonic subsidence curves, (Fig. 6C) emphasizes two important points:

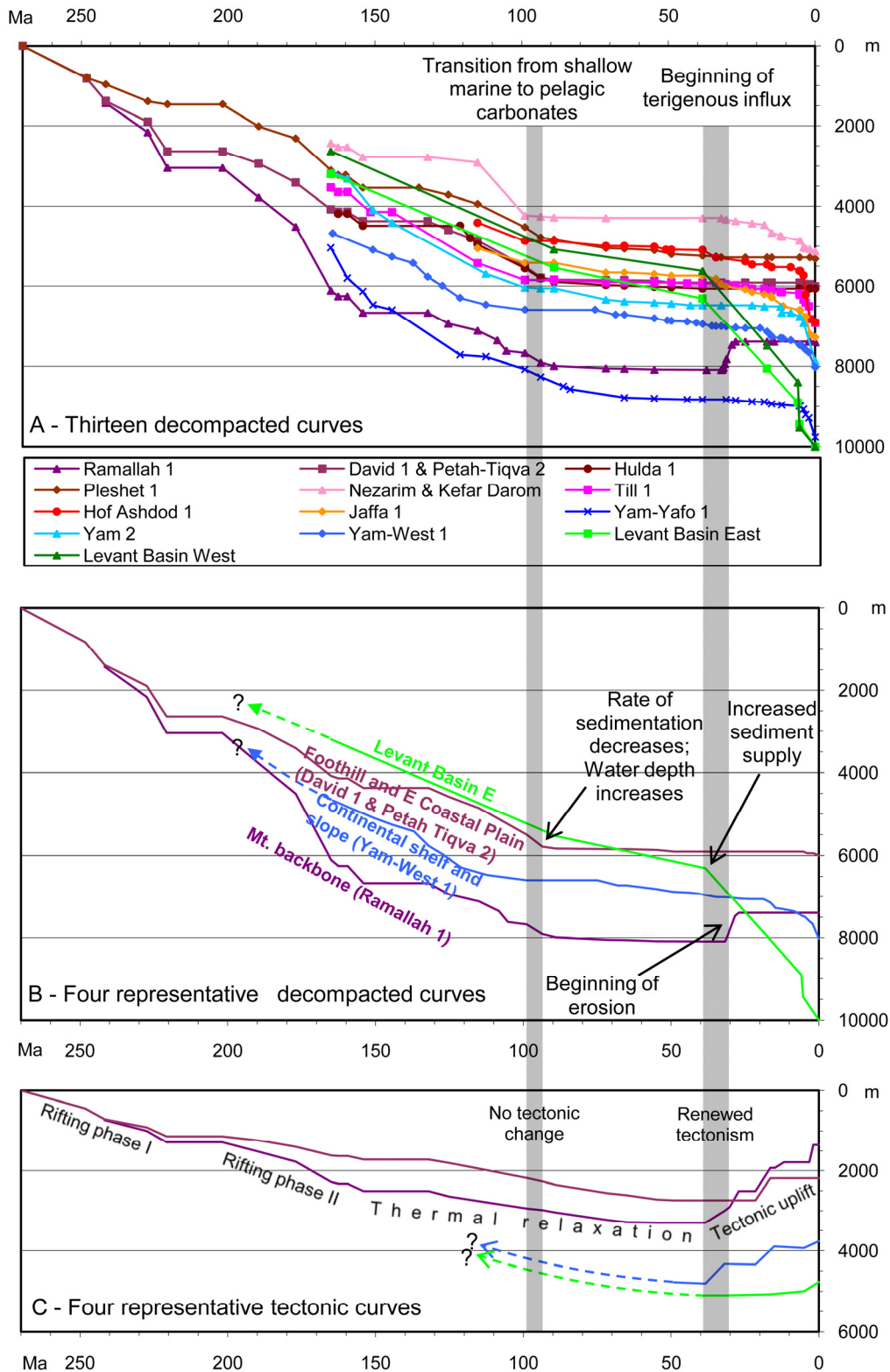


Figure 6: Composite presentation of the backstripping results. A. Decompacted curves of all wells demonstrating major regional processes seen in most wells. B. Four curves selected from A to represent the four structural blocks: mountain backbone block, the foothill- east coastal plain block, the continental shelf block, and Levant Basin block. C. Four representative tectonic curves (same locations as in B). These selected curves demonstrate the main tectono-sedimentary processes of the continental margin since their formation: Permo-Triassic (270-220 Ma) and Jurassic (200-150 Ma) rifting, subsequent prolonged thermal relaxation, and Late Tertiary renewal of tectonism (since ~37 Ma). Note: 1) the significance of the water depth correction indicated by comparing B and C, and 2) the decrease in sedimentation rates at ~90 Ma (B) does not reflect a tectonic change (C) and that the opposite direction of vertical motion in the Late Tertiary (B) does not reflect opposite directions of tectonic forces (C). Detailed in text.

1. The prominent decrease in the rate of total subsidence as seen in land wells (Ramalla-1 and David-1 & Petah Tiqva-2 wells) at 100-90 Ma does not reflect tectonic change, but rather, water deepening. The subsidence curves of these wells suggest that, up until the Turonian, rapid sedimentation of predominantly limestone and dolomite, kept up with subsidence rates and maintained a shallow water continental shelf. Then, at the beginning of the Senonian, deposition changed to pelagic chalks, sedimentation rates decreased, and the excess subsidence resulted in increasing water depth.
2. The total subsidence curves after 37 Ma show different trends (Fig. 6B): uplift in the Judea Mt. block (Ramalla-1 well), no change in the coastal plain block (David-1 & Petah Tiqva-2 wells), and subsidence in the continental shelf (Yam West-1 well) and Levant Basin blocks (pseudo well). However, after paleo-water-depth corrections, the tectonic curves (Fig. 6C) show that since 37 Ma all four regions were subjected to an upward (uplift) tectonic force. This does not mean that the entire region was actually uplifted. The relatively shallow landward region was uplifted, exposed, and truncated (Judea Mt. block), but the continental margin and especially the Levant basin, subsided due to an excessive load of terrigenous sediment influx to the basin (Fig. 6B). The coastal plain block in the transition zone between those two domains remained relatively stable (further discussed below) (Fig. 6B).

To examine these results in detail, Figure 7 presents the backstripping results of all wells zeroed to a common base line that shows the motion relative to 37 Ma. Most of the total subsidence curves (Fig. 7a) show no significant changes until the Pliocene. However, curves representing the tectonic component of the motion, set for the minimal (Fig. 7b), maximal (Fig. 7c) and inferred (Fig. 7d) paleo-water-depth reconstructions, reveal three phases of activity. The first phase in the Late Eocene to Early Oligocene (~37-32 Ma) consists of differential motions that accompanied the formation of the three morpho-structural steps described above. Regions at the foot (west) of the steps subsided (Hof Ashdod-1, Till-1, Jaffa-1, Netzarim-1 & Kefar darom-1), whereas regions at the elevated (east) side of the steps uplifted (e.g. Ramalla-1). The two later tectonic phases, in the Early Miocene and in the Pliocene, consist of a regional uplift seen in almost all wells.

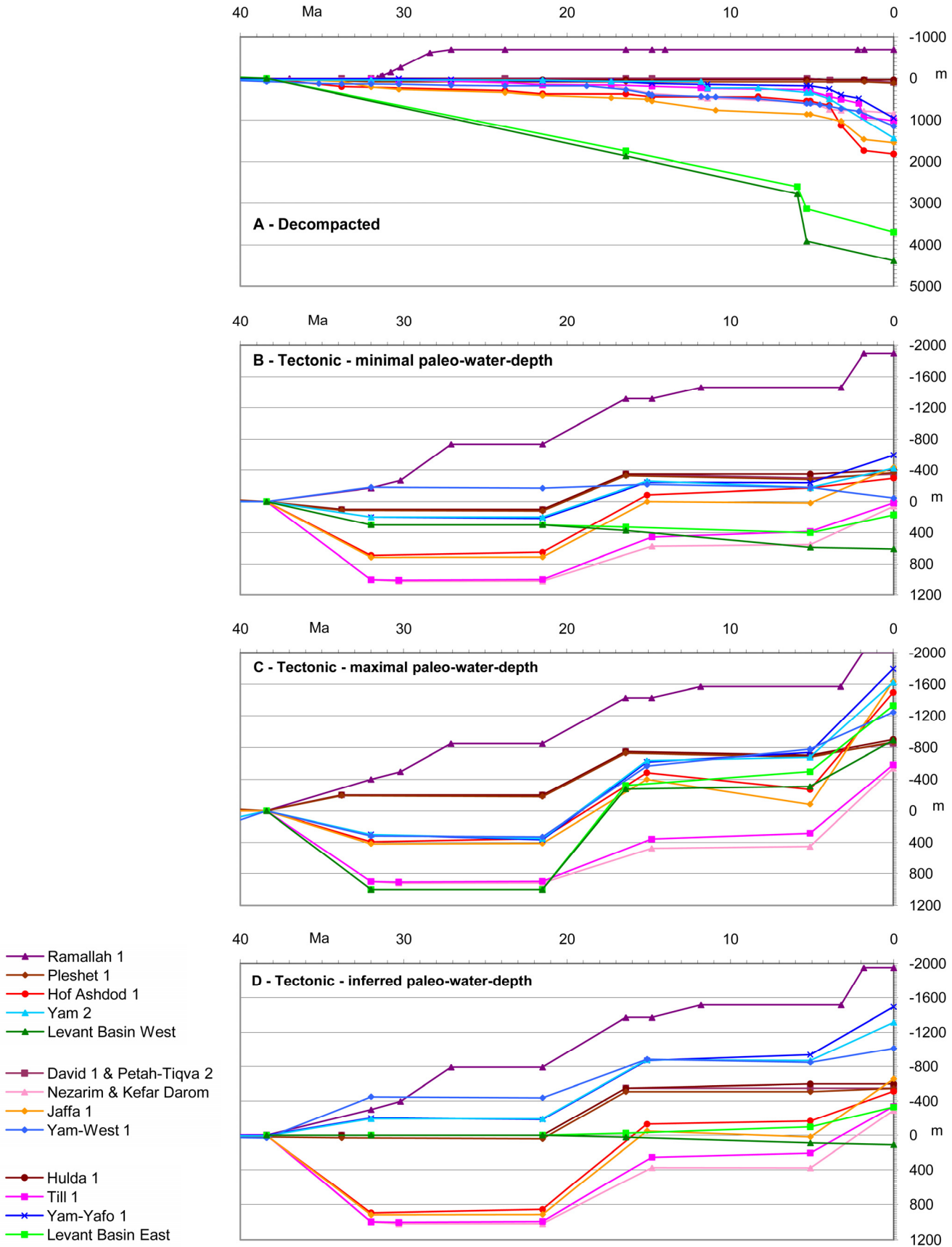


Figure 7: Subsidence curves for the past 40 m.y. with a common base line zeroed at the Middle Eocene. A. Decompacted curves of all wells indicating subsidence and deposition of most regions. B-D: Tectonic curves of a water loaded basin, considering minimal (B), maximal (C) and inferred (D) paleo-depth reconstructions. Note the differential tectonic movement during the period extending from the Late Eocene to the Early Oligocene (38-32 Ma), when some regions rose while others subsided (see text), and the regional uplift phases during the Early to Middle Miocene (21.5-15 Ma) and Late Pliocene (5.3-1.8 Ma), when the entire study area was subject to an upward tectonic force.

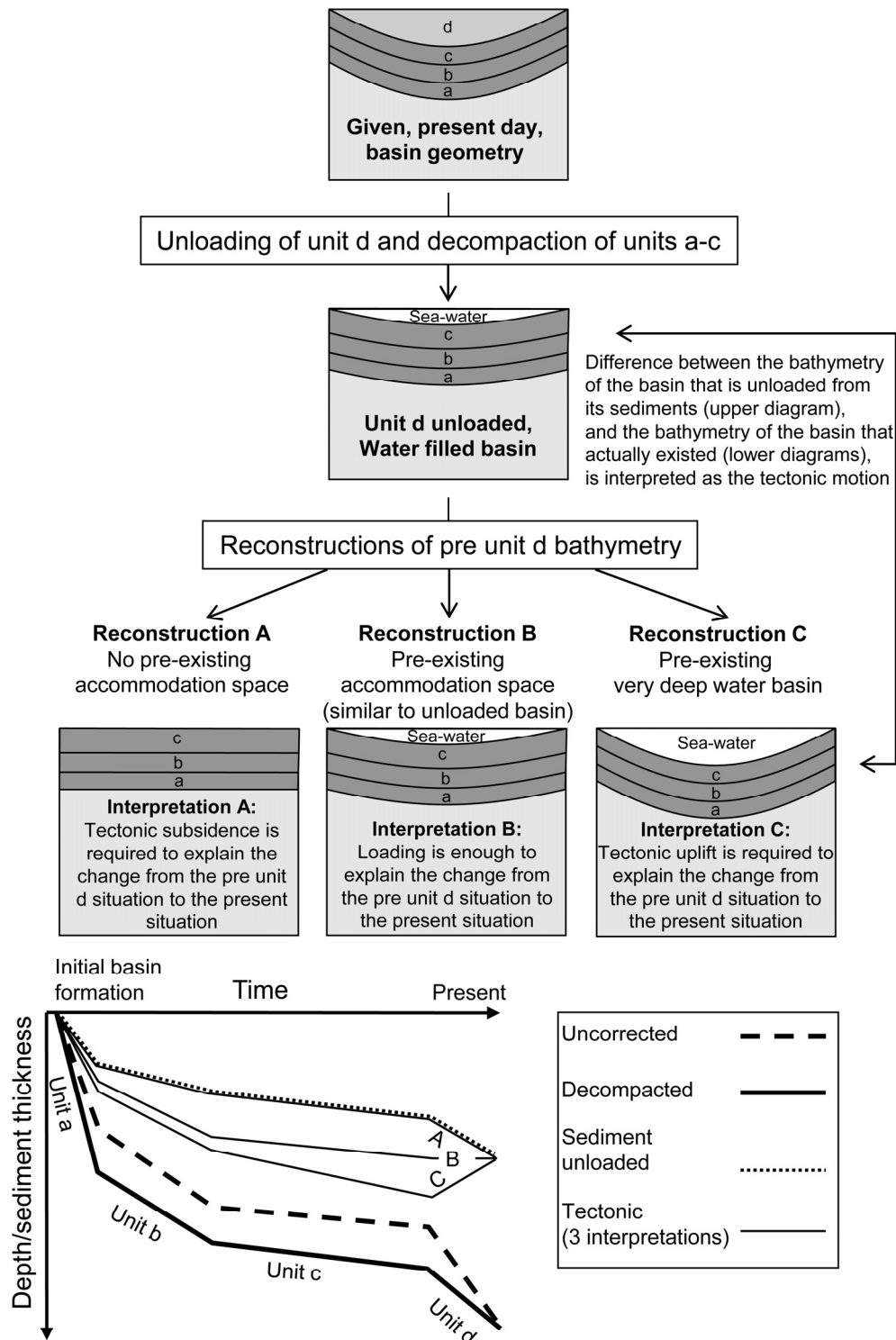


Figure 8: A schematic illustration showing the significance of paleo-water-depth reconstructions for tectonic interpretation. Note how the same sedimentary section can be interpreted in three different ways depending on the paleo-water-depth reconstruction.

4. DISCUSSION

4.1 Interpretation of the backstripping results

One of the conclusions drawn from the backstripping analysis is that the enhanced subsidence of the Levant Basin and its continental margin, since 37 Ma (Fig 6A,B; 7A), was mainly due to sedimentary loading rather than to deep tectonic forces. On the contrary, the deep tectonic force in most of the study area was upward, at least since the Early Miocene (Fig 6C; 7B-D). As a result, the relatively shallow region of the Judea Mt. was uplifted, exposed, and truncated, whereas the continental margin and the Levant basin that received a much greater influx of terrigenous material subsided under the sedimentary load in spite of the upward tectonic force.

The differentiation of the relative effects of isostatic subsidence in response to sedimentary loading and tectonic uplift was possible due to careful paleo-water-depth reconstructions. Figure 8 further demonstrates the significance of the paleo-water-depth correction for tectonic analysis by showing how a given sedimentary section may be interpreted in three different ways. In this example, a basin composed of four sedimentary units is analyzed to examine what the tectonic motion was during the deposition of the uppermost unit (Unit d). This example resembles the question studied here about the Late Tertiary deposition in the continental margin. Interpretation A in Figure 8 assumes no accommodation space before the accumulation of unit d and thus requires tectonic subsidence to account for the water-loaded basin geometry obtained by the unloading of Unit d. This resembles the interpretation of Tibor et al. [1992] who suggested that the southeast Mediterranean continental shelf subsided in the Pliocene due to the down flexing of the lithosphere under the load of the Nile delta deposits offshore Egypt. In contrast, Gvirtzman et al. [2008] preferred a B type interpretation (Fig. 8), in which a pre-existing deep-water basin filled by sediments can explain the rapid sedimentation in the Pliocene with no tectonic involvement. Nonetheless, the results of this study indicate a third interpretation of type C (Fig. 8). The paleo-water-depth reconstruction shows that the pre-Pliocene basin offshore Israel was much deeper than that obtained by sediment unloading. This requires an upward tectonic force to explain the present day situation.

Figure 9 illustrates both temporal and spatial implications of this upward tectonic force. It presents a simplified E-W cross section in four time stages, constructed to show the spatial and temporal variations in vertical motions of the crust and calculated tectonic forces across the major different sub-terrains (i.e. Levant Basin, Continental shelf and slopes, coastal plain and mountain backbone). These pairs of cross sections are displayed three times for minimal (Fig. 9A), maximal (Fig. 9B), and inferred (Fig. 9C) paleo-water-depth reconstructions.

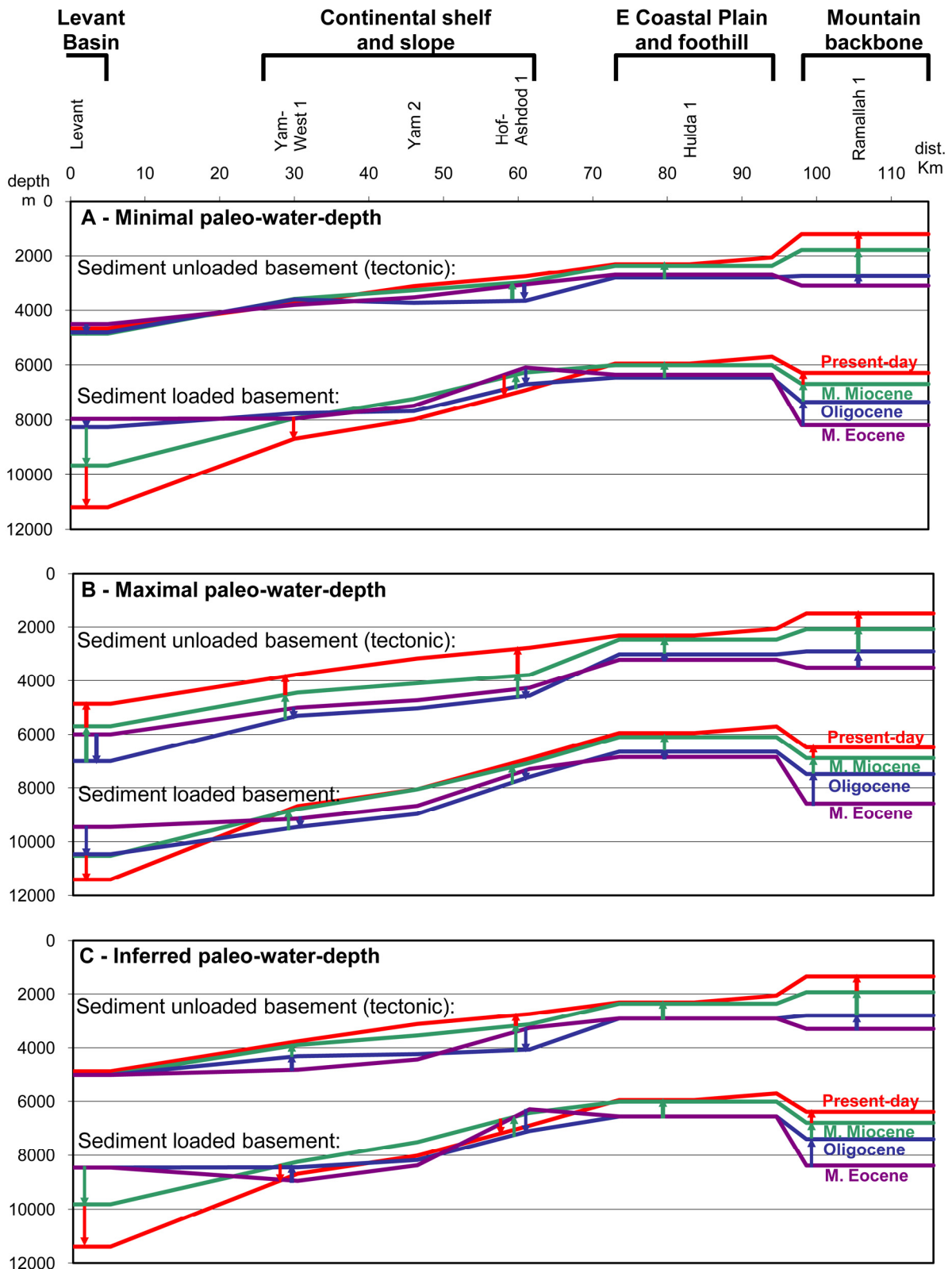


Figure 9: Reconstruction profiles of the top of the basement along an E-W cross-section (location in Fig. 1) in four time stages (Middle Eocene, Oligocene, Middle Miocene, and the present), considering minimal (A), maximal (B), and inferred (C) paleo-water-depth reconstructions. The four profiles at the lower part of each of the three pairs of graphs represent the top of the basement covered by the decompacted sediment and the water columns. The four profiles at the upper part of each of the three pairs of graphs represent the tectonically driven component of the crustal vertical motion calculated for a water-loaded basin. The temporal development of the tectonic profiles indicates that, if tectonic forces operated alone without an external sedimentary loading, most of the region would have been mainly uplifted. Note, however, that this is a two-dimensional presentation of a one-dimensional analysis, and that a flexural calculation would presumably provide different values as discussed in text.

The four profiles at the lower part of each of the three pairs of graphs (Fig. 9A, B, and C) represent the top of the basement covered by the decompacted sediment and the water columns in the Middle Eocene, Oligocene, Middle Miocene, and the present. These basement profiles for all three paleo-water-depth statuses show a prominent rotation of the continental margin around a horizontal axis, that produces a prolonged eastward uplift and westward subsidence.

The four profiles at the upper part of each of the three pairs of graphs represent the tectonically driven component of the crustal vertical motion calculated for a water-loaded basin. The temporal development of these profiles indicates that, if tectonic forces operated alone with no external sedimentary loading, most of the region would have been mainly uplifted. For the minimal (Fig. 9A) and inferred (Fig. 9C) paleo-water-depth reconstructions, this tectonic upward force decreases from nearly 2 km in the inland region to nearly zero at the Levant basin, where the only force that existed is sedimentary loading. On the other hand, for the maximal paleo-water-depth reconstruction (Figure 9B), a similar upward tectonic component is obtained for the entire area. In other words, sea floor at the Levant basin was raised from a depth of 3.5 km in the Middle Eocene to 1.6 km today in spite of the sedimentary loading. It is therefore necessary to infer a significant upward tectonic force even in the Levant basin. Accordingly, this reconstruction implies that the wavelength of the deep tectonic processes that uplifted and exposed the Arabian platform in the Late Tertiary extended far westward. They influenced the vertical motions far beyond the inland region into the continental margin and the Levant Basin.

4.2 1D versus 2D analysis

A One-dimensional analysis can have a few benefits over 2D and 3D backstripping. While treating one well at a time one can take advantage of the maximal stratigraphic resolution, whereas in a 2D or 3D analysis only units that are identified over the entire region can be backstripped. Moreover, lateral variations in ages of lithostratigraphic boundaries, which are quite common, can be treated when each well is analyzed separately, but must be neglected if a single age is assigned to each boundary. Our work took advantage of these possibilities to gain maximal stratigraphic resolution. In addition, the uncertainty in 2D or 3D calculations, resulting from unknown lateral variations in the rigidity of the lithosphere, may overcome the uncertainties resulting from other parameters. Therefore, at this stage we preferred to focus on paleo-water-depth analysis. Nevertheless, the limits of the 1D analysis should be taken into account, while interpreting the regional aspects of the results as discussed below.

A 1D analysis that assumes local (Airy) isostasy neglects the strength of the lithosphere and its ability to support loads by flexure [e.g. Watts, 2001]. This means that the results of this work underestimate the tectonic uplift in the Judea hills to an elevation of 1000 m above sea level, in spite of the offshore loading not considered when the Judea hills are analyzed alone. Similarly,

when the Levant Basin is analyzed alone and the unloading by erosion inland is not considered, the tectonic subsidence at the Levant basin is underestimated. However, considering the >100 km distance from the Judea hills to the Levant basin, the mutual influence of these two regions on one another is relatively small.

Therefore, the conclusion of no tectonic downward force in the Levant basin inferred based on the 1D analysis should be considered with caution. For maximal water-depth reconstructions, for which the 1D calculation indicates the existence of an upward tectonic force, 2D analysis would probably yield a somewhat reduced upward motion. Nevertheless, for the minimal water-depth estimation, involving flexural isostasy, this may result in a downward tectonic component in the Levant Basin. At this stage it is not clear whether such a downward component did exist and if so, whether it can be attributed to a residual fraction of the thermal subsidence that still existed 120 my after the Early Mesozoic rifting, or to yet another mechanism.

4.3 Possible mechanisms for uplift

The conclusion that a tectonic uplift affected the entire region extending from the Arabian Platform to the Levant continental margin since the Late Eocene is consistent with several fundamental observations. Marine sedimentation over the NW Arabian Platform abruptly ceased at the Late Eocene [Beydoun, 1991; Ziegler, 2001]. Sinai and southern Israel were exposed and eroded [e.g., Quennell, 1958; Picard, 1943; Garfunkel and Horowitz, 1966; Zilberman, 1992], and southwestern Jordan began uplifting [Feinstein et al., 2004; Feinstein et al., 2010]. Here we show that the Levant continental margin was also affected by this tectonic uplift force and suggest that that is part of a larger phenomenon that affected the NW Arabian Platform.

Two possible mechanisms can explain this regional tectonic uplift of the NW Arabian Platform and the Levant continental margin. The first relates to the collision between Arabia and Eurasia, which could have caused a long wavelength flexure of the Arabian plate. Interestingly, two uplift phases described in our study coincide with two stages of the Arabia-Eurasia convergence. The Late Eocene phase of uplift, accompanied by the formation of morpho-structural steps along the Eastern Mediterranean continental margin, coincide with the final closure of the Neo-Tethys and the onset of collision between the Eurasian crust and the thinned crust of the north Arabia continental margin [e.g. Vincent et al., 2007; Allen and Armstrong, 2008; Ballato et al., in press]. Furthermore, it coincides with a regional shortening event that affected the northern margin of Africa [Guiraud et al., 2005]. Similarly, the Early Miocene phase of uplift described here coincides with the main phase of collision between Eurasia and Arabia along the Zagros–Bitlis suture [e.g. Hempton, 1987; Yilmaz, 1993; Agard et al., 2005; Robertson et al., 2006; Ballato et al., 2010]. This mechanism of flexure, however, could affect only the early stages of the uplift, as long as the lithosphere below the Arabian Platform was still cold and thick.

A second possible mechanism for the tectonic uplift is a deep thermal process that thinned the lithosphere and caused a large-scale uplift. Huge volcanic fields, mainly east of the Red Sea - Dead Sea region [e.g. Garfunkel, 1989; Camp and Roobol, 1992; Krienitz et al., 2007] and xenoliths brought up with magma from depths of a few tens of kilometers [Stein et al., 1993] indicate a stage of lithospheric heating. Independent of surface observations, a thin lithosphere of nearly 65 km below Jordan [Hansen et al., 2007] and Israel [Mohsen et al., 2006] was derived from S-wave receiver function techniques. In addition, seismic tomography studies indicate anomalously hot mantle at a relatively shallow depth below Arabia that may also indicate a thin lithosphere [Kustowski et al., 2008]. However, heat flow in Jordan [Galansis et al., 1986; Förster et al., 2007] and Israel [e.g. Ben-Avraham et al., 1978] is normal at the present day, and was probably at this state since the Middle Miocene [e.g. Feinsein, 1987; Feinsein et al., 1989; Kohn et al., 1990]. Therefore, this mechanism of heating and thinning of the lithosphere could explain the regional uplift only if its influence on the near surface temperature gradient is minor. This could happen if the rising of the lithosphere-asthenosphere boundary is not enough to increase the temperature gradient significantly or, if the heat anomaly is too young to reach the surface. The latter possibility, however, requires that only the younger stages of uplift be explained by this mechanism.

5. SUMMARY AND CONCLUSIONS

1. Since the Late Eocene the NW Arabian Plateau begun uplifting whereas the Levant basin begun to subside and accumulate a thick (> 5 km) sedimentary section. The present elevation of the rising inland region is about 1 km whereas the present water depth of the Levant Basin is about 1.5 km.
2. A paleo-geographic study of the transition zone between the NW Arabian Platform and the Levant Basin during the Late Tertiary enabled a detailed reconstruction of paleo-water-depth from Israel's mountain backbone offshore. At the end of the Middle Eocene, *ca.* 37 my ago, seawater covered the entire region. Water depth increased from a few hundred meters in the region that eventually became Judea Mt. to 2-3.5 km in the Levant Basin. Since then, these regions moved in opposing vertical directions around a hinge line located approximately along the present day coastline.
3. Backstripping analysis of thirteen columnar stratigraphic sections based on oil wells in central Israel and offshore indicates that the emergence and uplift of the inland region cannot be explained only by an isostatic response to sediment unloading (erosion) and requires an (upward) tectonic force. On the other hand, the enhanced subsidence of the Levant Basin is mostly explained by isostatic response to sedimentary loading and does not require the involvement of

tectonic forces. The continental margin (and the Levant Basin in the maximal water depth scenario) presents a transition zone in which an upward tectonic force counteracts sedimentary loading and explains why the basin subsided less than expected from loading alone.

4. These backstripping results suggest that the entire study region was, in general, under the influence of an upward tectonic force. The tectonic uplift, which is so obvious in the uplifted inland region in the east, had also affected the continental margin to the west, although probably at a decreasing magnitude. This magnitude varies from 1.5-2 km in the Judea Mt. plateau to 0-2 km in the Levant Basin, depending on whether minimum or maximum paleo-water-depth, respectively is assumed.
5. Possible mechanisms for the regional widespread tectonic uplift of the Arabian Platform and its margin are long wavelength arching/doming of the Arabian plate, because of its collision with Eurasia, or heating and thinning of the lithosphere. The flexural mechanism could affect only a cold and thick lithosphere that existed during the early stages of uplift, while the thermal mechanism is more likely to explain the later stages of uplift during the extensive magmatism phase known from many previous studies.

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משרד התשתיות הלאומיות
המכון הגיאולוגי

השתפלות שולי הלבנט בטרצייר המאוחר: הפרדה בין עומס סדימנטים לטקטוניקה

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1. המכון הגיאולוגי

2. אוניברסיטת בן-גוריון בנגב

מחקרי תשתית לקידום חיפושי הידרוקרבונים בישראל
מוגש למשרד הממונה על הנפט של ישראל