Advanced 3-D Forward Stratigraphic Modeling of the East-Mediterranean Frontier Deepwater Basins: An Approach for Enhancing Reservoir Fairways Predictions*

Fadi H. Nader[1], Christine Souque[1], Jean-Claude Lecomte[1], Remy Deschamps[1], Benoit Chauveau[1], Didier Granjeon[1], Rob Staples[2], Estee Woon[2], Paul Tricker[2], and Alessandro Frascati[2]

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[1]IFP Energies nouvelles, Rueil-Malmaison, France (fadi-henri.nader@ifpen.fr)
[2]Shell International Exploration and Production B.V.

Abstract

This contribution presents a new approach for stratigraphic forward modeling, whereby the sedimentary filling and initial organic matter distribution of the frontier deepwater, gas-prone Levant Basin (East-Mediterranean region) are simulated. The reference (base) model covers an overall area in the order of 200,000 km^2, with cells grid resolution of 5 km^2 (horizontal) and less than 50m (vertical). This 3D model is constrained by paleogeographic and isopach maps; the latter based on reflection seismic data interpretation and 13 wells. Simulations span 90 Ma, from the Senonian (Coniacian to Maastrichtian ages) to present day, succeeding in demonstrating the transition from a carbonate dominated basinal post-rift phase to siliciclastic turbiditic and distal pelagic depositional systems during further deformation of the basin in the Cenozoic. The latter turbidites and pelagic deposits are associated with increasing detrital inputs due to the margin uplift and further subsidence in the basin. Mixed Miocene marginal carbonates and basinal siliciclastics systems, as well as the distribution of key potential thermogenic and biogenic source rocks, were also modeled. A series of scenarios were then applied to test various hypotheses of sediments input sources, timing of sediments entry, as well as their volumes and nature (i.e., siliciclastics/carbonates/organic matter). Consequently, the role of the different sources on the sediment distribution and the associated impacts on the reservoir play fairways and source rock distributions were better understood – particularly through sediment tracking innovative simulations.

Introduction

More than 60 trillion cubic feet (Tcf) of natural gas were recently discovered in the Levant Basin (East-Mediterranean region), offshore Israel, Cyprus and Egypt (Figure 1). New plays have been proposed, and new un-explored areas may yield additional significant discoveries – especially, offshore Cyprus and Lebanon (e.g. Nader, 2011; Montadert et al., 2014; Nader et al., 2016). Yet, the Eastern Mediterranean region is characterized by a lack of data, a complex geodynamic and tectono-stratigraphic evolutions, and high exploration costs. It is one of the typical frontier exploration areas, where numerical solutions, such as stratigraphic forward modeling (SFM), are becoming compulsory for enhancing reservoir play fairways predictions.

In the last two decades, a significant amount of 2D and 3D seismic reflection data has been acquired throughout the East-Mediterranean region. For instance, most of the Lebanese offshore was covered by both 2D and 3D seismic surveys, even before the closure of the first acreage licensing round (www.lpa.gov.lb). These activities generated a huge amount of new data on the sub-Messinian stratigraphic intervals across the East-Mediterranean region, sparking the interest for academic and industry-led investigations.

Recent research work, which were focused on the northern part of the Levant Basin and based on such substantial new data, provided new concepts for better understanding the crustal, structural and stratigraphic characteristics of this region, as well as its key petroleum systems (e.g. Ghalayini et al., 2015; Hawie et al., 2015; Bou Daher et al., 2016; Inati et al., 2017; Symeou et al., 2018; Papadimitriou et al., in press). These contributions together with the previous work of Abdel Aal et al. (2000) and Dolson et al. (2014) on the Nile Delta, Gardosh et al., 2006 and 2008 on offshore Israel and Bowman (2011) on offshore Syria, to name a few, encompass the collective geological knowledge of the East-Mediterranean region. In particular, Gvirtzman et al. (2014) and Hawie et al. (2015) have proposed 3D stratigraphic forward models for the southern and northern parts of the Levant Basin, respectively. Still, to date no comprehensive regional stratigraphic model covers the whole Levant Basin. The Eastern-Mediterranean region, within which this basin is nested (i.e. from the Sinai Hinge Zone and the Nile Delta in the south, the Levant Fracture System and the Palmyrides to the east, the Cyprus Arc in the north and the Eratosthenes Seamount and Herodotus Basin to the west; Figure 1) has to be investigated as a whole, and not fragmented, in order to achieve a pertinent overall geological understanding.

The first objective of this contribution is to demonstrate the reward of large-scale basin-wide (and beyond) investigations, in constraining the principal boundary conditions and key parameters for predictive facies distributions, essential for any successful petroleum exploration. Furthermore, we present, here a new approach for stratigraphic forward modeling (SFM), whereby the sedimentary filling and original organic matter distribution of the Levant Basin are simulated. Here, a variety of scenarios and iterations can be applied, tested and evaluated, leading to changing paradigms (confirming or refuting hypotheses), increasing probability of finding sweet spots, and lowering the overall risks of exploration in frontier provinces.

Methodology

The present study consisted in constructing a base stratigraphic forward model (SFM), and then running several simulations for the sedimentary and organic-rich facies distribution across the area of study and the investigated time span. DionisosFlowTM software (Granjeon, 1996) was used to build deterministic 4D multi-lithology SFMs, which reproduce the net product of sediment supply, transport and accommodation associated to uplift, subsidence and sea level fluctuations for large-scale sedimentary systems. Simulations combine empirical water and gravity-driven diffusion equations based on: (i) linear slope-driven diffusion (transport proportional to slope), referred to as hill-slope creeping; and (ii) and a non-linear water and slope-driven diffusion equation, known as water discharge driven transport (for more details refer to Hawie et al., 2015). Estimating the initial TOC and HI variations of organic-rich intervals was made based on a new numerical solution embedded in DionisosFlowTM, which is detailed in Bruneau et al. (2017), and references therein.

The reference (base) model covers an overall area in the order of 200,000 km^2, with cells grid resolution of 5 km^2 (horizontal) and less than 50m (vertical). It covers a time span of 90 Ma, from the Senonian (Coniacian to Maastrichtian ages) to present day. The main input data for SFMs include those concerning the accommodation space, and those related to the sediments (illustrated in Figure 2). Sediment erosion, transport and deposition can be simulated based on subsidence rate, eustasy and sediment supply. Carbonate production is modeled using bathymetry, wave/drift energies and ecological controlling factors. Sediment transport is controlled by combining river discharge and slope parameters as well as flooding and slope instability for catastrophic sedimentary processes.

The constructed 3D model is constrained by paleo-geographic and isopach maps, as well as seismic interpretation and well data (facies and sedimentary architecture). Figure 3 and Figure 4 show the principal input and output data that were used for calibrating the models. Seismic-data based isopach (thickness) maps were provided for each major stratigraphic interval (Figure 3A). The SFM of the same interval resulted in simulated thicknesses, and thereafter thickness error maps (Figure 3B) were generated. The thickness error maps were used to help in calibrating the related models. The simulated sediment distribution maps (Figure 3C) were also compared to the generalized sediment proportions in five wells (pie charts in Figure 3C and Figure 3D). Besides, seismo-stratigraphic interpretation of about 13 regional seismic profiles that were tied to wells have been used to construct gross depositional environments (GDE) maps (Figure 4A) for each investigated interval (check Figure 5). Key 2D sections (Figure 4B), illustrating the sedimentary facies and architectures, were built based on the available seismic data and wells. These were also used to compare with the results of the SFMs and tune the simulations' parameters (cf. Hawie et al., 2015). Figure 5 shows a portion of a typical 2D seismic profile with the major reflectors and key stratigraphic intervals, which have been used to construct the SFMs presented in this study.

A series of scenarios/simulations were then applied in order to test various hypotheses of sediments input sources, timing of sediments entry, as well as their volumes and nature (i.e., siliciclastics/carbonates). The sand versus shale net to gross ratios were also taken into account and compared to the available well data (Figures 3C, 3D). Hence, the role of the different sources on the sediment distribution, and the associated impacts on the reservoir and source rock distributions were better understood. Source tracking of sediments helped in highlighting the influence of each proposed input point and the distribution of related play fairways.

The organic matter (OM) distribution simulations are achieved after the construction and optimization of the base SFM. The initial characteristics of organic-rich intervals (e.g. TOC, HI, OI) are also controlled by the applied and tested stratigraphic constraints (e.g., thicknesses, sedimentation rates). The principal input parameters are: (i) the primary OM production maps (PP), expressed in $gC/m^2/yr$; (ii) the transport capacity, defined by the diffusion coefficient associated with the bed-load transport law; (iii) the water mixing capacity that allows to modulate oxygen renewal (wind and bottom current effects); (iv) the hydrogen index (HI in mg/g) for strongly degraded marine organic matter and for non-degraded marine organic matter; and (v) the terrestrial organic matter concentration in rivers, values from 0 to 10 % of the total sediment discharge.

The principal resulting properties of the achieved OM simulations are: (i) bulk TOC (weight %), deduced from the relative contribution of the different sediments (both inorganic and organic); (ii) bulk HI (mg/g), deduced from the relative contribution of the different organic matters (both marine and terrestrial) and from the depositional environment (degradation of marine organic matter); (iii) sedimentation rate (m/My) at the see-floor interface after the degradation phase in the water column; (iv) burial efficiency (%) (similar to the preservation rate) associated to the degradation in the first centimeters below sea-floor interface; and (v) the redox conditions Ox (ratio), reflecting three main regimes: oxic (0.25 < Ox < 1), dysoxic (0.05 < Ox < 0.25) and anoxic (Ox < 0.05).

Results and Discussion

The 3D reference (base) SFM covers the stratigraphic evolution of the East-Mediterranean region, and in particular the Levant Basin and its margins, from 90 to 6 Ma in four time intervals (Senonian-Eocene, Oligocene, Lower Miocene, Upper Miocene), or imbricated sub-models. These intervals were bound by key seismic horizons, which were converted to depth and used as input data (Figure 5). Hundreds of simulations were run in order to secure the best results. Not all stratigraphic intervals, mentioned above, will be presented here. The Miocene interval, which includes the known reservoirs – i.e., Tamar sands – will be used to demonstrate the SFM results, while the Senonian-Eocene interval, which is known for region-scale source rocks – ca. Campanian Chekka source rocks – is proposed to present the distribution of OM distributions.

Hawie et al. (2015) already demonstrated that multiple sources for sediment input are necessary to fill in adequately the northern Levant Basin. Here, several input sources have been tested and evaluated in order to achieve the best possible source-to-sink basin modeling, validated by seismic data and scarce calibrating wells. Hence, (clastic) sediment input sources included the proto-Nile (East and West), Sinai, southern Levant and eastern margin, as well as paleo-Euphrates (northeast) and Anatolian (northwest) sources (check Figure 2). The resulting thickness map for the Lower Miocene interval fits well with the isopach map provided from seismic data (Figure 6). Areas known to have a major structural deformation component, such as the Cyprus Arc, which cannot be taken into account at this stage with stratigraphic forward modeling, resulted with no doubt in the highest thickness errors (Figure 6). Otherwise, the overall thickness error did not exceed 100m for input thickness values in the order of 1200m.

The Thickness Error Map (Figure 6) represents a critical tool that allowed tuning the input parameters in an iterative way, and further evaluating their range. In fact, in frontier basins with scarce hard well data for calibration, the thickness maps and interpreted seismic facies (turned into GDE maps; Figure 2, Figure 3, and Figure 4) are the basis for evaluating the simulations. Only five wells were used to calibrate the lithology across the Lower Miocene model (well locations indicated in Figure 7). Net-to-Gross lithology proportions were calculated from available well logs and compared to the lithology proportions (ca. sand%, detrital shales%, fines%, carbonates%), resulting from the simulations. The input parameters of the SFM were improved – while remaining in meaningful ranges – in an iterative way until the best thickness and lithology matching was achieved.

Figure 7 shows the resulting lithology distribution maps for the Lower Miocene interval (carbonates%, mixed fines%; sand%, and detrital shales%). Comparison between well logs and simulated lithologies is also indicated for the sand% in Figure 7C (but it was applied for all lithology types). The primary locations for the carbonates remain the Eratosthenes Seamount domain and the eastern margins (especially its southern part), while sands are mainly found in the south (Nilotic/Sinai regions) and the southern – and the northern eastern – margins. In general, where the sand/shale sediment sources prevail, no carbonates are found (and vice-versa).

The source tracking method allows to assess the origin of the sediments (i.e., sands) observed in different wells and in average simulated sediment proportions maps. This was applied for the various stratigraphic intervals. Figure 8 shows the resulting source tracking maps for the Upper Miocene sand (Base Serravallian to Tortonian). The sand input sources such as the proto-Nile (West and East; Figures 8A and 8B, respectively), the Sinai (Figure 8C), and Paleo-Euphrates (Figure 8D) could be evaluated separately, by tagging them individually. Throughout the simulation, these tagged sediments can be tracked, resulting in specific basin-scale distribution map per sediment source (Figure 8). Following the increase of the Paleo-Euphrates input throughout the Miocene (through Tortonian times), the sands from the Paleo-Euphrates travels far south and reaches the wells of Aphrodite and Wadi Sura wells. This technique is quite interesting as it can be used to predict and evaluate play fairways

Bou Daher et al. (2014) and Bou Daher et al. (2015) investigated Santonian to Paleocene marls and fine grained carbonates in north and south Lebanon, respectively (Figure 9A). They assessed their organic matter (OM) content, petroleum source rock potential, and depositional environment. TOC, Rock-Eval, and vitrinite reflectance (VRr) results reveal excellent immature petroleum source rocks within the Campanian - Lower Maastrichtian interval with TOC up to 11.6 wt%, hydrogen index (HI) up to 872 mg/g TOC, Tmax up to 433°C and VRr average of 0.36%. Biomarker ratios and maceral analysis suggest a marine depositional environment with a dominance of algal as well as submicroscopic OM. Original sediment composition and redox sensitive geochemical parameters suggest deposition of the OM rich intervals under an oxygen minimum zone (OMZ) that was emplaced and controlled by primary productivity and nutrient supply. Consequently, Bou Daher et al. (2015) proposed a conceptual depositional model for the Upper Cretaceous OM rich rocks of the eastern Mediterranean proposing deposition under a productivity belt localized along the inner and outer shelf leading to a decrease in source rock quality and a shift in kerogen type toward the deeper parts of the Levant Basin (Figure 9B).

Bou Daher et al. (2015) conceptual model has been used for the OM distribution simulations in the present study. From organic matter composition and redox sensitive geochemical parameters, OM rich intervals are believed to have deposited under an oxygen minimum zone controlled by high primary productivity. Upwelling areas are invoked to explain these source rock signature and distribution (ring belt along the inner and outer shelf; Figure 9).

A first series of simulations were achieved by maintaining a constant high primary productivity (ca. 400 gC/m²/yr) and high water mixing. This allowed the initiation of a typical OMZ similar to those observed under upwelling zone occurring in an open ocean, and in line with the model proposed by Bou Daher et al. (2015). Then, instead of maintaining a constant organic primary production throughout the simulations, bathymetry (from the optimized SFM, result of this study) was used to control this parameter. Such approach constitutes an effective way to model upwelling (primary productivity, PP, controlled by bathymetry) resulting in high PP zones, restricted to shelves. Figure 10 shows the results of the simulations, demonstrating hence the viability – and most likely possibility – of the conceptual model proposed by Bou Daher et al. (2015). The initial TOC% distribution across the study area shows belts typical of upwelling, controlled by bathymetry (Figure 10A). Furthermore, initial TOC values exceeding 5% could be mapped. The resulting areas of high TOC% are in line with field investigations (e.g. Bou Daher et al., 2014) and would point out for viable thermogenic petroleum systems at the Levant eastern margins and around Eratosthenes (Figure 10B). These results are coherent with belts of high initial hydrogen index and very low oxygen index, indicating anoxic depositional environments.

Conclusions

This contribution presents some of the results of stratigraphic forward modeling (SFM) of the East-Mediterranean region (covering about 200,000 km^2, with cells grid resolution of 5 km^2 and less than 50m thick). Though the produced SFM covers four major stratigraphic intervals spanning 90 to 6 Ma., only the Senonian-Eocene and Miocene intervals are presented in this study. The former interval was used to illustrate the simulation of organic matter distribution, and the Miocene intervals for the facies fairways distribution – including sediment source-to-sink tracking techniques.

The Senonian-Eocene interval includes some of the most prominent source rocks in the East-Mediterranean regions, whose distribution across the area – and in particular, the Levant Basin – is not well established. By taking into account the recent analytical investigations of Bou Daher et al. (2015) on these source rocks and the resulting conceptual model for upwelling and source rock depositional belts along a typical oxygen minimum zone, we were able to demonstrate the viability of such hypothesis and it's fitting with the SFM. The resulting distribution maps of high initial TOC%, provides insights on the locations of the potential source rocks – elementary for petroleum systems assessment ahead of exploration.

The Miocene intervals include the gas-prone Tamar sands, whose extension throughout the Levant Basin is still enigmatic. The proposed SFM demonstrated the need for multiple sediment sourcing and helped in evaluating the significance of each potential input source for these plays, while keeping meaningful calibration with the interpreted thickness maps and facies. In addition, the sediment tracking approach indicates the proportions of sands from their original provenance source, mapping as such the reservoir fairways from its source to its sink. It is therefore clear that the principal input for the Tamar sands must be the southern sources (e.g. proto-Nile, Sinai), while important northern sources, such as Paleo-Euphrates, would have affected mainly the northern Levant in the Late Miocene.

Acknowledgments

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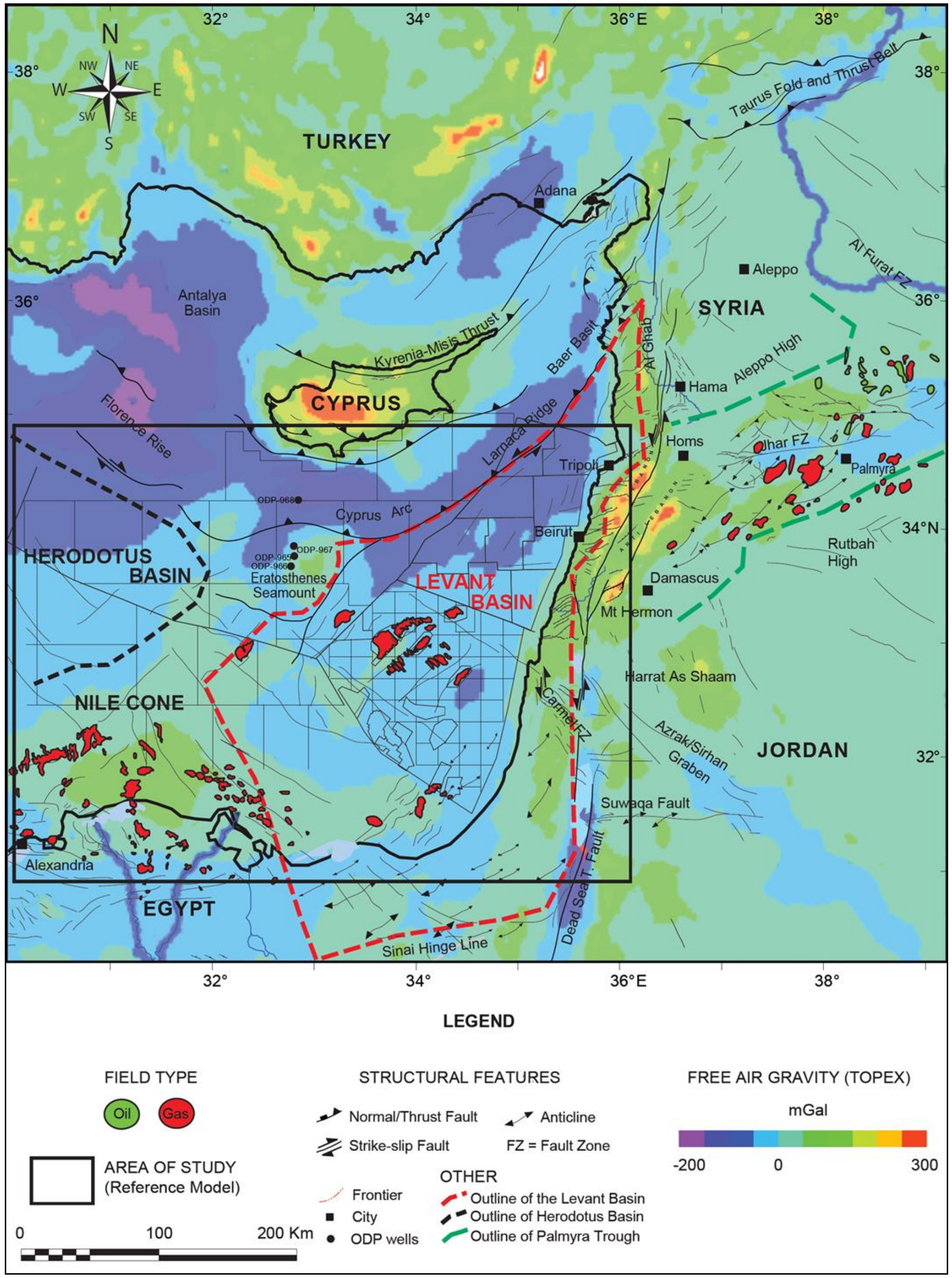

Figure 1. General map showing the Levant Basin and the major oil/gas fields and discoveries in the East Mediterranean and adjacent regions overlain on Free Air Gravity map (TOPEX Database) (Nader et al., 2016 – and references therein). Structural features are from Wood (2015).

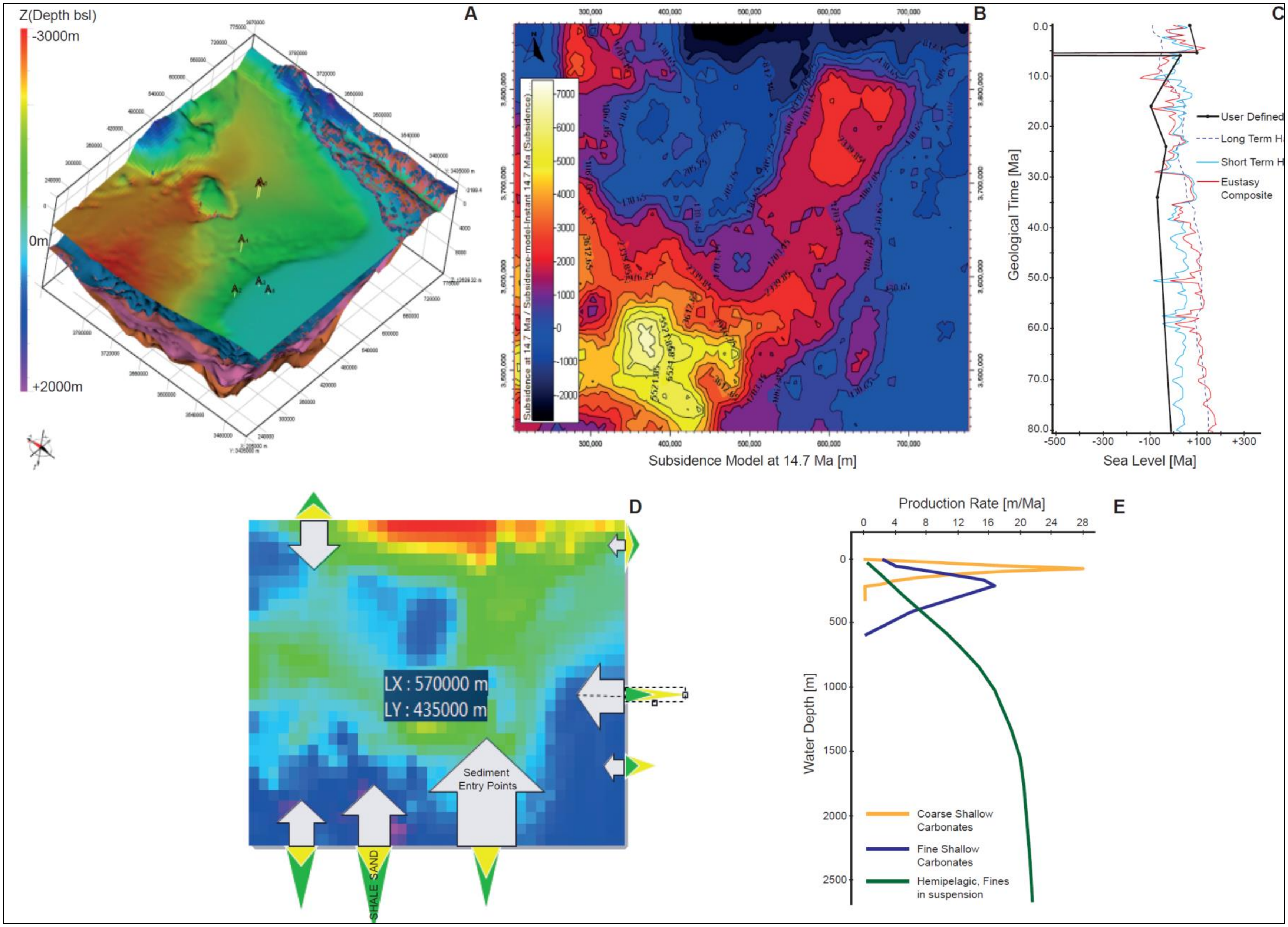

Figure 2. Key parameters for constructing the East-Mediterranean stratigraphic forward model: (i) Input data related to the accommodation space evolution (present-day geometry in A, subsidence in B, eustatic sea-level variations in C); and (ii) sediment input (clastic dans/shale input in D, and in-situ carbonate production with respect to depth in E).

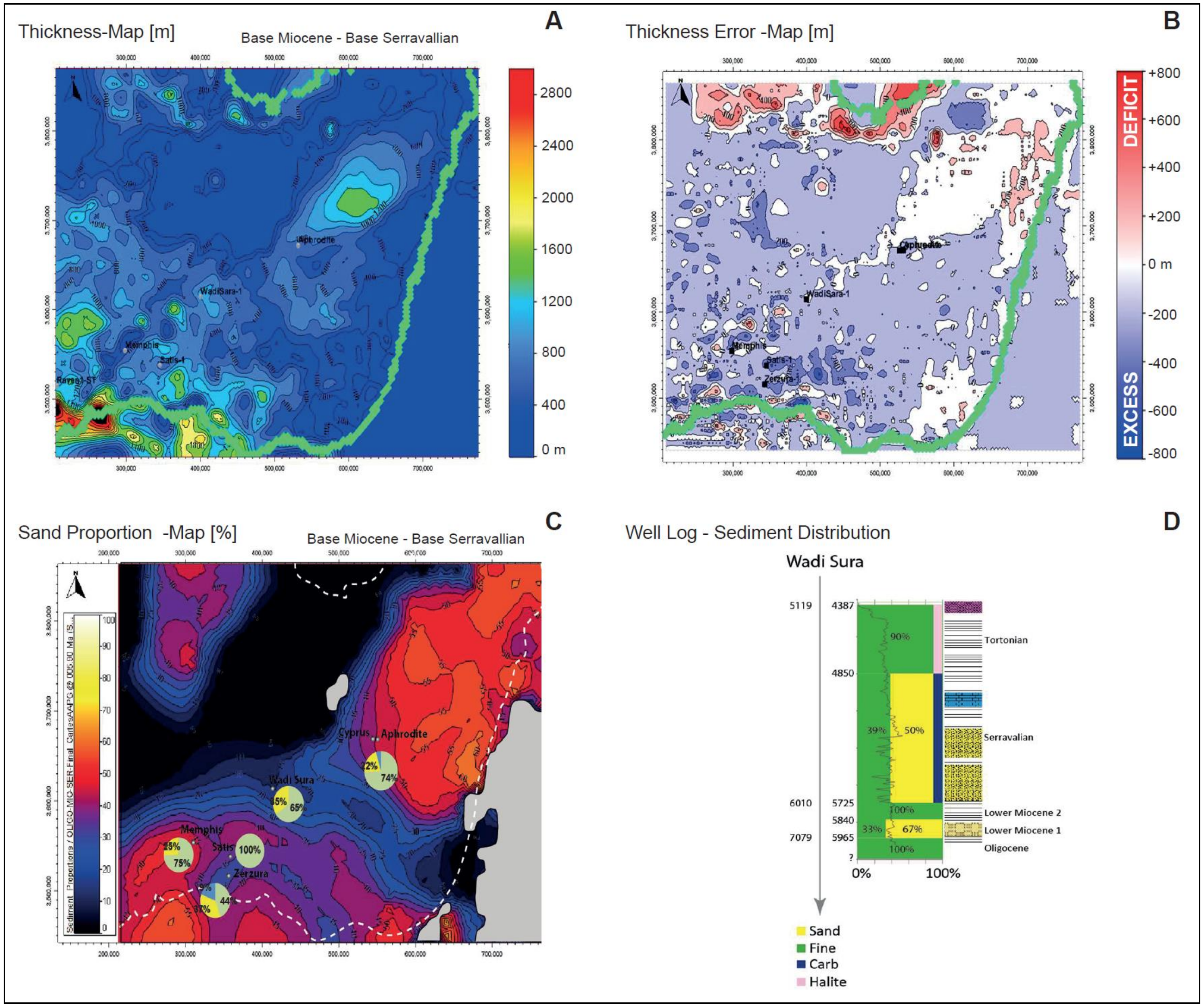

Figure 3. Input and resulting output data for stratigraphic modeling and calibration: A) Input thickness map (in m) of the Base Miocene to Base Serravallian interval; B) thickness error map of the same interval, showing the difference between the resulting simulation and original (input) thicknesses (in m) – highlighting the areas of deficit and excess in sediment thickness, a necessary tool for calibrating the model; C) Sand proportion map for the Base Miocene to Base Serravallian interval, result of modeling compared to pie-charts sediment proportions in control wells; and D) Typical simplified well log showing the extracted sediment type proportions (e.g. sand%, Fine%, Carb%), visualized as pie-charts in (C) – where sand is in yellow, shales in green and carbonates in blue. Calibration is made against seismic facies (interpreted GDE mas/sections) and hard log data (interpreted lithologies, NTG curves, Vshale, Gamma Ray, Resistivity).

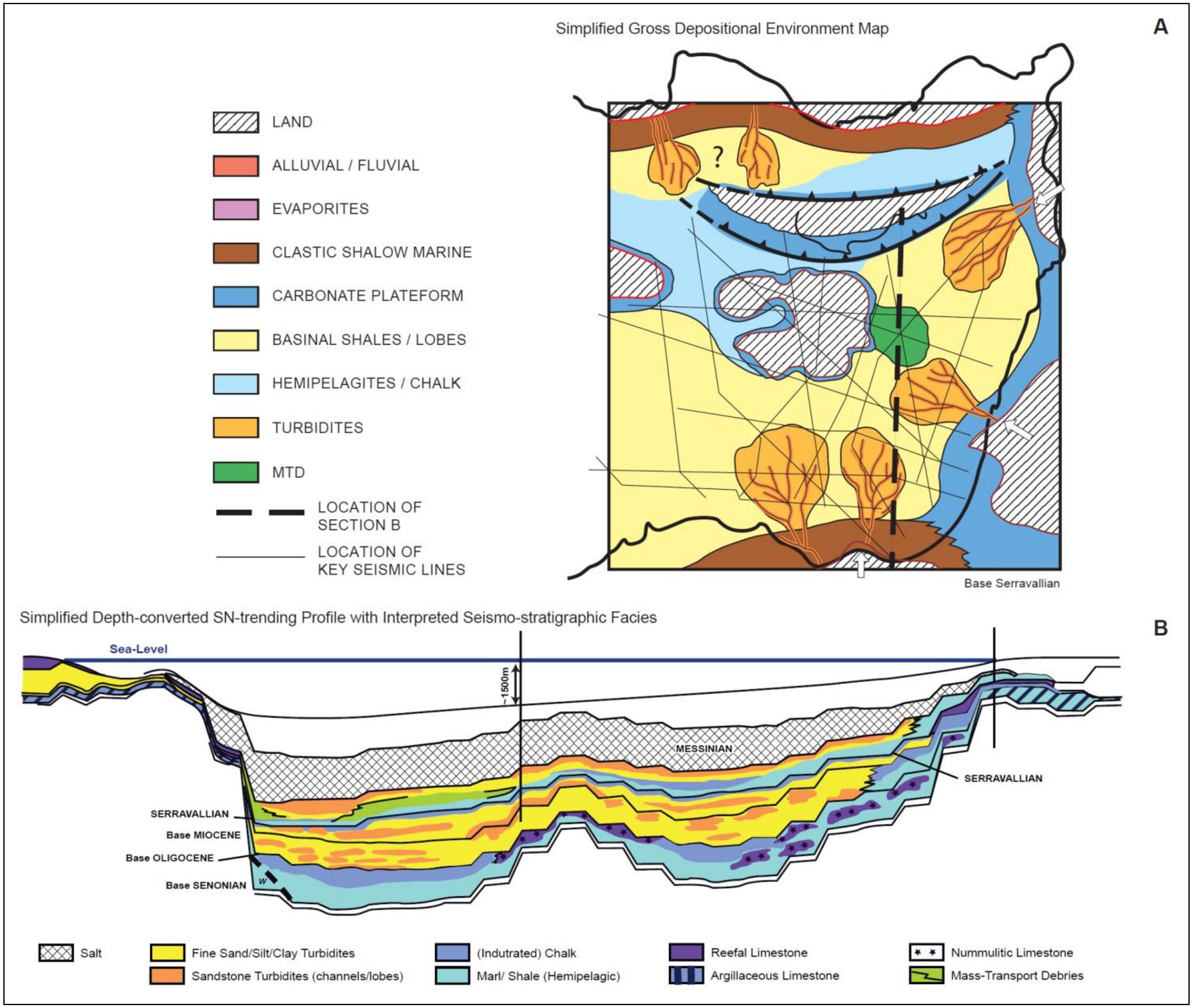

Figure 4. Input data for stratigraphic modeling and calibration: A) Simplified GDE map of the Base Serravallian, based on seismic interpretation (locations of the key 2D seismic profiles are also indicated); B) South-North trending depth converted profile (location indicated in A), showing the interpreted seismo-stratigraphic facies (also calibrated by wells where logs are available). Depth horizons along this profile, are extracted from the constructed stratigraphic model in DionisosFlow™. Calibration is made against seismic facies (interpreted GDE maps/sections) and hard log data (interpreted lithologies, NTG curves, Vshale, Gamma Ray, Resistivity).

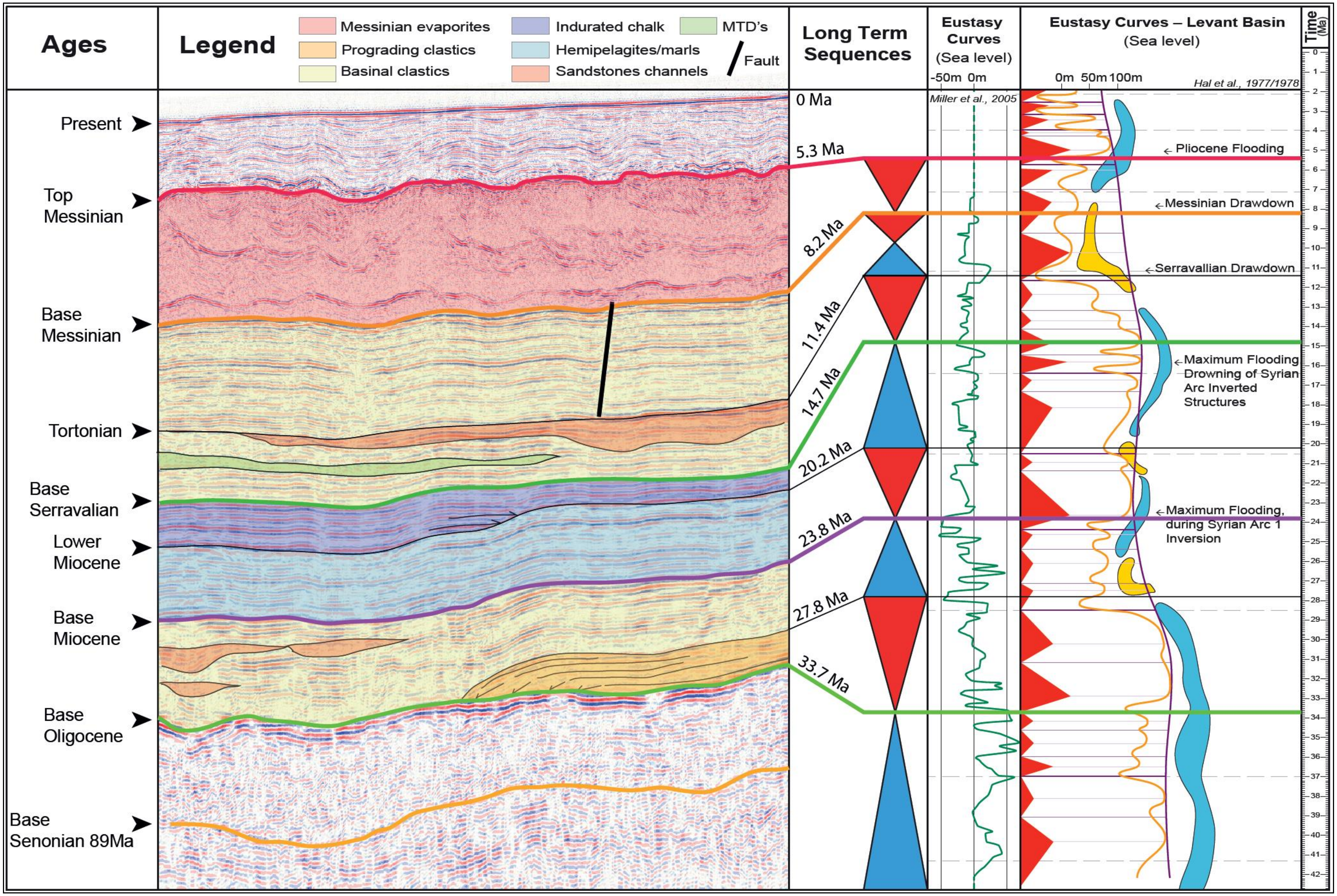

Figure 5. Location of the different interpreted horizons (arrows) in a representative seismic section trending west-east, towards the eastern margin), and their correlation with the eustatic variations and stratigraphic cycles. These horizons, as well as the intermediate ones, correspond to the times at which simplified deposition environment maps (e.g. Figure 4A) were drawn and used for constructing the SFM for the Eastern-Mediterranean region.

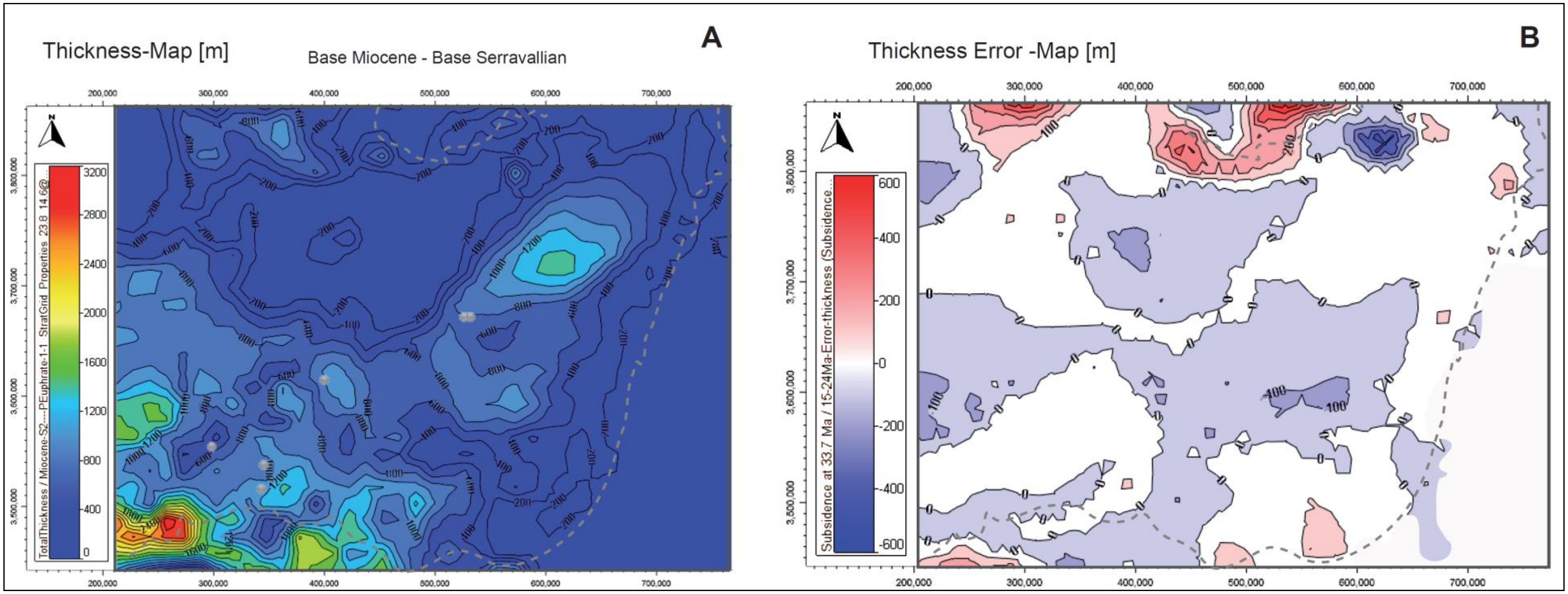

Figure 6. Simulated thickness for the Lower Miocene SFM across the East-Mediterranean study area and the Thickness Error Map showing the difference between the related isopach map (for the same interval, from the depth-converted seismic data) and modeling results. In most of the study area, the thickness error does not exceed 100m, indicating an acceptable match.

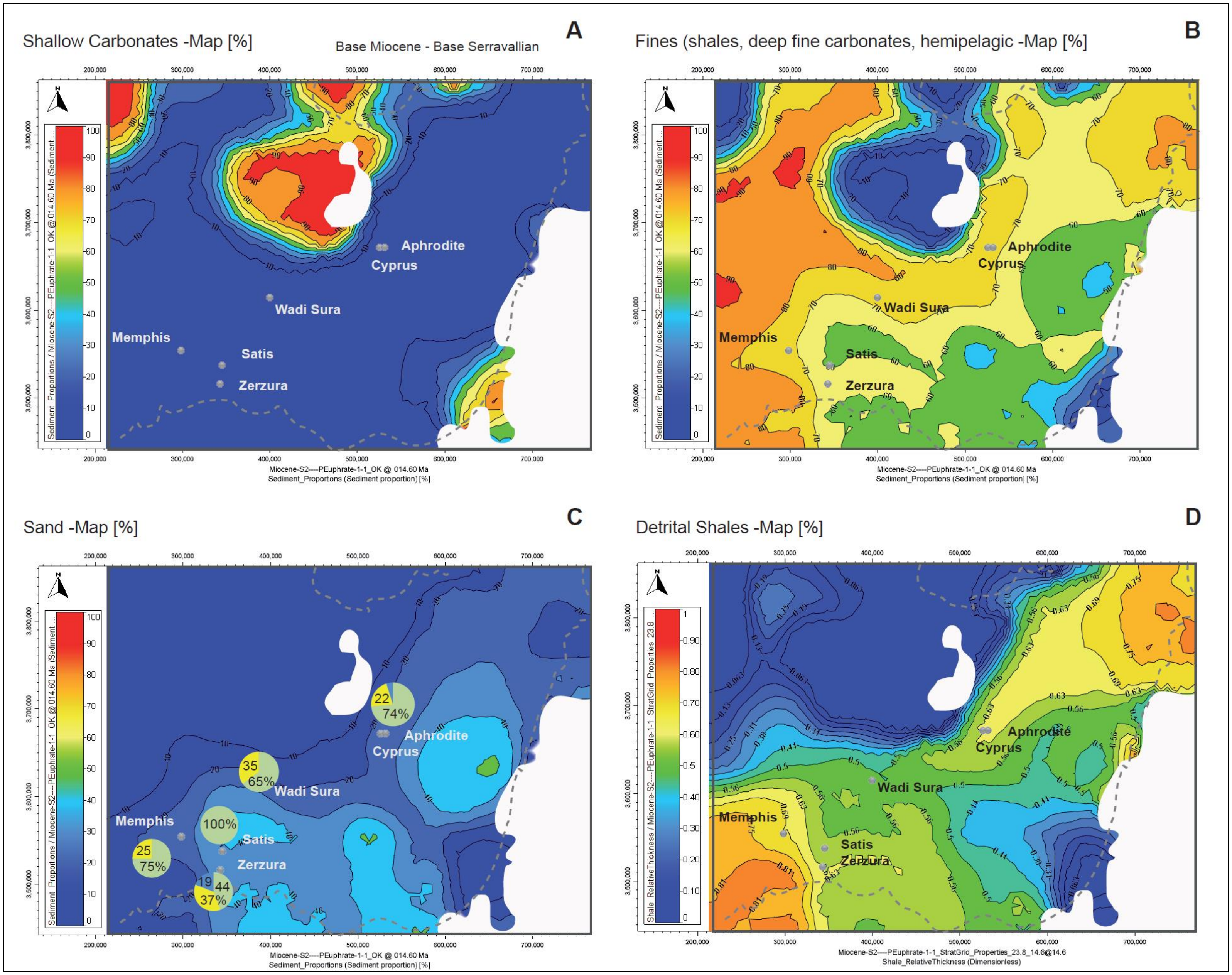

Figure 7. Average sediment proportions maps, output of the constructed SFM for the East-Mediterranean region (A: %shallow carbonates; B: %fines; C: %sand; and D: %detrital shales). The percentage of detrital shale is a part of the fines but is represented for its implications on the detrital organic matter distribution. Pie charts of similar lithology types are indicated in C (yellow: sand; green: shale; blue: carbonates).

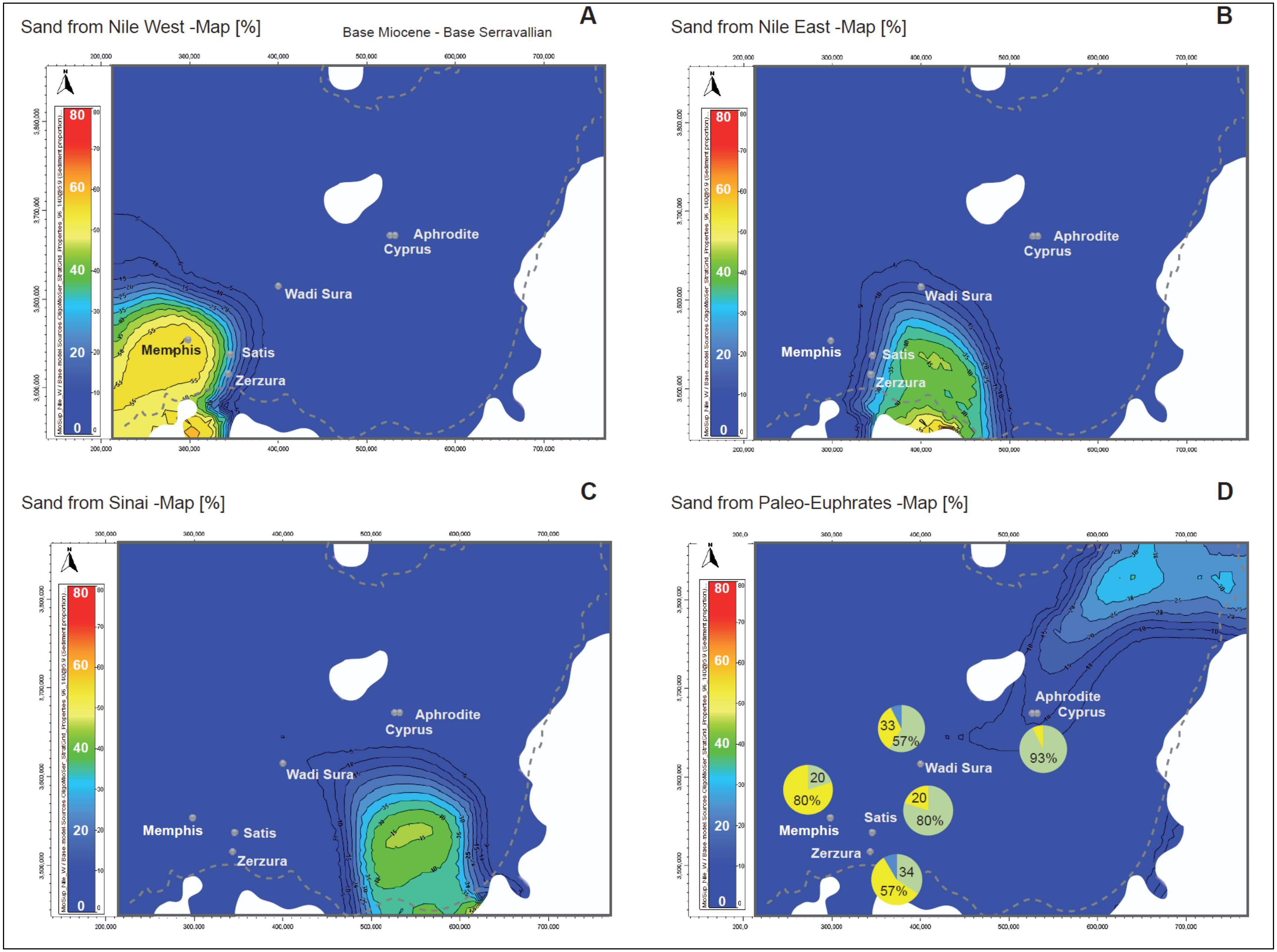

Figure 8. Distribution of the sands from the different sources in the area of interest for the Upper Miocene interval. The colour code goes from zero (dark blue) to 80% (red), and the isocontour interval is 5%. White: negligible total thickness. Sediment lithologies distributions in wells for the same interval are represented by pie-charts in (D) – yellow: sand; green: shale; and blue: carbonates

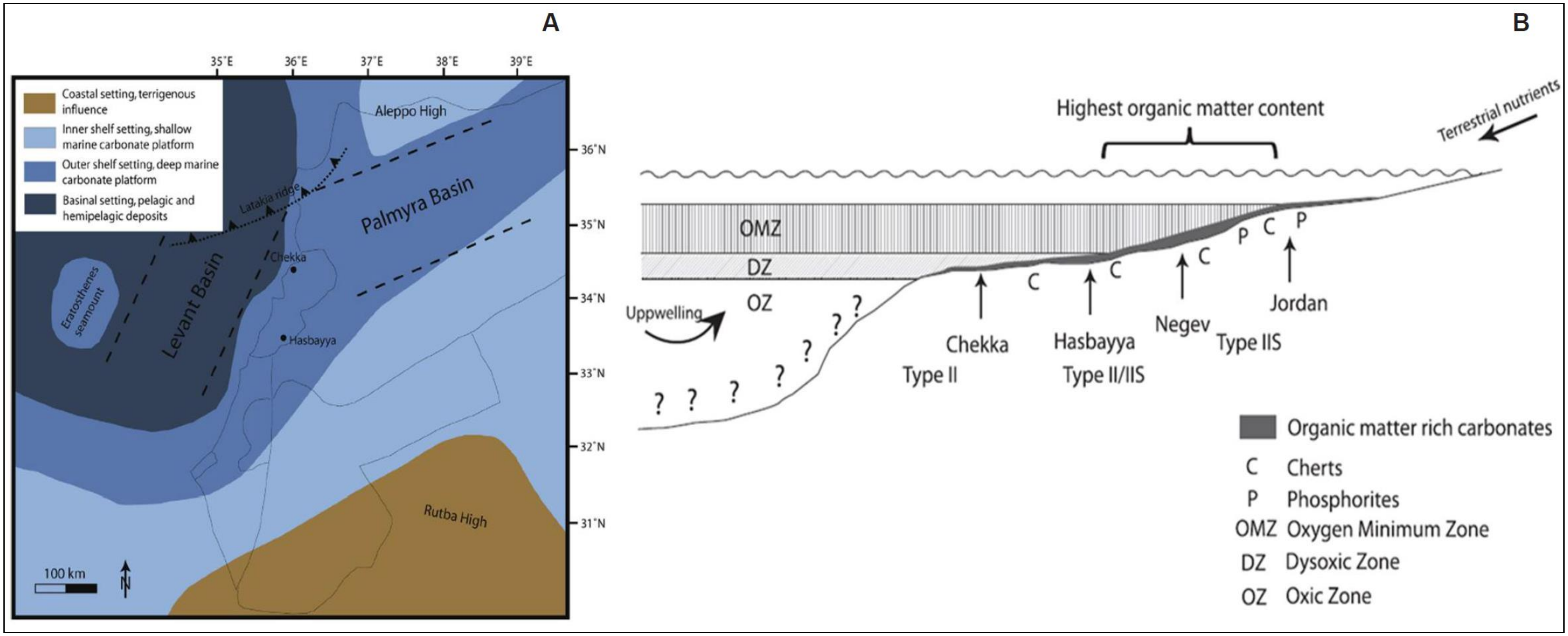

Figure 9. (A) Simplified depositional map for the Upper Cretaceous (Campanian) organic-rich carbonates including known source rocks in the Levant region; (B) Conceptual depositional model for the Campanian – Lower Maastrichtian organic matter rich carbonates (from Bou Daher et al., 2015). Organic sulfur compounds increasing with TOC (type II and IIS) suggest strong anoxic to euxinic environments. Source rock quality decrease from the shelf to the deeper part of the basin.

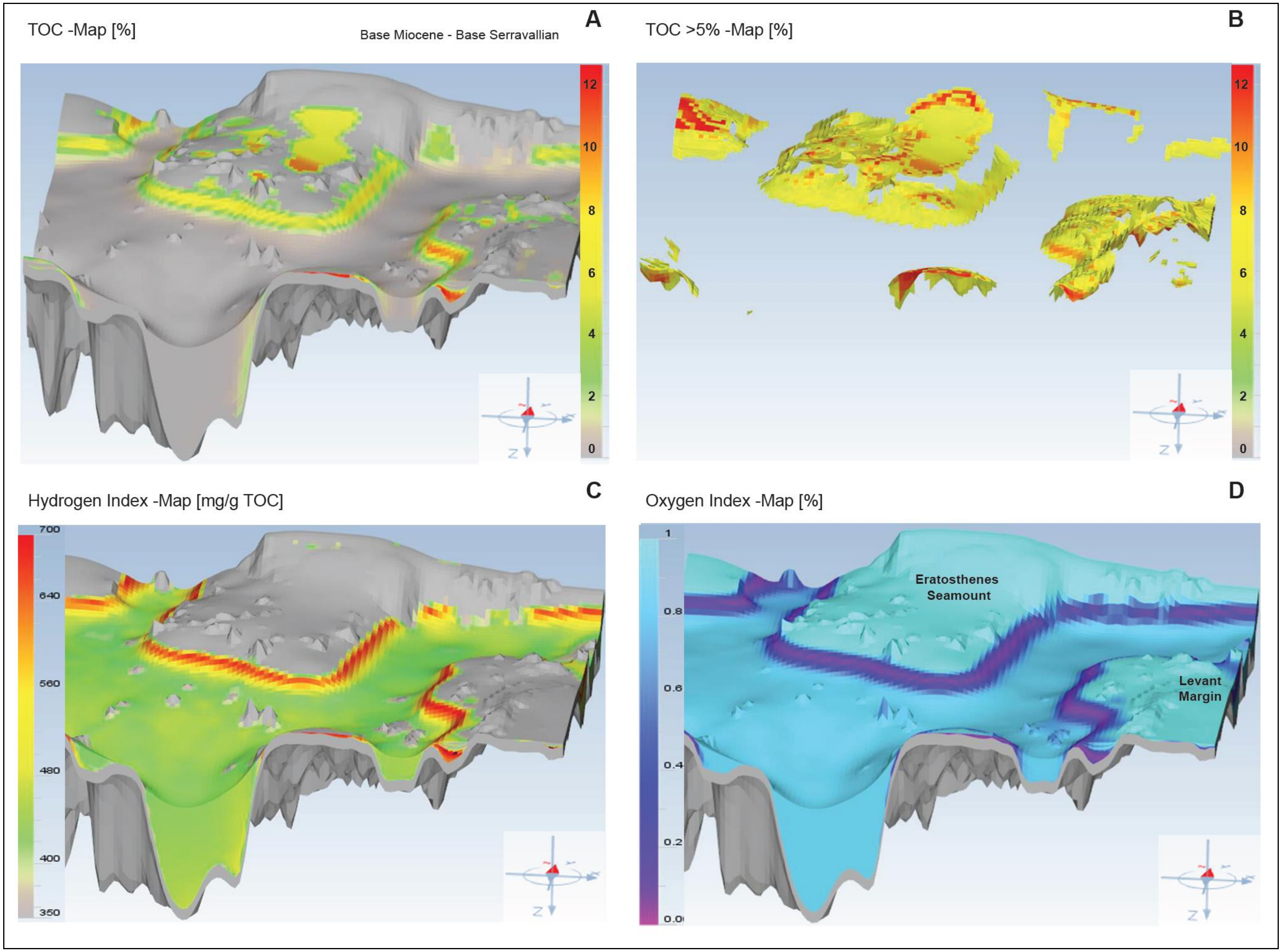

Figure 10. Simulation results of initial TOC% (A), TOC>5% (B), hydrogen index (mg/g TOC; C), and oxygen index (D) for the Senonian-Eocene package, demonstrating the upwelling depositional environment and source rocks belts that are controlled by primary production and bathymetry.