



HAL
open science

The accretion of the Levant continental shelf alongside the Nile Delta by immense margin-parallel sediment transport

Elchanan Zucker, Zohar Gvirtzman, Didier Granjeon, Daniel Garcia-Castellanos, Yehouda Enzel

► To cite this version:

Elchanan Zucker, Zohar Gvirtzman, Didier Granjeon, Daniel Garcia-Castellanos, Yehouda Enzel. The accretion of the Levant continental shelf alongside the Nile Delta by immense margin-parallel sediment transport. *Marine and Petroleum Geology*, 2021, 126, pp.104876. 10.1016/j.marpetgeo.2020.104876 . hal-03150787

HAL Id: hal-03150787

<https://ifp.hal.science/hal-03150787v1>

Submitted on 24 Feb 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 The accretion of the Levant continental shelf alongside the Nile 2 Delta by immense margin-parallel sediment transport

3 **Elchanan Zucker**^{1,2}, **Zohar Gvirtzman**^{1,2}, **Didier Granjeon**³, **Daniel Garcia-Castellanos**⁴,
4 **Yehouda Enzel**¹

5 ¹ *The Fredy and Nadine Herrmann Institute of Earth Sciences, The Hebrew University of*
6 *Jerusalem, Jerusalem 91904, Israel*

7 ² *Geological Survey of Israel, Yesha'yahu Leibowitz 32, Jerusalem, Israel*

8 ³ *Department of Geology-Geophysics-Geochemistry, IFP Energies nouvelles, 1 à 4 avenue de*
9 *Bois, Préau, 92852 Rueil-Malmaison, France*

10 ⁴ *Instituto de Ciencias de la Tierra Jaume Almera, ICTJA-CSIC, Barcelona, Spain*

11

12 **ABSTRACT**

13 Following the termination of the Messinian salinity crisis ~5.3 million years ago, massive
14 sedimentation in the Eastern Mediterranean Sea formed the huge Nile Delta. Alongside delta
15 propagation, a continental shelf was accreted along the Levant margin. For several decades it was
16 assumed that these two sedimentary structures were closely connected. Levant shelf deposits are
17 composed of Nile-derived sediments and present-day measurements show that sand is currently
18 being transported alongshore from the Nile Delta to offshore Israel. This study reexamines the
19 existing paradigm about sediment transport and shelf-delta connection. We show that longshore
20 sand transport is just a small part of a much larger process termed here margin-parallel sediment
21 transport (MPST). Sand is transported in a nearshore shallow-water belt where marine currents are
22 highly energetic. At the same time, shale is transported at greater depths over the deeper shelf and

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

23 the continental slope where marine currents are weaker. To model the accretion of the Levant shelf
24 alongside the Nile Delta we use a 3D, diffusion-based, stratigraphic modeling tool (DionisosFlow)
25 with a new module representing MPST. Our results show that margin-parallel transport of silt and
26 clay in the deeper waters accounts for the bulk of deposition offshore Israel and is responsible for
27 the development of the Levant shelf. Moreover, though MPST has begun coevally with delta
28 formation, massive accretion of the Levant shelf was delayed by 2-3 My. Initially, a continental
29 shelf formed offshore Sinai, then offshore Israel, and most recently along the Lebanon coast. Our
30 model also demonstrates the significant lithological differences observed between sedimentation
31 in front of the Nile River mouth and along adjacent continental margin. High energy down slope
32 sediment transport carries sand, silt, and clay, whereas margin-parallel currents are relatively weak
33 and carry mainly silt and clay. One exception within the margin-parallel system is the highly
34 energetic nearshore current that transports sand. Thus, we point out, MPST is an efficient separator
35 between shale and sand.

36
37
38 **INTRODUCTION**

38 The Nile Delta and its associated sedimentary cone are the largest in the Mediterranean Sea and
39 one of the largest worldwide (Fig. 1). Five and a half million years ago, during the Messinian
40 salinity crisis (Hsü et al., 1973; Ryan and Cita, 1978), the Mediterranean sea-level dropped and an
41 approximately 1.5-km deep canyon (EoNile) incised into the Egyptian continental margin of the
42 Mediterranean (Barber, 1981; Said, 1981; Fig. 2A). After this crisis, at the beginning of the
43 Pliocene (5.3 Ma), when normal marine conditions resumed, sediments quickly filled this EoNile
44 canyon and prograded from the canyon mouth into the open sea (Said, 1981; Sestini, 1989; Stanley
45 and Warne, 1998). Today, after 5.3 My of progradation, the modern Nile Delta and its deep-sea

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

fan and sedimentary cone spread ~200 km Northward from the ancient canyon mouth and ~400 km in an east-west direction (Fig. 1). The thickness of the Pliocene-Quaternary (PQ) sediments building the Nile Delta and cone reaches ~4000 m in its depocenter offshore Egypt (Fig. 2B). Alongside this PQ delta development, a continental shelf was accreted in the southeastern Mediterranean, offshore Sinai and Israel (termed here the Levant shelf, Fig. 1). The shelf deposits offshore Israel are composed of Nile-derived sediments. It was hypothesized that the accretions of both these features are coeval (Buchbinder and Gvirtzman, 1976; Emery et al., 1960; Gvirtzman, 1970; Nachmias, 1969; Shukri, 1950; Shukri and Philip, 1960). Using sedimentological and seismic data, numerous studies support that sediment transport is in a coast-parallel direction (Buchbinder et al., 1993; Carmel et al., 1985; Davis et al., 2012; El Din and Mahar, 1997; Emery et al., 1960; Emery and Bentor, 1960; Goldsmith and Golik, 1980; Golik et al., 1999; Golik, 2002, 1997, 1993; Klein et al., 2007; Manohar, 1981; Perlin and Kit, 1999; Schattner et al., 2015; Schattner and Lazar, 2016; Shoshany et al., 1996; Stanley, 1989; Zaghloul et al., 1982; Zviely et al., 2007, 2006). In addition, present day measurements and estimations of sediment fluxes indicate that effective longshore transport delivers large amounts of sand mainly northwards along the Nile-Levant littoral cell (e.g., Rosentraub and Brenner, 2007; Zviely et al., 2007 and references within). These observations and summaries have focused most of the research for several decades on the near-shore sand transport (Fig. 1, Black arrows). However, as new observations for the relative young age (mainly Pleistocene) of the Levant continental shelf become available (Bar, 2009; Bar et al., 2013; Ben-Zeev and Gvirtzman, 2019; Elfassi et al., 2019), we question this existing view. If the Levant shelf coevolved alongside the Nile cone, why did its accretion start much later? The answer to this question presents major implications for understanding sediment transport along continental margins, in general, and

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

69 particularly to the sedimentary source of the Levant shelf. Since current sediments moving over
70 the Levant shelf do derive from the Nile Delta, what are the main controlling processes that
71 transport sediments along the continental margin and what types of sediments are transported by
72 these processes?

73 In what follows we develop, first the concept, and then the quantification of margin-parallel
74 sediment transport (MPST) not limited to sand grain size and not limited to the nearshore belt.
75 Earlier evidence regarding a mid-shelf mud-dominated belt shaped by oceanographic processes,
76 were documented in the Gulf of Lions at the mouth of the Rhone River (Rabineau et al., 2005; and
77 references therein) and suggested for the Levant margins by Schattner et al. (2015). Here, we
78 further develop this concept exploring the hypothesis that deeper and distal currents first conveyed
79 large amounts of clays and silts along the ancient continental margin and only then, after generating
80 this clay and silt foundation, the shelf was established on top with sand transport, as we see it
81 today. I.e., we hypothesize that only after filling the quite large accommodation space with the
82 finer grains and generating the shallow water environment, sand could have started to accumulate
83 as we observe today on the present-day shelf.

84 Here, we test this hypothesis using the stratigraphic simulation software DionisosFlow (Granjeon,
85 1997, 2014; Granjeon and Joseph, 1999). DionisosFlow is a state-of-the-art, 3-D stratigraphic
86 modeling tool that produces synthetic stratigraphy according to prescribed subsidence history, sea-
87 level variations, sediment supply, water discharge, and sediment distribution by diffusion. The
88 problem is that to date, DionisosFlow has no module to simulate margin-parallel transport at
89 shallow (alongshore) or deep (off shelf) waters. Therefore, we added to it a new module that may
90 answer some of the above questions. The new module includes a simple advection law in which
91 sediment flux is defined by the user, and deposition rate is calculated from this flux accounting for

1
2
3
4 92 mass conservation. This volumetric exercise is constrained by ages and thicknesses of units. The
5
6 93 sediment flux maps obtained by trial and error, indicate how much sediments pass through each
7
8
9 94 point in the basin at various modelled time steps.

10
11 95 To account for lithological variations across the margin we also develop a depth-dependent
12
13 96 function for the sand/shale ratio for the deposited sediments and the resulting stratigraphic section
14
15
16 97 is calibrated by well data. Our results in terms of sediment flux and sand/shale ratio can be the
17
18
19 98 basis for future physically based simulations that can better examine how surficial, intermediate,
20
21 99 and deep marine currents transport sand and shale along various prescribed morphologies of
22
23 100 continental margins.

24
25
26 101

27 28 102 **GEOLOGICAL BACKGROUND**

29 103 Sediment transport along the Nile littoral cell

30
31 104 The Nile littoral cell is one of the longest in the world with shorelines extending along ~700 km
32
33 105 from the Nile Delta to northern Israel (Inman and Brush, 1973; Inman and Jenkins, 1984). The
34
35
36 106 source of this littoral cell is in the Nile River, it passes along the shallow (up to 30 m deep)
37
38
39 107 nearshore water belt of the Levant, with current northernmost terminal deposition at the Haifa Bay
40
41
42 108 (Buchbinder et al., 1993; Carmel et al., 1985; and the other references quoted in the above
43
44
45 109 introduction). Some sediments that are transported northward turn west, fall off the shelf and then
46
47
48 110 deposited along the continental slope of the Levant (Ben-Gai et al., 2005; Schattner et al., 2015;
49
50
51 111 Schattner and Lazar, 2016; see data about Units 3-4 below). In addition to the nearshore transport,
52
53 112 Woodward et al. (2007) showed that present-day Nile sediments extend across the Levant and
54
55 113 Herodotus basins as far as Rhodes, Crete and north of Cyprus.

56
57
58
59
60
61
62
63
64
65

1
2
3
4 114 Longshore transport usually refers to the net movement of coastal and nearshore sand parallel to
5
6 115 the shore (Seymour, 2005). This transport is either by currents carrying sand in suspension or by
7
8
9 116 waves on the seabed (i.e., bedload transport). It is easier to measure concentration of suspended
10
11 117 sediment, but quite difficult to measure the bedload component. Quantitative estimates of
12
13 118 longshore transport, therefore, are based commonly on inferences from the suspended sediment
14
15
16 119 concentrations indicating that longshore transport is at a maximum under the breaking waves and
17
18
19 120 in the swash zone on the beach face (Seymour, 2005).
20
21

22 121 The annual longshore flux of sand from the Nile Delta (Fig. 1) eastward is estimated at about 10^6
23
24 122 $\text{m}^3 \text{yr}^{-1}$ (Inman et al., 1993, 1976; Inman and Jenkins, 1984). Offshore Sinai, this flux slightly
25
26
27 123 decreases to $\sim 8.5 \times 10^5 \text{ m}^3 \text{yr}^{-1}$ and $\sim 7 \times 10^5 \text{ m}^3 \text{yr}^{-1}$ off Port Said and off El Arish, respectively
28
29
30 124 (Inman et al., 1976). This flux is estimated at $4.5 \times 10^5 \text{ m}^3 \text{yr}^{-1}$ and $\sim 10^5 \text{ m}^3 \text{yr}^{-1}$ at Ashkelon and
31
32 125 Herzlia (Fig. 1), respectively (Perlin and Kit, 1999). Only a small portion ($\sim 8.5 \times 10^4 \text{ m}^3 \text{yr}^{-1}$) of the
33
34 126 initial sand flux reaches the currently considered final sink at Haifa Bay (Zviely et al., 2007).
35
36

37 Different Hypotheses 38

39 128 An important point was raised by Schattner et al. (2015) who argued that longshore transport is
40
41
42 129 limited to the shallow (<30 m depth) and narrow (350-400 m) near-shore belt and cannot explain
43
44 130 the deposition at greater depths. In addition, we stress that longshore transport only moves sand
45
46
47 131 and silt, whereas the PQ shelf is mainly composed of shales (Yafo Formation) with only its topmost
48
49 132 part composed of sand (Kurkar Group, e.g., Gvirtzman and Buchbinder, 1978).
50

51 133 Based on bathymetric, seismic, and oceanographic data, Schattner et al. (2015) suggest that since
52
53
54 134 the Pleistocene-Holocene transition ($\sim 11 \text{ ka}$) fast water currents, termed the Levant Jet System
55
56 135 (LJS; Fig. 1, red arrows), mobilizes sediments along the continental margin not only nearshore,
57
58
59 136 but also in intermediate and deep waters (between 0 and 400 m water depths).
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

137 Timing of the Levant shelf accretion

138 A general PQ age was assigned for the continental shelf offshore Israel (e.g., Ben-Avraham, 1978;
139 Ben-Gai et al., 2005; Gvirtzman and Buchbinder, 1978; Tibor et al., 1992). However, recent
140 reexaminations of the biostratigraphy led Bar et al. (2009) to propose that most of the shelf was
141 accreted later and that is composed primarily of Pleistocene sediments. This relatively young age
142 is supported by Elfassi et al. (2019) and Ben-Zeev and Gvirtzman (2020) who demonstrate that
143 after the Pliocene the pattern of sedimentation in the Levant Basin changed drastically; from
144 thicker accumulation in the deep basin to thicker accumulation along the continental margin.
145 Particularly interesting and crucial is the observation that the preferred deposition along the margin
146 was delayed by 2-3 My after the commencement of the Nile Delta formation offshore Egypt (Ben
147 Zeev and Gvirtzman, 2020). This, once more, raises the question why did margin-parallel sediment
148 transport and shelf accretion begun so late? Why were sediments not transported along the Sinai-
149 Israel margin already during their initial supply in the Pliocene?
150 Hypothetically, this can be answered by proposing that external forcing such as climate or ocean
151 circulation could have triggered margin-parallel marine currents only in the Pleistocene.
152 Alternatively, we hypothesize here, sediment transport along continental margins is a strong depth-
153 dependent process that becomes more effective under certain bathymetry conditions. In the case
154 of the Nile, we hypothesize that only after 2-3 My of delta accretion, the continental margin
155 offshore Sinai could have become an effective conduit for sediment transport and large amounts
156 of sediments started arriving to offshore Israel.

157 **METHODS**

158 **Diffusion modeling in sediment transport**

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

159 Since the early work of Culling (1960) and Young et al. (1973) and with the lack of specific
160 information on the actual terms in physical sedimentology processes, diffusion laws have been
161 used in geomorphology and geology to represent large-scale, spatially-averaged transport of
162 sediment by creep, overland flow, and channel flow (e.g., Begin et al., 1981; Paola et al., 1992).
163 Diffusive sediment transport states that the transport capacity of a water flow is proportional to the
164 local basin slope and water discharge. It has been used in modeling sediment transport along
165 alluvial fans, rivers and floodplains (Begin et al., 1981; Ben Moshe et al., 2008; Coulthard, 1999;
166 Murray and Paola, 1994; Parker et al., 1998), mountains, foreland basins (Jordan and Flemings,
167 1991; Tucker and Slingerland, 1994) and passive margins (Rabineau et al., 2005).

168 Since the 1980s, when seabed morphology was shown to resemble lowland landscapes (e.g.,
169 Adams et al., 1998; Galloway, 1998; Mitchell and Huthnance, 2007; Schlager and Adams, 2001),
170 laws of landscape evolution were extended to simulating progradation of deltas (Kenyon and
171 Turcotte, 1985) and continental shelves (Granjeon, 1997; e.g., Jordan and Flemings, 1991;
172 Kaufman et al., 1991; Mitchell and Huthnance, 2008; Rivenæs, 1997).

173 DionisosFlow is a 3D stratigraphic forward modeling tool aiming to simulate geometry and facies
174 of sedimentary units on a scale of several tens to hundreds of kilometers and over geological
175 intervals of 10^3 - 10^8 years (Granjeon, 2009; Granjeon and Joseph, 1999; Granjeon and Wolf, 2007);
176 these are the scales of the problem at hand. At these spatial and temporal scales and the needed
177 resolution, unfortunately, there is practically no way to apply physically based modeling. Using a
178 diffusive approach for sediment transport (Gerber et al., 2009; Kaufman et al., 1991; Lai and
179 Capart, 2007; Mitchell and Huthnance, 2008; Schlager and Adams, 2001; Spinewine et al., 2011;
180 Steckler et al., 1999; Van Heijst et al., 2001), DionisosFlow averages the cumulative mass
181 movement in time steps that combine many individual flows. In this way, DionisosFlow, for

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

182 example, ignores individual turbidites, but considers their cumulative mass movement. Similarly,
183 and important for our study, it does not account for the discontinuity between fluvial and submarine
184 systems in cases that sediments temporarily settle down on the delta front or inner shelf and only
185 later are transported downslope by gravity-driven processes. For simplicity, it assumes that flows
186 continue seaward either directly by hyperpycnal flow or by slope failures.

187 DionisosFlow formulates two large-scale sedimentary processes: slow creep and fast transport
188 driven by water discharge (Tucker and Slingerland, 1994; Willgoose et al., 1991). Creep is
189 simulated by a linear, slope-driven diffusion equation (i.e., transport is proportional to gradient).
190 Water-driven flow is simulated by a non-linear water- and slope-driven diffusion equation.
191 Combining the driving equations of these transport laws (Granjeon, 2014; Granjeon and Joseph,
192 1999) leads to the sediment transport equation:

$$(1) \quad Q_S = -(K_S + K_w Q_w^n S^{m-1}) \vec{\nabla} h$$

194 Where Q_s is sediment flux [km^2/yr]; h [m] is topographic elevation; K_s and K_w [km^2/yr] are the
195 diffusion coefficient, respectively for slow creep transport and water flow process; Q_w is
196 dimensionless local water discharge at the cell; S is local gradient of basin slope; n and m are
197 constants, usually ranging between 1 and 2. Transport equation and mass conservation are applied
198 to each grain size, leading to definition of local sedimentation or erosion. Sedimentation occurs
199 where transport capacity decreases (by decreasing gradient or slower water flow) and erosion
200 occurs where transport capacity increases.

201 The capability of DionisosFlow to simulate the production of large-scale systems such as deltas,
202 fluvial plains, shelf plains, incised valleys, and deep water systems was tested and validated in
203 several studies including, for example: (1) the XES 02 flume experiments designed to reproduce

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

204 fluvial plain and incised valleys (Granjeon, 2014); (2) Synthetic case studies built to investigate
205 the impact of millennial-scale climatic and eustatic cycles on the growth of a delta and the
206 associated fluvial channel belts and incised valleys (Csato et al., 2014; Rabineau et al., 2006,
207 2005); (3) On modern delta, shelf, and deep-water turbiditic systems such as the Niger Delta
208 (Laurent et al., 2020) and the Orinoco deep-sea fans (Deville et al., 2015).

209 **Simulating margin-parallel sediment transport**

210 The margin-parallel transport module developed here begins with a sediment flux map describing
211 the intensity [km²/My] of the flux transported through a given location in a coast-parallel,
212 dynamically updated direction, which evolves with time. The flux obeys a simple user-defined
213 advection law that accounts for mass conservation, i.e., when the flux decreases, sediments depart
214 from the suspension plume and deposit. The rate of deposition, SED [km/My] is:

$$(2) \quad \begin{cases} \vec{q}_{mp} = Q_{mp}(x, y) \cdot \vec{n} \\ SED(x, y) = -div(\vec{q}_{mp}) \end{cases}$$

216 With q_{mp} the margin-parallel sediment flux [km²/My], Q_{mp} the user-defined intensity of this flux,
217 n a unit vector parallel to the closest shoreline [dimensionless], and SED [km/My] the
218 sedimentation rate induced by this margin-parallel sediment transport.

219 The sand/shale ratio within the deposited sediment is computed from a given depth-dependent
220 function, derived from observations. In addition to this deposition rule, we use the classical
221 diffusion equations to transport sediments as soon as they reach the sea floor. By the end of this
222 computation, we obtain a stratigraphic layer whose thickness is compared to observations. By trial-
223 and-error (i.e., sensitivity over a range), the flux map is corrected, and simulations rerun until they
224 satisfy borehole and geophysical observations.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

225

226 **Data**

227 Basin structure

228 The stratigraphic PQ sequence simulated here is bounded by the present-day bathymetry at its top
229 and the base Pliocene surface at its bottom. Bathymetry (Fig. 1) is taken from ETOPO1 (Amante
230 and Eakins, 2009). The base Pliocene structure map (Fig. 2A) is after Zucker et al., (2019). The
231 PQ isopach (Fig. 2B), which is the subtraction of Fig. 2A from Fig. 1, defines a major depocenter
232 under the Nile Delta and cone (reaching a thickness of 4 km) and a secondary and connected, local
233 depocenter under the Israeli coastal plain and shelf (reaching a thickness of 2 km). Resolving these
234 two depocenters - a delta and an adjacent continental shelf - are the targets of this simulation.

235 Paleo-bathymetry

236 For the paleo-bathymetry at 5.3 Ma (Fig. 3A), which is the surface on which we begin to model
237 deposition, we used the base Pliocene map corrected for the load of the overlying sediments (PQ
238 section). For this flexural backstripping procedure, we assumed an average density of 2000 kg/m^3
239 for unloaded sediments, adopting a pure elastic thin plate approach to isostasy and an elastic
240 thickness of 30 km, a relatively large value consistent with the old tectonothermal age of the
241 northeast African margin. For the decompaction of the underlying sediments, we considered an
242 approximately 10-km thick pre-Pliocene section. The decompaction results are very insensitive to
243 the depth of the base of this layer because only the upper ~2 km retains a significant porosity.
244 Details about this pseudo-3D (planform) flexural backstripping procedure are described in Garcia-
245 Castellanos et al. (2003) and in Amadori et al. (2018). To correct for post-Miocene tectonics, the
246 sediment-unloaded map was smoothed in the area of the Rosetta and Tamsah faults (Fig. 2A),

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

247 which were active in the PQ (Aal et al., 2000). In addition, the northern Levant Basin that subsided
248 towards the Cyprus Arc during the Plio-Quaternary (Ben-Avraham, 1978; Kempler, 1998;
249 Robertson, 1998; Schattner, 2010) was uplifted by ~200 m. The uncertainty of post Miocene
250 tectonics is discussed below.

251 Subsidence

252 Subsidence (Fig. 3B) is calculated in the model by taking the difference between the
253 paleobathymetry at 5.3 Ma (Fig. 3A) and the present-day base Pliocene surface (Fig. 2A), the
254 surface which should be obtained at the end of simulation. Average subsidence rate for the entire
255 simulation is taken as the total calculated subsidence divided by 5.3 My. This assures that at the
256 end of the simulation, the modeled and observed base Pliocene surfaces will coincide to allow
257 comparing the modeled and observed bathymetries (Fig. 3C).

258 Sediment supply

259 A first order approximation for sediment supply is derived from the total volume of the PQ isopach
260 (Fig. 2B) divided by 5 million years (i.e., 70,330 km³/My). From this number we subtract biogenic
261 carbonates produced in the water column. Well samples and logs from the Israeli coastal plain
262 indicate that the Plio-Quaternary Yafo Formation contains ~10% calcite in the form of micro- and
263 nano-fossils (Gvirtzman, 1970). Considering that 10% of the total PQ volume did not arrive from
264 the clastic feeders, we initially applied 90% of the total deposited volume. After a set of trials
265 constrained by the sediment thickness maps, we applied an average value of 64,417 km³/My
266 (~91.5%) to represent sediment supply by the Nile River for the entire duration of the model. It is
267 interesting to note that this average value obtained from sediment volume is on the same order of
268 magnitude as the sediment yield presently measured at the mouth of the Nile River (60,000

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

269 km³/My, Syvitski and Milliman, 2007). Sand/shale ratio for Nile sediments was taken as 20% and
270 carbonate production was taken as 5,910 km³/My.

271 Margin-parallel transport

272 Regarding present-day measurements of longshore transport (references above) it should be noted
273 that they refer only to the sand fraction (1000 km³/My from Nile Delta to Sinai; 850 km³/My at
274 Port Said, 700 km³/My at El Arish; 450 km³/My at Ashkelon; 100 km³/My at Herzlia; and 85
275 km³/My arrive to Haifa Bay). The big unknown in our simulation is the total amount of sediments
276 (sand to clay) moving along the continental margin nearshore, on and off the shelf.

277 A lower limit for the total sediment flux along the Levant continental margin is obtained from the
278 average deposition rate along the Israeli margin since the early Pliocene. Considering a rectangular
279 200 km (Rafah to Southern Lebanon) by 20 km (approximately the mean width of shelf) by 2 km
280 (thickness of PQ section offshore Tel Aviv), the total volume of the Israeli shelf is about 8,000
281 km³. Dividing this by 5.3 million years, yields ~1500 km³/My. This set a minimal constraint for
282 the flux that entered the Israeli margin from offshore Sinai, because the actual flux includes
283 sediments that continued northward to offshore Lebanon. No siliclastic sediments can enter the
284 shelf from the onshore carbonate platform of the Levant. It is interesting to note that this estimated
285 minimum value of total sediment flux triples the sand flux (~500 km³/My) currently entering to
286 Israeli margins at Rafah (the southern boundary of the Gaza strip between El Arish and Ashkelon).
287 Below, the unknown flux of sediments along the Levant continental margin is modeled by trial-
288 and-error.

289 Water discharge

290 Present day water discharge of the Nile River is 2830 m³/s (Milliman and Syvitski, 1992). The
291 paleo-discharge of the ancient Nile River can be further, but only roughly, constrained by

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

292 paleogeographic (drainage area) and paleoclimatic (rain) considerations and compared with
293 modern rivers worldwide that have similar drainage areas (Dai and Trenberth, 2002; Milliman and
294 Syvitski, 1992; Syvitski and Milliman, 2007). Although we are aware of the impact of Quaternary
295 climatic changes on the Nile discharge, for the lack of data and for the sake of simplicity, we took
296 the present-day value as a constant throughout the entire duration of the model.

297
Diffusion coefficients

299 Efficiency of sediment transport depends on difficult-to-quantify factors such as grain size,
300 lithology, roundness, water depth, water discharge, vegetation, river type and more. In practice,
301 coefficients used to model various basins do not always express the same factors and their values
302 vary greatly from case to case. One reason for this large range is that efficiency of diffusion can
303 be controlled either by the diffusion coefficient or by the amount of water pushing the sediments
304 (Equation 1). Accordingly, Gvirtzman et al. (2014) and Hawie et al. (2015) showed that by
305 constraining water discharge, the range of possible diffusion coefficients is narrowed. Recent
306 stratigraphic forward models run at a basin scale, using diffusion laws to simulate slow creep and
307 water flow processes, and calibrated on seismic and well log data suggested the following range
308 of values (Table 1): K_s (slow creep) is about 0.001 to 0.05 km²/ky for sand, and 0.001 and 0.1
309 km²/ky for shale; while K_w (water flow process) is about 50 to 2,000 km²/ky for sand in terrestrial
310 environments, 100 to 4,000 km²/ky for shale in terrestrial environments, 0.01 to 20 km²/ky for
311 sand in marine environments, and 0.063 to 100 km²/ky for shale in marine environments (Csato et
312 al., 2014, 2013; Gvirtzman et al., 2014; Harris et al., 2016; Hawie et al., 2018, 2017; Zhang et al.,

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

313 2019). Here we take the present-day water discharge of the Nile as a starting point and identify the
314 best-fit diffusion coefficients of shale and sand inside these ranges by trial and error.

315 Sand/shale ratio

316 Present-day measurements of sediment composition at the seabed offshore Israel (Almogi-Labin
317 et al., 2012) indicate the presence of three coast-parallel belts (Fig. 4A): (a) An almost pure, well-
318 sorted sand belt from the shoreline to a water depth of 35 m. (b) A silt-dominated belt from water
319 depths of 35-100 m in which the amount of silt gradually grows from a few percent at a depth of
320 35 m to 85% at depths of 60-100 m. The rest is shale; this shale represents only a few percent of
321 the total sediment volume near the coast and 10-15% at depths of 60-100 m. (c) A shale dominated
322 belt at depths >100 m, where sand is negligible. For modeling we simplified these observations to
323 only two components (sand and shale) with a depth-dependent ratio shown in Fig. 4B.

324
325 **Modeling strategy**

326 The first objective of this modeling study is to obtain the diffusion parameters that explain the Nile
327 Delta formation with the given values of water discharge and sediment supply. For this, we first
328 use DionisosFlow without the added new module of MPST. Considering that the base of the
329 simulated PQ package is forced to coincide with the observed base Pliocene surface (see above
330 constraints for subsidence), testing the model is carried out by comparing the modeled and
331 observed bathymetries. If bathymetry fits, sediment thickness also fits. This stage of the modeling
332 is expected to provide a rough fit between the model and observations at the delta area, but not at
333 the Levant margin.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

334 The second objective is to simulate the formation of the Levant shelf. For this, we apply all model
335 parameters realized in the first stage (and particularly the diffusion coefficients) and rerun
336 DionisosFlow; this time the runs include the upgraded module for margin-parallel transport. By
337 numerous trial-and-error runs, we identify the sediment flux maps that yield the better fit between
338 model and observation. For calibration of the lithostratigraphy, we use a published
339 lithostratigraphic section that distinguishes the sandy Kurkar Group from the shales of the Yafo
340 Formation (data from Gvirtzman and Buchbinder, 1978). For chronostratigraphic calibration, we
341 use the subdivision of the PQ section offshore Israel identified for four dated seismic units (Ben-
342 Zeev and Gvirtzman, 2019; Elfassi et al., 2019).

RESULTS

Stage 1: basic model without the margin-parallel sediment transport (MPST)

346 Fig. 5 presents the simulated bathymetry from 5.3 Ma to the present, using the basic model without
347 the MPST. The parameters for sediment distribution that generate this model are listed in Table 1.
348 These results demonstrate that the model successfully produces the Nile Delta, but essentially fails
349 to produce the Levant shelf. The general fit between model and present-day observations in
350 bathymetry and thickness (Fig. 6A) is evident in section AA' crossing the Nile Delta. Moreover,
351 comparison to a published geological section in that area from Kellner et al. (2009) indicates that
352 even the subdivision between Pliocene and Quaternary is modeled quite well (Fig. 6C). On the
353 other hand, offshore Israel there is only a poor fit between model and observations (Fig. 7A, B).
354 This discrepancy in the east-west cross sections is primarily because the model produces by far
355 too little deposition offshore Israel (Fig. 8A). The map presenting the discrepancy in thickness
356 between model and observations (Fig. 8B) further indicates that the sediment, unaccounted for at

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

357 the Levant margin (~2 km, blue colors), is compensated by excess sediments in the Herodotus
358 Basin (200-900 m, red); i.e., the sediments were delivered there. This discrepancy strengthens our
359 hypothesis that without a large margin-parallel sediment supply, it is impossible to simulate the
360 formation of the Levant continental shelf.

361 Except for this discrepancy, which is related to the lack of margin-parallel transport, the generally
362 good agreement between model and observations offshore the Nile Delta (e.g., Fig. 6) indicates
363 that (1) sediment distribution in the model functions quite well, and (2) average values of Q_w , Q_s
364 for the entire simulated interval are suitable approximations. We therefore take model parameters
365 obtained in the first modeling stage and continue to the next stage.

366

Stage 2: Adding the margin-parallel sediment transport (MPST) to the model

368 Fig. 9 shows the simulated bathymetry from 5.3 Ma to the present, using the upgraded model,
369 which includes the margin-parallel sediment transport (MPST) module. Unlike the basic model
370 (Fig. 5), here with the addition of this module, a shallow continental shelf is produced (orange
371 color) offshore Israel with nearly a 2-km-thick section deposited there (Fig. 10A). Throughout the
372 studied area, the model produces a thickness within <200 m from the observed thickness (Fig.
373 10B); this is quite a satisfactory result as this value is within <10% of the total observed thickness.
374 Two modeled chronostratigraphic cross sections offshore Caesarea and Ashdod demonstrate the
375 good fit with observations (Fig. 11). Furthermore, Two lithological sections at the same location
376 (Fig. 12) indicate that sand is accumulated only in the upper part of the section. This is also
377 consistent with observations as the age of the Kurkar Group varies laterally, from Pliocene-
378 Pleistocene inland to only Pleistocene at the coastline (Fig. 12C, Gvirtzman and Buchbinder,
379 1978). According to our model, farther west at the shelf area, the age of the sandy Kurkar Group

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

380 is limited to a few hundred thousands of years and to only several tens of thousands of years near
381 the shelf edge (Fig. 12). The noticeable sand intercalations into the shaly section represent intervals
382 of eustatically low sea levels (Haq et al., 1987) used as part of the model input.

383 The successful simulation of sand deposition and its accretion in the shallow environment is the
384 outcome of the depth-dependent sand/shale ratio (Fig. 4) that was fed to the model. This depth
385 dependency is also expressed in Fig. 13 and indicates that more sand was deposited offshore Israel
386 during the latter part of stratigraphic sequence accretion (1.8-0 Ma), when a shallow shelf was
387 already developed.

388

389 **Rates, accretion, and shelf buildup**

390 To summarize our results, we compare modeled and observed sedimentation rates in the Levant
391 Basin over the four time intervals of 5.3-2.6 Ma, 2.6-1.8 Ma, 1.8-0.35 Ma, and 0.35-0 Ma (i.e.,
392 interval durations of 2.7, 0.8, 1.45, and 0.35 My), which were defined as traceable
393 chronostratigraphic zones by Elfassi et al. (2019) based on seismic- and bio-stratigraphy. These
394 four stratigraphic units are the basis for the four thickness maps prepared by Ben Zeev and
395 Gvirtzman (2019) and are the basis for the rates we use in the comparison with the modeling. The
396 division of the thickness of the four units corresponds to the above interval durations.

397 Deposition rates calculated for the basic model (without MPST), indicate that deposition was not
398 sufficient to form a continental shelf in the Levant (Fig. 14). In the upgraded model that includes
399 MPST a continental shelf is gradually built; this buildup is observed in the model to occur first,
400 offshore Sinai, then offshore Israel, and most recently offshore Lebanon. The calculated rates of
401 accretion are consistent with observations but present some exceptions. Unit 2 (Gelasian) in the
402 actual stratigraphy presents an increase in sedimentation rate both in the southwest, near the Nile

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

403 Delta, and along the Levant margin (Fig. 14). This could have been an expression of a temporal
404 increase of the Nile's sediment discharge, which we do not model. Furthermore, the Israel Slump
405 Complex that provided ~1,000 km³ of sediments from the Levant slope to the basin (Frey Martinez
406 et al., 2005) in a short episode, limited to Unit 2 (Elfassi et al., 2019) and is not modelled either.
407 In addition, our model ignores other local sediment contribution that may have reached the basin
408 from the east (e.g., the Yafo sand member, Druckman et al., 1995; Frey-Martinez et al., 2007; Frey
409 Martinez et al., 2005; Gardosh et al., 2009).

410 The importance of the MPST is demonstrated by comparing (Fig. 15) sedimentation rates in the
411 deep basin and at the continental margin (locations appear as white dots in Fig. 14). In the basic
412 model, without MPST, the difference between these two localities is minor and the rate of
413 sedimentation is relatively low in both. This is because the model depends almost entirely on slow
414 and gradual diffusion of sediments from the Nile Delta through and into the deep basin. On the
415 other hand, with the addition of the MPST, increasingly more sediments arrive and deposit along
416 the continental margin of the Levant and as a result less sediments reach and deposit in the deep
417 basin.

418 **Margin-parallel sediment flux**

419 Sediment flux maps obtained by trial-and-error are shown in Fig. 16A-B. In these maps each pixel
420 represents a flux (km²My⁻¹) in a coast-parallel direction (approximately to the northeast).
421 Integrating the pixels along an east-to-west transect across the continental margin, provides the
422 total northward sediment flux (km³My⁻¹) through that transect line (Fig. 16C-D).

423 During the first modeled interval (5.3-1.8 Ma), calculated sediment flux offshore Rafah was ~2500
424 km³My⁻¹ (Fig. 16D, blue line). Most of these sediments were trapped and deposited offshore Israel

1
2
3
4 426 while very little volume continued north of Haifa. This has changed during the 1.8-0 Ma interval
5
6 427 with flux offshore Rafah reaching $\sim 5,300 \text{ km}^3\text{My}^{-1}$ and the flux offshore Haifa increased to ~ 3000
7
8
9 428 $\text{km}^3\text{My}^{-1}$ (Fig. 16D, red line). Subtracting the modeled flux north of Haifa from the flux offshore
10
11 429 Rafah indicates that about $2300 \text{ km}^3\text{My}^{-1}$ of sediments were trapped in the shelf south of Haifa;
12
13
14 430 this is not very different from the volume deposited during the first interval ($2500 \text{ km}^3\text{My}^{-1}$).
15
16 431 The modelled total sediment fluxes are difficult to compare to present-day observations that
17
18
19 432 measure only the sand flux, but they do produce satisfactory results for deposition and the quite
20
21 433 correct thickness. Sand fluxes are easier to compare (Fig. 16C). They show that during the early
22
23
24 434 interval less than $100 \text{ km}^3\text{My}^{-1}$ had entered the Israeli margin from the south (Rafah) and these
25
26 435 were trapped almost immediately (Fig. 16C, blue line). During the 1.8-0 Ma interval nearly 350
27
28
29 436 $\text{km}^3\text{My}^{-1}$ of sand entered from offshore Rafah, most of it trapped before reaching Ashdod, and
30
31 437 about $40 \text{ km}^3\text{My}^{-1}$ of sand arrived at Haifa (Fig. 16C, red line). These results are slightly lower
32
33
34 438 than the present-day observations and may be improved by a sensitivity analysis that will include
35
36 439 changes in the sand/shale ratio considered in the model input. In general, approximately 6% of the
37
38 440 modeled sediment flux offshore Israel is sand, concentrated in near coastal areas.
39
40
41 441 The two flux maps (Figs. 16A, 16B) indicate a northward shift of transport and alongshore
42
43 442 deposition propagation between the first and second sequences. Initially sediments were primarily
44
45
46 443 trapped offshore Sinai and only then offshore Israel. Moreover, during the first interval sediment
47
48 444 transport offshore Israel occurred mainly at deep waters (i.e., west of the first isobath after isobath
49
50
51 445 0 m - isobaths 200 m in Fig. 16A), whereas during the second interval transport mostly occurred
52
53 446 on the shelf (i.e., east of isobaths 200 m depth in Fig. 16B).
54
55
56 447

57
58 448 **DISCUSSION**
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

449 **Continental shelves and river deltas**

450 Development of continental shelves adjacent to river deltas is quite common, but the dependency
451 of the shelf evolution on sediment transport from the nearby delta is not fully resolved. Here we
452 study the accretion of the Levant shelf alongside the Nile Delta, exploring coevality and the
453 dependency of the Levant shelf on sediment transport from the Nile Delta. First, we show that
454 longshore sand transport is only a small fraction of a much larger process, termed here
455 MPST. In the Levant shelf, sand accumulation in the past 5 My comprises only about 6% of
456 the total volume of sediments that arrived from the Nile Delta. Furthermore, without the
457 large transport of silt and clay in the deeper waters, deposition offshore Israel probably
458 would have been negligible, and the Levant shelf never would have developed (Fig. 14).

459 Our observations and modelling results indicate that MPST has begun coevally with delta
460 formation, but at first, developed quite slowly. Initially, a continental shelf formed offshore
461 Sinai, then offshore Israel, and most recently along the Lebanon coast, where it is probably
462 still in its initial buildup stage. Throughout this time, longshore sand transport and
463 deposition has taken place near the coastline, but only recently (sometime in the last
464 hundreds or tens of thousands of years), when the shelf became shallow enough, sand
465 transport and deposition expanded westward. We hypothesize that this westward
466 expansion was more pronounced during eustatic sea-level drops.

467 Our results emphasize the importance of deep-water, margin-parallel currents for sediment
468 transport (e.g., Rebesco, 2018, 2005; Rebesco et al., 2014; Rebesco and Camerlenghi, 2008;
469 Schattner and Lazar, 2016 and references within), which is studied less than longshore sand
470 transport (see introduction) and is still poorly understood. The argument that sand transport along
471 the Levant margin occurs within a wide depth range (0-400 m), was first proposed by Schattner et

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

al. (2015), arguing that sediments are transported by the Levant jet system (LJS), which is a fast water current related to the present day thermohaline circulation in the Eastern Mediterranean. According to Schattner et al. (2015) this jet system initiated during the Pleistocene-Holocene transition (~11 ka), intensifying after the last glacial maximum (LGM). Our results show that MPST started coevally with the Nile Delta formation (5.3 Ma) and intensified at the beginning of the Pleistocene (2.6 Ma). We do not have any knowledge of the water circulation during the Pliocene and Pleistocene. However, based on our knowledge of the depositional history, we infer the paleo-sediment fluxes. These fluxes indicate margin-parallel transport much earlier than the Holocene, even at depths greater than 400 m. At the nearest shore environments, where they are dependent on eustatic sea levels, it is possible that the last emplacement of the jet occurred following the last glacial. If the current interglacial is a clue to the past, this could have been a cyclic occurrence during the Quaternary with early interglacials experiencing an increase in Nile River discharge and sediment supply to its delta accompanied by pronounced LJS that intensified the MPST. Such a cyclic process may have facilitated the construction of the Levant continental shelf.

Obviously, our model is not driven by physical processes. However, it presents a first step in transforming available data about sediment deposition in and on shelves (thickness and lithology) into sediment fluxes. This is essential for future physically based simulations that can examine how surficial, intermediate, and deep marine currents transport sediments along various morphologies of continental margins.

Margin-parallel vs. margin-perpendicular sediment transport

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

494 In the Levant margin sand is forming a relatively thin sequence at the top of the shelf,
495 reaching ~180 m at the coastline and wedging out landwards. Sand grains comprise 90-
496 100% of this sequence (i.e., the Kurkar Group; Fig. 12). Conversely, sand is spread
497 throughout the entire thickness (>3.5 km) of the PQ section of the Nile Delta, ; from its base
498 to its top and from its eastern to western edges, comprising a maximum of 50% (Fig. 6B). We
499 propose that this profound difference in sand content is an expression of the available energy
500 for transport. Sediment flow from the river mouth straight down to the deep basin is
501 stronger in comparison with margin-parallel flow that keeps a nearly constant elevation.
502 Accordingly, offshore the Nile River mouth, sand grains were transported straight
503 downslope over large distances since the early Pliocene. On the other hand, the much weaker
504 margin-parallel currents transported only fine grains that had built the shaly Levant shelf.
505 One exception within the margin-parallel system is the highly energetic nearshore current
506 that transported sand continuously since the Pliocene. This, however, is limited, here and
507 probably elsewhere, to a very narrow zone and very shallow water depth. Thus, the
508 combination of near shore energetic currents and deeper weaker currents produce an
509 efficient differentiation between shale and sand deposits, although they source at the same
510 river mouth. Such differentiation characterizes margin-parallel sub-horizontal sediment
511 transport in contrast with the margin-perpendicular steep-gradient transport.

512 An additional basin-wide expression of the margin-parallel vs. the common margin-
513 perpendicular transport is deltas growing thicker towards the open sea more than they grow
514 wider along the adjacent continental margins. The Nile Delta started developing immediately
515 following the recovery from the Messinian salinity crisis (early Pliocene) and then it had
516 propagated 150-200 km from the river mouth northward within about 1 My (Fig. 9). At the

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

517 same time the Levant coast started receiving small amounts of sand (Pleshet Formation,
518 Gvirtzman and Buchbinder, 1969). The shelf, which has existed earlier (probably was
519 initially forming in the Miocene) presumably was very narrow (Buchbinder and Zilberman,
520 1997; Gvirtzman and Buchbinder, 1969). Only 2-3 My after the beginning of delta formation
521 a notable shelf began developing in the Levant margin (Figs. 9, 11).

522

523 Implications for shelf exposure during sea level drops

524 The youngest stage (tens or hundreds of thousands of years) of delta development is the
525 extension of sand deposition 10-20 km westward during eustatic lowstands (Fig. 13). These
526 results are consistent with the proposal of Amit et al. (2011) that only around 180-200 ky,
527 the Nile Delta has been accreted to levels that its surface could have been exposed during
528 eustatic low stands. Only then, the sand surface and deposits of the delta and the northern
529 Sinai shelf could have been subaerially exposed and initiate their eolian transport under the
530 windy glacial climate in northern Sinai. This sand transport has generated the northern Sinai
531 dune fields and abraded the sand grains into coarse silts that comprise the loess of the Negev
532 (Amit et al., 2011; Crouvi et al., 2008). We hypothesize that some of the shelf sand was also
533 exposed and was involved in the accretion of the Eastern Mediterranean coastal plain (Harel
534 et al., 2017).

535

536 CONCLUSIONS

- 537 1. Longshore sand transport is a part of a much broader process termed here margin-
538 parallel sediment transport (MPST). Sand is transported in a nearshore shallow
539 water belt where marine currents are highly energetic. Shale transport occurs at

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

540 greater depths over the deeper shelf and the continental slope where marine
541 currents are weaker.

2. Without the large transport of silt and clay in the deeper waters, deposition offshore
542 Israel probably would have been negligible, and the Levant shelf never would have
543 developed.
544

3. The delay in the formation of the Levant continental shelf relative to the Nile Delta is
545 not a result of external forcing. MPST has begun coevally with delta formation but
546 developed slower. Initially, a continental shelf formed offshore Sinai, then offshore
547 Israel, and most recently along the Lebanese coast.
548

4. Throughout this time, longshore sand transport and deposition has taken place very
549 close to the coastline, but only recently (last hundreds of thousands or tens of
550 thousands of years), when the shelf became shallow enough, sand transport and
551 deposition expanded 10-20 km westwards. This implies subaerial exposure of sandy
552 landscape during recent eustatically low stands.
553

5. Down slope sediment transport into deep basins is relatively energetic and carries
554 sand, silt, and clay, whereas margin-parallel currents are relatively weak and carry
555 mainly silt and clay. One exception within the margin-parallel system is the highly
556 energetic nearshore current that transport sand. Thus, MPST is an efficient
557 differentiator between shale and sand.
558

559
560 **ACKNOWLEDGMENTS**

561 This study was supported by the Israeli Ministry of Energy and by the Mediterranean
562 Research Center of Israel (MERC I). The article is further based upon work of COST Action

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

563 “Uncovering the Mediterranean salt giant” (MEDSALT) supported by the European
564 Cooperation in Science and Technology.

565 **REFERENCES**

566 Aal, A.A., El Barkooky, A., Gerrits, M., Meyer, H., Schwander, M., Zaki, H., 2000. Tectonic
567 evolution of the Eastern Mediterranean Basin and its significance for hydrocarbon
568 prospectivity in the ultradeepwater of the Nile Delta. *Lead. Edge* 19, 1086–1102.
569 <https://doi.org/10.1190/1.1438485>

570 Adams, E.W., Schlager, W., Wattel, E., 1998. Submarine slopes with an exponential
571 curvature. *Sediment. Geol.* 117, 135–141.

572 Almogi-Labin, A., Calvo, R., Elyashiv, H., Amit, R., Harlavan, Y., Herut, B., 2012. Sediment
573 characterization of the Israeli Mediterranean shelf (10-100 m).

574 Amadori, C., Garcia-Castellanos, D., Toscani, G., Sternai, P., Fantoni, R., Ghielmi, M., Di Giulio,
575 A., 2018. Restored topography of the Po Plain-Northern Adriatic region during the
576 Messinian base-level drop—Implications for the physiography and
577 compartmentalization of the palaeo-Mediterranean basin. *Basin Res.* 30, 1247–1263.

578 Amante, C., Eakins, B.W., 2009. ETOPO1 arc-minute global relief model: procedures, data
579 sources and analysis.

580 Amit, R., Enzel, Y., Crouvi, O., Simhai, O., Matmon, A., Porat, N., McDonald, E., Gillespie, A.R.,
581 2011. The role of the Nile in initiating a massive dust influx to the Negev late in the
582 middle Pleistocene. *Geol. Soc. Am. Bull.* 123, 873–889.
583 <https://doi.org/10.1130/B30241.1>

584 Bar, O., 2009. The shaping of the continental margin of central Israel since the Late
585 Eocene—Tectonics, morphology and stratigraphy. *Geol. Surv. Isr. Rep. GSI/32/2009.*

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

586 Bar, O., Gvirtzman, Z., Feinstein, S., Zilberman, E., 2013. Accelerated subsidence and
587 sedimentation in the levant basin during the late tertiary and concurrent uplift of the
588 arabian platform: Tectonic versus counteracting sedimentary loading effects.
589 *Tectonics* 32, 334–350. <https://doi.org/10.1002/tect.20026>

590 Barber, P.M., 1981. Messinian subaerial erosion of the proto-Nile Delta. *Mar. Geol.* 44, 253–
591 272. [https://doi.org/10.1016/0025-3227\(81\)90053-0](https://doi.org/10.1016/0025-3227(81)90053-0)

592 Begin, Z.B., Meyer, D.F., Schumm, S.A., 1981. Development of longitudinal profiles of alluvial
593 channels in response to base-level lowering. *Earth Surf. Process. Landforms* 6, 49–68.
594 <https://doi.org/10.1002/esp.3290060106>

595 Ben-Avraham, Z., 1978. The structure and tectonic setting of the levant continental margin,
596 Eastern Mediterranean. *Tectonophysics* 46, 313–331. [https://doi.org/10.1016/0040-1951\(78\)90210-X](https://doi.org/10.1016/0040-1951(78)90210-X)

598 Ben-Gai, Y., Ben-Avraham, Z., Buchbinder, B., Kendall, C.G.S.C., 2005. Post-Messinian
599 evolution of the Southeastern Levant Basin based on two-dimensional stratigraphic
600 simulation. *Mar. Geol.* 221, 359–379. <https://doi.org/10.1016/j.margeo.2005.03.003>

601 Ben-Zeev, Y., Gvirtzman, Z., 2019. When two Salt Tectonic systems meet: gliding downslope
602 the Levant Margin and salt-squeezing from under the Nile Delta. The Hebrew
603 University of Jerusalem.

604 Ben Moshe, L., Haviv, I., Enzel, Y., Zilberman, E., Matmon, A., 2008. Incision of alluvial
605 channels in response to a continuous base level fall: Field characterization, modeling,
606 and validation along the Dead Sea. *Geomorphology* 93, 524–536.
607 <https://doi.org/10.1016/J.GEOMORPH.2007.03.014>

608 Ben Zeev, Y., Gvirtzman, Z., 2020. WHEN TWO SALT TECTONICS SYSTEMS MEET: GLIDING

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

609 DOWNSLOPE THE LEVANT MARGIN AND SALT OUT-SQUEEZING FROM UNDER THE
610 NILE DELTA. *Tectonics* e2019TC005715.

611 Buchbinder, B., Gvirtzman, G., 1976. The break-up of the Tethys Ocean into the
612 Mediterranean Sea, the Red Sea, and the Mesopotamian Basin during the Miocene: a
613 sequence of fault movements and desiccation events, in: Abstract of the First
614 Congress Pacific Neogene Stratigraphy. pp. 32–35.

615 Buchbinder, B., Martinotti, G.M., Siman-Tov, R., Zilberman, E., 1993. Temporal and spatial
616 relationships in Miocene reef carbonates in Israel. *Palaeogeogr. Palaeoclimatol.*
617 *Palaeoecol.* 101, 97–116. [https://doi.org/10.1016/0031-0182\(93\)90154-B](https://doi.org/10.1016/0031-0182(93)90154-B)

618 Buchbinder, B., Zilberman, E., 1997. Sequence stratigraphy of Miocene-Pliocene carbonate-
619 siliciclastic shelf deposits in the eastern Mediterranean margin (Israel): effects of
620 eustasy and tectonics. *Sediment. Geol.* 112, 7–32. [https://doi.org/10.1016/S0037-](https://doi.org/10.1016/S0037-0738(97)00034-1)
621 [0738\(97\)00034-1](https://doi.org/10.1016/S0037-0738(97)00034-1)

622 Carmel, Z., Inman, D.L., Golik, A., 1985. Directional wave measurement at Haifa, Israel, and
623 sediment transport along the Nile littoral cell. *Coast. Eng.* 9, 21–36.
624 [https://doi.org/10.1016/0378-3839\(85\)90025-0](https://doi.org/10.1016/0378-3839(85)90025-0)

625 Coulthard, T.J., 1999. Modelling upland catchment response to Holocene environmental
626 change.

627 Crouvi, O., Amit, R., Enzel, Y., Porat, N., Sandler, A., 2008. Sand dunes as a major proximal
628 dust source for late Pleistocene loess in the Negev Desert, Israel. *Quat. Res.* 70, 275–
629 282. <https://doi.org/10.1016/j.yqres.2008.04.011>

630 Csato, I., Catuneanu, O., Granjeon, D., 2014. Millennial-Scale Sequence Stratigraphy:
631 Numerical Simulation With Dionisos. *J. Sediment. Res.* 84, 394–406.

1
2
3
4 632 <https://doi.org/10.2110/jsr.2014.36>
5
6
7 633 Csato, I., Granjeon, D., Catuneanu, O., Baum, G.R., 2013. A three-dimensional stratigraphic
8
9 634 model for the Messinian crisis in the Pannonian Basin, eastern Hungary. *Basin Res.* 25,
10
11 635 121–148. <https://doi.org/10.1111/j.1365-2117.2012.00553.x>
12
13
14 636 Culling, W.E.H., 1960. Analytical Theory of Erosion. *J. Geol.* 68, 336–344.
15
16 637 <https://doi.org/10.1086/626663>
17
18
19 638 Dai, A., Trenberth, K.E., 2002. Estimates of freshwater discharge from continents:
20
21 639 Latitudinal and seasonal variations. *J. Hydrometeorol.* 3, 660–687.
22
23
24 640 Davis, M., Matmon, A., Rood, D.H., Avnaim-Katav, S., 2012. Constant cosmogenic nuclide
25
26 641 concentrations in sand supplied from the Nile River over the past 2.5 m.y. *Geology* 40,
27
28 642 359–362. <https://doi.org/10.1130/G32574.1>
29
30
31 643 Deville, E., Mascle, A., Callec, Y., Huyghe, P., Lallemand, S., Lerat, O., Mathieu, X., Padron De
32
33 644 Carillo, C., Patriat, M., Pichot, T., Loubrieux, B., Granjeon, D., 2015. Tectonics and
34
35 645 sedimentation interactions in the east Caribbean subduction zone: An overview from
36
37 646 the Orinoco delta and the Barbados accretionary prism. *Mar. Pet. Geol.* 64, 76–103.
38
39 647 <https://doi.org/10.1016/j.marpetgeo.2014.12.015>
40
41
42 648 Druckman, Y., Buchbinder, B., Martinotti, G.M., Siman Tov, R., Aharon, P., 1995. The buried
43
44 649 Afiq Canyon (eastern Mediterranean, Israel): a case study of a Tertiary submarine
45
46 650 canyon exposed in Late Messinian times. *Mar. Geol.* 123, 167–185.
47
48 651 [https://doi.org/10.1016/0025-3227\(94\)00127-7](https://doi.org/10.1016/0025-3227(94)00127-7)
49
50
51 652 El Din, S.H.S., Mahar, A.M., 1997. Evaluation of sediment transport along the Nile Delta
52
53 653 coast, Egypt. *J. Coast. Res.* 23–26.
54
55
56 654 Elfassi, Y., Gvirtzman, Z., Katz, O., Aharonov, E., 2019. Chronology of post-Messinian faulting
57
58
59
60
61
62
63
64
65

1
2
3
4 655 along the Levant continental margin and its implications for salt tectonics. *Mar. Pet.*
5
6 656 *Geol.* 109, 574–588. <https://doi.org/10.1016/J.MARPETGEO.2019.05.032>
7
8
9 657 Emery, K.O., Bentor, Y.K., 1960. The continental shelf of Israel. State of Israel, Ministry of
10
11 658 Development, Geological Survey.
12
13
14 659 Emery, K.O., Neev, D., Bentor, Y.K., 1960. Mediterranean beaches of Israel. State of Israel,
15
16 660 Ministry of Agriculture, Division of Fisheries, the Sea
17
18
19 661 Frey-Martinez, J., Hall, B., Cartwright, J., Huuse, M., 2007. Clastic Intrusion at the Base of
20
21 662 Deep-water Sands: A Trap-forming Mechanism in the Eastern Mediterranean. *Am.*
22
23
24 663 *Assoc. Pet. Geol.* 49–63. <https://doi.org/10.1306/1209849M873255>
25
26
27 664 Frey Martinez, J., Cartwright, J., Hall, B., 2005. 3D seismic interpretation of slump
28
29 665 complexes: examples from the continental margin of Israel. *Basin Res.* 17, 83–108.
30
31 666 <https://doi.org/10.1111/j.1365-2117.2005.00255.x>
32
33
34 667 Galloway, W.E., 1998. Siliciclastic slope and base-of-slope depositional systems: component
35
36 668 facies, stratigraphic architecture, and classification. *Am. Assoc. Pet. Geol. Bull.* 82, 569–
37
38 669 595.
39
40
41 670 Garcia-Castellanos, D., Vergés, J., Gaspar-Escribano, J., Cloetingh, S., 2003. Interplay between
42
43 671 tectonics, climate, and fluvial transport during the Cenozoic evolution of the Ebro
44
45 672 Basin (NE Iberia). *J. Geophys. Res. Solid Earth* 108.
46
47 673 <https://doi.org/10.1029/2002JB002073>
48
49
50
51 674 Gardosh, M.A., Druckman, Y., Buchbinder, B., 2009. The Late Tertiary Deep-Water
52
53 675 Siliciclastic System of the Levant Margin—An Emerging Play Offshore Israel. *Am. Assoc.*
54
55 676 *Pet. Geol. Search Discov. Artic.* 10211.
56
57
58
59 677 Gerber, T.P., Amblas, D., Wolinsky, M.A., Pratson, L.F., Canals, M., 2009. A model for the long-
60
61
62
63
64
65

1
2
3
4 678 profile shape of submarine canyons. *J. Geophys. Res.* 114, F03002.
5
6
7 679 <https://doi.org/10.1029/2008JF001190>
8
9 680 Goldsmith, V., Golik, A., 1980. Sediment transport model of the southeastern Mediterranean
10
11 681 coast. *Mar. Geol.* 37, 147–175. [https://doi.org/10.1016/0025-3227\(80\)90015-8](https://doi.org/10.1016/0025-3227(80)90015-8)
12
13
14 682 Golik, A., 2002. Pattern of sand transport along the Israeli coastline. *Isr. J. Earth Sci.* 51.
15
16 683 Golik, A., 1997. Dynamics and management of sand along the Israeli coastline. *Bull.*
17
18
19 684 *Oceanogr. MONACO-NUMERO Spec.* 97–110.
20
21 685 Golik, A., 1993. Indirect evidence for sediment transport on the continental shelf off Israel.
22
23 686 *Geo-Marine Lett.* 13, 159–164. <https://doi.org/10.1007/BF01593189>
24
25
26 687 Golik, A., Rosen, D.S., Brachia, V., 1999. Management of the Israeli coastal sand resources.
27
28 688 CAMPIsrael, *Mediterr. Action Plan*, UNEP Isr. Minist. Environ. IOLR ReportH28/1999,
29
30
31 689 Haifa).
32
33
34 690 Granjeon, D., 2014. 3D forward modelling of the impact of sediment transport and base
35
36 691 level cycles on continental margins and incised valleys, in: *From Depositional Systems*
37
38
39 692 *to Sedimentary Successions on the Norwegian Continental Margin*. John Wiley & Sons,
40
41 693 Ltd, Chichester, UK, pp. 453–472. <https://doi.org/10.1002/9781118920435.ch16>
42
43
44 694 Granjeon, D., 2009. 3D stratigraphic modeling of sedimentary basins. *AAPG Search Discov.*
45
46 695 *Artic.*
47
48
49 696 Granjeon, D., 1997. *Modélisation stratigraphique déterministe: Conception et application*
50
51 697 *d'un modèle diffusif 3D multilithologique*. Univ. of Rennes.
52
53
54 698 Granjeon, D., Joseph, P., 1999. Concepts and applications of a 3-D multiple lithology,
55
56 699 *diffusive model in stratigraphic modeling*.
57
58
59 700 Granjeon, D., Wolf, S., 2007. 3D stratigraphic modeling in complex tectonics area, in:
60
61
62
63
64
65

1
2
3
4 701 Abstract of the AAPG Annual Convention and Exhibition. AAPG Search and Discovery
5
6 702 Long Beach, California, USA.
7
8
9 703 Gvirtzman, G., 1970. The Saqiye Group in the coastal plain and Hashfela regions, Israel, Isr.
10
11 704 Geol. Surv., Rep. OD'S.
12
13
14 705 Gvirtzman, G., Buchbinder, B., 1978. The Late Tertiary of the coastal plain and continental
15
16 706 shelf of Israel and its bearing on the history of the Eastern Mediterranean, Initial
17
18 707 reports of the deep sea drilling project.
19
20
21 708 Gvirtzman, G., Buchbinder, B., 1969. Outcrops of Neogene Formation in the Central and
22
23 709 Southern Coastal Plain, Hashephela and Beer Sheva'Regions, Israel. Geological Survey.
24
25
26 710 Gvirtzman, Z., Csato, I., Granjeon, D., 2014. Constraining sediment transport to deep marine
27
28 711 basins through submarine channels : The Levant margin in the Late Cenozoic. Mar.
29
30 712 Geol. 347, 12–26.
31
32
33
34 713 Haq, B., Hardenbohl, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic
35
36 714 (250 million years ago to present). Sci. York.
37
38
39 715 Harel, M., Amit, R., Porat, N., Enzel, Y., 2016. Evolution in of the southeastern Mediterranean
40
41 716 coastal plain, in: Quaternary of the Levant: Environments, Climate Change, and
42
43 717 Humans. Cambridge University Press Cambridge.
44
45
46 718 Harris, A.D., Covault, J.A., Madof, A.S., Sun, T., Sylvester, Z., Granjeon, D., 2016. Three-
47
48 719 Dimensional Numerical Modeling of Eustatic Control On Continental-Margin Sand
49
50 720 Distribution. J. Sediment. Res. 86, 1434–1443. <https://doi.org/10.2110/jsr.2016.85>
51
52
53
54 721 Hawie, N., Barrois, A., Marfisi, E., Murat, B., Hall, J., El-Wazir, Z., Al-Madani, N., Aillud, G.,
55
56 722 2015. Forward Stratigraphic Modelling, Deterministic Approach to Improve Carbonate
57
58 723 Heterogeneity Prediction; Lower Cretaceous, Abu Dhabi, in: Abu Dhabi International
59
60
61
62
63
64
65

1
2
3
4 724 Petroleum Exhibition and Conference. Society of Petroleum Engineers.
5
6
7 725 <https://doi.org/10.2118/177519-MS>
8
9 726 Hawie, N., Covault, J.A., Dunlap, D., Sylvester, Z., 2018. Slope-fan depositional architecture
10
11 727 from high-resolution forward stratigraphic models. *Mar. Pet. Geol.* 91, 576–585.
12
13
14 728 <https://doi.org/10.1016/J.MARPETGEO.2017.12.033>
15
16 729 Hawie, N., Deschamps, R., Granjeon, D., Nader, F.H., Gorini, C., Müller, C., Montadert, L.,
17
18
19 730 Baudin, F., 2017. Multi-scale constraints of sediment source to sink systems in frontier
20
21 731 basins: a forward stratigraphic modelling case study of the Levant region. *Basin Res.*
22
23
24 732 29, 418–445. <https://doi.org/10.1111/bre.12156>
25
26 733 Hsü, K.J., Ryan, W.B.F., Cita, M.B., 1973. Late Miocene dessication of the Mediterranean.
27
28
29 734 *Nature* 242, 240–244.
30
31 735 Inman, D.L., Brush, B.M., 1973. The coastal challenge. *Science* (80-). 181, 20–32.
32
33
34 736 <https://doi.org/10.1126/science.181.4094.20>
35
36 737 Inman, D.L., Elwany, M.H.S., Khafagy, A.A., Golik, A., 1993. Nile Delta profiles and migrating
37
38
39 738 sand blankets, in: *Coastal Engineering 1992*. pp. 3273–3284.
40
41 739 Inman, D.L., Jenkins, S.A., 1984. The Nile littoral cell and man’s impact on the coastal littoral
42
43
44 740 zone in the SE Mediterranean, in: *Proceedings of the 17th International Coastal*
45
46 741 *Engineering Conference*. ASCE Sydney, Australia, pp. 1600–1617.
47
48
49 742 Inman, D.L., Nordstrom, C.E., Flick, R.E., 1976. Currents in submarine canyons: An air-sea-
50
51 743 land interaction. *Annu. Rev. Fluid Mech.* 8, 275–310.
52
53
54 744 Jordan, T.E., Flemings, P.B., 1991. Large-scale stratigraphic architecture, eustatic variation,
55
56 745 and unsteady tectonism: A theoretical evaluation. *J. Geophys. Res. Solid Earth* 96,
57
58
59 746 6681–6699. [https://doi.org/10.1029/90JB01399@10.1002/\(ISSN\)2169-](https://doi.org/10.1029/90JB01399@10.1002/(ISSN)2169-)
60
61
62
63
64
65

1
2
3
4 747 9356.LTSLC1
5
6
7 748 Kaufman, P., Grotzinger, J., McCormick, D., 1991. Depth-dependent diffusion algorithm for
8
9 749 simulation of sedimentation in shallow marine deposition systems. *Sediment. Model.*
10
11
12 750 *Computer Simulations Methods Improv. Param. Defin.*
13
14 751 Kellner, A., Khawaga, H. El, Brink, G., Brink-larsen, S., Hesham, M., Abu, H., Saad, E., Atef, A.,
15
16 752 Young, H., Finlayson, B., 2009. Depositional History of the West Nile Delta – Upper
17
18
19 753 Oligocene to Upper Pliocene, in: AAPG International Conference and Exhibition, Cape
20
21 754 Town, South Africa.
22
23
24 755 Kempler, D., 1998. Eratosthenes Seamount: The possible spearhead of incipient continental
25
26 756 collision in the eastern Mediterranean. *Proc. Ocean Drill. Progr. Sci. Results* 160, 709–
27
28
29 757 722. <https://doi.org/10.2973/odp.proc.sr.160.031.1998>
30
31
32 758 Kenyon, P.M., Turcotte, D.L., 1985. Morphology of a delta prograding by bulk sediment
33
34 759 transport. *Geol. Soc. Am. Bull.* 96, 1457. <https://doi.org/10.1130/0016->
35
36 760 [7606\(1985\)96<1457:MOADPB>2.0.CO;2](https://doi.org/10.1130/0016-7606(1985)96<1457:MOADPB>2.0.CO;2)
37
38
39 761 Klein, M., Zviely, D., Kit, E., Shteinman, B., 2007. Sediment transport along the coast of
40
41 762 Israel: examination of fluorescent sand tracers. *J. Coast. Res.* 1462–1470.
42
43
44 763 Lai, S.Y.J., Capart, H., 2007. Two-diffusion description of hyperpycnal deltas. *J. Geophys. Res.*
45
46 764 112, F03005. <https://doi.org/10.1029/2006JF000617>
47
48
49 765 Laurent, D., Marsset, T., Droz, L., Granjeon, D., Molliex, S., Picot, M., Rabineau, M., 2020. 4D
50
51 766 forward stratigraphic modelling of the Late Quaternary Congo deep-sea fan: Role of
52
53
54 767 climate/vegetation coupling in architectural evolution. *Mar. Geol.* 429, 106334.
55
56 768 Manohar, M., 1981. Coastal processes at the Nile Delta coast. *SHORE & BEACH* 49, 8–15.
57
58
59 769 Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/Tectonic Control of Sediment Discharge to
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

770 the Ocean: The Importance of Small Mountainous Rivers. *J. Geol.* 100, 525–544.
771 <https://doi.org/10.1086/629606>

772 Mitchell, N.C., Huthnance, J.M., 2008. Oceanographic Currents and the Convexity of the
773 Uppermost Continental Slope. *J. Sediment. Res.* 78, 29–44.
774 <https://doi.org/10.2110/jsr.2008.006>

775 Mitchell, N.C., Huthnance, J.M., 2007. Comparing the smooth, parabolic shapes of interfluves
776 in continental slopes to predictions of diffusion transport models. *Mar. Geol.* 236, 189–
777 208. <https://doi.org/10.1016/J.MARGEO.2006.10.028>

778 Murray, A.B., Paola, C., 1994. A cellular model of braided rivers. *Nature* 371, 54.

779 Nachmias, J., 1969. Source rocks of the Saqiye Group sediments in the coastal plain of
780 Israel—a heavy mineral study. *Isr. J. Earth-Sciences* 18, 1–16.

781 Paola, C., Heller, P.L., Angevine, C.L., 1992. The large-scale dynamics of grain-size variation
782 in alluvial basins, 1: Theory. *Basin Res.* 4, 73–90.

783 Parker, G., Paola, C., Whipple, K.X., Mohrig, D., 1998. Alluvial fans formed by channelized
784 fluvial and sheet flow. I: Theory. *J. Hydraul. Eng.* 124, 985–995.

785 Perlin, A., Kit, E., 1999. Longshore sediment transport on Mediterranean coast of Israel. *J.*
786 *Waterw. Port, Coastal, Ocean Eng.* 125, 80–87.

787 Rabineau, M., Berné, S., Aslanian, D., Olivet, J.L., Joseph, P., Guillocheau, F., Bourillet, J.F.,
788 Ledrezen, E., Granjeon, D., 2005. Sedimentary sequences in the Gulf of Lion: a record of
789 100,000 years climatic cycles. *Mar. Pet. Geol.* 22, 775–804.

790 Rabineau, M., Berné, S., Olivet, J.-L., Aslanian, D., Guillocheau, F., Joseph, P., 2006. Paleo sea
791 levels reconsidered from direct observation of paleoshoreline position during Glacial
792 Maxima (for the last 500,000 yr). *Earth Planet. Sci. Lett.* 252, 119–137.

1
2
3
4 793 Rebesco, M., 2018. Sedimentary Environments: Contourites. Ref. Modul. Earth Syst.
5
6
7 794 Environ. Sci. <https://doi.org/10.1016/B978-0-12-409548-9.09094-1>
8
9 795 Rebesco, M., 2005. SEDIMENTARY ENVIRONMENTS | Contourites. Encycl. Geol. 513–527.
10
11
12 796 <https://doi.org/10.1016/B0-12-369396-9/00497-4>
13
14 797 Rebesco, M., Camerlenghi, A., 2008. Contourites. Elsevier.
15
16 798 Rebesco, M., Hernández-Molina, F.J., Van Rooij, D., Wåhlin, A., 2014. Contourites and
17
18
19 799 associated sediments controlled by deep-water circulation processes: State-of-the-art
20
21
22 800 and future considerations. Mar. Geol. 352, 111–154.
23
24 801 <https://doi.org/10.1016/J.MARGEO.2014.03.011>
25
26 802 Rivenæs, J.C., 1997. Impact of sediment transport efficiency on large-scale sequence
27
28
29 803 architecture: results from stratigraphic computer simulation. Basin Res. 9, 91–105.
30
31
32 804 <https://doi.org/10.1046/j.1365-2117.1997.00037.x>
33
34 805 Robertson, A.H.F., 1998. Tectonic significance of the Eratosthenes Seamount: A continental
35
36
37 806 fragment in the process of collision with a subduction zone in the eastern
38
39 807 Mediterranean (Ocean Drilling Program Leg 160). Tectonophysics 298, 63–82.
40
41
42 808 [https://doi.org/10.1016/S0040-1951\(98\)00178-4](https://doi.org/10.1016/S0040-1951(98)00178-4)
43
44 809 Rosentraub, Z., Brenner, S., 2007. Circulation over the southeastern continental shelf and
45
46
47 810 slope of the Mediterranean Sea: Direct current measurements, winds, and numerical
48
49 811 model simulations. J. Geophys. Res. 112, C11001.
50
51
52 812 <https://doi.org/10.1029/2006JC003775>
53
54 813 Ryan, W.B.F., Cita, M.B., 1978. The nature and distribution of Messinian erosional surfaces
55
56
57 814 — Indicators of a several-kilometer-deep Mediterranean in the Miocene. Mar. Geol. 27,
58
59 815 193–230. [https://doi.org/10.1016/0025-3227\(78\)90032-4](https://doi.org/10.1016/0025-3227(78)90032-4)
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

816 Said, R., 1981. The Geological Evolution of the River Nile, The GEOLOGICAL EVOLUTION of
817 the RIVER NILE. Springer Science & Business Media, New York, NY.
818 https://doi.org/10.1007/978-1-4612-5841-4_1

819 Schattner, U., 2010. What triggered the early-to-mid Pleistocene tectonic transition across
820 the entire eastern Mediterranean? *Earth Planet. Sci. Lett.* 289, 539–548.
821 <https://doi.org/10.1016/J.EPSL.2009.11.048>

822 Schattner, U., Gurevich, M., Kanari, M., Lazar, M., 2015. Levant jet system-effect of post LGM
823 seafloor currents on Nile sediment transport in the eastern Mediterranean. *Sediment.*
824 *Geol.* 329, 28–39. <https://doi.org/10.1016/j.sedgeo.2015.09.007>

825 Schattner, U., Lazar, M., 2016. Hierarchy of source-to-sink systems — Example from the
826 Nile distribution across the eastern Mediterranean. *Sediment. Geol.* 343, 119–131.
827 <https://doi.org/10.1016/j.sedgeo.2016.08.006>

828 Schlager, W., Adams, E.W., 2001. Model for the sigmoidal curvature of submarine slopes.
829 *Geology* 29, 883–886.

830 Sestini, G., 1989. Nile Delta: a review of depositional environments and geological history.
831 *Geol. Soc. London, Spec. Publ.* 41, 99–127.
832 <https://doi.org/10.1144/GSL.SP.1989.041.01.09>

833 Seymour, R.J., 2005. Longshore Sediment Transport. *Encycl. Coast. Sci.* 600.

834 Shoshany, M., Golik, A., Degani, A., Lavee, H., Gvirtzman, G., 1996. New evidence for sand
835 transport direction along the coastline of Israel. *J. Coast. Res.* 311–325.

836 Shukri, N.M., 1950. The mineralogy of some Nile sediments. *Q. J. Geol. Soc.* 106, 466–467.
837 <https://doi.org/10.1144/GSL.JGS.1950.106.01-04.23>

838 Shukri, N.M., Philip, G., 1960. The mineralogy of some recent deposits in the Arish-Gaza

1
2
3
4 839 area. Bull. Fac. Sci. Cairo Univ. 35, 73–85.
5
6
7 840 Spinewine, B., Sun, T., Babonneau, N., Parker, G., 2011. Self-similar long profiles of
8
9 841 aggrading submarine leveed channels: Analytical solution and its application to the
10
11 842 Amazon channel. J. Geophys. Res. 116, F03004.
12
13
14 843 <https://doi.org/10.1029/2010JF001937>
15
16 844 Stanley, D.J., Warne, A.G., 1998. Nile Delta in Its Destruction Phase. J. Coast. Res. 14, 794–
17
18
19 845 825.
20
21 846 Stanley, J.D., 1989. Sediment Transport on the Coast and Shelf Between the Nile Delta and
22
23
24 847 Israeli Margin as Determined by Heavy Minerals. J. Coast. Res. 5, 813–828.
25
26 848 Steckler, M.S., Mountain, G.S., Miller, K.G., Christie-Blick, N., 1999. Reconstruction of
27
28
29 849 Tertiary progradation and clinoform development on the New Jersey passive margin
30
31 850 by 2-D backstripping. Mar. Geol. 154, 399–420. <https://doi.org/10.1016/S0025->
32
33
34 851 [3227\(98\)00126-1](https://doi.org/10.1016/S0025-3227(98)00126-1)
35
36 852 Syvitski, J.P.M., Milliman, J.D., 2007. Geology, geography, and humans battle for dominance
37
38
39 853 over the delivery of fluvial sediment to the coastal ocean. J. Geol. 115, 1–19.
40
41 854 Tibor, G., Ben-Avraham, Z., Steckler, M., Fligelman, H., 1992. Late Tertiary subsidence
42
43
44 855 history of the southern Levant Margin, eastern Mediterranean Sea, and its implications
45
46 856 to the understanding of the Messinian Event. J. Geophys. Res. 97, 17593.
47
48
49 857 <https://doi.org/10.1029/92JB00978>
50
51 858 Tucker, G.E., Slingerland, R.L., 1994. Erosional dynamics, flexural isostasy, and long-lived
52
53
54 859 escarpments: A numerical modeling study. J. Geophys. Res. Solid Earth 99, 12229–
55
56 860 12243. <https://doi.org/10.1029/94JB00320>
57
58
59 861 Van Heijst, M., Postma, G., Meijer, X.D., Snow, J.N., Anderson, J.B., 2001. Quantitative
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

862 analogue flume-model study of river-shelf systems: principles and verification
863 exemplified by the Late Quaternary Colorado river-delta evolution. *Basin Res.* 13, 243–
864 268.

865 Willgoose, G., Bras, R.L., Rodriguez-Iturbe, I., 1991. Results from a new model of river basin
866 evolution. *Earth Surf. Process. Landforms* 16, 237–254.
867 <https://doi.org/10.1002/esp.3290160305>

868 Woodward, J.C., Macklin, M.G., Krom, M.D., Williams, M.A.J., Gupta, A., 2007. The Nile:
869 evolution, Quaternary river environments and material fluxes. *Large rivers*
870 *Geomorphol. Manag.* 13, 712.

871 Young, A., Carson, M.A., Kirkby, M.J., 1973. Hillslope Form and Process. *Geogr. J.* 139, 140.
872 <https://doi.org/10.2307/1795822>

873 Zaghoul, Z.M., El-Nasharty, F.A., Isa, I.A., 1982. Post-Aswan High Dam changes of the Nile
874 Delta coast, east of Ras El Bar, interpreted from aerial photographs. *Remote Sens. Arid*
875 *semi-arid lands* 877–883.

876 Zhang, J., Burgess, P.M., Granjeon, D., Steel, R., 2019. Can sediment supply variations create
877 sequences? Insights from stratigraphic forward modelling. *Basin Res.* 31, 274–289.
878 <https://doi.org/10.1111/bre.12320>

879 Zucker, E., Gvirtzman, Z., Steinberg, J., Enzel, Y., 2019. Salt tectonics in the Eastern
880 Mediterranean Sea: Where a giant delta meets a salt giant. *Geology*.
881 <https://doi.org/10.1130/G47031.1>

882 Zviely, D., Kit, E., Klein, M., 2007. Longshore sand transport estimates along the
883 Mediterranean coast of Israel in the Holocene. *Mar. Geol.* 238, 61–73.
884 <https://doi.org/10.1016/J.MARGE0.2006.12.003>

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

885 Zviely, D., Sivan, D., Ecker, A., Bakler, N., Rohrlich, V., Galili, E., Boaretto, E., Klein, M., Kit, E.,
886 2006. Holocene evolution of the Haifa Bay area, Israel, and its influence on ancient tell
887 settlements. *The Holocene* 16, 849–861.

889 **FIGURE CAPTIONS**

890 Figure 1: Topography and bathymetry map of the Eastern Mediterranean. Her = Herzliya.
891 Ash = Ashkelon. ESM = Eratosthenes Seamount. Black circles mark oil and gas wells:
892 1=Mira, 2=Hannah 01, 3=Sara, 4=Hof Ashdod 01, 5=Yam 02, 6=Yinnon, 7=Maanit 01,
893 8=Caesarea. Black line w/triangles mark the Hellenic–Cyprus subduction. Dashed brown
894 lines = Locations of cross sections. Black arrows – longshore sand transport (after Inman
895 and Jenkins, 1984). Red arrows – LJS (after Schattner et al., 2015)

896 Figure 2: (A) Structural map of the base of the Pliocene. Black lines are faults after Aal et al.
897 (2000). (B) A map showing the thickness of the Plio-Quaternary sedimentary sequence.
898 Present-day coastline (gray line) is shown for reference. Figure after Zucker et al (2019).

899 Figure 3: (A) Reconstructed bathymetry for 5.3 Ma (obtained by flexural unloading of the
900 PQ sediment from the base Pliocene map, see text). (B) Subsidence since the time of the
901 base of the Pliocene sequence (5.3 Ma) until today. (C) 2D Illustration of the relationships
902 between the data presented in Figs. 1-3.

903 Figure 4: (A) Sediment grain size as documented on the present-day seabed offshore Israel
904 (after Almogi-Labin et al., 2012); the data indicate the coast-parallel distribution of the
905 sand, silt, and clay belts. (B) Depth dependent sand/shale ratio parameters introduced in
906 the model. Generated following Almogi-Labin et al. (2012).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

907 Figure 5: Maps illustrating the evolution of the bathymetry through time as modeled by
908 DionisosFlow using the basic sediment transport model without the MPST (see text). Red
909 lines show locations of cross sections. (A) Same as Fig. 3A.

910 Figure 6: (A) Model results using a basic sediment transport that show a good fit with a
911 cross section (B-B', see 6D for location) after Kellner et al. (2009) across the Nile Delta. (B)
912 Cross section A-A' (see D for location) of the Nile Delta sand [%] that builds the delta at the
913 end of the model that includes MPST (see text). (C) Interpreted seismic composite line
914 across the Nile Delta (Kellner et al., 2009). (D) Location map of cross sections B-B', and A-
915 A'. Dashed black line in cross section A-A', which shows present-day bathymetry. Color bar
916 is the same for Figs. 6A and 6C.

917 Figure 7: (A and B) Results of chronostratigraphic model using basic sediment transport
918 that indicate a bad fit to the observed present-day bathymetry reference (black dotted line)
919 across the Levant continental margin. Black vertical lines mark locations of oil and gas
920 wells with their names written above (see wells and cross section locations in Fig. 1).

921 Figure 8: (A) Total sediment thickness (from 5.3-0.0 Ma) as simulated without MPST (see
922 text). (B) The difference in sequence thickness between simulated (A) and observed.

923 Figure 9: Bathymetry evolution through time as modeled by DionisosFlow implementing
924 MPST. Note the difference between this model, which produces the Levant shelf, and the
925 basic model that does not (Fig. 5). Red lines show locations of cross sections.

926 Figure 10: (A) Total sediment thickness, from 5.3 to 0.0 Ma generated by simulation
927 including MPST (see text). (B) Difference between simulated (A) and observed sediment
928 thickness. Note the relatively small difference here in comparison with the basic, without
929 MPST, model (Fig. 8b).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

930 Figure 11: (A and C) Chrono-stratigraphy of sections across the Levant margin derived
931 from the model after adding the MPST. These sections show a good fit to observed sections
932 based on seismic data (B and D). Black vertical lines in cross sections mark locations of oil
933 and gas wells. Well names and cross section locations are in Fig. 1.

934 Figure 12: Simulated MPST cross sections (A and B) showing the resulted Kurkar (Mainly
935 sand) and Yafo Formations (mainly shale); black rectangle in B shows the location of the
936 enlarged cross section (C) (after Gvirtzman and Buchbinder, 1978). The sand fingers into
937 the shaly section of Yafo Formation is the result of including the eustatic curve of Haq et al.
938 (1987) in the model. (D) Location map. Color bar is the same for cross sections A and B.

939 Figure 13: The total sand thickness as simulated for the lower sequence (5.3-2.6 Ma) and
940 for the upper sequence (2.6 -0.0 Ma), using the model without and with the MPST laws. (A)
941 Lower sequence, using the basic model. (B) Lower sequence, using the MPST model. (C)
942 Upper sequence, using the basic model. (D) Upper sequence, using the MPST model.

943 Figure 14: Sedimentation rates generated by both modeled scenarios in comparison with
944 the observed sedimentation, divided into the four chronostratigraphic units determined by
945 Ben Zeev and Gvirtzman (2020). White dots mark the locations points taken, one in the
946 deep basin and a second at the continental margin, for calculating sedimentation rates
947 measured in figure 15.

948 Figure 15: Comparing sedimentation rates for the models without and MPST (red and gray,
949 respectively) and the observed (black) sedimentation rate, divided in to two locations:
950 Deep basin (solid line) and continental margin (dashed line). Locations in figure 14.

951 Figure 16: Sediment flux maps obtained by trial and error for lower (A) and upper (B)
952 sequences printed over isobaths representing 3 Ma and 1 Ma, respectively. Each pixel in the

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

953 maps represents the flux ($\text{km}^2\text{My}^{-1}$) in a coast-parallel direction. Total sediment (D) and sand
954 (C) fluxes crossing margin-perpendicular transects during deposition of lower and upper
955 sequences. Curve representing the observed sand flux is based on references listed in the
956 introduction.

957

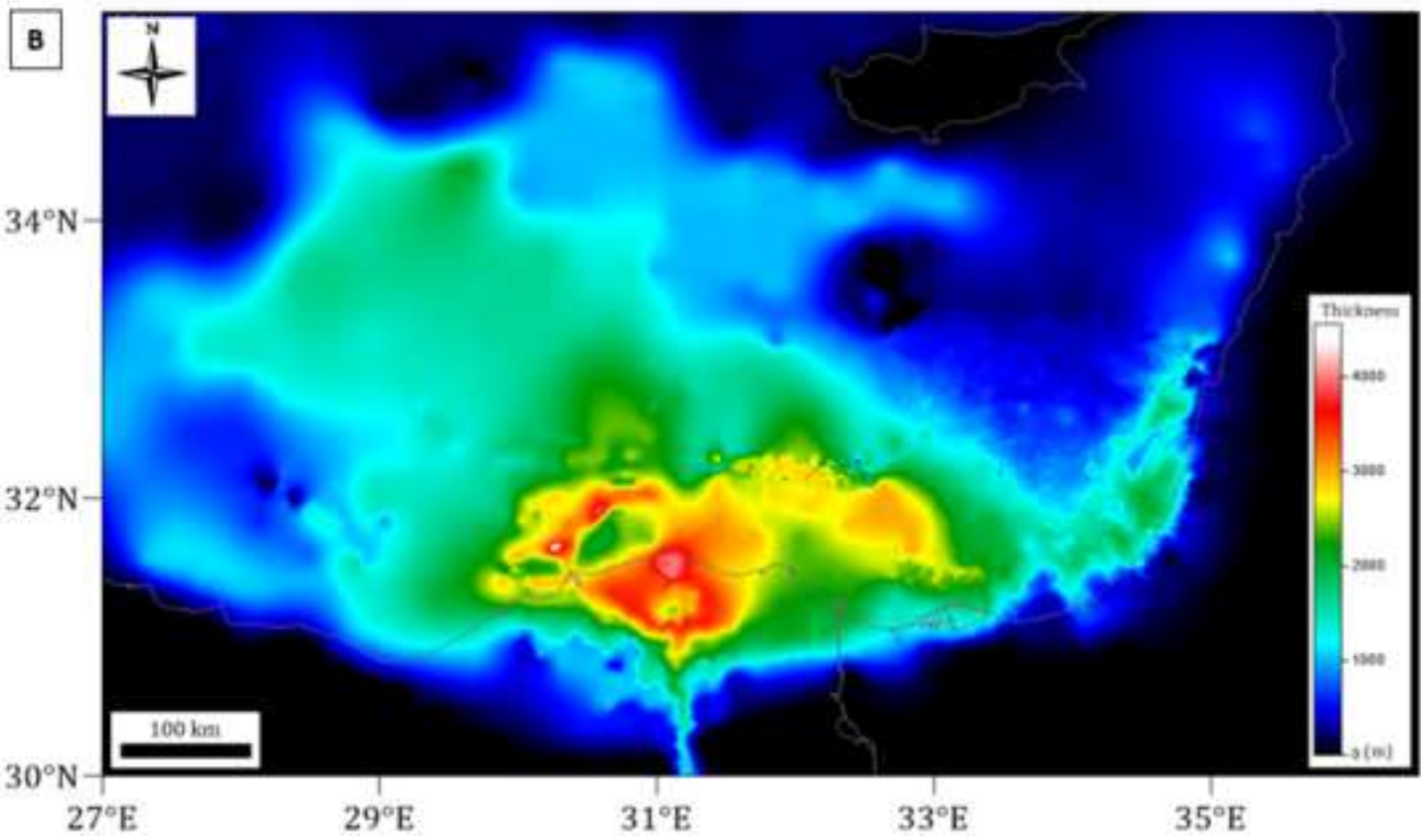
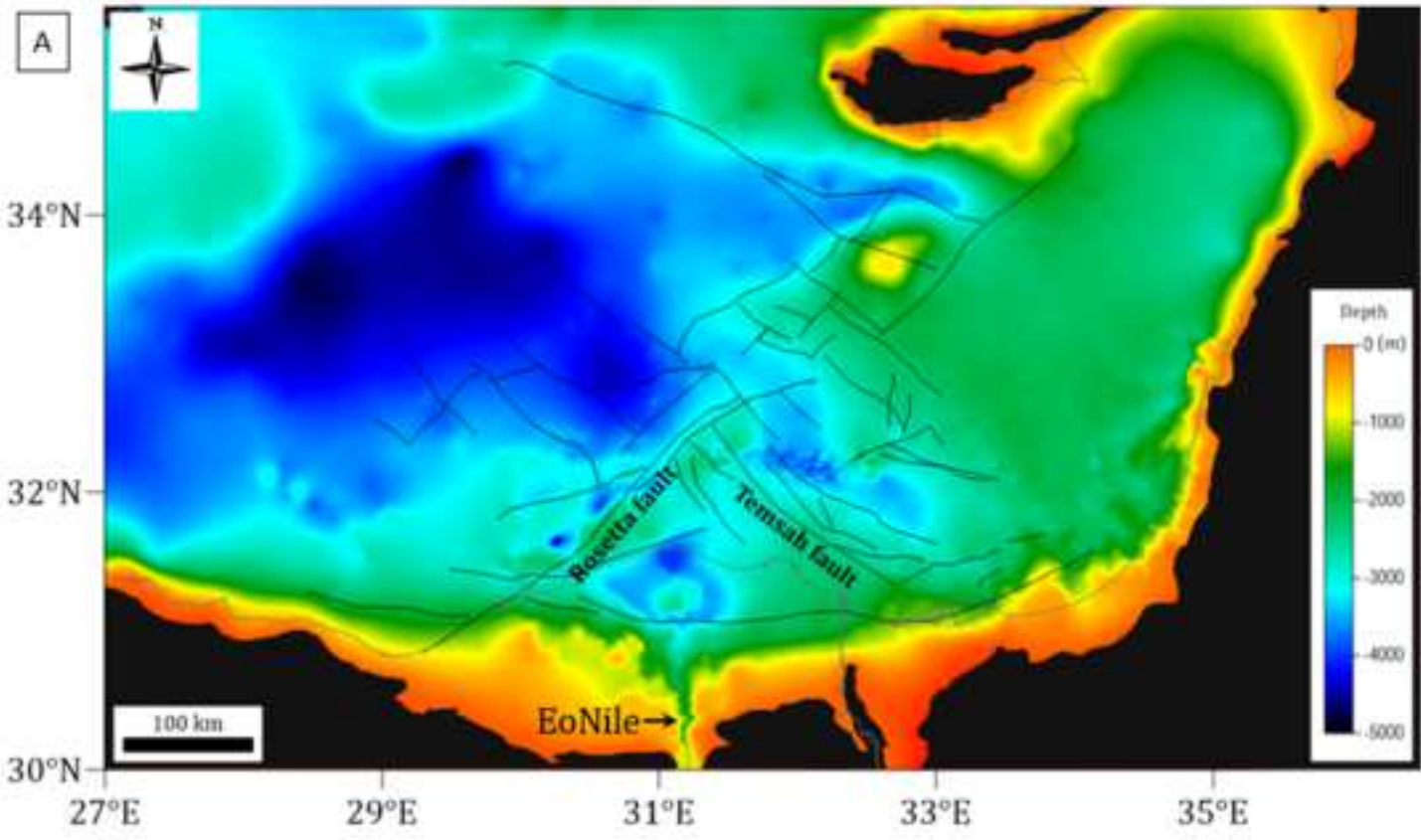
958 Table 1: Model parameters from the literature and this study.

959

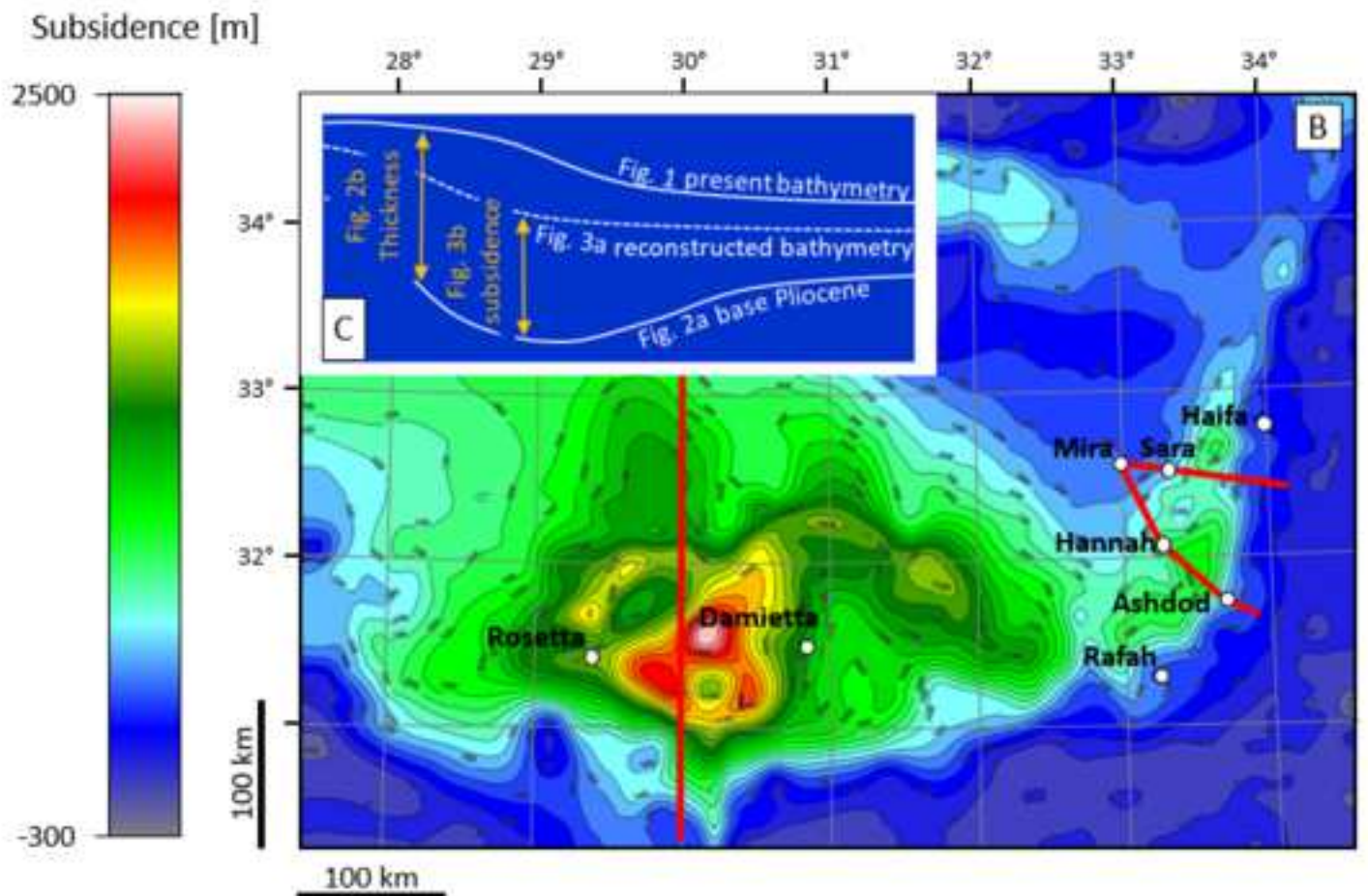
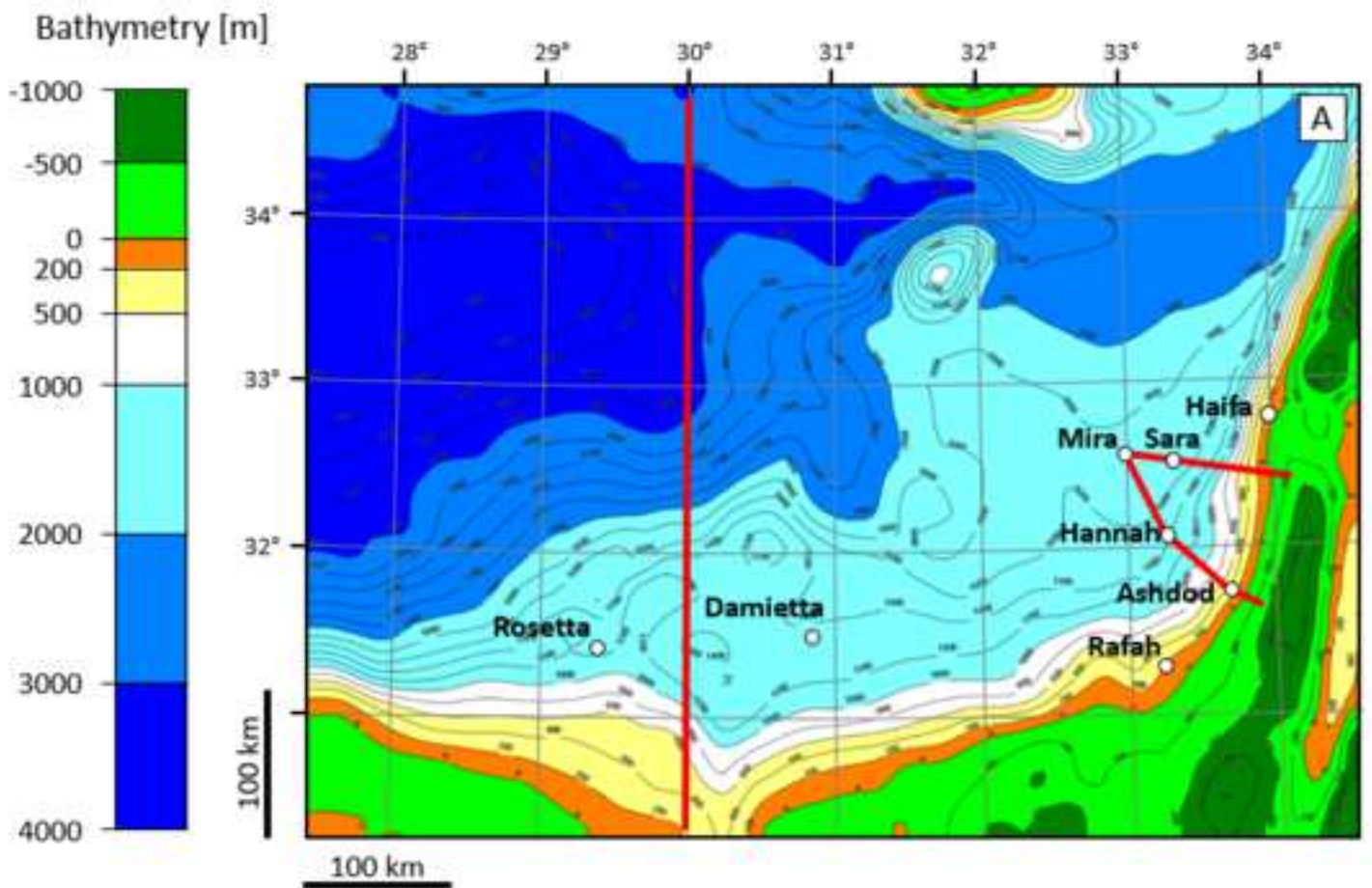
Figure 2

[Click here to access/download;Figure;Fig 2.PNG](#)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

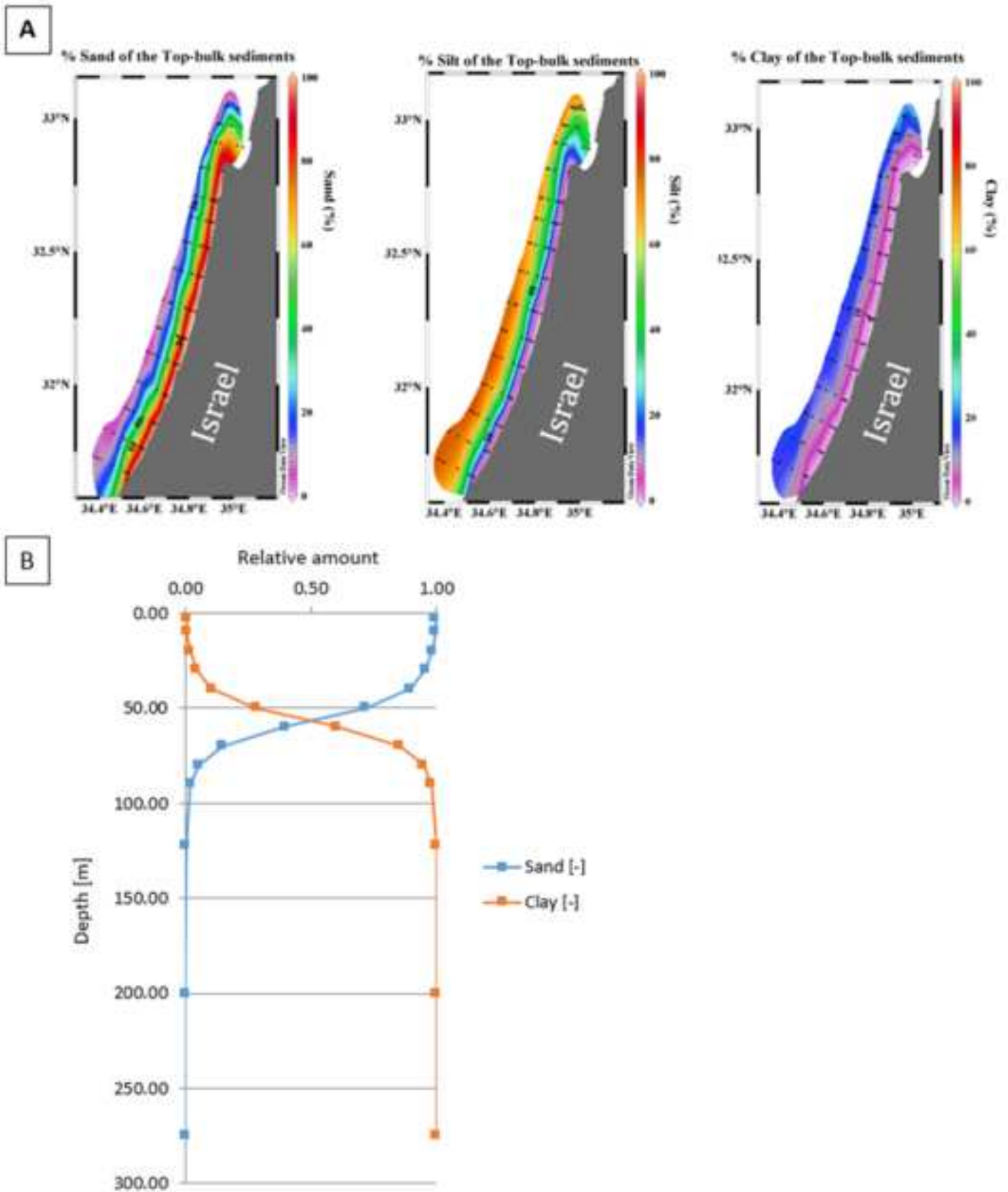
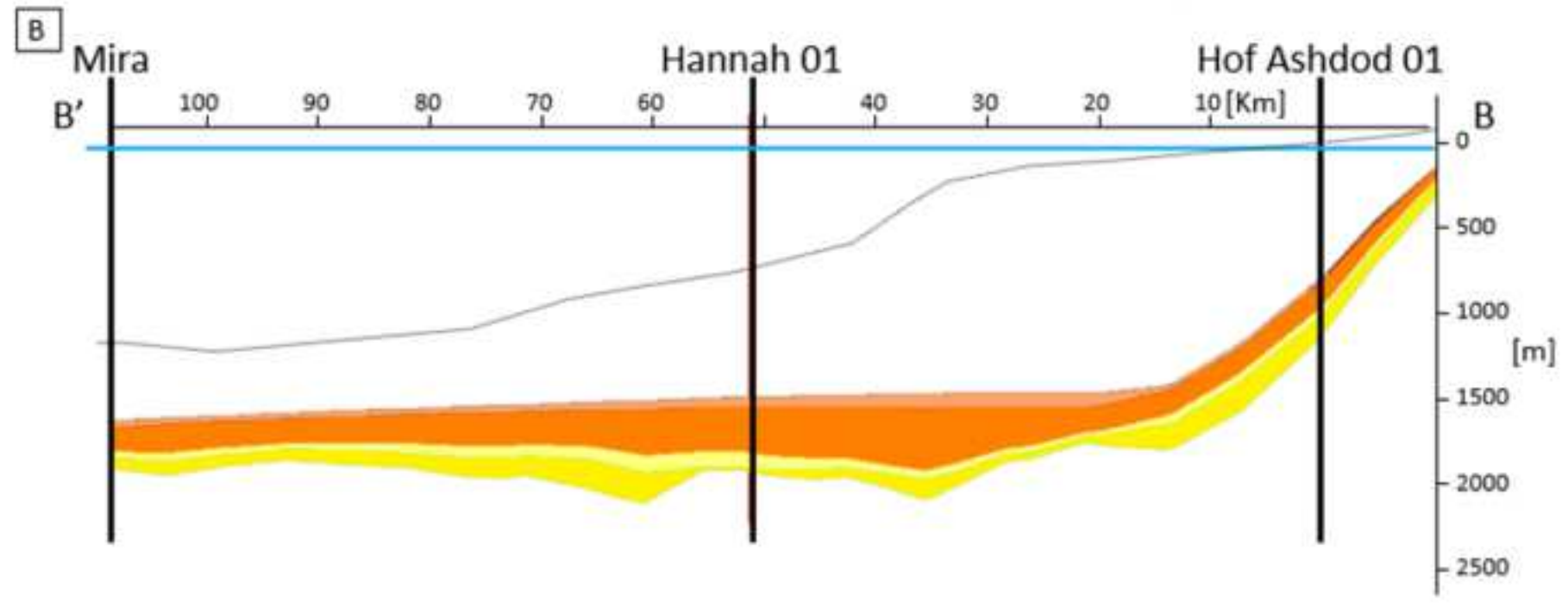
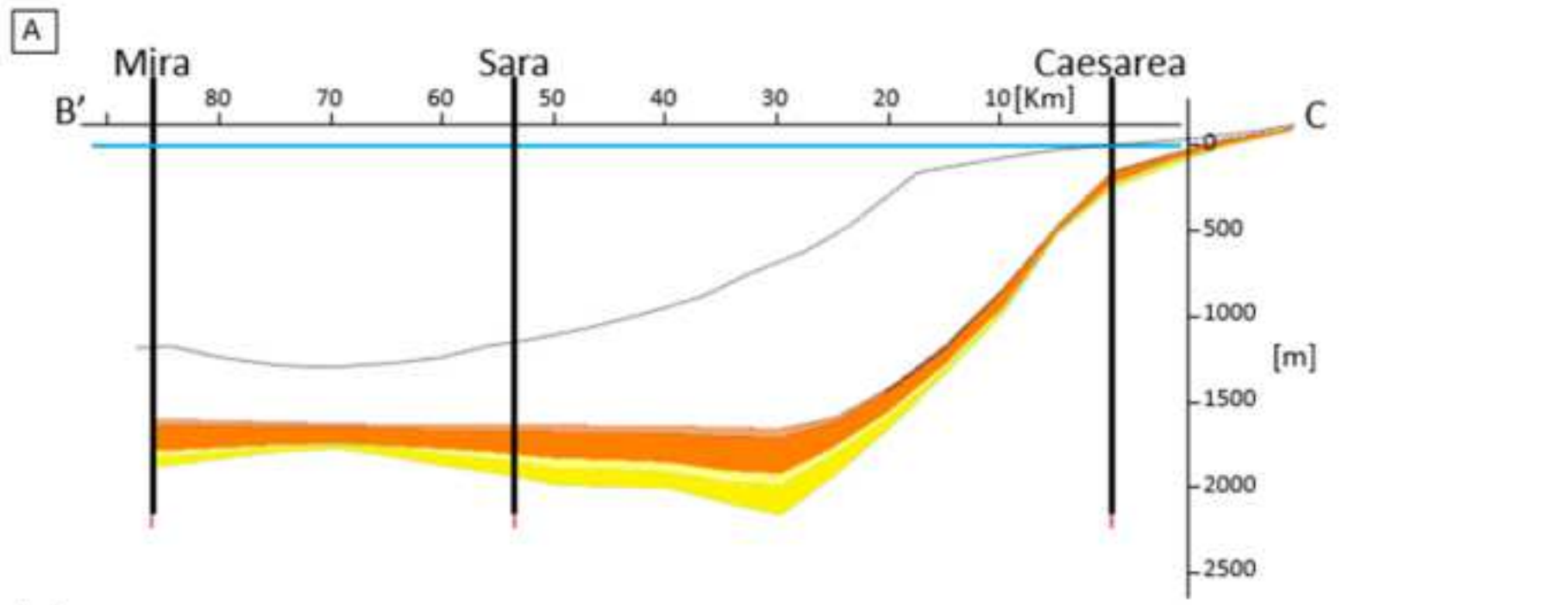
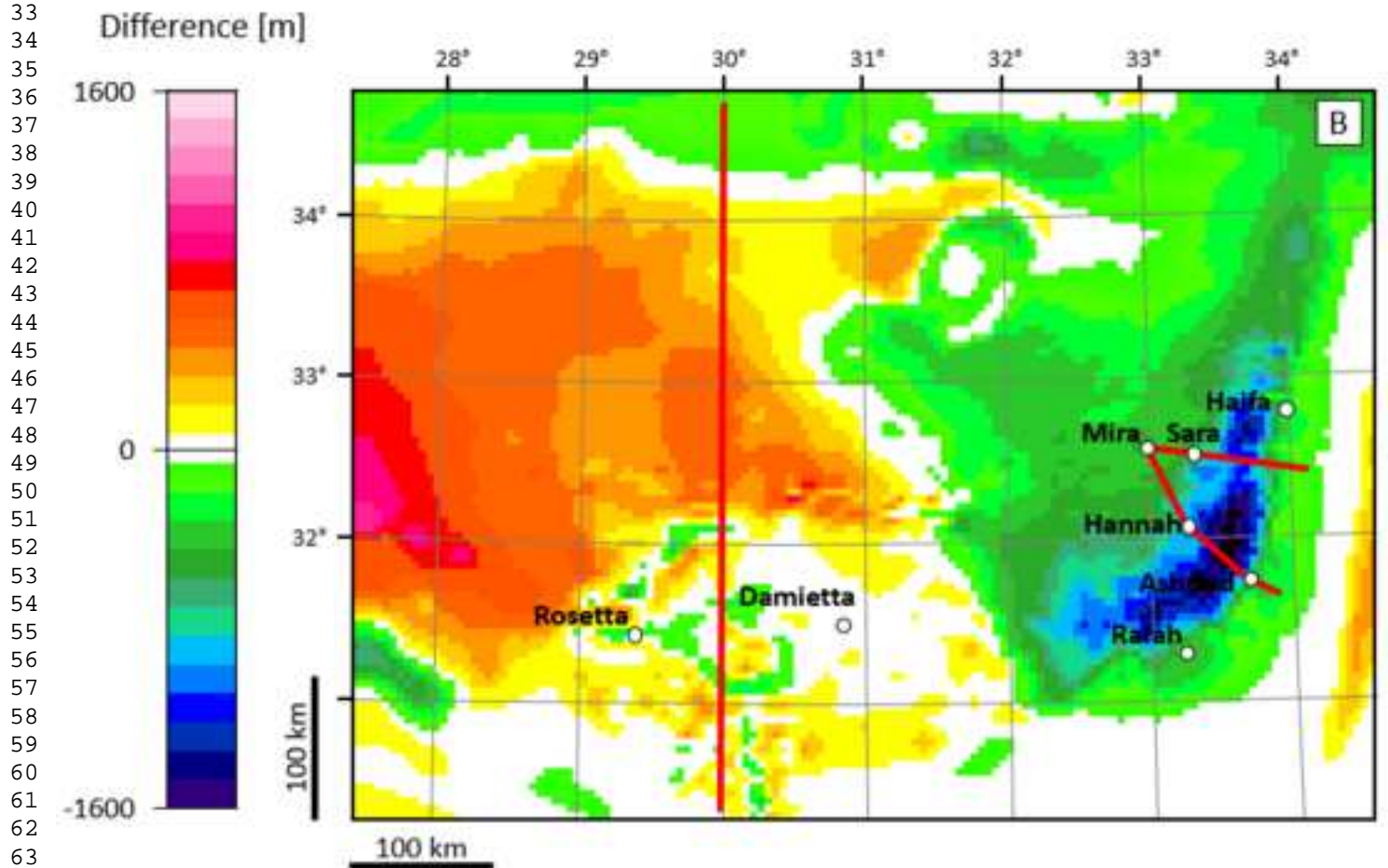
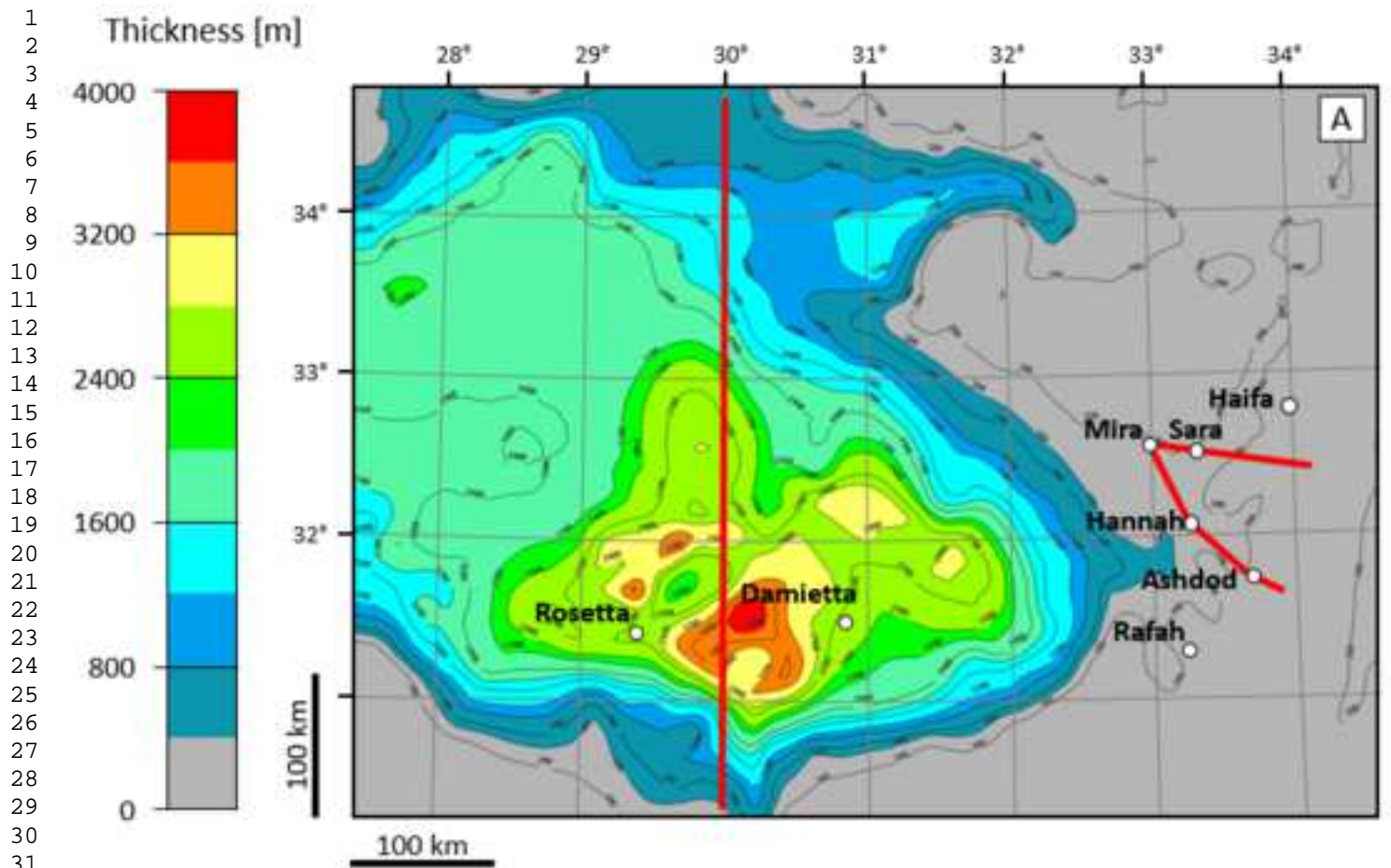


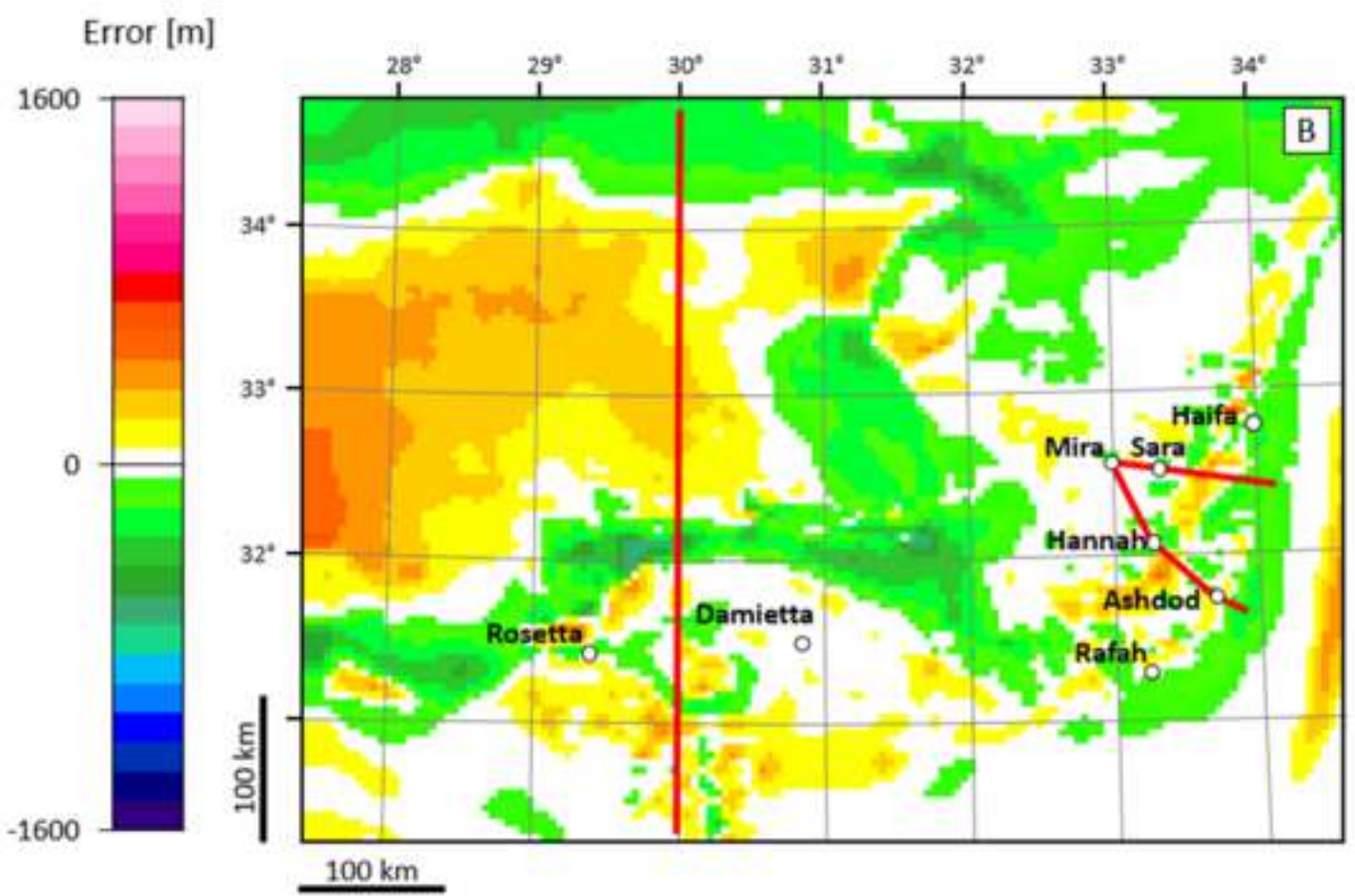
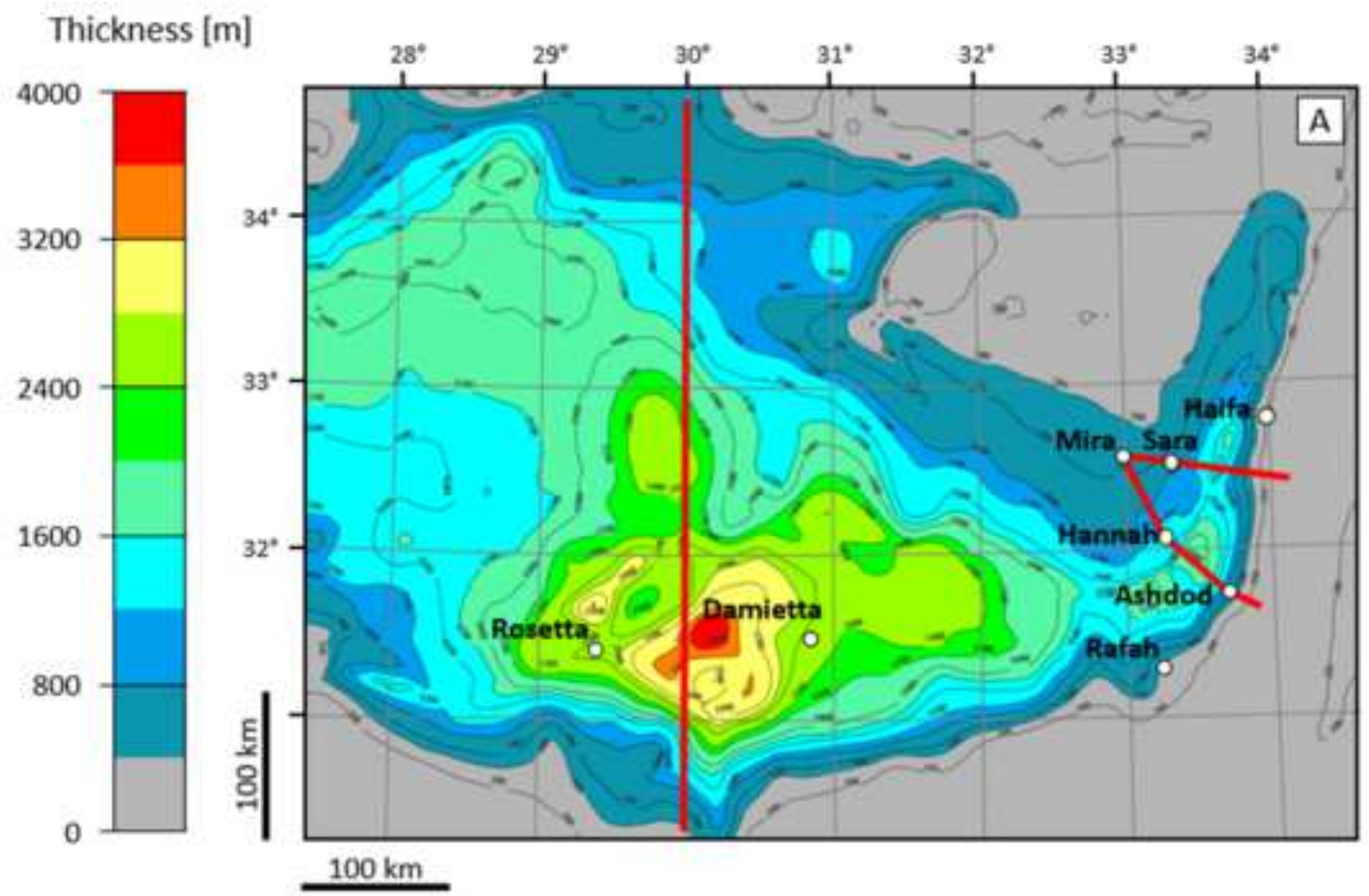
Figure 7



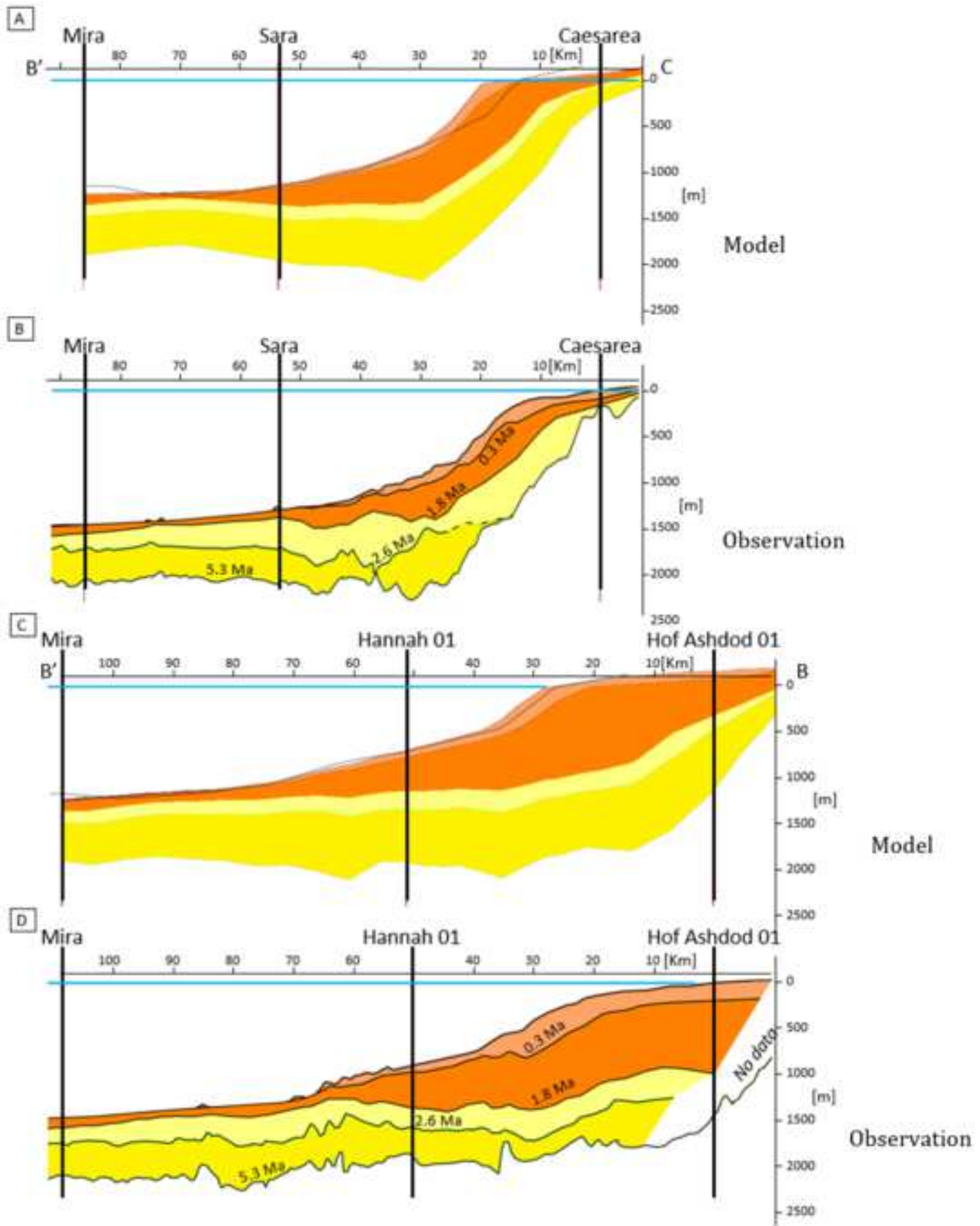
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49



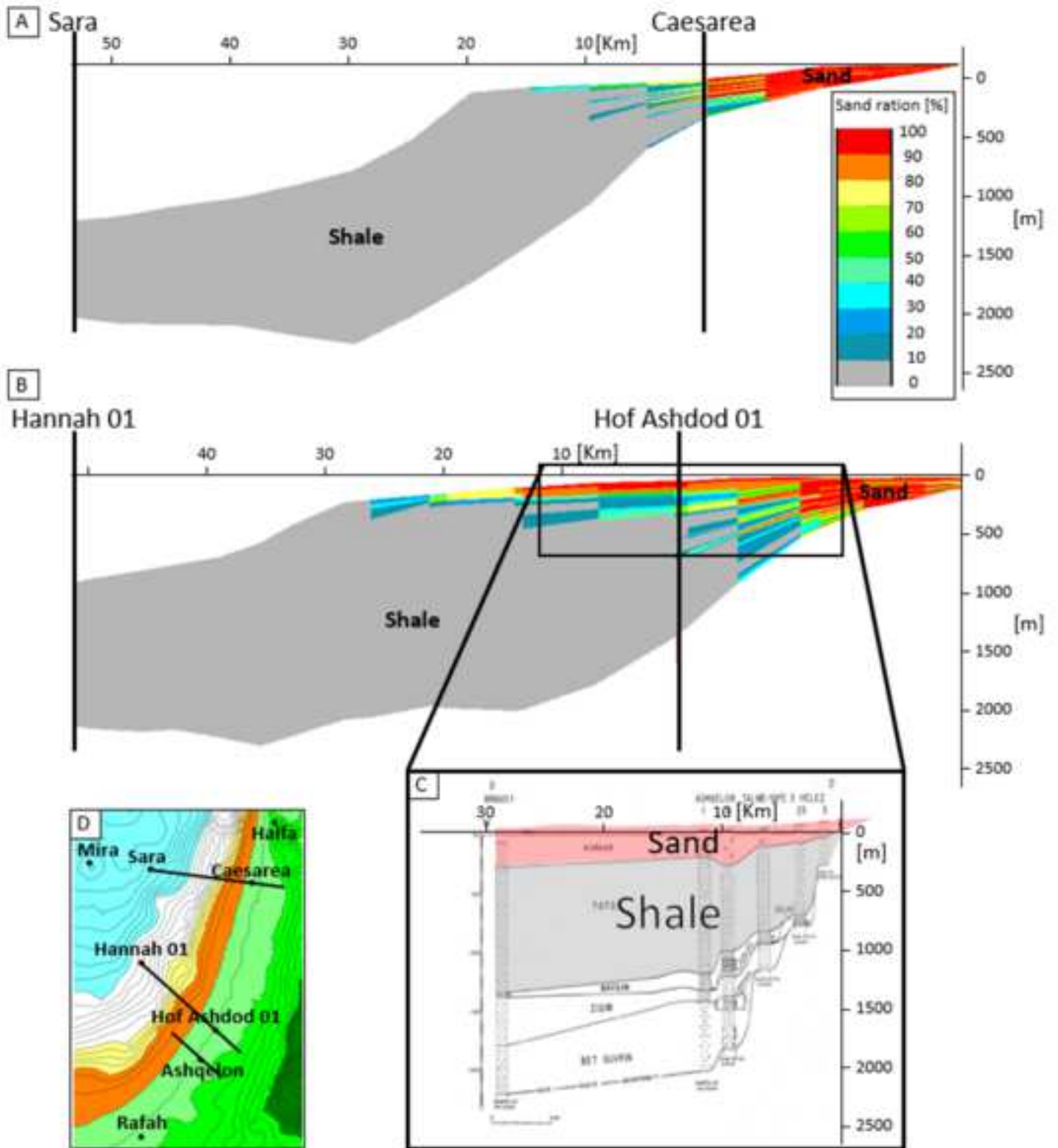
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

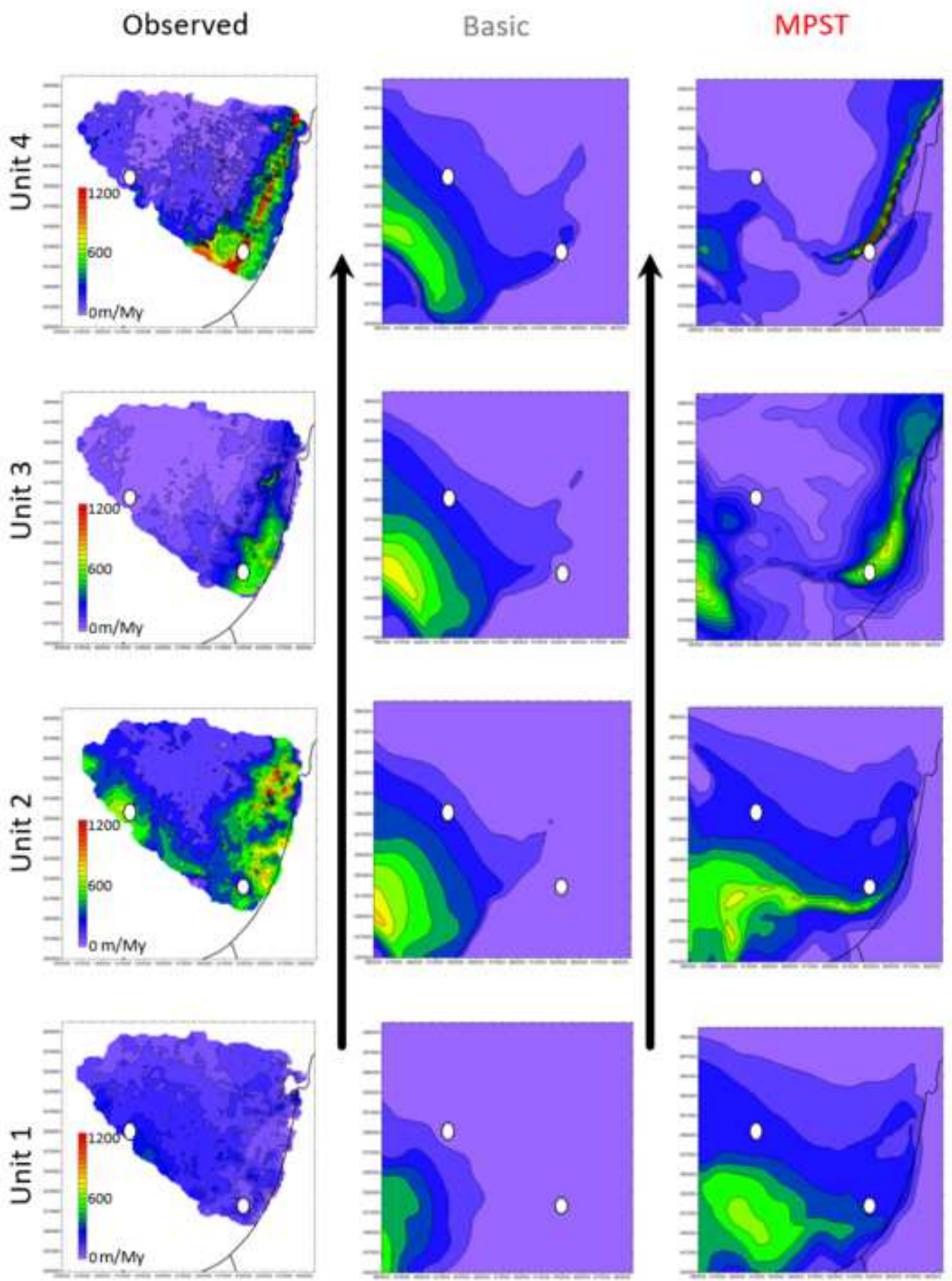
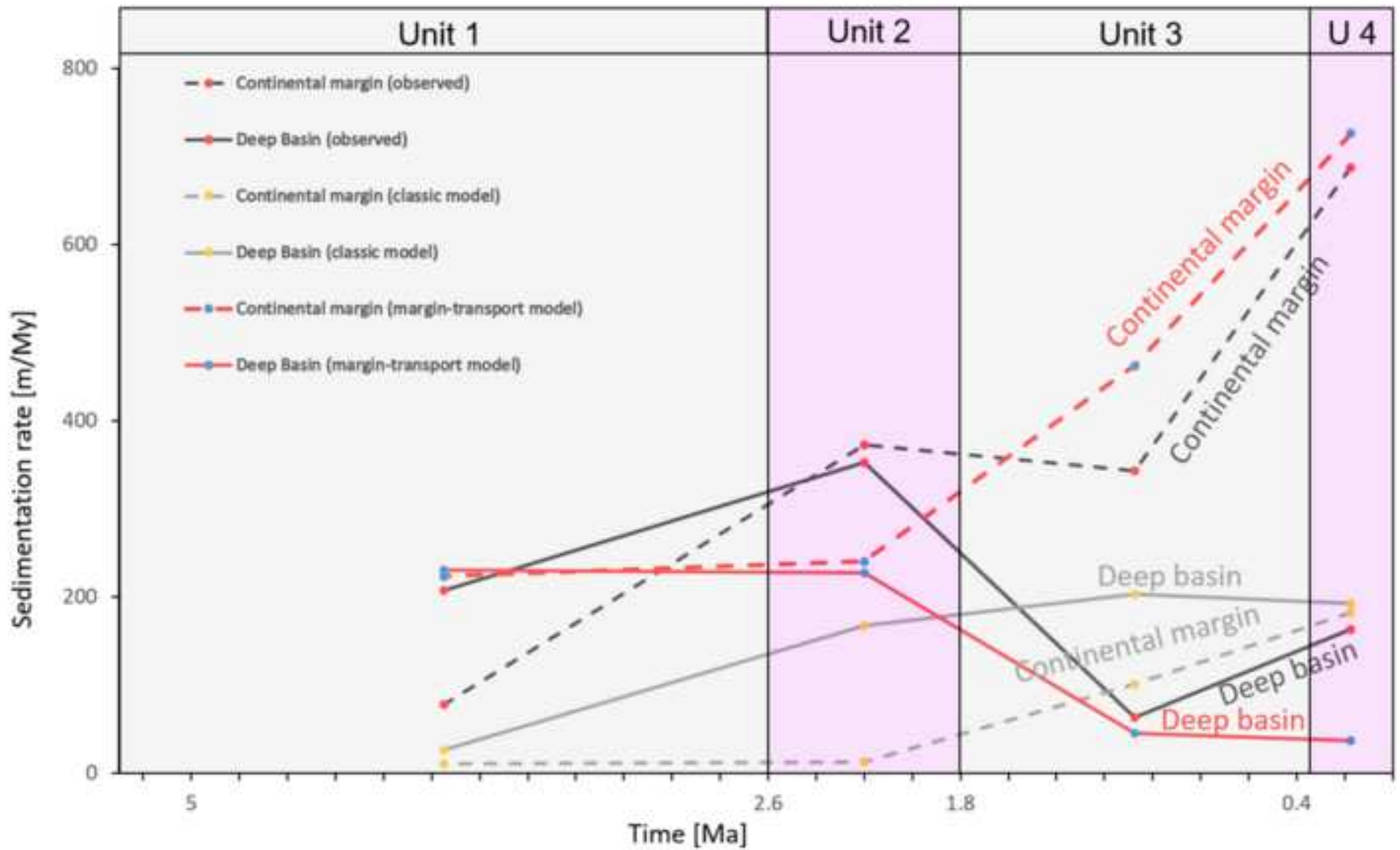
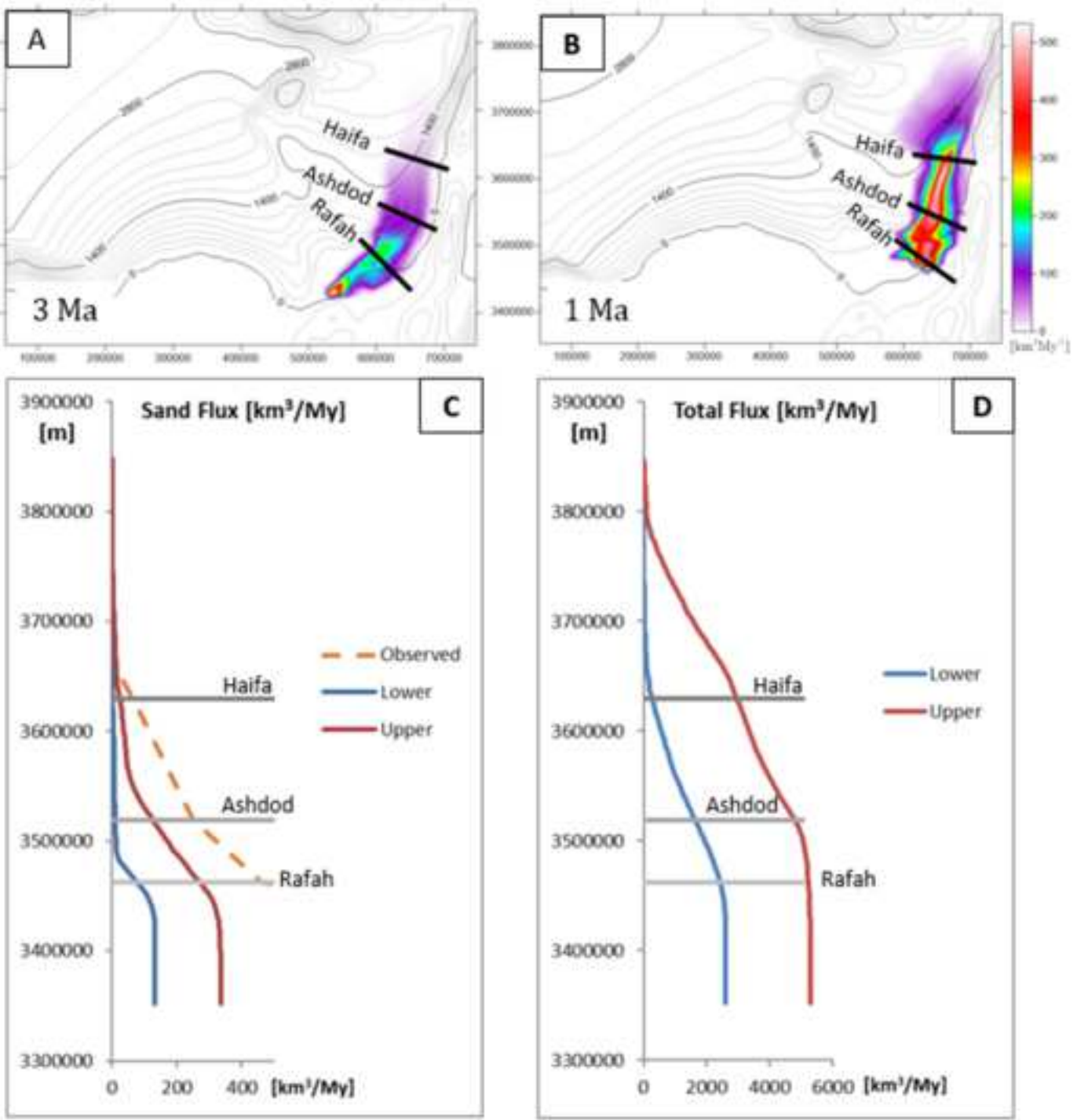


Figure 15



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

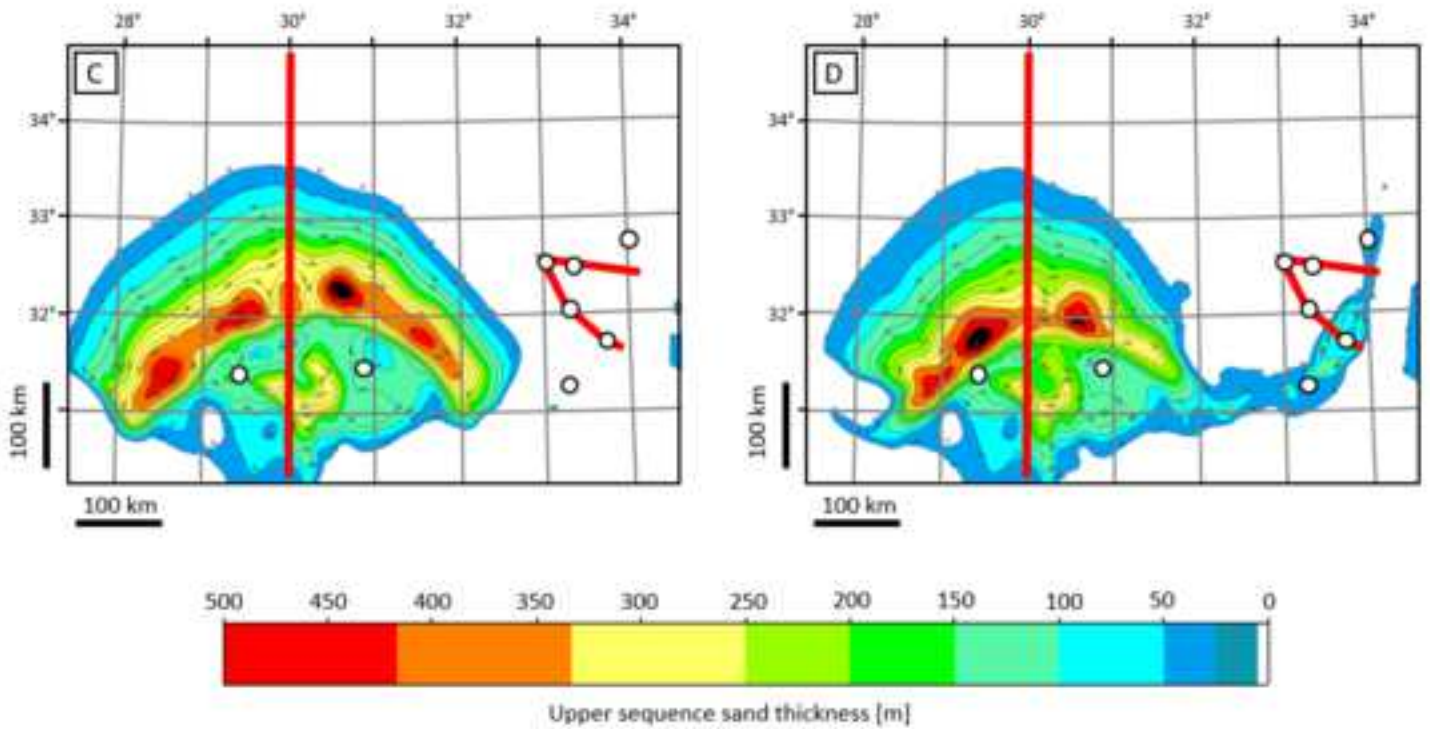
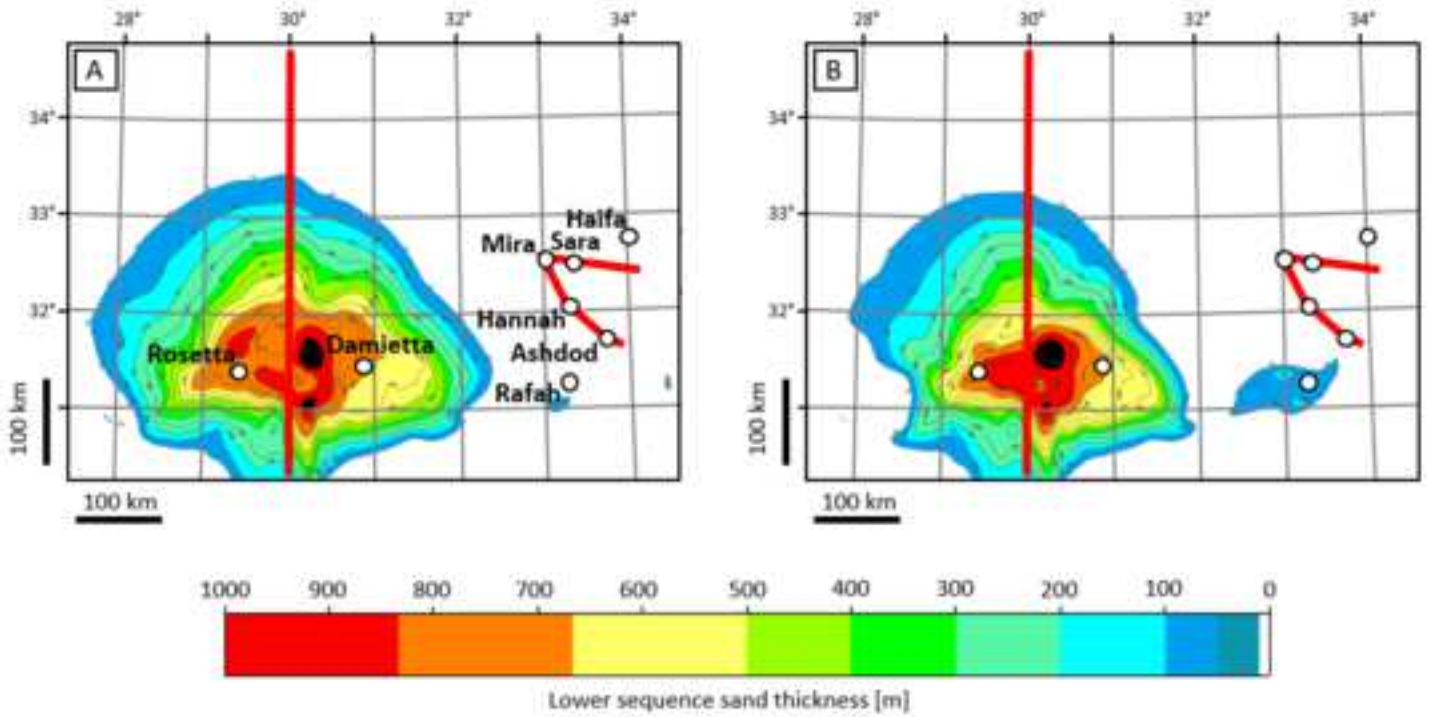
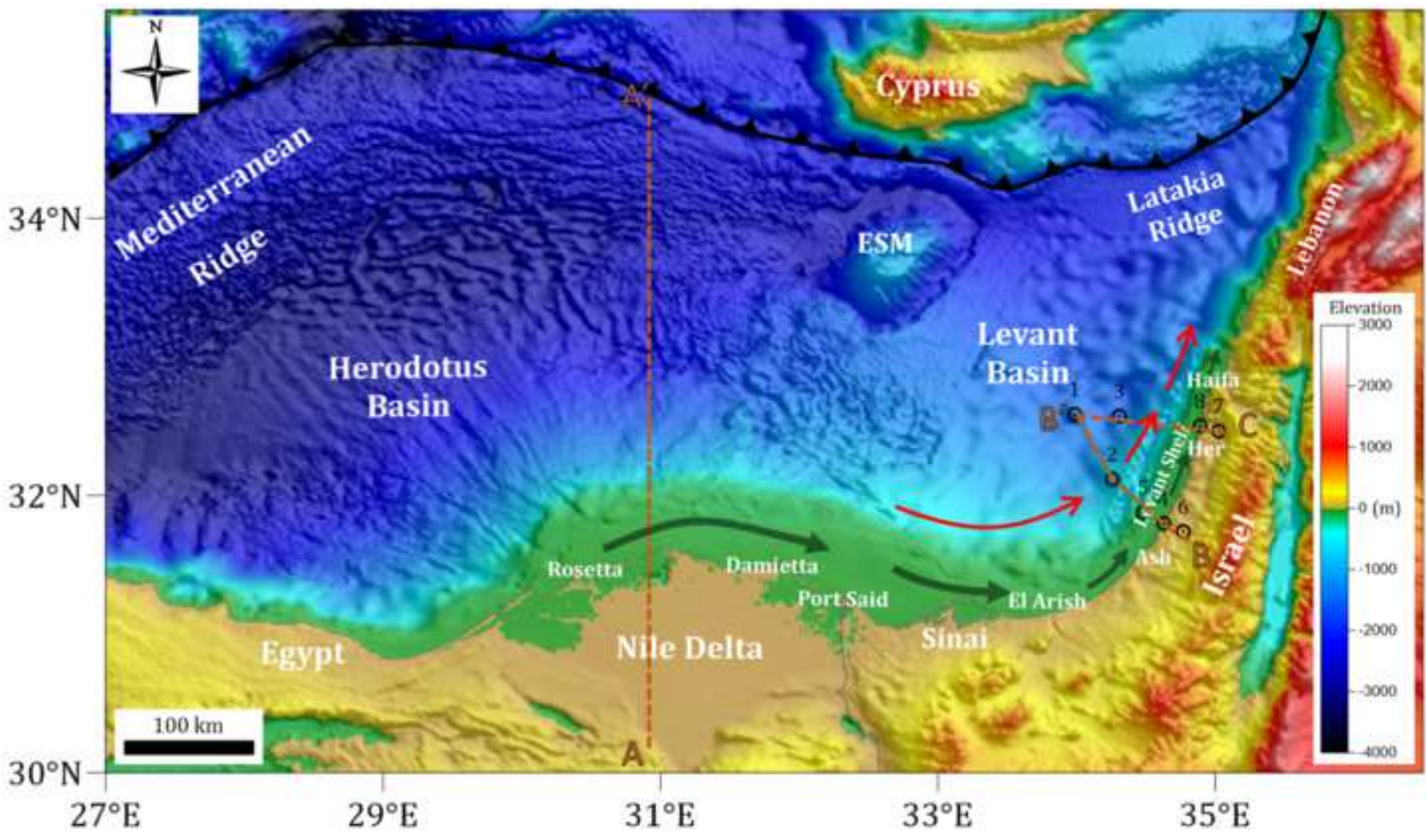
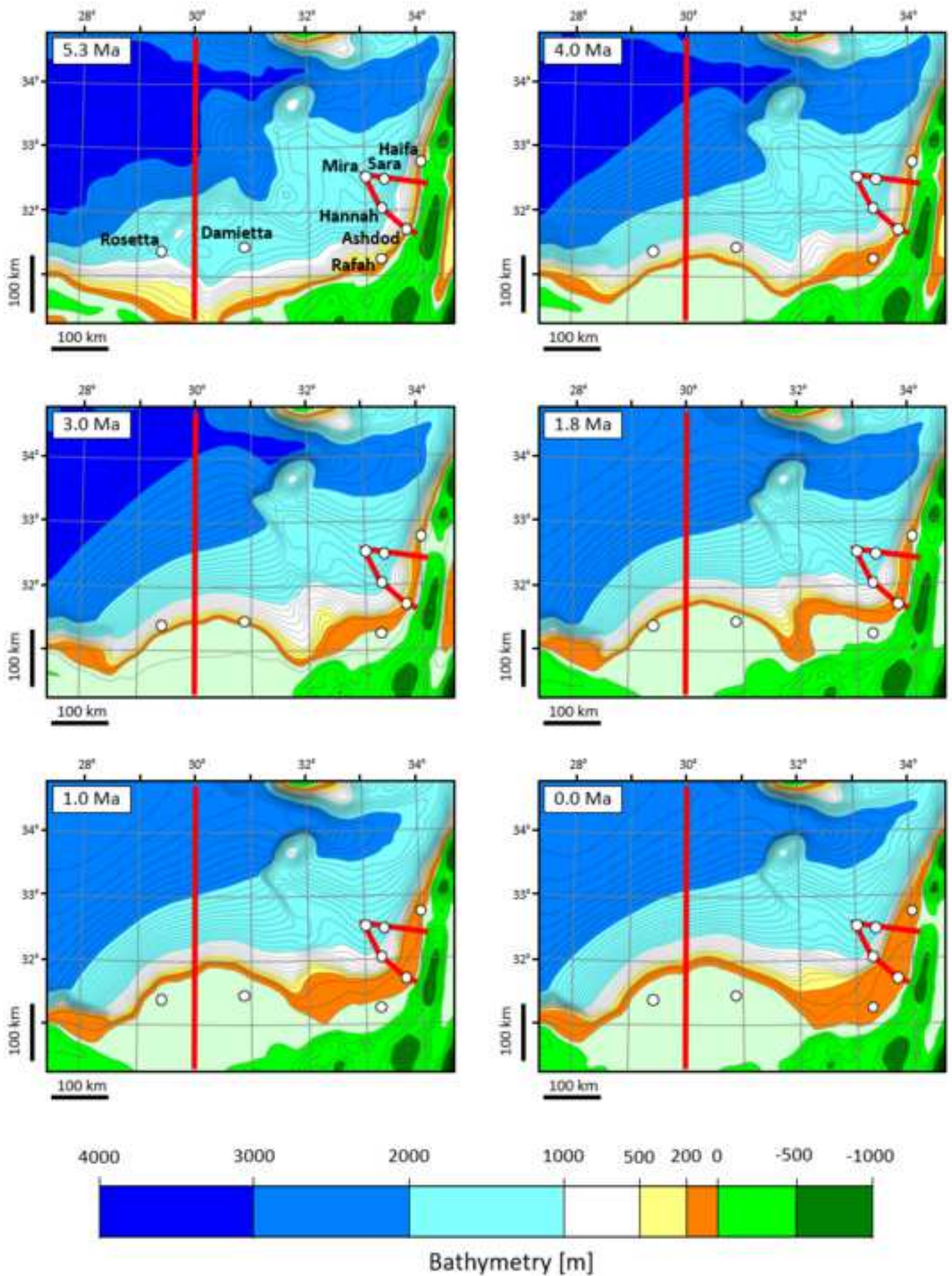


Figure 1

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

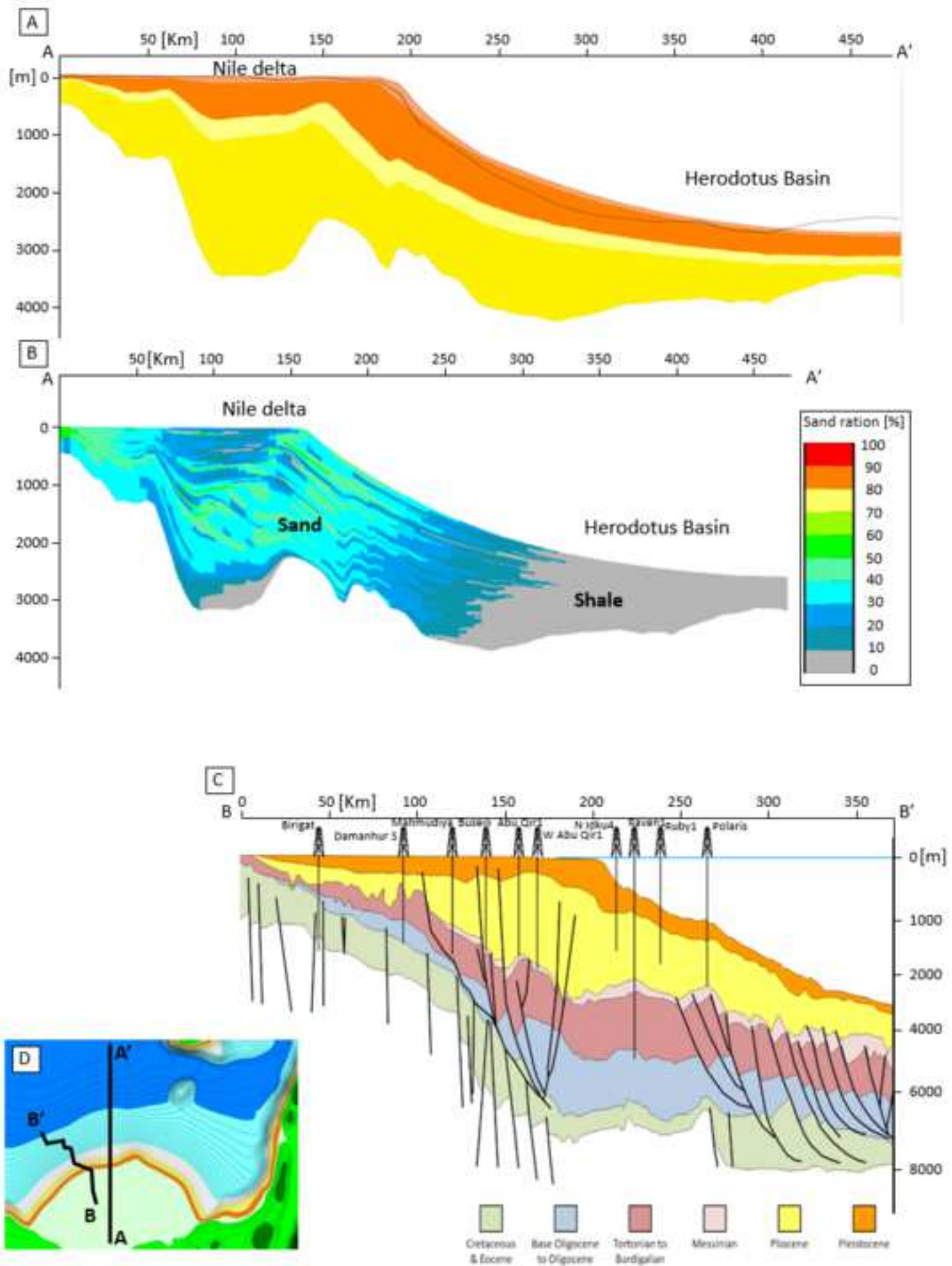
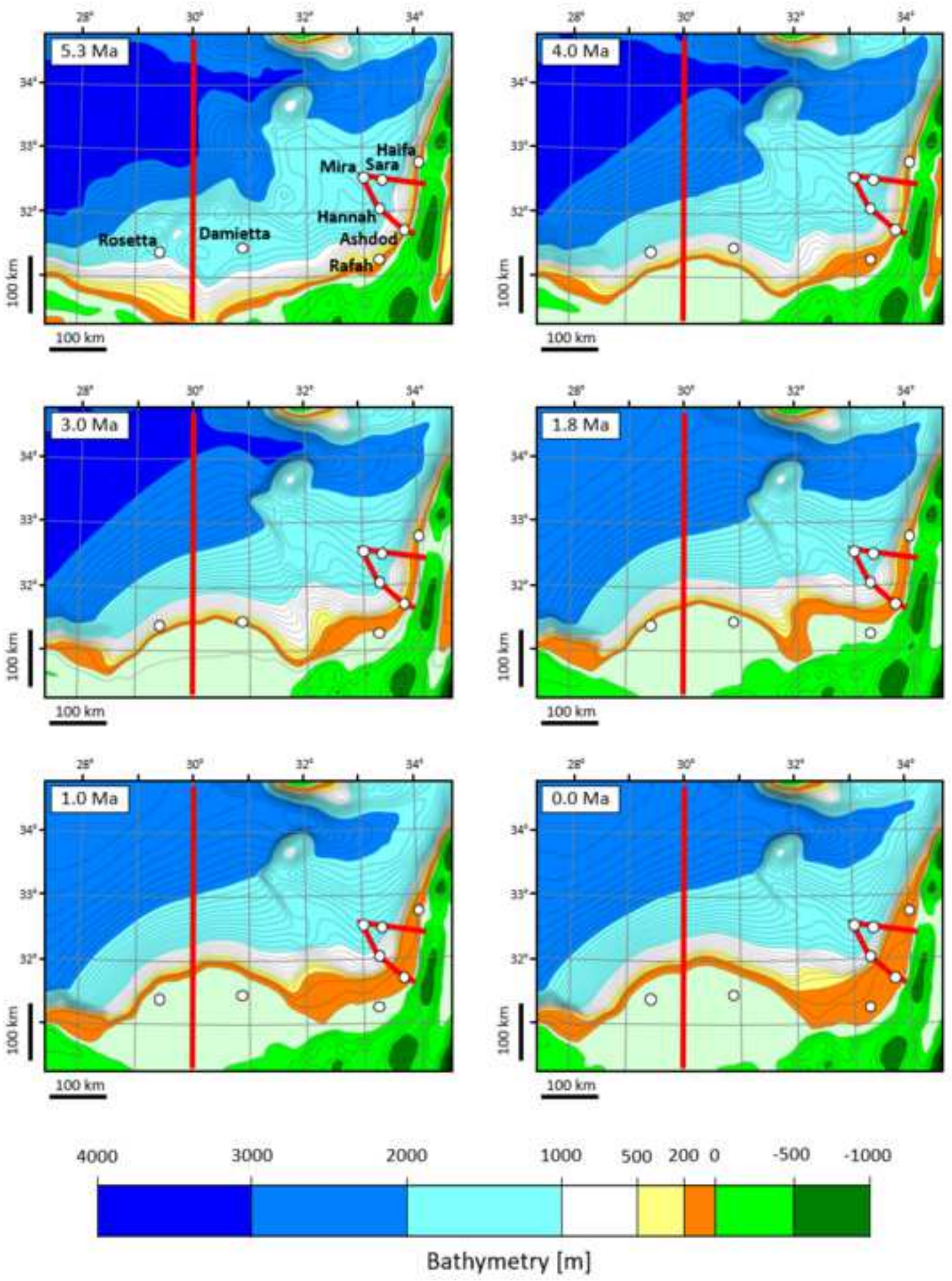


Figure 9

[Click here to access/download;Figure;Fig 9 AR.PNG](#)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65



Diffusion Coefficient [km²/ky]

Sand

		K gravity terrestrial [km ² /ky]	K gravity marine [km ² /ky]	K water terrestrial [km ² /ky]	K water marine [km ² /ky]
Csato et al., 2014	Delta	0.001	0.001	250	5
Zhang et al., 2018	Delta	0.05	0.005	50	0.01
Csato et al., 2013	Margin	0.001	0.001	2000	0.4
Harris et al., 2016	Margin	0.001	0.001	250	1
Gvirtzman et al., 2014	Turbidites	0.001	0.001	Not Defined	2
Hawie et al., 2017	Turbidites	0.001	0.001	Not Defined	0.3
Hawie et al., 2018	Turbidites	0.001	0.007	Not Defined	20
range		0.001 - 0.05	0.001 - 0.005	50 - 2000	0.01 - 20
Levant (this study)	Delta and Margin	0.001	0.001	100	0.5

Shale

		K gravity terrestrial [km ² /ky]	K gravity marine [km ² /ky]	K water terrestrial [km ² /ky]	K water marine [km ² /ky]
Csato et al., 2014	Delta	0.001	0.001	1000	5
Zhang et al., 2018	Delta	0.1	0.05	100	0.1
Csato et al., 2013	Margin	0.001	0.001	4000	10
Harris et al., 2016	Margin	0.001	0.001	1000	5
Gvirtzman et al., 2014	Turbidites	0.001	0.001	Not Defined	10
Hawie et al., 2017	Turbidites	0.001	0.001	Not Defined	0.063
Hawie et al., 2018	Turbidites	0.001	0.001	Not Defined	100
range		0.001 - 0.1	0.001 - 0.05	100 - 4000	0.063 - 100
Levant (this study)	Delta and Margin	0.01	0.01	500	2.5