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M Rodriguez, D Sakellariou, Christian Gorini, A Janin, Elia d'Acremont, Laetitia Le Pourhiet, N Chamot-Rooke, K Tsampouraki-Kraounaki, I Morfis, G Rousakis, et al.

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## Evolution of the North Anatolian Fault from a diffuse to a localized shear zone in the North Aegean Sea during the Plio-Pleistocene

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Complete List of Authors:	Rodriguez, Mathieu; Ecole Normale Supérieure, geosciences Sakellariou, Dimitris; Hellenic Center for Marine Research, Institute of Oceanography Gorini, Christian; Institut des Sciences de la Terre de Paris Janin, Alexandre; Laboratoire de Géologie de l'Ecole Normale Supérieure d'Acremont, Elia; Université Pierre et Marie Curie, ISTEP le pourhiet, laetitia; Sorbonne University Chamot-Rooke, Nicolas; CNRS Ecole normale supérieure, Laboratoire de Géologie Tsampouraki-Kraounaki, Konstantina; Hellenic Center for Marine Research Morfis, Iannis; Hellenic Center for Marine Research Rousakis, George; Hellenic Center for Marine Research Henry, Pierre; CEREGE Lurin, Aude; Université Toulouse III Paul Sabatier Delescluse, Matthias; Laboratoire de Géologie de l'Ecole Normale Supérieure Briole, Pierre; Laboratoire de Géologie de l'Ecole Normale Supérieure, Laboratoire de Géologie Rigo, Alexis; Laboratoire de Géologie de l'Ecole Normale Supérieure Arsenikos, Stavros; Beicip-Franlab Bulois, Cédric; Laboratoire de Géologie de l'Ecole Normale Supérieure Fernandez Blanco, david; Instituto de Ciencias del Mar Beniest, Anouk; Vrije Universiteit Amsterdam Grall, Celine; La Rochelle Université Chanier, Frank; Université de Lille Faculté des Sciences et Technologies Caroir, Fabien; Université de Lille Faculté des Sciences et Technologies Dessa, Jean-Xavier; UPMC, Géoazur Oregioni, Davide; GeoAzur Necessian, Alexandre; Institut de Physique du Globe de Paris, UMR CNRS 7154
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1 **Evolution of the North Anatolian Fault from a diffuse to a localized shear zone in the North**

2 **Aegean Sea during the Plio-Pleistocene**

3 Rodriguez, M. <sup>1</sup>; Sakellariou, D. <sup>2</sup>; Gorini, C. <sup>3</sup>; Janin, A. <sup>1</sup>; D'Acemont, E. <sup>3</sup>; LePourhiet, L. <sup>3</sup>; Chamot-  
 4 Rooke, N. <sup>1</sup>; Tsampouraki-Kraounaki, K. <sup>2</sup>; Morfis, I. <sup>2</sup>; Rousakis, G. <sup>2</sup>; Henry, P. <sup>4</sup>; Lurin, A. <sup>1</sup>;  
 5 Delescluse, M. <sup>1</sup>; Briole, P. <sup>1</sup>; Rigo, A. <sup>1</sup>; Arsenikos, S. <sup>5</sup>; Bulois, C. <sup>1</sup>; Fernández-Blanco, D. <sup>7</sup>; Beniést,  
 6 A. <sup>8</sup>; Grall, C. <sup>9</sup>; Chanier, F. <sup>10</sup>; Caroir, F. <sup>10</sup>; Dessa, J-X. <sup>6</sup>; Oregioni, D. <sup>6</sup>; Nercessian, A. <sup>11</sup>

7  
 8 *1 - Laboratoire de Géologie, Ecole normale supérieure, PSL research university, CNRS UMR 8538, 24*  
 9 *rue Lhomond, 75005 Paris, France*

10 *2- Institute of Oceanography, Hellenic Center of Marine Research, GR-19013 Anavysos, Greece*

11 *3-Sorbonne Université, UPMC Université Paris 06, UMR 7193, IStEP, F-75005, Paris, France.*

12 *4- Centre Européen de Recherche Et d'Enseignement Des Géosciences de L'Environnement, Aix-*  
 13 *Marseille Université, Marseille, France*

14 *5- Beicip-Franlab, Rueil-Malmaison, France*

15 *6- Géoazur, Université de Nice-Sophia Antipolis-CNRS-OCA, France*

16 *7- Barcelona Center for Subsurface Imaging, Instituto de Ciencias del Mar, CSIC, Barcelona, Spain*

17 *8- Department of Earth Sciences, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands*

18 *9- LIENSs, La Rochelle University, La Rochelle, France*

19 *10- Univ. Lille, CNRS, Univ. Littoral Côte d'Opale, UMR 8187, LOG, Laboratoire d'Océanologie et de*  
 20 *Géosciences, F59000 Lille, France*

21 *11- Université de Paris, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France*

22 **Abstract**

23 **The North Anatolian Fault is the ~1200-km-long active continental transform boundary between**  
 24 **Anatolia and Eurasia. This strike-slip system initiated around 10-12 Ma and experienced**  
 25 **diachronous episodes of strain localization along its strike. The structural evolution of the ~350-**  
 26 **km-long fault segments crossing the North Aegean Sea remains to be accurately investigated.**  
 27 **There, the modern North Anatolian Fault is localized along two main branches: the northern**  
 28 **branch ends at the North Aegean Trough and the southern branch ends at the Edremit-Skyros**

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3 29 **Trough. The Evia Basin is located in the North Aegean Domain between the North Anatolian Fault**  
4  
5 30 **and the Corinth Rift. This study presents seismic reflection lines crossing the aforementioned**  
6  
7 31 **structures of the North Aegean Domain, which document their subsurface structure and the**  
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9 32 **sedimentary record of their activity since the Messinian. The seismic-reflection dataset is tied to**  
10  
11 33 **regional-scale stratigraphic markers, which constrains the age of main tectonic events related to**  
12  
13 34 **the formation of the North Anatolian Fault. The seismic-reflection lines show that the two main**  
14  
15 35 **branches of the North Anatolian Fault became localized structures at 1.3-2 Ma, coevally with the**  
16  
17 36 **formation of the Evia Basin. Since 2 Ma, the North Aegean Troughs developed as a series of**  
18  
19 37 **horsetail basins propagating westwards at the termination of the branches of the North Anatolian**  
20  
21 38 **Fault. On a regional scale, the wide and diffuse North Anatolian transtensive shear zone active**  
22  
23 39 **from Serravalian to Late Pliocene turned into a narrower shear zone at the two main branches of**  
24  
25 40 **the North Anatolian Fault since the Early Pleistocene. This abrupt episode of strain localization**  
26  
27 41 **occurred in the frame of the major Early Pleistocene change in stress regime from NE-SW to N-**  
28  
29 42 **S extension, which has been observed throughout the Aegean Sea.**  
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35 44 **Keywords:** *Continental tectonics; strike-slip and transform; Transform faults; Normal faulting;*  
36  
37 45 *Tectonics and landscape evolution; Europe; Crustal imaging.*  
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## 41 47 **1- Introduction**

42  
43 48 Transform faults are major lithospheric-scale tectonic structures acting as plate boundaries (Woodcock,  
44  
45 49 1986; Mann, 2007), along which relative plate motion occurs horizontally along the fault's strike. The  
46  
47 50 accumulated relative plate motion along transform boundaries juxtaposes sections of the lithosphere  
48  
49 51 with different histories, ages, and hence, mechanical properties (Ben Zion & Sammis, 2003). The  
50  
51 52 complex rheology of the continental domain results in both localized (e.g. the Dead Sea Fault; Garfunkel  
52  
53 53 & Ben-Avraham, 1996) and diffuse continental transform systems (e.g. the Trans-Alboran Shear Zone;  
54  
55 54 Lafosse *et al.*, 2020). Some transform systems have also being shown to alternate localized and diffuse  
56  
57 55 strain along their strike (e.g. the San Andreas Fault; Wesnousky, 2005; and the North Anatolian Fault;  
58  
59 56 Sengör *et al.*, 2019).  
60

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2  
3 57 Field studies reveal that continental transforms initiate as several hundreds of kilometers-wide  
4  
5 58 distributed areas of deformation, forming a shear zone that is composed of scattered oblique en-échelon  
6  
7 59 strands (Tchalenko & Ambraseys, 1970; Sengör *et al.*, 2005; Wesnousky, 2005; Mann, 2007; Sengör *et*  
8  
9 60 *al.*, 2014). During fault initiation, motion is distributed over several individual fault segments. As finite  
10  
11 61 relative motion increases, fault strands progressively connect into continuous and localized strike-slip  
12  
13 62 fault segments. The increased connection of fault strands shapes narrower shear zones (<100-km- wide)  
14  
15 63 with local structural complexities in stepover (releasing or restraining bends). The localization of strike-  
16  
17 64 slip segments leaves some initial oblique strands deactivated. The timing of strain localization within  
18  
19 65 the wide shear zone may differ from one fault segment to another. The lifetime of such shear systems in  
20  
21 66 the continental setting is in the order of  $10^7$  yrs (Sengör *et al.*, 2019). Analog models reproduce the  
22  
23 67 transition from an initial diffuse shear zone composed of Riedel faults to a localized fault formed by the  
24  
25 68 linkage of shear segments (Tchalenko, 1970; Dooley & Schreurs, 2012; Lefevre *et al.*, 2020).

26  
27  
28 69 The North Anatolian Fault system, located in the Eastern Mediterranean domain (Fig. 1, 2), is the 1200-  
29  
30 70 km-long dextral strike-slip boundary between the Anatolian and Eurasian tectonic plates (Fig. 1, 2),  
31  
32 71 which connects the Anatolia-Arabia-Eurasia triple junction in the East (Hubert Ferrari *et al.*, 2010) to  
33  
34 72 the Hellenic Subduction Zone (Flerit *et al.*, 2004; Sakellariou *et al.*, 2018; Ferentinos *et al.*, 2018). The  
35  
36 73 North Anatolian Fault triggers frequent earthquakes above  $M_w \sim 7$  (e.g. Izmit and Duzce events in 1999;  
37  
38 74 Hubert-Ferrari *et al.*, 2000; Bulut *et al.*, 2018) and its submarine segments are a potential source of  
39  
40 75 tsunamis (Hébert *et al.*, 2005; Reicherter *et al.*, 2010; Janin *et al.*, 2019).

41  
42  
43 76 The North Anatolian Fault transects continental lithosphere with significant along-strike strength  
44  
45 77 variations, inherited from the successive geological events that shaped the Hellenides mountain belt  
46  
47 78 prior to its collapse. As such, the North Anatolian Fault is a relevant case-study of a post-orogenic  
48  
49 79 transform fault (Le Pourhiet *et al.*, 2014; Jolivet *et al.*, 2021).

50  
51 80 The objective of this study is to constrain the structural evolution of the ~350-km-long segment of the  
52  
53 81 North Anatolian Fault crossing the North Aegean Sea (Fig. 3, 4), on the basis of a set of multibeam data  
54  
55 82 (Ypother cruises, 2013-2016; Sakellariou *et al.*, 2018) and seismic-reflection profiles (NAFAS cruise,  
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57 83 2017; Rodriguez *et al.*, 2018; vintage seismic lines published in Beniest *et al.*, 2016).

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3 84 The present dataset covers some of the major tectonic structures encountered in the North Aegean  
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5 85 Domain, namely the North Aegean Trough, the Edremit-Skyros Trough and the Evia Basin (Fig. 2-4).  
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7 86 There, the different steps of formation of the North Anatolian Fault remained poorly constrained due to  
8  
9 87 the lack of seismic-reflection and stratigraphic data (Krijgsman *et al.*, 2022). We define some regional  
10  
11 88 stratigraphic markers for the period spanning the Messinian to the present-day (Laigle *et al.*, 2000;  
12  
13 89 Beniest *et al.*, 2016; Ferentinos *et al.*, 2018) to reach a precision in the ages of tectonic events  
14  
15 90 comparable to the segments of the North Anatolian Fault observed in the Marmara Sea (Le Pichon *et*  
16  
17 91 *al.*, 2014). Finally, we provide structural maps of the post-Messinian evolution of the North Aegean  
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19 92 Domain, from the Yeniçağa Fork east of Marmara to the Evia Basin in Greece (Fig. 2). Overall, our  
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21 93 structural reconstructions of the North Anatolian Fault document the strain localization within a post-  
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23 94 orogenic continental shear zone and the time of effective formation of such tectonic plates.  
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## 28 96 **2- Geological Background**

### 29 97 **2-1-Present-day configuration of the North Anatolian Fault in the North Aegean Domain**

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31  
32 98 The North Anatolian Fault is the plate boundary between Anatolia and Eurasia, with a current dextral  
33  
34 99 strike-slip rate of 23 mm.yr<sup>-1</sup> (Le Pichon *et al.*, 2003; Reilinger *et al.*, 2006; Le Pichon & Kreemer, 2010;  
35  
36 100 Pérouse *et al.*, 2012; Müller *et al.*, 2013). The finite amount of dextral motion along the North Anatolian  
37  
38 101 Fault is estimated to 85±5 km, with some ambiguities in areas where slip is distributed over several fault  
39  
40 102 strands (Sengör *et al.*, 2005). The finite offset results from strike-slip rates that grew from ~3 mm.yr<sup>-1</sup>  
41  
42 103 in the earliest stages of formation of the fault system to near-current slip rates since the Early Pleistocene  
43  
44 104 (Hubert Ferrari *et al.*, 2010).

45  
46  
47 105 In this study, the North Aegean Domain is defined as the area bounded to the south by the North Cycladic  
48  
49 106 Detachment System, to the north by the Rhodope Detachment System, to the west by the Vardar Suture  
50  
51 107 Zone and to the East by the Yeniçağa fork (Fig. 1, 2). The total amount of slip-rate along the North  
52  
53 108 Anatolian Fault is accommodated by its northern and southern branches in the North Aegean Domain  
54  
55 109 (Fig. 1, 2; Le Pichon *et al.*, 2003).

56  
57  
58 110 The northern branch of the North Anatolian Fault crosses the Marmara Sea (i.e. the Main Marmara  
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60 111 Fault; Le Pichon *et al.*, 2001), then runs along the Gelibolu Peninsula and the Gulf of Saros until it

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3 112 connects the North Aegean Trough (Fig. 2). The North Anatolian Fault makes a  $\sim 30^\circ$  bend at the  
4  
5 113 connection between the Saros Gulf and the North Aegean Trough (Roussos & Lyssimachou, 1991;  
6  
7 114 Koukouvelas & Aydin, 2002). The strike-slip rate of relative motion along the northern branch decreases  
8  
9 115 from  $21.2 \text{ mm yr}^{-1}$  at the Gulf of Saros to  $\sim 5 \text{ mm yr}^{-1}$  at the Sporadhes archipelago (Müller *et al.*, 2013).  
10  
11 116 The southern branch of the North Anatolian Fault crosses the Biga Peninsula and connects the Edremit-  
12  
13 117 Skyros Trough in the Aegean Sea (Fig. 2). The strain distribution of the southern branch of the North  
14  
15 118 Anatolian Fault (Fig. 2-4) is diffuse onland in Turkey (Sümer *et al.*, 2018), whereas it is expressed as a  
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17 119 localized structure offshore (Papanikolaou *et al.*, 2019). The strike-slip rate along the southern branch  
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19 120 is on the order of  $10 \text{ mm.yr}^{-1}$  (Müller *et al.*, 2013).  
20  
21  
22 121 Both the North Aegean and the Edremit-Skyros Troughs reveal horsetail structures (Fig. 3-4). Horsetail  
23  
24 122 structures are commonly observed at the termination of strike-slip faults (Basile & Brun, 1999): they  
25  
26 123 consist in numerous oblique splays rooting on the main strike-slip faults and isolating a series of  
27  
28 124 transtensive basins. On one hand, the North Aegean Trough is  $\sim 150\text{-km}$ -long, up to  $80\text{-km}$ -wide and  
29  
30 125  $1600\text{-m}$ -deep (Brooks & Ferentinos, 1980; Papanikolaou *et al.*, 2002; Sakellariou *et al.*, 2018;  
31  
32 126 Ferentinos *et al.*, 2018), running from the Lemnos Deep to the Sporadhes archipelago (Fig. 3, 4). On the  
33  
34 127 other hand, the Edremit-Skyros Trough is  $70\text{-km}$ -long, up to  $50\text{-km}$ -wide, and  $1050\text{-m}$ -deep (Fig. 3, 4;  
35  
36 128 Papanikolaou *et al.*, 2019). There, the southern branch of the North Anatolian Fault acts as a marginal  
37  
38 129 structure, which bounds the southern flank of the trough over its entire length and splits into two  $45$  to  
39  
40 130  $66\text{-km}$ -long oblique splays isolating sub-basins.  
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43 131

## 45 132 **2-2- Tectonic configuration of the North Anatolian Fault in the North Aegean Domain since the** 46 47 133 **Middle Miocene**

48  
49 134 The formation of the North Anatolian Fault results from the influence of several geodynamic drivers,  
50  
51 135 including Arabia-Eurasia collision, the dynamics of the Hellenic trench retreat and the resulting  
52  
53 136 differential in gravitational potential between the Anatolian plateau and the Aegean Sea (Jolivet &  
54  
55 137 Faccenna, 2000; Faccenna *et al.*, 2006; Brun & Faccenna, 2008; Le Pourhiet *et al.*, 2012; Jolivet *et al.*,  
56  
57 138 2015; Brun *et al.*, 2016; England *et al.*, 2016).  
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3 139 Most of the constraints on the history of the North Anatolian Fault in the North Aegean Domain are  
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5 140 based on the study of the Marmara Sea and its surroundings. At least three successive major strike-slip  
6  
7 141 systems, evolving into a continuous frame of shearing of the continental lithosphere, have been  
8  
9 142 identified on the basis of seismic data tied to industrial wells (Sengör *et al.*, 2014; Le Pichon *et al.*, 2014;  
10  
11 143 2015).

13 144 A first diffuse strike-slip system emplaced in Late Serravalian-Tortonian (12-10 Ma), in the area that is  
14  
15 145 now enclosed between the Thrace basin and the Sakarya suture (Fig. 1, 2). A part of this first strike-slip  
16  
17 146 system is still active as the southern branch of the North Anatolian Fault, where the pattern of drainage  
18  
19 147 networks recorded a structural reorganization around 0.5-1.3 Ma (Demoulin *et al.*, 2013).

21 148 A second strike-slip system is evidenced at the South Marmara Fault and the Ganos segment, both  
22  
23 149 corresponding to positive flower structures formed at a restraining bend (Fig. 2; Le Pichon *et al.*, 2014;  
24  
25 150 2015; Karakas *et al.*, 2018). These structures record the beginning of the localization of the North  
26  
27 151 Anatolian Shear System in the Pliocene (Armijo *et al.*, 1999; Le Pichon *et al.*, 2014; 2015). The South  
28  
29 152 Marmara Fault goes extinct around 3.5 Ma, while the Ganos segment is still active and forms a well-  
30  
31 153 localized, >130-km-long dextral strike-slip fault (Armijo *et al.*, 1999).

34 154 The third, localized strike-slip system corresponds to the northern branch of the North Anatolian Fault,  
35  
36 155 expressed as the Main Marmara Fault in the Marmara Sea (Le Pichon *et al.*, 2001; 2003; Carton *et al.*,  
37  
38 156 2007). Estimates of the age of the Main Marmara Fault range between 0.5 and 2.5 Ma (Rangin *et al.*,  
39  
40 157 2004; Grall *et al.*, 2012, 2013; Le Pichon *et al.*, 2015). The Main Marmara Fault crosses the Gelibolu  
41  
42 158 Peninsula and connects the Gulf of Saros at the entrance of the Aegean Sea through the Ganos strike-  
43  
44 159 slip segment (Fig. 2; McNeill *et al.*, 2004).

47 160 The age of formation of the North Aegean Trough and the Skyros-Edremit Trough is roughly  
48  
49 161 constrained in the Late Pliocene-Early Pleistocene (Laigle *et al.*, 2000; Beniest *et al.*, 2016), a period  
50  
51 162 which encompasses several stages of evolution of the North Anatolian Fault.

53 163 Onland, a series of sedimentary basins (Fig. 2; namely the Strymon, Orfanos, Prinos, Drama, Sandanski,  
54  
55 164 Mygdonia basins and grabens) formed in the Serravalian segmenting the Rhodope Metamorphic Core  
56  
57 165 Complex until the Early Pliocene (Brun & Sokoutis, 2018). Traces of Late Miocene extension and  
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3 166 differential subsidence are further observed in the Gulf of Thermaïkos and offshore the Chalkidiki  
4  
5 167 peninsula (Varesis & Anastasakis, 2021).

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## 9 169 **2-3- Structure of the lithosphere in the North Aegean Domain**

11 170 In the North Aegean Domain, the continental lithosphere keeps the record of a complex geological  
12  
13 171 history, from the closure of Mesozoic Oceans (i.e. the Vardar and Pindos Oceans, Schettino & Turco,  
14  
15 172 2011; Okay & Tüysuz, 1999) to the building of the Hellenides Mountain Belt and its subsequent collapse  
16  
17 173 in the wake of the Early Cenozoic collision between Adria and Pelagonia domains (Handy *et al.*, 2010).

18 174 A series of metamorphic core complexes emplaced in the North Aegean Domain from the Late Eocene  
19  
20 175 to the Middle Miocene (Rhodope Core complex, 45-Myrs-old; North Cycladic Detachment System, 15-  
21  
22 176 20 Myrs-old; Jolivet & Brun, 2010; Le Pourhiet *et al.*, 2012; Jolivet *et al.*, 2013).

23  
24 177 As a result, the North Aegean lithosphere displays an unusual layering, with a shallow brittle ductile  
25  
26 178 transition (<10 km, Brun & Sokoutis, 2018) and a thinned lithospheric mantle. The Moho depth ranges  
27  
28 179 between 20 and 30 km (Sodoudi *et al.*, 2006). Rayleigh wave anisotropy reveals the existence of a  
29  
30 180 thermal anomaly located right in between the two segments of the North Anatolian Fault in the North  
31  
32 181 Aegean domain, within the lower crust and the lithospheric mantle (Endrun *et al.*, 2011).

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35 182

## 36 37 38 183 **3- Material and Methods**

### 39 184 **3-1- Topography & seafloor bathymetry**

40  
41 185 The Digital Elevation Model used for the maps of the North Aegean Domain (Fig. 1-4) combines data  
42  
43 186 from the Shuttle Radar Topography Mission (SRTM) at 3 seconds and the multibeam dataset acquired  
44  
45 187 during the Ypother oceanographic cruises between 2013-2016 (Sakellariou *et al.*, 2018), here gridded  
46  
47 188 at 25 m.

48  
49  
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### 51 190 **3-2- Seismic profiles**

52  
53 191 In this study, we present a new seismic-reflection dataset collected during the NAFAS (North Anatolian  
54  
55 192 Fault in the North Aegean Sea) expedition in summer 2017, onboard the R/V Tethys II. The expedition  
56  
57 193 focused on the North Aegean Trough, the Edremit-Skyros Trough and the Evia Basin. The NAFAS

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2  
3 194 dataset is complementary documented by a set of vintage seismic-reflection dataset collected in the 70's  
4  
5 195 and partly explored in Beniest *et al.* (2016). All the seismic-reflection profiles are displayed on the  
6  
7 196 figures with a vertical exaggeration of 14, with their related simplified cross-section at 1:1 scale.  
8  
9 197 Seismic reflection profiles were shot using a GI airgun and a 24-trace streamer with 400-m maximum  
10  
11 198 offset. The GI gun was triggered in harmonic mode (2 x 24 cubic inches) every 6s, with an acquisition  
12  
13 199 speed of 4.1 knots, leading to a shot interval of 12.5 m. The trace record length is 5500 ms with a 1-ms  
14  
15 200 sample interval. Only 8 out of 24 traces were working with a maximum offset of 200-m and a maximum  
16  
17 201 CDP (Common Depth Point) fold of 4. The depth of penetration of the signal reaches about 3 seconds  
18  
19 202 two-way travel time (TWT). The processing workflow consists in geometry setting, water-velocity  
20  
21 203 normal move-out, stacking, deconvolution and Kirchhoff finite difference post-stack migration.  
22  
23  
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25

### 26 205 **3-3-Multibeam and interpretation of geological structures on seismic-reflection profiles**

28 206 The geological mapping of tectonic structures is based on the seafloor signature of the structure on the  
29  
30 207 multibeam data and the expression of these features on the seismic-reflection lines (Fig. 5). The offshore  
31  
32 208 structural maps provided in this study (Fig. 4-5) are slightly modified from Papanikolaou *et al.* (2002;  
33  
34 209 2019) and Sakellariou *et al.* (2018), considering our new seismic dataset.

36 210 The North Aegean Domain is dominated by a large variety of strike-slip structures (Fig. 5):

38  
39 211 *-Negative flower structures:* Most of the sub-basins isolated by the oblique splays within the horsetail  
40  
41 212 terminations correspond to negative flower structures. The negative flower structures are bounded by  
42  
43 213 normal faults of opposite dip and connect into a single strike-slip fault at depth.

45 214 *-Transpressive structures:* They correspond to positive flower structures and push-up structures, formed  
46  
47 215 by a set of strike-slip faults with a reverse component.

49 216 Tectonic processes control the distribution of clastic sedimentary deposits in the study area (Fig. 6).  
50  
51 217 Prior to the onset of the North Anatolian Fault, scattered distal deltaic rivers flood the area, marked by  
52  
53 218 moderate incision along the thalweg. Since the onset of tectonic subsidence, the rivers form channel-  
54  
55 219 levee systems close to the slope break and evolve downslope into canyons with V-shape morphologies  
56  
57 220 (Fig. 6a). The complex distribution of faults and basins within the North Aegean Trough results in a  
58  
59 221 scattered distribution of submarine landslides, identified according to their multibeam signature (arcuate

1  
2  
3 222 scar and block falls at the edge of the slope, fig. 6c) and their related mass transport deposits (marked a  
4  
5 223 chaotic-to-transparent seismic facies). Some of the steepest slopes display undulated seafloor (fig. 6b),  
6  
7 224 underlain by a series of wavy reflectors, which could be interpreted as sediment waves resulting from  
8  
9 225 creeping of sediments in interaction with bottom-current controlled deposition (Faugères *et al.*, 2002;  
10  
11 226 Shillington *et al.*, 2012). The tectonic structures also influence the circulation of oceanic bottom-  
12  
13 227 currents. Where the current intensity is strong, the axis of the current is associated with a rough seafloor,  
14  
15 228 which is an indicator of the strong sediment sorting. The attenuation of the intensity of the oceanic  
16  
17 229 currents promotes the building of a series of fault-controlled contourite drifts (*sensu* Rebesco *et al.*,  
18  
19 230 2014). The architecture of these contourite drifts display typical sigmoid to mounded configurations  
20  
21 231 (Fig. 6e), characterized by important lateral thickness variations of the sedimentary layers, with pinched-  
22  
23 232 out reflectors close to the current axis and thicker deposits away from it. Fluid escape features are  
24  
25 233 commonly observed close to the main faults and on the extrados of the main rollover structures (Fig. 4).  
26  
27 234 Fluid escape features are expressed as dense networks of conduits leading to small offsets of the  
28  
29 235 sedimentary layers or undulated to chaotic series of reflectors on the seismic dataset (Fig. 6d). At the  
30  
31 236 seafloor, the area of fluid escape form fields of coalescing circular depressions (Fig. 5e, Papatheodorou  
32  
33 237 *et al.*, 1993).  
34  
35  
36 238 The clastic input to the North Aegean Sea implies that most of the structures related to the North  
37  
38 239 Anatolian Fault are growth structures. The timing of formation of the strike-slip structures is constrained  
39  
40 240 from the age of onset of the fanning of the sediments. Although many second-order unconformities  
41  
42 241 linked to periodic sea-level and climatic variations are encountered in the study area (Lykousis, 2009;  
43  
44 242 Piper & Anastasakis, 2013), we here focus on the major unconformities corresponding to the main  
45  
46 243 tectonic episodes related to the evolution of the North Anatolian Shear Zone, i.e. the unconformities  
47  
48 244 corresponding to a significant tilt of the seafloor.  
49  
50  
51  
52

245

#### 246 **4- Stratigraphy of the North Aegean Domain**

##### 247 **4.1. The pre-Messinian period and the Messinian Event**

248 Field studies in the Thermaïkos, Thrace and Saros Basins document two Eocene to Oligocene silici-  
249 clastic units ontop of the metamorphic basement (Turgut & Eseller, 2000; Siyako & Huvaz, 2007;

1  
2  
3 250 Islamoglu *et al.*, 2008). Seismic profiles tied to wells evidence the continuity of these units offshore in  
4  
5 251 the North Aegean Domain, with a major angular unconformity at the Oligocene-Miocene boundary  
6  
7 252 (Beniest *et al.*, 2016; Varesis & Anastasakis, 2021). Industrial wells located in the Prinos Basin  
8  
9 253 (Proedrou & Papaconstantinou, 2004) provide precise constraints on the ages of the geological events  
10  
11 254 related to the Messinian Salinity Crisis, with the salt mobile unit dated between 5.97 and 5.33 Ma, and  
12  
13 255 earliest traces of the Messinian stage dated around 7.15 Ma (Karakitsios *et al.*, 2017).

15 256 We identify on the seismic dataset the contact between the Late Miocene Unit and the Messinian Event  
16  
17  
18 257 according to the following criteria:

19  
20 258 *-Late Miocene Unit:* During the Miocene, fluvial and floodplain deposits cover the North Aegean  
21  
22 259 Domain (Melinte-Dobrinescu *et al.*, 2009; Suc *et al.*, 2015). Drilling sites in the Prinos Basin that reach  
23  
24 260 Tortonian layers document an alternation of marine shales and turbidites in a distal marine environment,  
25  
26 261 followed by sandstone with marl and coal intercalations (Karakitsios *et al.*, 2017; Varesis & Anastasakis,  
27  
28 262 2021). On seismic data, the Late Miocene Unit is expressed by a series of interbedded channel systems  
29  
30 263 (Fig. 7).

31  
32 264 *-Messinian Event:* The Messinian is dominantly expressed as an erosive surface in the North Aegean  
33  
34 265 Domain (Fig. 7), with a few evaporitic units scattered in some basins (e.g. Prinos; Mascle & Martin,  
35  
36 266 1990; Proedrou & Sidiropoulos, 1992; Proedrou & Papaconstantinou, 2004). Offshore Thermaïkos, the  
37  
38 267 thickness of the Messinian Unit displays important lateral variations, culminating at 0.8 s TWT (Varesis  
39  
40 268 & Anastasakis, 2021).

41  
42  
43 269

#### 45 270 **4.2. Plio-Pleistocene Period**

46  
47 271 The Pleistocene stratigraphy has mainly been constrained on the basis of sequence stratigraphy studies,  
48  
49 272 investigating the influence of sea level variations and oceanic current activity using the architecture of  
50  
51 273 sedimentary bodies (Sakellariou & Galanidou, 2017; Tripsanas *et al.*, 2016). In the North Aegean  
52  
53 274 Domain, sequence stratigraphy studies in the Thermaïkos Gulf (Lykousis, 2009) and offshore the Biga  
54  
55 275 Peninsula (Isler *et al.*, 2008) identified the reflectors corresponding to MIS (Marine Isotopic Stage) 2  
56  
57 276 (18 ka) to MIS 12 (430 ka). Additional stratigraphic constraints are obtained from the study of contourite  
58  
59 277 drifts in the Southern Aegean Domain since MIS 11 (420 ka), with an increased current intensity, and

1  
2  
3 278 hence, erosive events during interglacial periods (Tripsanas *et al.*, 2016). In the vicinity of the North  
4  
5 279 Aegean Trough, some coring document pro-delta formations during the Late Quaternary (last ~150 kyrs;  
6  
7 280 Piper & Perissoratis, 1991; Lykousis *et al.*, 2002).

8  
9 281 Unfortunately, the published reports of the Prinos wells (Proedrou & Papaconstantinou, 2004) do not  
10  
11 282 provide stratigraphic details for the detritic Plio-Pleistocene sequence.

12  
13 283 The only available stratigraphic constraints in the offshore Aegean Domain prior MIS12 are located at  
14  
15 284 the Myrtoon Basin (Anastasakis & Piper, 2005; Anastasakis *et al.*, 2006), which is about 250-km away  
16  
17 285 from our study area (Fig. 1). There, the age of the sedimentary layers is fairly well constrained as far as  
18  
19 286 2.8 Ma on the basis of correlation with DSDP Site 378 in the nearby Cretan Basin (Hsu *et al.*, 1978) and  
20  
21 287 the age of volcanic layers coming from Milos Island (Fytikas *et al.*, 1976, 1986; Anastasakis & Piper,  
22  
23 288 2005; Calvo *et al.*, 2012). This set of reflectors is also observed offshore the Evoikos Gulf (about 100  
24  
25 289 to 150 km away from our study area, Fig. 1) and their age is confirmed at 2 Ma upon the base of the sea-  
26  
27 290 level dependance of progradational packages of fluvial deposits (Anastasakis & Piper, 2013). However,  
28  
29 291 the Cycladic Plateau (Fig. 1, 7) has isolated the Myrtoon and Evoikos area (Fig. 1) from the North  
30  
31 292 Aegean Domain at various periods of sea-level lowstands (Sakellariou & Galanidou, 2017).

32  
33 293 In order to investigate whether the stratigraphic constraints obtained at the Myrtoon Basin can be  
34  
35 294 correlated as far north as the North Aegean Domain, we compare a seismic-reflection profile collected  
36  
37 295 in the Myrtoon Basin (from Anastasakis & Piper, 2005) with a profile collected at the southern  
38  
39 296 termination of the Evia Basin, i.e. north of the Cycladic Plateau, here considered as the key feature of  
40  
41 297 the boundary between the north and south Aegean domains (Fig. 7). Despite a difference of resolution  
42  
43 298 between the two datasets, both profiles share similarities with respect to the seismic facies of the  
44  
45 299 Pliocene series up to a key reflector dated at 1.3 Ma (Fig.7).

46  
47 300 Based on sequence stratigraphy studies and correlation with the Myrtoon Basin, we consider that four  
48  
49 301 Plio-Pleistocene key reflectors, corresponding to regional volcanic deposits and sapropel events  
50  
51 302 (Anastasakis & Piper, 2005), can be defined in the North Aegean Domain (fig. 7), separating four main  
52  
53 303 seismic units:

54  
55  
56  
57 304 - *Reflector D* (2.8 Ma): In the wake of the Messinian event, numerous Gilbert deltas developed in the  
58  
59 305 surroundings of the Aegean Domain, followed by marine clastic sediments throughout the Pliocene,

1  
2  
3 306 characterized by distal channel systems (Proedrou & Papaconstantinou, 2004; Anastasakis & Piper,  
4  
5 307 2005). Anastasakis & Piper (2006) show the regional transition from terrestrial to full marine facies  
6  
7 308 occurred regionally at the boundary between the middle and upper Pliocene. A key reflector, labeled D,  
8  
9 309 seals the seismic unit interpreted as the episode of delta fan supply in the Aegean Sea (Fig. 7; Anastasakis  
10  
11 310 & Piper, 2005). This seismic unit is characterized by the signature of distal channel-levee systems,  
12  
13 311 marked by an alternation of minor downlap and onlap that reflects their successive avulsions. Reflector  
14  
15 312 D is the top reflector of a series of three high-amplitude reflectors sealing the systems of delta fans. The  
16  
17 313 reflector D is dated at ~2.8 Ma from Milos volcanics (Anastasakis & Piper, 2005).

18  
19  
20 314 - *Reflector C* (~2 Ma): Reflector C corresponds to an erosive surface, dated between 1.6 and 2.1 Ma  
21  
22 315 from the volcanic deposits related to the Oros eruption (Pe-Piper *et al.*, 1983; Dietrich *et al.*, 1988).  
23  
24 316 Sequence stratigraphy studies in the Evoikos Gulf suggest the age of reflector C to be closer to 2 Ma  
25  
26 317 than 1.6 Ma (a reflector distinct from C being dated at 1.6 Ma, Piper & Anastasakis, 2013).

27  
28 318 -*Reflector B* (~1.3 Ma): Reflector B marks the onset of progradational wedges in the Aegean Sea, dated  
29  
30 319 around 1-1.4 Ma with lava flows (Anastasakis & Piper, 2005). The age has been refined at 1.3-1.4 Ma  
31  
32 320 from sequence stratigraphy studies in the Evoikos Gulf (Piper & Anastasakis, 2013).

33  
34  
35 321 -*Reflector A* (~430-480 ka): Reflector A is defined by a set of sequence stratigraphic constraints  
36  
37 322 available in the North Aegean Domain. It corresponds to MIS 12 (~430-480 ka). Our picking and spatial  
38  
39 323 correlation of reflector A in the North Aegean Trough agrees with the work of Ferentinos *et al.* (2018).  
40

41 324

## 42 43 325 **5- RESULTS**

### 44 45 326 **5-1- Structure of the North Aegean Trough (Northern Branch of the North Anatolian Fault)**

#### 46 47 327 5-1-1- The connection between the Gulf of Saros and the North Aegean Trough

48  
49 328 At the northeastern entrance of the North Aegean Trough, the Main Splay of the North Anatolian fault  
50  
51 329 makes a bend, which is expressed on the seafloor by a series of push-up ridges (Fig. 3-4). The Main  
52  
53 330 Splay forms a steep, ~5 to 10° slope, which is covered by an undulated seafloor. There, a set of secondary  
54  
55 331 fault splays connects along the main fault. A 15-km-long ridge, referred to as the Medusa High (Masclé  
56  
57 332 & Martin, 1990; Sakellariou *et al.*, 2018), runs parallel to the North Anatolian Fault in the area of  
58  
59  
60

1  
2  
3 333 bending (Fig. 3-4). A second splay, referred to as the Athos Splay, runs at  $40^\circ$  with respect to the North  
4  
5 334 Anatolian Fault and terminates at the tip of the Athos Peninsula (Fig. 3-4).  
6  
7 335 Seismic line 701 is perpendicular to the Athos splay (Fig. 8) and seismic line 702 crosses the area  
8  
9 336 between the main splay and the Medusa High (Fig. 9). The Main Splay runs across an area of chaotic  
10  
11 337 reflectors and forms a flower structure. The Athos Splay is an apparent normal fault dipping at  $55^\circ$   
12  
13 338 southward, consistent with focal mechanisms at this location (Kiratzi & Louvari, 2003). The footwall  
14  
15 339 reveals a buried tilted block (Fig. 8). A dense network of normal faults, most of them being blind on the  
16  
17 340 seafloor, connects into a set of three flower structures in the basin, located at the footwall of the Athos  
18  
19 341 Splay (Fig. 8). The Medusa High (Fig. 9) corresponds to an elongated push-up structure (Masclé &  
20  
21 342 Martin, 1990; Sakellariou *et al.*, 2018).  
22  
23  
24 343

#### 26 344 5-1-2- The central segment of the North Aegean Trough offshore the Chalkidiki Peninsula

28 345 The Main Splay of the North Anatolian Fault runs within a 40-km-long, 15-km-wide, asymmetric  
29  
30 346 spindle-shaped trough (Fig. 3-4). Focal mechanisms confirm the strike-slip motion along the strike of  
31  
32 347 the Main Splay and suggest a minor component of transtension locally (Kiratzi & Louvari, 2003;  
33  
34 348 Kourouklas *et al.*, 2022). The Main Splay is sub-vertical and blind on the seafloor due to mass-wasting  
35  
36 349 sedimentation rates higher than its vertical slip-rate ( $\sim 0.4$ -s TWT -thick package of mass transport  
37  
38 350 deposits on Line 603; Fig. 11). It forms a growth-synform structure on Line 602 (Fig. 10) and promotes  
39  
40 351 the uplift of the basement on line 603 (Fig. 11). The sedimentary cover of both flanks of the spindle-  
41  
42 352 shape basin displays an undulated configuration upslope, which becomes more chaotic downslope.  
43  
44 353 The Sithonia Splay is a second strike-slip fault trending  $60^\circ$ NE. To the west, a network of normal faults,  
45  
46 354 dipping  $20^\circ$  to the North, roots diagonally to the Sithonia Splay and forms a horsetail structure offshore  
47  
48 355 the Kassandra Peninsula, where focal mechanisms indicate normal faulting (Kourouklas *et al.*, 2022).  
49  
50 356 The multibeam map reveals two sedimentary basins along the Sithonia Splay: a first one, located on the  
51  
52 357 southern flank of the eastern segment of the fault and a second one, located on the northern flank of the  
53  
54 358 western segment of the fault (Fig. 5). The Sithonia Splay is subvertical in its central part, forming a  
55  
56 359 short-wavelength, symmetric growth-synform structure on Line 602 (Fig. 10). Line 603 indicates a  
57  
58 360 strong component of subsidence with a well-marked fanning of the sediments on the northern side of  
59  
60



1  
2  
3 361 the Sithonia Splay (Fig. 11). The westward increase of the subsidence corresponds to the transition  
4  
5 362 toward the transtensional regime of the horsetail termination (Fig. 5).

6  
7 363 The Main Splay of the North Anatolian Fault and the Sithonia Splay are separated by a Central Structural  
8  
9 364 High (Fig. 3-4). The Central Structural High is a ~50-km-long elongated feature, with two highs  
10  
11 365 culminating at 700-m and 550-m depth. The Central Structural High appears as an antiform structure,  
12  
13 366 with undulations in the sedimentary cover (Fig. 10-11). The part of the antiform which is still exposed  
14  
15 367 at the seafloor corresponds to a basement high. A field of apparent normal faults with short and uneven  
16  
17 368 offsets is observed between the Central Structural High and the Sithonia Splay (Fig.10-11).

19  
20 369

21  
22 370 *5-1-3- Termination of the horsetail in the Thermaïkos-Skopelos area*

23  
24 371 Offshore Skopelos, the geometry of the Main Splay of the North Anatolian Fault changes from a strike-  
25  
26 372 slip fault to a low-angle normal fault (Fig. 3-4), which runs along Pelion and the Thermaïkos Gulf  
27  
28 373 (Laigle *et al.*, 2000). The seismic reflection profile 103 (Fig. 12) crosses all the splays from Skopelos  
29  
30 374 Island to Kassandra Peninsula. We observe a large-scale rollover structure in the hanging wall of the  
31  
32 375 North Anatolian Fault, bending along the Main Splay, acting here as a north-dipping low-angle (~20°)  
33  
34 376 normal fault. Focal mechanisms however indicate pure strike-slip motion in this area (Kourouklas *et al.*,  
35  
36 377 2022), which suggests that the normal fault is turning into a strike-slip fault. The configuration of the  
37  
38 378 low-angle normal fault isolates a 20-km long, 10-km-wide trough along the Main Splay, filled-in by  
39  
40 379 mass transport deposits (Fig. 12). The hinge of the rollover is dissected by numerous synthetic and  
41  
42 380 antithetic normal faults. These fault systems cross a field of coalescing circular depressions spreading  
43  
44 381 over ~200-km<sup>2</sup>, which corresponds to a series of short-wavelength undulated reflectors on the seismic,  
45  
46 382 focused on the uppermost ~0.4 s TWT (Fig. 12). The field of circular depressions is interpreted as the  
47  
48 383 result of fluid escape (Fig. 3-4).

49  
50  
51 384 The Central Splay (Fig. 3-4), roots on the Central Structural High, then bends across the extrados of the  
52  
53 385 rollover into a 25-km-long, 15-km-wide, 1450-m-deep trough, formed by a system of normal faults. The  
54  
55 386 normal fault scarps reach 350-m-high at the seafloor along the slope of the Gulf of Thermaïkos and  
56  
57 387 localize a system of slope-apron canyons.

1  
2  
3 388 The seismic line 201 (Fig. 13) crosses the area between the major low-angle ( $\sim 35^\circ$  dip) normal fault  
4  
5 389 where the North Anatolian Fault ends and the termination of the Sithonia Splay. The hanging wall forms  
6  
7 390 a syncline basin, filled-in by sediments characterized by the short-wavelength undulated facies formed  
8  
9 391 by fluid escape. The system of normal faults crossing the slope of the Gulf of Thermaïkos forms a series  
10  
11 392 of horst and graben (Fig. 13). The termination of the Sithonia Splay is a set of two sub-parallel listric  
12  
13 393 faults, dipping  $20^\circ$  to  $30^\circ$  to the north, with their associated rollover structures dissected by synthetic  
14  
15 394 and antithetic normal faults (Fig. 13), consistent with the focal mechanisms at this location (Kourouklas  
16  
17 395 *et al.*, 2022).  
18  
19  
20 396

### 21 22 397 **5-2-Structure of the Edremit-Skyros Trough (Southern Branch of the North Anatolian Fault)**

23  
24 398 The structure of the Edremit-Skyros horsetail is described in details in Papanikoalou *et al.* (2019). In  
25  
26 399 this study, we present three new seismic profiles, which cross all the key structures of the Edremit-  
27  
28 400 Skyros Trough.

29  
30 401 The seismic profile 801 (Fig. 14) crosses the Venus plateau, an oblique splay of the horsetail, the deepest  
31  
32 402 basin of the trough, here expressed as a growth syncline, and the main system of sub-parallel low-angle  
33  
34 403 ( $\sim 25^\circ$  dip) normal faults bounding the Skyros Island, which isolates a half-graben. The seismic line 802  
35  
36 404 (Fig 15) crosses the southern branch of the North Anatolian Fault and the southern edge of the Edremit-  
37  
38 405 Skyros Trough. It reveals a series of angular unconformities associated to tilted blocks. On the seismic  
39  
40 406 profile 803 (Fig. 16), the oblique splays of the horsetail appear as normal faults isolating either half-  
41  
42 407 grabens or growth synclines, dominantly filled-in by mass transport deposits. The subsidence increases  
43  
44 408 towards the Skyros Island. Normal faults segment the bulge of the growth-synclines. In this area,  
45  
46 409 sedimentation rates exceed the vertical slip-rate at the faults, resulting in their smooth aspect on the  
47  
48 410 seafloor.  
49  
50 411

### 51 52 53 412 **5-3- Structure of the Evia Basin**

54  
55 413 The Evia basin consists in a 90-km-long series of three subsiding basins, up to 1000-m deep, separated  
56  
57 414 by structural highs (Fig 3-4). On the seismic lines (Fig 17), all the Evia sub-basins appear as a series of  
58  
59 415 tilted half grabens bounded by a major normal fault on their SW flank. The maximum thickness of the

1  
2  
3 416 post-Messinian sediments reaches  $\sim 1$  s (TWT). The series emplaced before the formation of the structure  
4  
5 417 display seismic facies typical of distal detritic sedimentation, while the syn-tectonic series display a  
6  
7 418 fanning configuration recording the progressive subsidence of the structure. Only minor Mass Transport  
8  
9 419 Deposits are observed within the growth structures, which results from the  $\sim 20^\circ$  steep slope formed by  
10  
11 420 the main normal fault that does not allow the storage of sediments. The structural thresholds appear as  
12  
13 421 positive flower structures in line with the trend of the North Anatolian Fault, with uplifted segments of  
14  
15 422 the basement and a dense pattern of faults on their flanks.  
16  
17  
18 423

#### 20 424 **5-4- A diffuse fault system buried in the offshore North Aegean Domain**

21  
22 425 The seismic lines collected during the NAFAS cruise in 2017 together with the compilation of vintage  
23  
24 426 seismic lines (Masclé & Martin, 1990; Beniest *et al.*, 2016) reveal fossil structures buried under the  
25  
26 427 sediments of the North Aegean Domain and locally crosscut by the horsetail structures.  
27

28 428 The first structure is encountered in the area of the connection between the Saros Gulf and the North  
29  
30 429 Aegean Trough, at the -W-E trending Athos splay (Fig 3-4). There, the seismic line 701 (Fig 8) reveals  
31  
32 430 a buried tilted block sealed by a series of onlap terminations of the sedimentary layers.  
33

34 431 The second structure also corresponds to a tilted graben, located at the plateau isolated between the  
35  
36 432 North Aegean Trough and the Edremit-Skyros Trough (Fig. 18). This graben is referred to as the Venus  
37  
38 433 graben.  
39  
40

41 434

#### 43 435 **5-5- Chronology of tectonic events in the North Aegean Sea**

44  
45 436 The series of angular unconformities labeled from A to D records the main tectonic events that shaped  
46  
47 437 the North Aegean Domain since the Messinian (Fig 7).  
48

##### 49 438 **5-5-1. The North Aegean Trough**

50  
51 439 Unconformity D, dated at 2.8 Ma, records the end of the tectonic episode expressed by the series of  
52  
53 440 tilted blocks composed of the Athos (Fig. 8) and Venus (Fig. 18) grabens. This unconformity also marks  
54  
55 441 the deactivation of a series of push-up structures located in the area of the Central Structural High (line  
56  
57 442 603, Fig 11). At the termination of the Sithonia Splay (line 201, Fig 13) offshore Kassandra Peninsula,  
58  
59  
60

1  
2  
3 443 this unconformity marks the onset of a fanning configuration of the sediments and, therefore, the onset  
4  
5 444 of the tilt of the graben.

6  
7 445 The second key angular unconformity C, dated at 2 Ma, is well identified by onlap terminations over  
8  
9 446 the underlying, tilted deposits in the North Aegean Trough (e.g. in the vicinity of Skopelos at line 103,  
10  
11 447 Fig 12). This unconformity marks the onset of the fanning configuration of the sediments observed all  
12  
13 448 along the Sithonia Splay (line 201, Fig 13; line 602-603, Fig 10-11), and hence, the formation of this  
14  
15 449 still-active splay within the North Aegean Trough. The amplitude of slope incision features remains  
16  
17 450 poorly disturbed by this tectonic episode (e.g. at the edge of the Thermaikos Gulf, line 201, Fig 13),  
18  
19 451 which indicates a still rather low subsidence rate.

20  
21  
22 452 These unconformities D and C record the Late Pliocene-Early Pleistocene change in the pattern of strain  
23  
24 453 localization within the North Anatolian Shear Zone. These unconformities also pre-date the first stage  
25  
26 454 of the formation of the North Aegean horsetail structure, with the activation of the Sithonia Splay.

27  
28 455 The third angular unconformity B, dated at ~1.3 Ma, records the formation of the termination of the  
29  
30 456 central splay (observed at line 103, Fig 12). Across the edge of the Thermaikos Gulf, the 1.3 Myrs-old  
31  
32 457 unconformity corresponds to an increase in the amplitude of the slope incisions features (line 201, Fig  
33  
34 458 13), which indicates a major increase in the overall subsidence, the channels digging deeper to catch  
35  
36 459 their equilibrium line. The Mass Transport Deposits associated to this episode are the thickest (~0.2-0.3  
37  
38 460 s TWT) encountered within the North Aegean Domain since the Messinian. At the connection between  
39  
40 461 the North Aegean Trough and the Saros Gulf, the 1.3 Myrs-old unconformity records the formation of  
41  
42 462 the Athos Splay and the main uplift of the Medusa High (Fig 8-9). There, the mean vertical slip-rate of  
43  
44 463 the Athos normal fault increased from a  $0.13 \text{ mm.yr}^{-1}$  during the 2-1.3 Ma interval to  $0.22 \text{ mm.yr}^{-1}$  since  
45  
46 464 1.3 Ma. Overall, this set of observations indicates a major structural reorganization of the northern  
47  
48 465 branch of the North Anatolian Fault at 1.3 Ma, marked by a drastic increase in subsidence rates within  
49  
50 466 the sub-basins of the North Aegean Trough.

51  
52  
53 467 Finally, unconformity A, dated at ~0.5 Ma, records the onset of the Main Splay of the North Anatolian  
54  
55 468 Fault all across the North Aegean Trough (Ferentinos *et al.*, 2018). The formation of the Main Splay is  
56  
57 469 best recorded offshore Skopelos (line 103, Fig 12), the segment of the fault running at the edge of the  
58  
59 470 Central High being affected by current and gravity-driven erosion (line 602, Fig 10). The activation of

1  
2  
3 471 the Main Splay induced a change in the activity of the Sithonia Fault, with an increase of the vertical  
4  
5 472 slip-rate from 0.16 mm.yr<sup>-1</sup> during the 1.3-0.48 Ma interval to 0.3 mm.yr<sup>-1</sup> since 0.48 Ma. However, the  
6  
7 473 vertical slip-rate of the faults related to the Central Splay remained steady.  
8

9 474

#### 11 475 5-5-2. The Skyros-Edremit Trough

13 476 The unconformity C (2 Ma) is overlapped by a tilted series of reflectors on the southern edge of the trough  
14  
15 477 (line 803, Fig. 16). This unconformity marks the first stages of the formation of the Southern branch of  
16  
17 478 the North Anatolian Fault offshore Skyros. Unconformity B (1.3 Ma) corresponds to the increase in the  
18  
19 479 subsidence rate (up to 0.45 mm.yr<sup>-1</sup>) at the hanging wall of the normal fault system running along Skyros  
20  
21 480 Island (Fig. 14, 15, 16). Unconformity A (~0.5 Ma) is well expressed close to the oblique splay 1 and  
22  
23 481 marks an increase in subsidence at the hanging wall of this splay (Fig. 15). Unconformity A therefore  
24  
25 482 records the formation of the oblique splay 1 (Fig. 16).  
26  
27

28 483

#### 30 484 5-5-3. The Evia basin

32 485 The onset of subsidence within the Evia Basin is dated between 2 and 1.3 Ma based on unconformities  
33  
34 486 B and C (Fig. 17). This marks the base of the fanning configuration of the sedimentary infill. The main  
35  
36 487 formation episode of the Evia Basins is therefore coeval with the increase in subsidence at Corinth and  
37  
38 488 the first step of strain localization at both the northern and southern branches of the North Anatolian  
39  
40 489 Fault.  
41  
42

43 490

### 45 491 6- Discussion

47 492 The present-day configuration of the North Aegean Domain shows the gradual kinematic transition from  
48  
49 493 the strike-slip deformation that dominates in the northeastern Aegean Domain to the dip-slip  
50  
51 494 deformation encountered in the Northwest Aegean Domain (Mouslopoulou *et al.*, 2007a,b). Our new  
52  
53 495 set of geological constraints allows us to refine the framework of strain localization of the North  
54  
55 496 Anatolian Shear Zone in the North Aegean Domain and highlights the westward propagation of the  
56  
57 497 strike-slip dominated area since the Late Miocene. The new geological constraints obtained from the  
58  
59  
60

1  
2  
3 498 seismic-reflection dataset are summarized in Figure 19 and integrated to the previously available  
4  
5 499 constraints on the geological events of the area.  
6

7 500

9 501 6-1. Mode of formation of horsetail structures: the North Aegean and Edremit-Skyros Troughs

11 502 The formation of the horsetail terminations of both the northern and southern branches of the North  
12  
13 503 Anatolian Fault occurs in the frame of the westward propagation of the North Anatolian Fault within  
14  
15 504 the prevailing NNE-SSW to N-S extensional conditions of the western North Aegean Domain. The  
16  
17 505 horsetail configuration emplaces where the strike-slip fault connects a system of low-angle normal faults  
18  
19 506 inherited from the extensive stage.

21  
22 507 The North Aegean and the Edremit-Skyros Troughs are horsetail terminations that are currently at  
23  
24 508 different steps of their development. Although the formation of both structures initiated at the same age  
25  
26 509 (~2 Ma), the lower slip rate along the southern branch of the North Anatolian Fault leads the Edremit-  
27  
28 510 Skyros to be structurally less mature. This differential stage of horsetail structural evolution allows us  
29  
30 511 to investigate the tectonic and sedimentary processes at their origin.

32 512 On one hand, the Edremit-Skyros Trough corresponds to the evolution of a single horsetail structure.  
33  
34 513 The oblique splays of the Edremit-Skyros Trough formed first along the main detachment fault, then  
35  
36 514 migrated eastwards (oblique splay 1 formed at 0.5 Ma).

38 515 On the other hand, the North Aegean Trough consists in three horsetail basins (at the end of the Sithonia,  
39  
40 516 Central and Main Splays) that merged in a single one. Our seismic dataset highlights the successive  
41  
42 517 activation of the Sithonia Splay at 2 Ma, the Central Splay at 1.3 Ma and the Main Splay at 0.5 Ma,  
43  
44 518 which corresponds to the westward propagation of the northern branch of the North Anatolian Fault (Fig  
45  
46 519 18). The distance between the negative flower structure at the end of each splay is on the order of 30 to  
47  
48 520 50-km. This corresponds to the distance added to the northern branch of the North Anatolian Fault every  
49  
50 521 0.7-0.8 Ma in the frame of its westward propagation. The three main splays of the North Aegean Trough  
51  
52 522 have remained active since their inception. The decrease in slip rates observed in GPS measurements at  
53  
54 523 the Sporadhes Archipelago (Müller *et al.*, 2013) may be the result of slip partitioning over each major  
55  
56 524 splay of the North Aegean Trough (Fig. 1).  
57  
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59  
60

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2  
3 525 This framework of structural evolution of the horsetail terminations encountered in the North Aegean  
4  
5 526 Domain provides a ground-truth validation of analog modeling tests performed by Basile & Brun (1999).  
6  
7 527 In their models (Fig 20), a horsetail termination initially consists in an en-échelon normal fault system  
8  
9 528 trending perpendicular to the main strike-slip displacement zone, composed of oblique Riedel splays.  
10  
11 529 As the relative motion between the adjacent blocks increases, the Riedel splays progressively connects  
12  
13 530 the en-échelon normal fault system. For dextral motion, the first Riedel fault forms to the east of the  
14  
15 531 horsetail and the subsequent splays propagate westwards. Accordingly, the en-échelon normal faults are  
16  
17 532 first captured in the overall horsetail structure in the east. The western en-échelon normal faults are  
18  
19 533 progressively captured within the horsetail structure during its maturation. While some grabens  
20  
21 534 associated to the en-échelon normal faults are captured by the oblique splays, others are crosscut by the  
22  
23 535 propagating main displacement zone. Once initiated, all the oblique splays remain active during the  
24  
25 536 lifetime of the horsetail.  
26  
27  
28  
29

537

30 538 6-2. The Plio-Pleistocene transition from a wide North Anatolian Shear Zone to a localized North  
31  
32 539 Anatolian Fault  
33

34  
35 540 Our structural analysis further highlights the Late Pliocene change in stress regime (Lyberis, 1984) at  
36  
37 541 the scale of the North Aegean Domain (Fig. 21). From the Serravalian to the Late Pliocene, the North  
38  
39 542 Anatolian Shear Zone consisted in a diffuse system of en-échelon normal faults connected through  
40  
41 543 dextral transfer faults, thereby isolating a series of basins. These basins include a set of Late Miocene-  
42  
43 544 Early Pliocene basins compartmentalizing the Rhodope Core complex (Brun & Sokoutis, 2018) and the  
44  
45 545 series of basins identified at sea in the vicinity of the North Aegean Trough, including the Athos and  
46  
47 546 Venus grabens, deactivated at 2.8 Ma (Fig. 21a).  
48

49 547 Our reconstructions at 2 and 1.3-0.8 Ma (Fig. 21b-c) show the period of transition from the wide shear  
50  
51 548 zone to the two main branches of the North Anatolian Fault; i.e. the period of effective propagation of  
52  
53 549 the North Anatolian Fault in the North Aegean Sea. This transition is roughly coeval with the  
54  
55 550 deactivation of the South Marmara Fault dated by Le Pichon *et al.* (2015) and the subsequent activation  
56  
57 551 of the Main Marmara Fault. While propagating westward, the strike-slip segments of the North  
58  
59 552 Anatolian Fault either connected or crosscut the Late Pliocene system of en-échelon grabens including  
60

1  
2  
3 553 the Athos and Venus grabens. Unconformity C (Fig. 21c-d) records the first stage of formation of the  
4  
5 554 northern and southern branches of the North Anatolian Fault at the North Aegean Trough and the  
6  
7 555 Edremit-Skyros Trough, whereas unconformities B and A marks the successive steps of development  
8  
9 556 of these basins.

11 557 If we consider the series of Serravalian-Pliocene basins dissecting the Rhodope Core complex (Brun &  
12  
13 558 Sokoutis, 2018) as the earliest traces of the North Anatolian Shear Zone in the North Aegean Domain,  
14  
15 559 then the North Anatolian Shear Zone remained a diffuse transtensive system for about 5 to 7 Myrs until  
16  
17 560 the Messinian, with a first step of localization marked by the formation of the Ganos-Saros segment at  
18  
19 561 ~5 Ma (Armijo *et al.*, 1999). The Anatolia-Eurasia relative motion used to be distributed over this  
20  
21 562 transtensive system composed of multiple en-échelon fault segments prior to Messinian. The enhanced  
22  
23 563 localization of the North Anatolian Shear Zone in the North Aegean Domain evidenced here at 2-1.3  
24  
25 564 Ma coincides with the Early Pleistocene increase in slip-rates along the North Anatolian Fault (Hubert  
26  
27 565 Ferrari *et al.*, 2010). The localization of the North Anatolian Fault therefore contributed to the Early  
28  
29 566 Pleistocene change in stress regime recorded over the entire Aegean, previously attributed to a change  
30  
31 567 in the dynamics of the Hellenic Subduction Zone (Lyberis, 1984; Mascle & Martin, 1990; Armijo *et al.*,  
32  
33 568 1992; Sakellariou & Tsampouraki-Kraounaki, 2016).

34  
35  
36  
37 569 In this frame, the 'wide shear-stage' of the North Anatolian Shear Zone and the diachronous strain  
38  
39 570 localization within it lasted several million years longer in the western North Aegean Domain than east  
40  
41 571 of the Yeniçaga Fork (Fig. 21; Sengör *et al.*, 2005). Some fault segments are localized since the  
42  
43 572 Messinian (e.g. the Ganos-Saros fault) while others formed in the Early Pleistocene (e.g. the North  
44  
45 573 Aegean and the Edremit-Skyros Troughs). This implies that some diffuse en-échelon systems (e.g.  
46  
47 574 Chalkidiki or Marmara at 3.5-4 Ma) remain active while major, several hundred-km-long localized fault  
48  
49 575 segments (e.g. Ganos-Saros segment) exist in between (Fig. 21). Further strain localization involved the  
50  
51 576 abandonment of Late Miocene-Early Pliocene en-échelon faults (e.g. Strymon, Drama, Prinos) and  
52  
53 577 major transfer strike-slip faults (e.g. transfer faults within the Thrace basin, the South Marmara Fault).

54  
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56 578

## 579 **7-Conclusions**



1  
2  
3 580 Our study documents multiple episodes of strain localization within the North Anatolian Shear Zone in  
4  
5 581 the North Aegean Domain. During the Late Serravalian to the Early Pliocene, the North Anatolian Shear  
6  
7 582 Zone was a diffuse transtensive fault zone. During the Late Pliocene, strike-slip strain localized along  
8  
9 583 some fault segments (e.g. the Ganos-Saros segment) while remained diffuse in others (Prinos, Strymon,  
10  
11 584 Drama, Thrace basins, Fig 21). Offshore sediments record the first abrupt step of strain localization  
12  
13 585 along the northern and southern branches of the North Anatolian Fault in the North Aegean Domain at  
14  
15 586 2-1.3 Ma. This is coeval with the general increase of slip rate along the entire North Anatolian system  
16  
17 587 and the regional change in stress regime over the Aegean Sea. Further westward propagation and  
18  
19 588 localization along the northern and southern branches formed the North Aegean and Skyros-Edremit  
20  
21 589 Troughs as horsetail structures. The North Aegean Trough results from the formation of three successive  
22  
23 590 horsetails, formed at 2 Ma, 1.3 Ma and 0.5 Ma and propagating westward at a rate of 40 to 60 km.Myr<sup>-1</sup>.  
24  
25  
26 591  
27  
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29  
30

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40  
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42  
43  
44

### 45 600 **Author's contributions:**

46  
47 601 **Conception of the project** : M. Rodriguez; C. Gorini; D. Sakellariou; L. Lepourhiet; E. d'Acremont;  
48  
49 602 S. Arsenikos; F. Chanier; P. Briole

50  
51 603 **NAFAS cruise organization, Data acquisition and processing** : M. Rodriguez; A. Janin; E.  
52  
53 604 d'Acremont; N. Chamot Rooke; K. Tsampouraki-Kraounaki ; I. Morfis; G. Rousakis; A. Lurin; M.  
54  
55 605 Delescluse; D. Oregioni ; J.-X. Dessa; A. Nercessian

56  
57 606 **Multibeam acquisition and interpretation** : D. Sakellariou; I. Morfis; G. Rousakis; K. Tsampouraki  
58  
59 607 Karounaki ; M. Rodriguez  
60

1  
2  
3 608 **Seismic interpretation** : M. Rodriguez; A. Janin; A. Lurin; C. Gorini; D. Sakellariou  
4

5 609 **Geological expertise, integration of the results to the geological background**: M. Rodriguez; D.  
6

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8

9 611 Chanier; F. Caroir; L. Lepourhiet  
10

11 612  
12

13 613 **Data availability:**

14  
15 614 Seismic reflexion dataset available on request to Dr. M. Rodriguez ([rodriguez@geologie.ens.fr](mailto:rodriguez@geologie.ens.fr)) and Dr  
16

17  
18 615 M. Delescluse ([delescluse@geologie.ens.fr](mailto:delescluse@geologie.ens.fr)).  
19

20 616 Multibeam dataset available on emodnet <https://emodnet.ec.europa.eu/en/bathymetry>  
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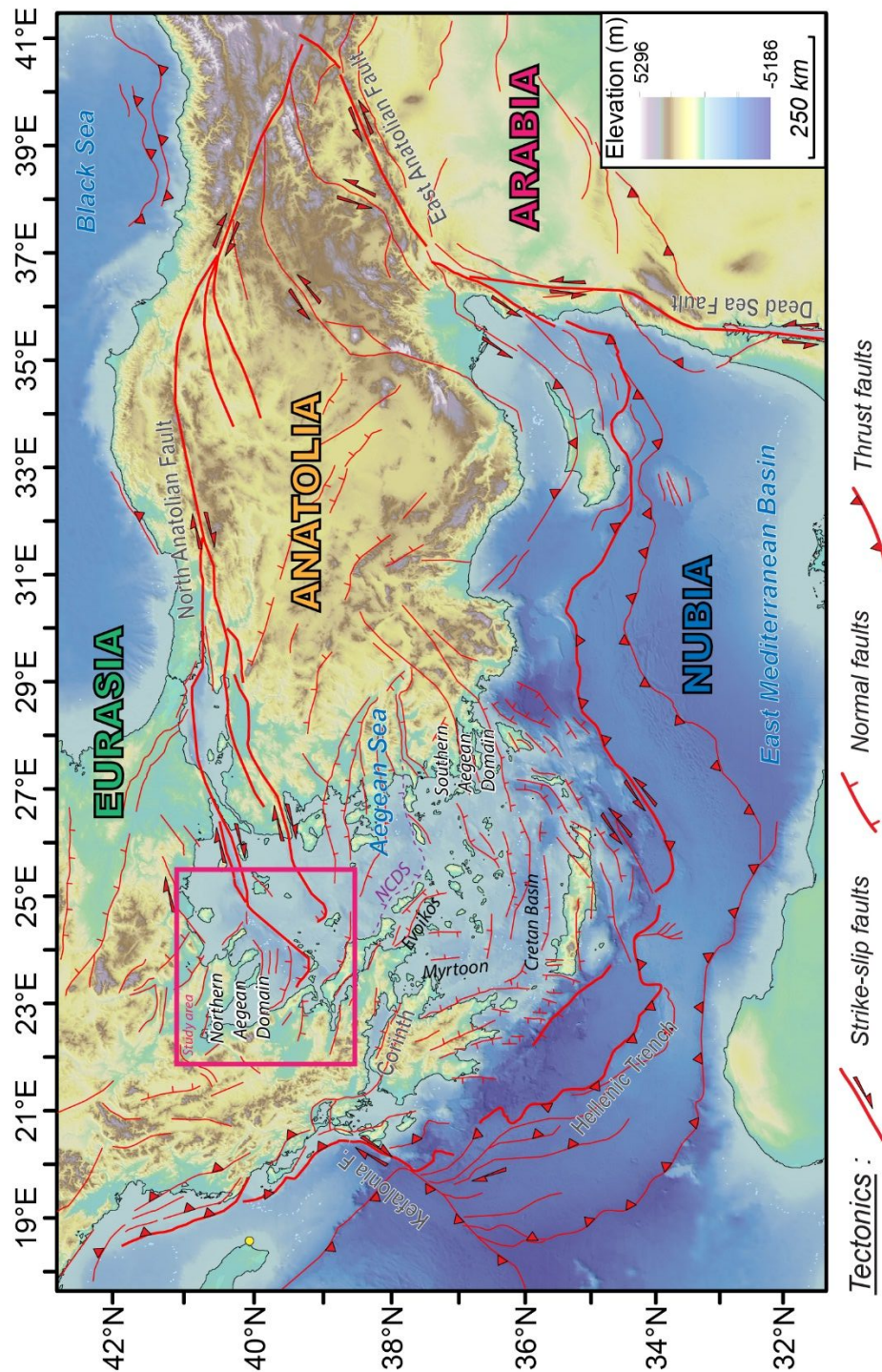
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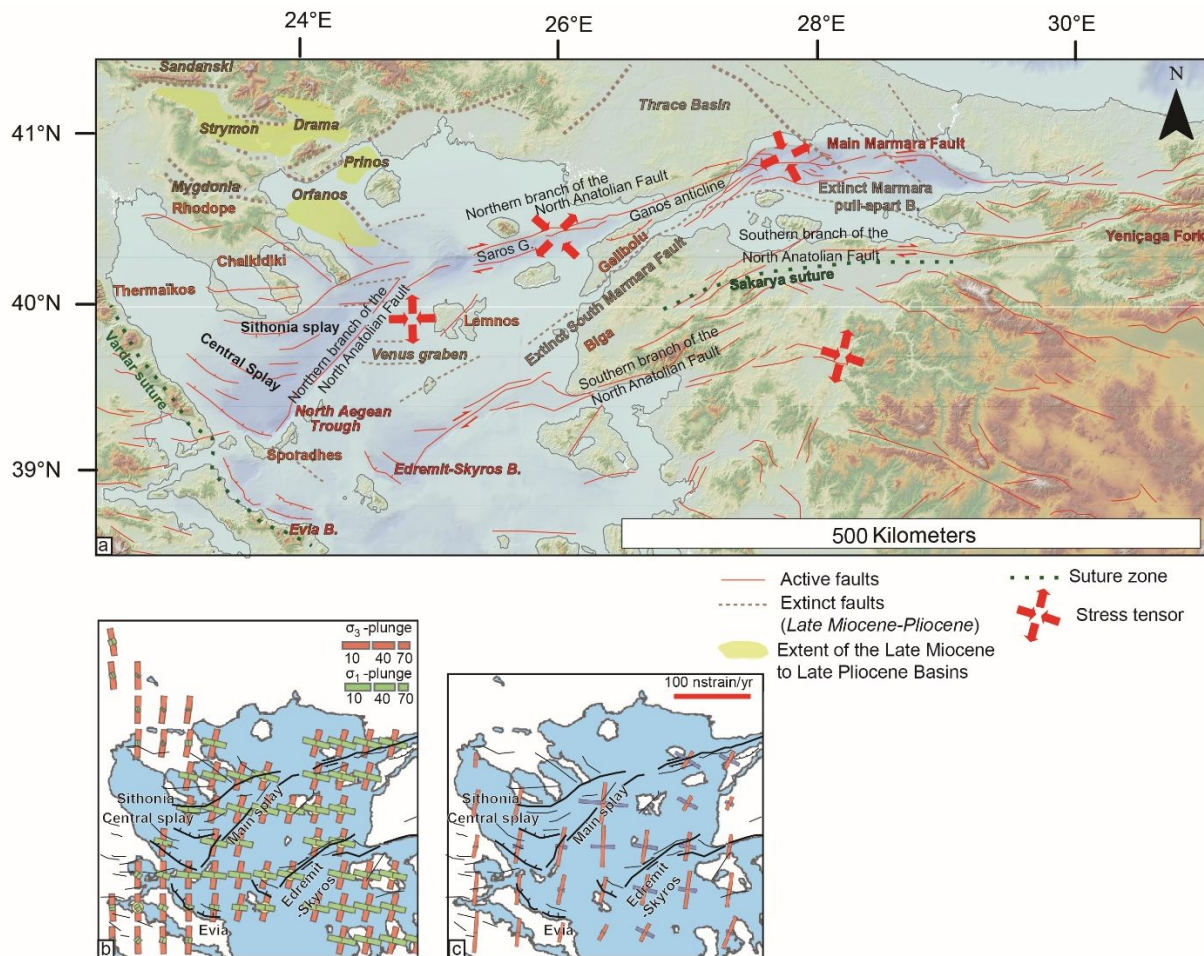
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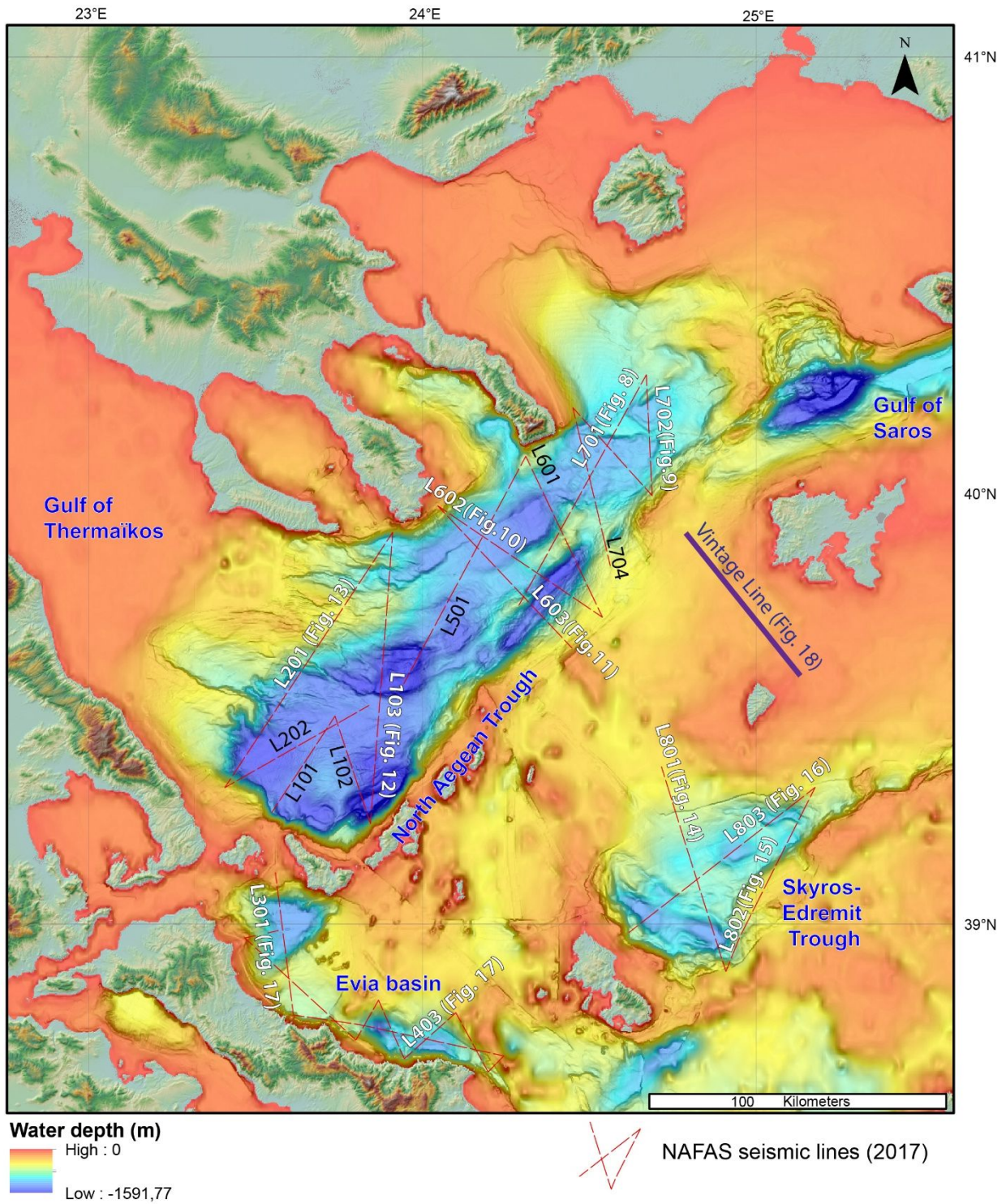
636 **Figures:**

637

638 **Figure 1:** Tectonic framework of the Eastern Mediterranean Sea (active faults from Kreemer and  
 639 Chamot-Rooke, 2004 and Chamot-Rooke et al., 2005). The tectonic escape of Anatolia results from  
 640 interactions between Arabia-Eurasia and the Hellenic trench retreat. NCDS: North Cycladic Detachment  
 641 System



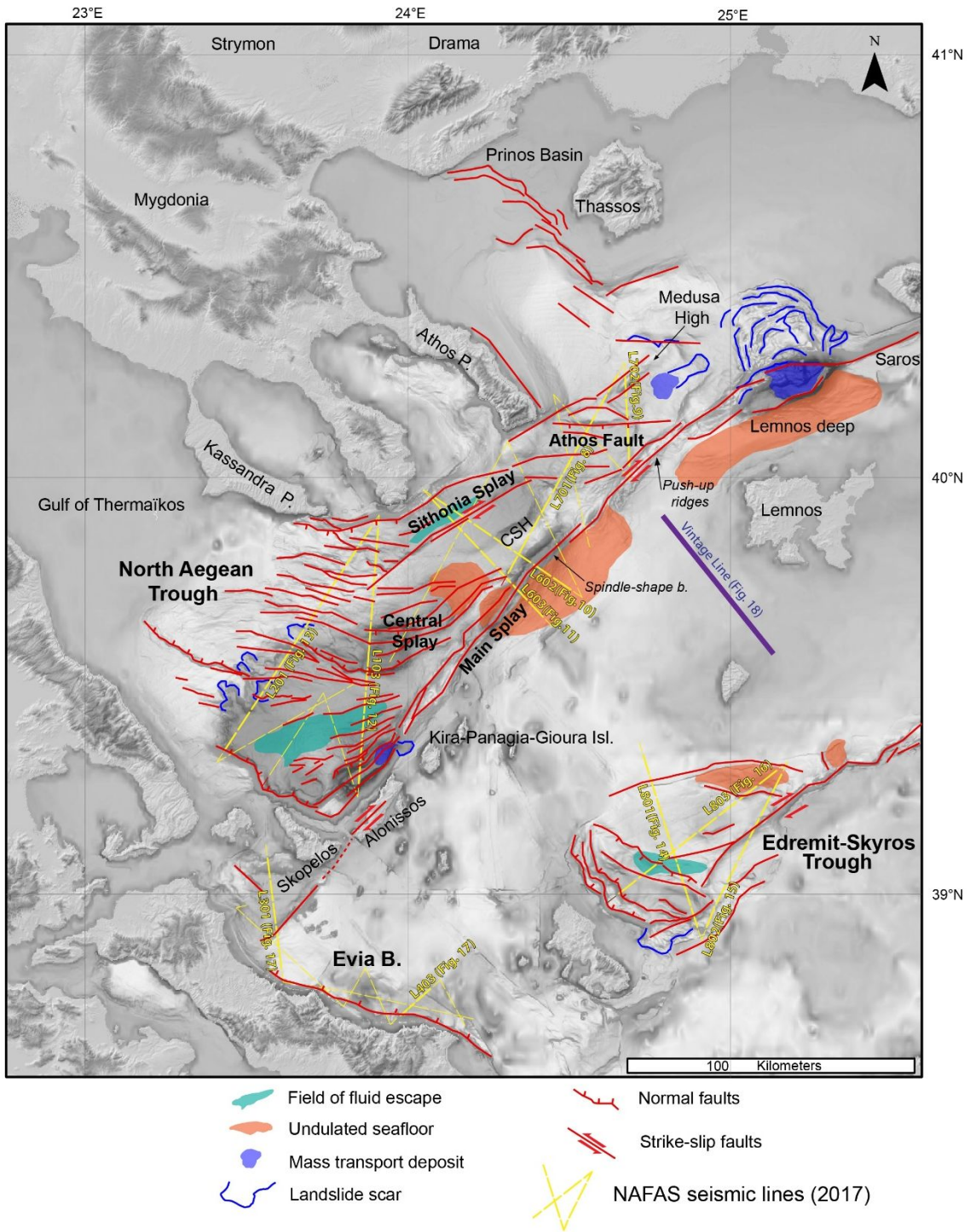
642  
 643 **Figure 2:** a) Structural map of the segment of the North Anatolian Shear Zone in the North Aegean  
 644 Domain, modified after Lyberis (1984), Koukouvelas and Aydin (2002), Yalçin et al. (2016);  
 645 Sakellariou et al. (2018), Papanikolaou et al. (2002; 2019). The stress tensors are from Gürer et al.  
 646 (2016); Sümer et al. (2018). The location of the Late Miocene-Late Pliocene basins (Strymon,  
 647 Mygdonia, Drama, Orfanos, Prinos) is from Brun and Sokoutis (2018). b) Present-day stress tensors and  
 648 c) strain rate, from Floyd et al. (2010) and Konstantinou et al. (2016).



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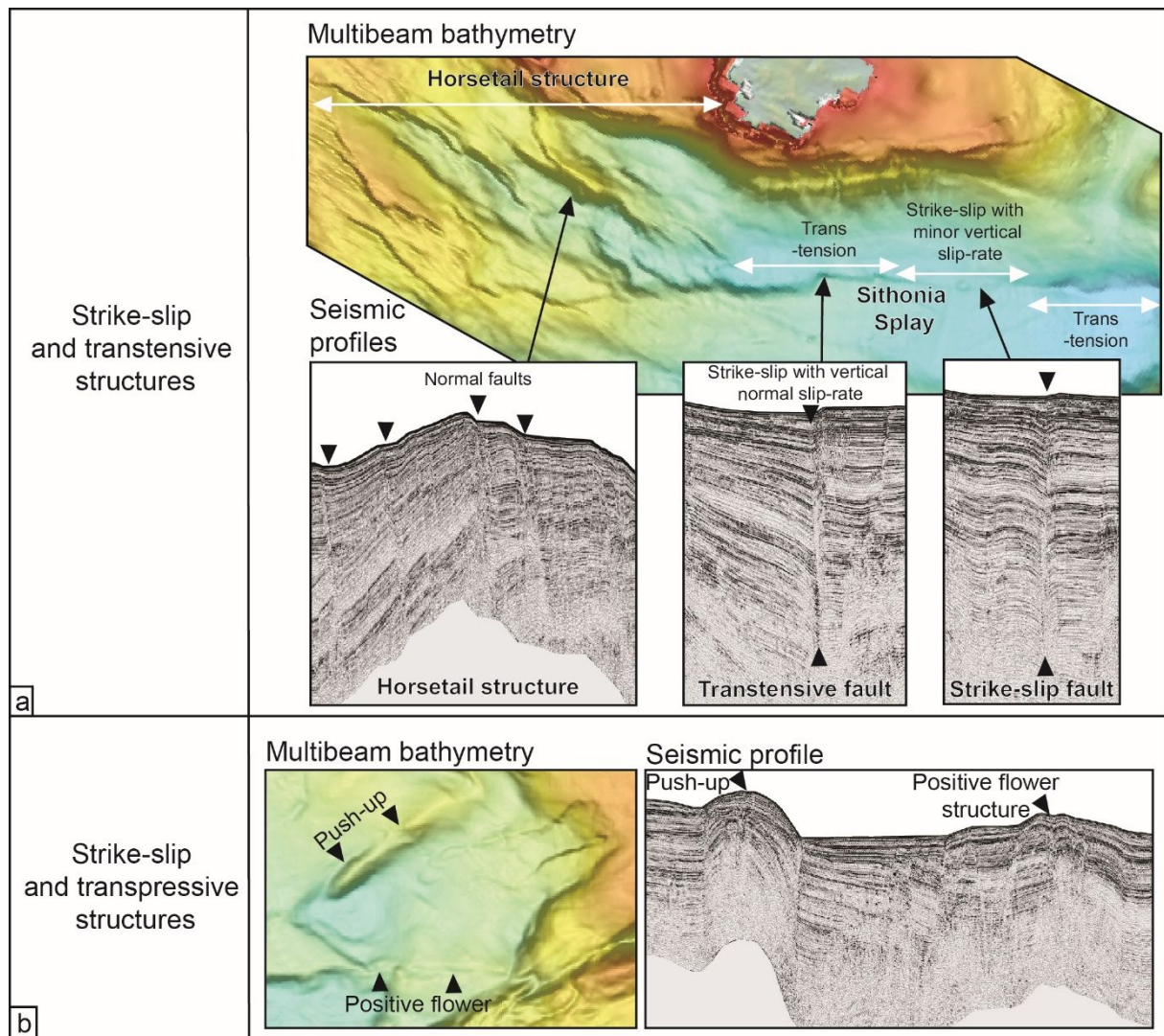
650 **Figure 3:** Topographic and bathymetric map of the North Aegean Domain and location of the seismic

651 lines published in this study (Sakellariou et al. 2018; Papanikolaou et al., 2002; 2019)

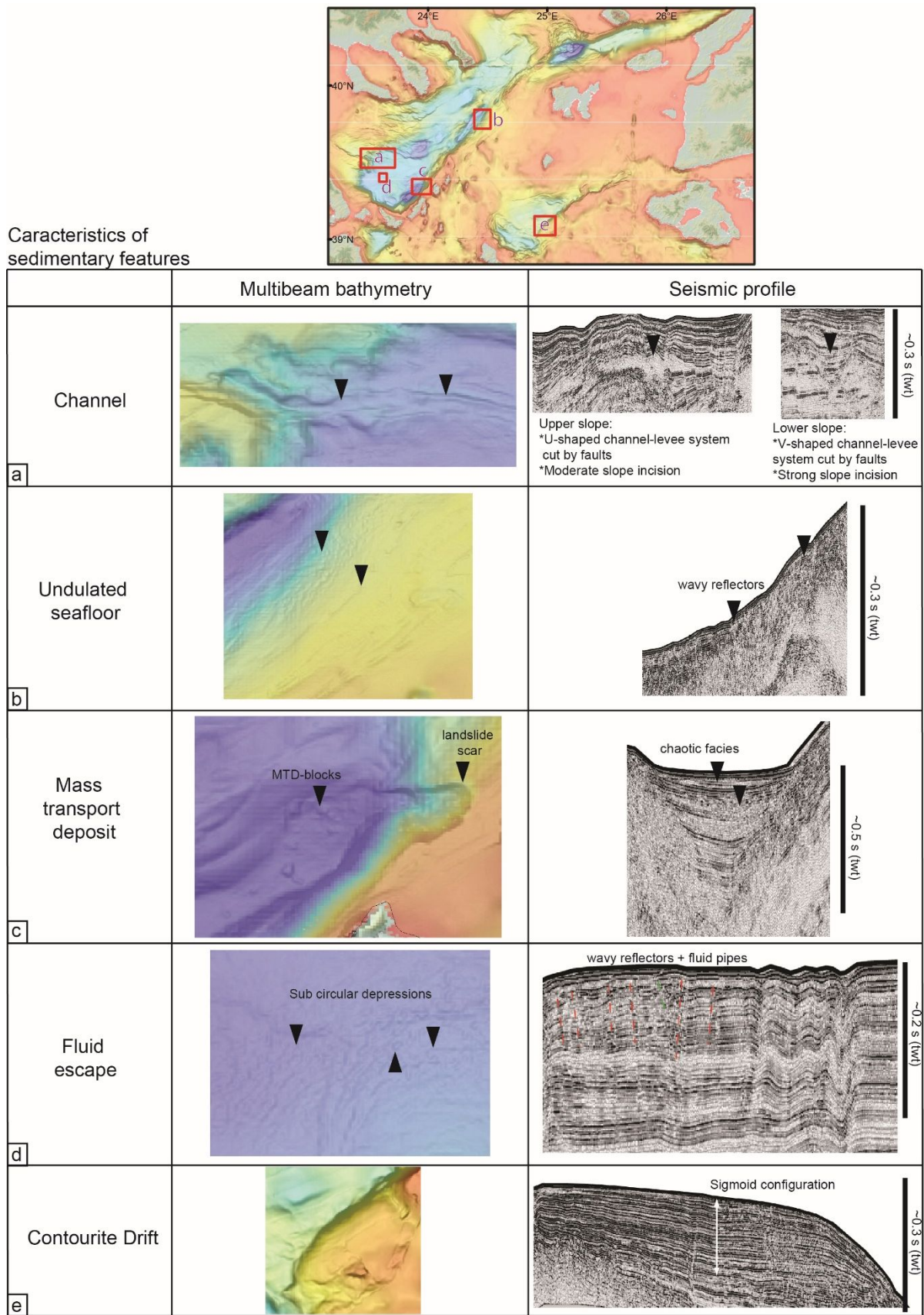


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653 **Figure 4:** Structural map of the active faults of the North Aegean Trough and the Edremit-Skyros  
 654 Trough and the main sedimentary features (modified after Sakellariou et al. 2018; Papanikolaou et al.,  
 655 2002; 2019). CSH: Central Structural High



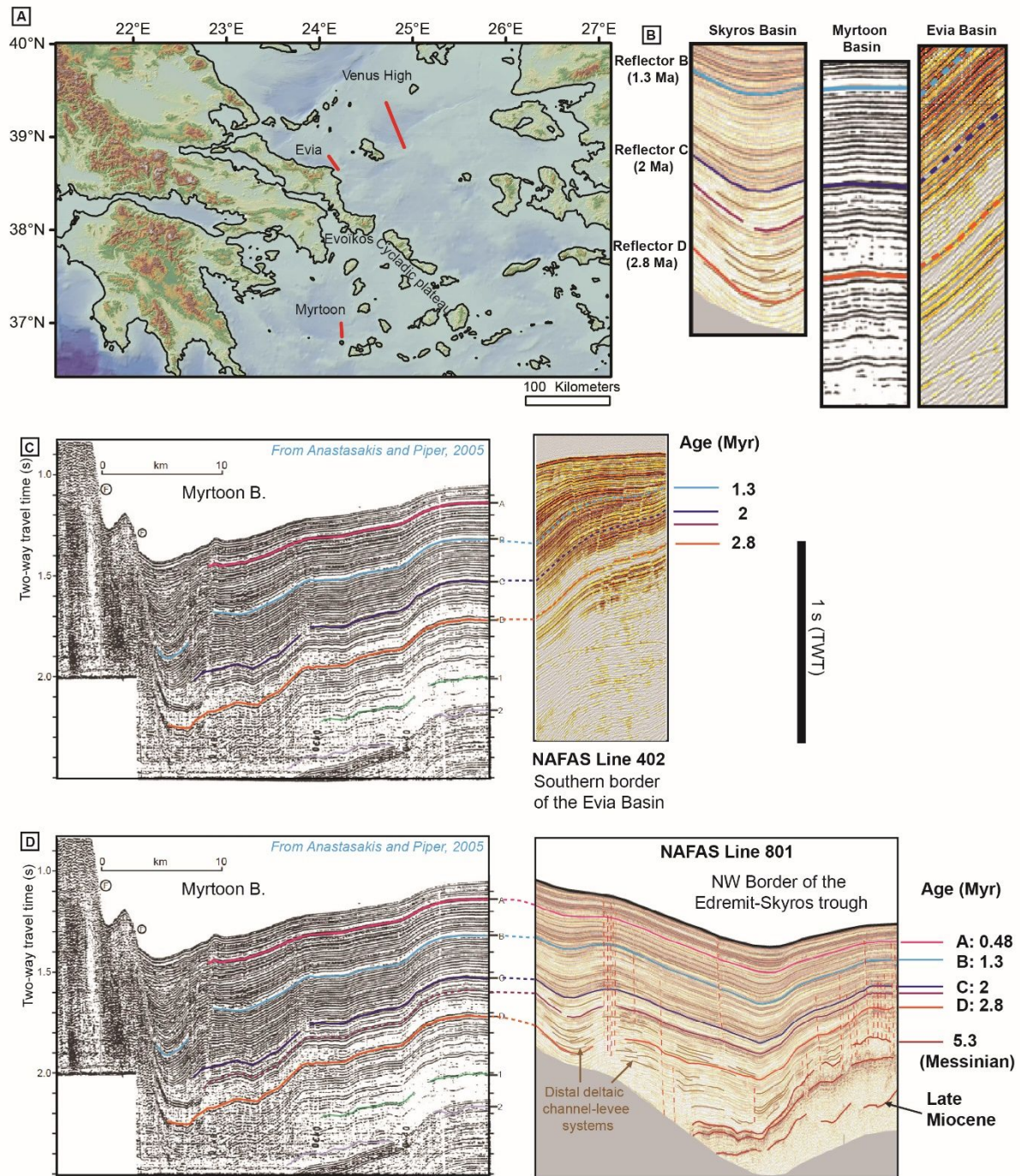
**Figure 5:** Criteria of identification of transtensive and transpressive strike-slip structures on the multibeam and seismic-reflection dataset, with the examples of a) the Sithonia Splay and b) the Athos Splay



661

662 **Figure 6:** Classification of the facies of the main sedimentary features observed on the multibeam and  
663 seismic dataset in the study area

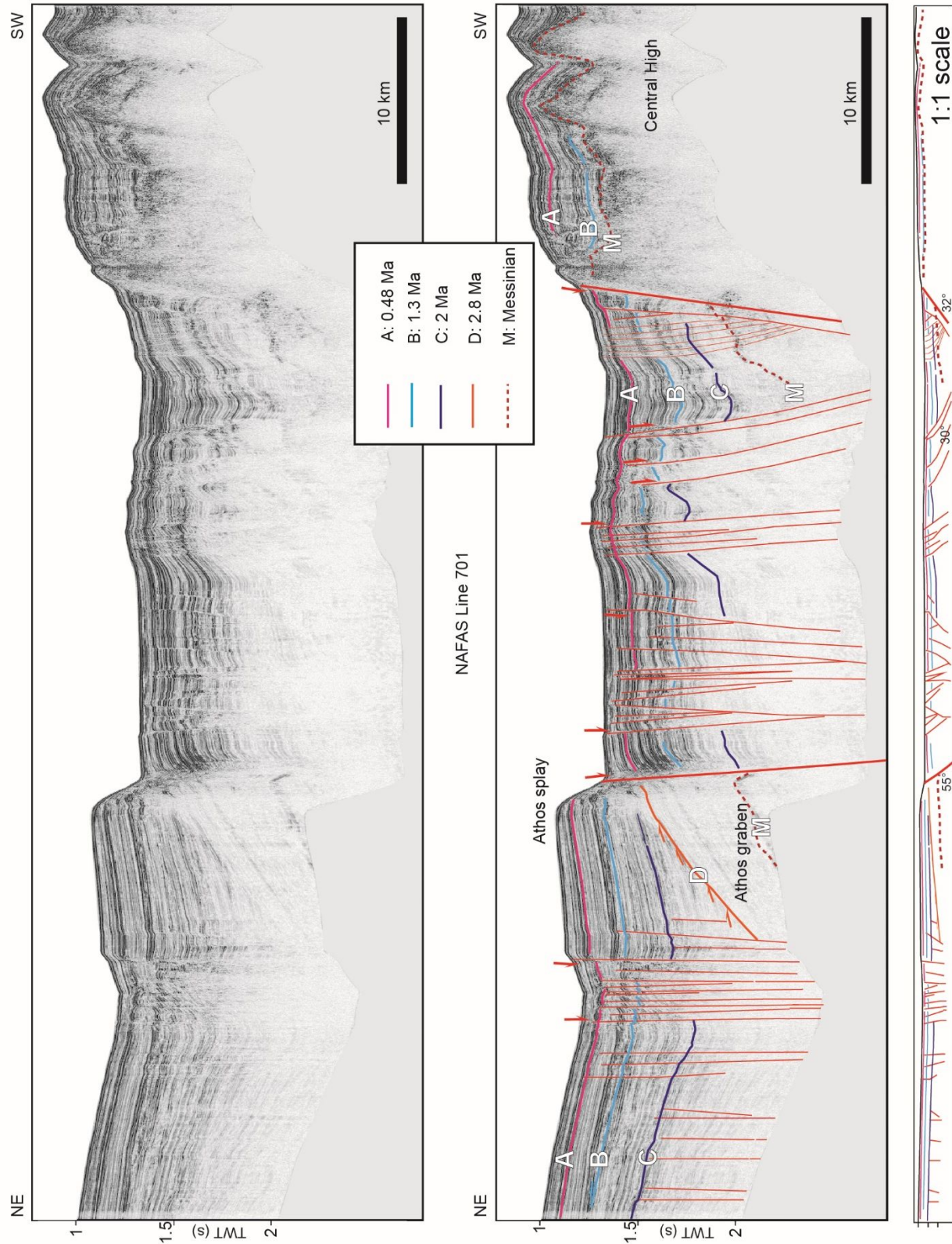




664

665 **Figure 7:** Stratigraphic correlation between the Myrtoon basin (Anastasakis and Piper, 2005), the Evia

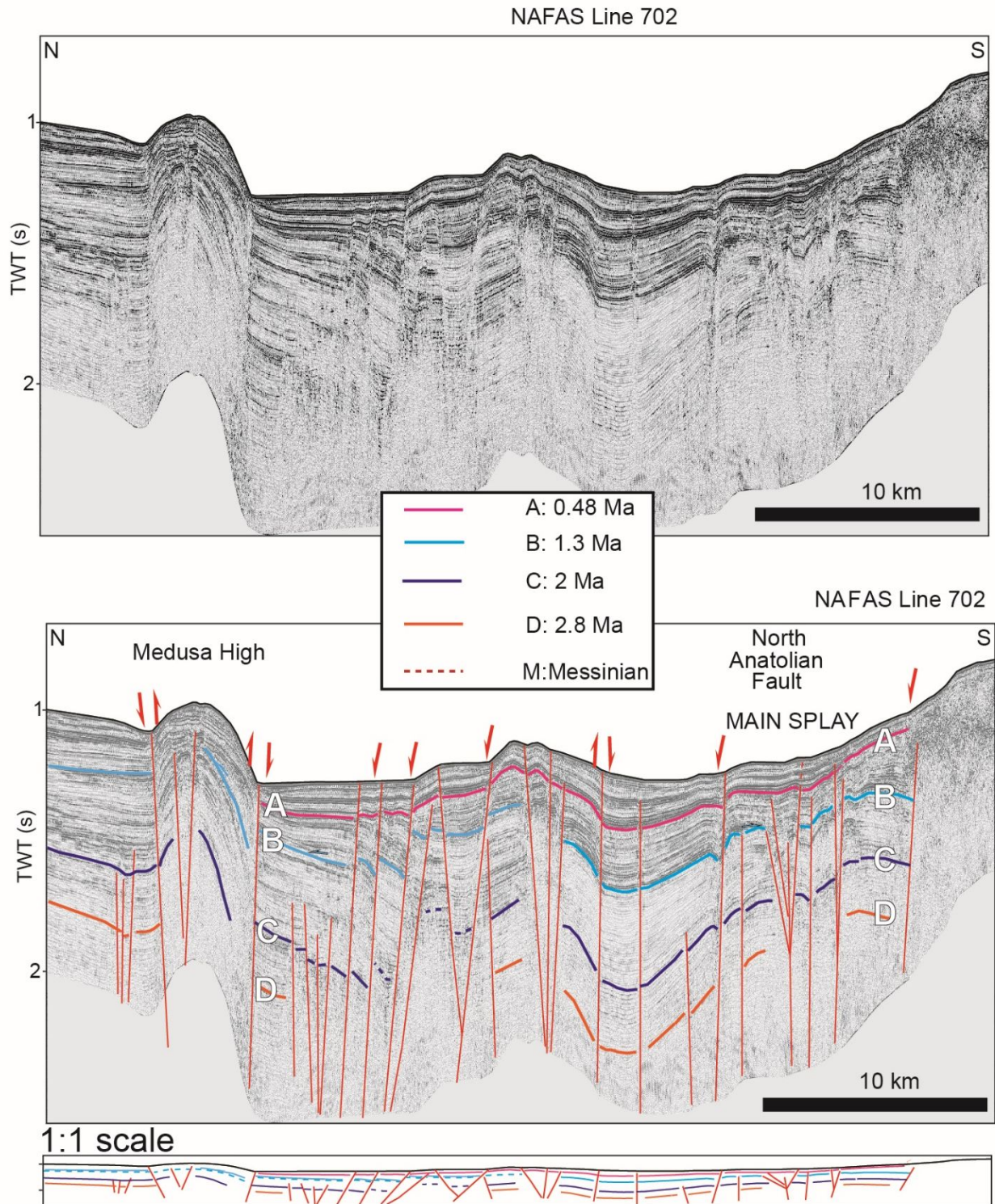
666 Basin and the NW border of the Edremit-Skyros Trough



667

668 **Figure 8:** Seismic line 701 from the NAFAS cruise, crossing the Athos Splay and the North Anatolian

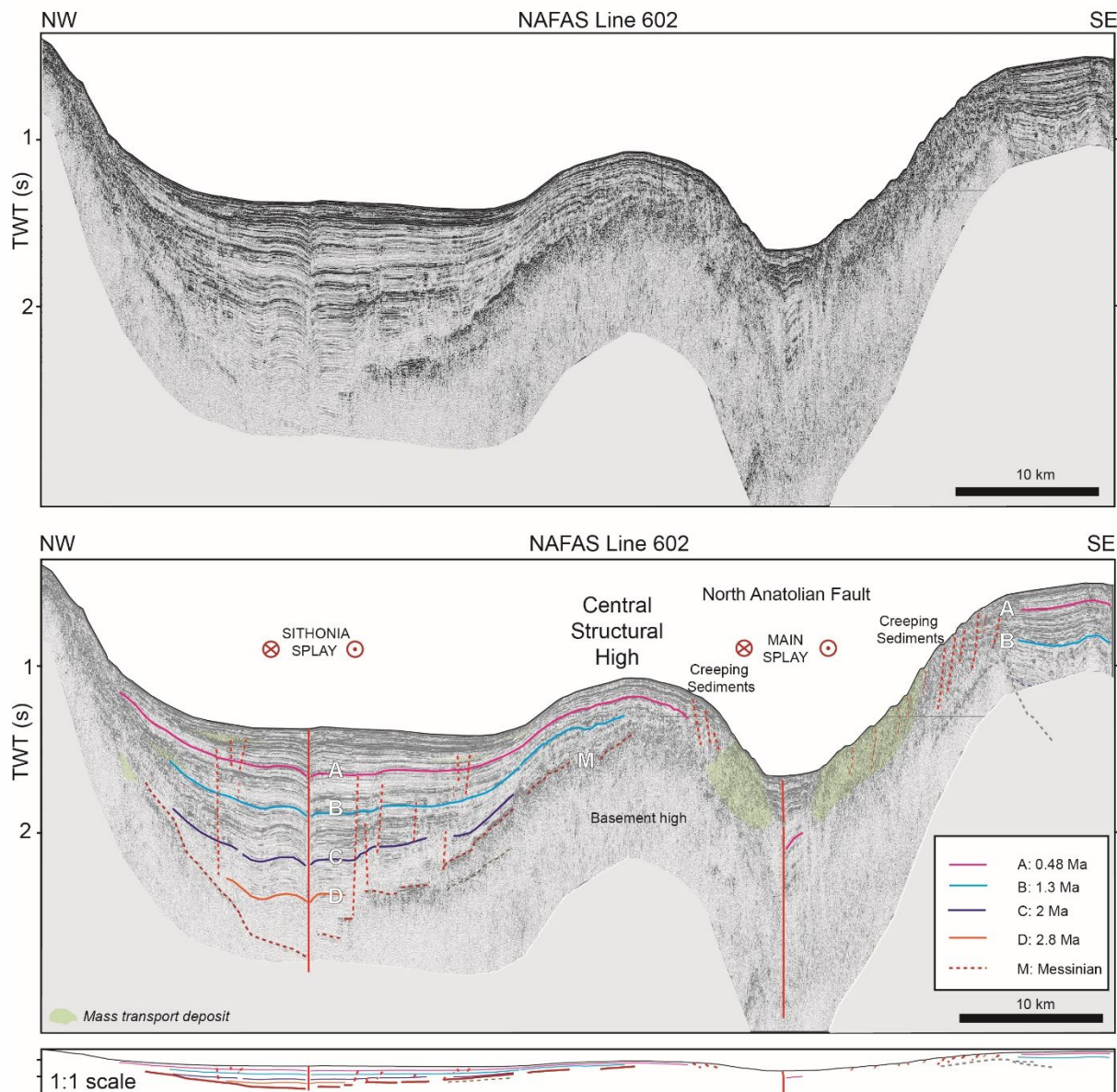
669 Fault at the entrance of the North Aegean Trough. See figure 3 for location.



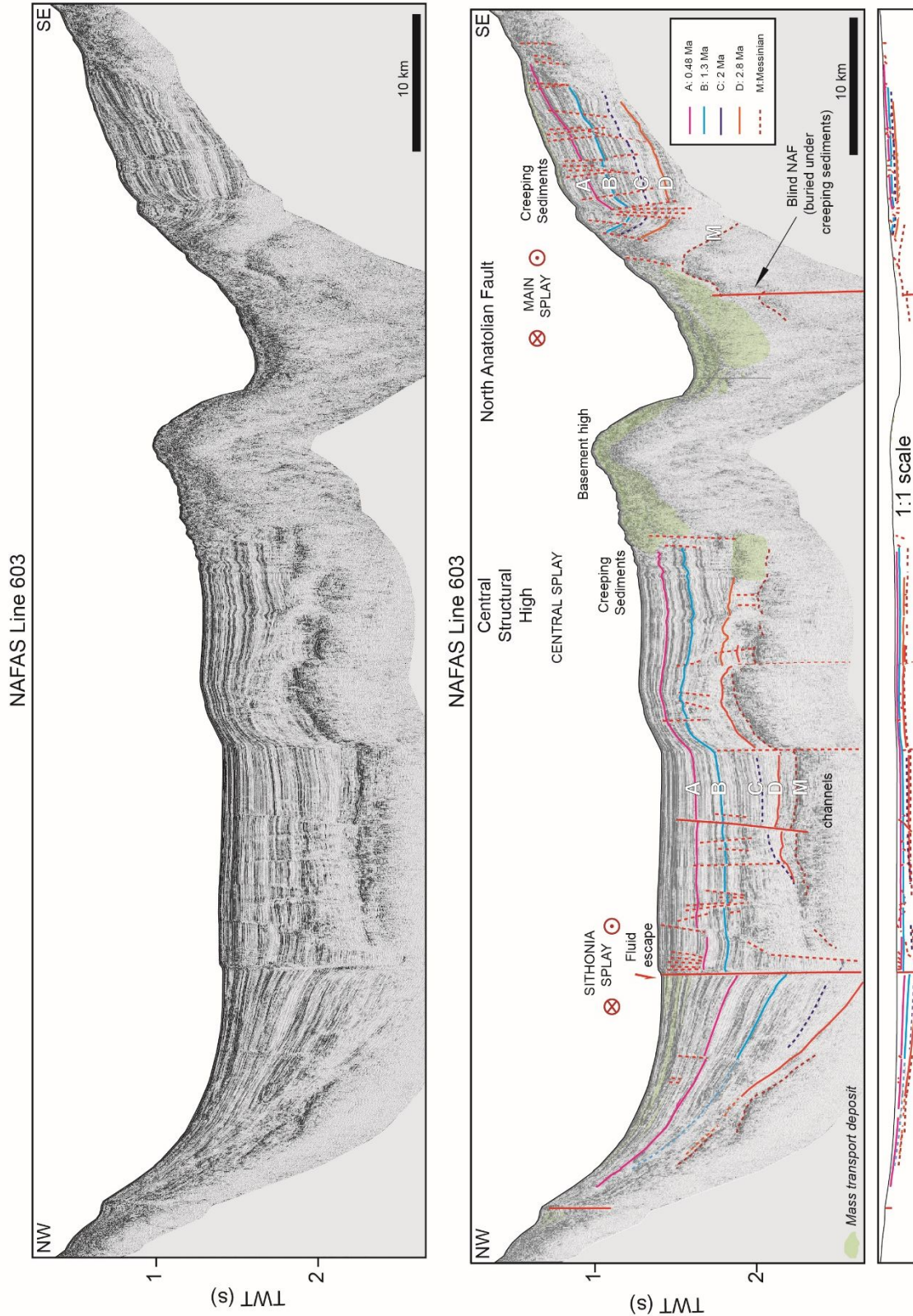
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671 **Figure 9:** Seismic line 702 from the NAFAS cruise, crossing the Medusa High and the North Anatolian

672 Fault. See figure 3 for location.



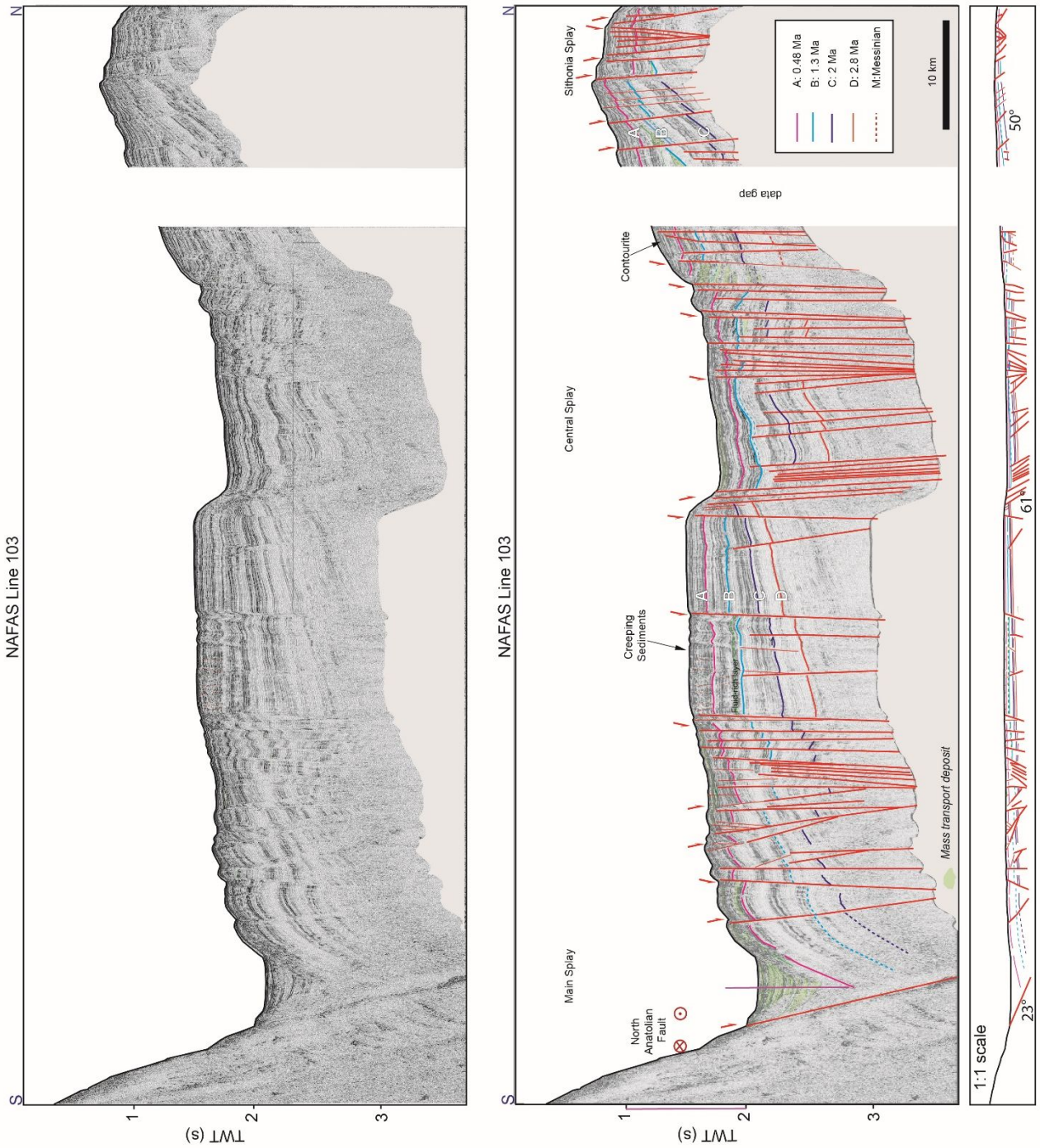
673  
 674 **Figure 10:** Seismic line 602 from the NAFAS cruise, crossing the main splay of the North Anatolian  
 675 Fault, the central high and the Sithonia splay within the North Aegean Trough. See figure 3 for location.



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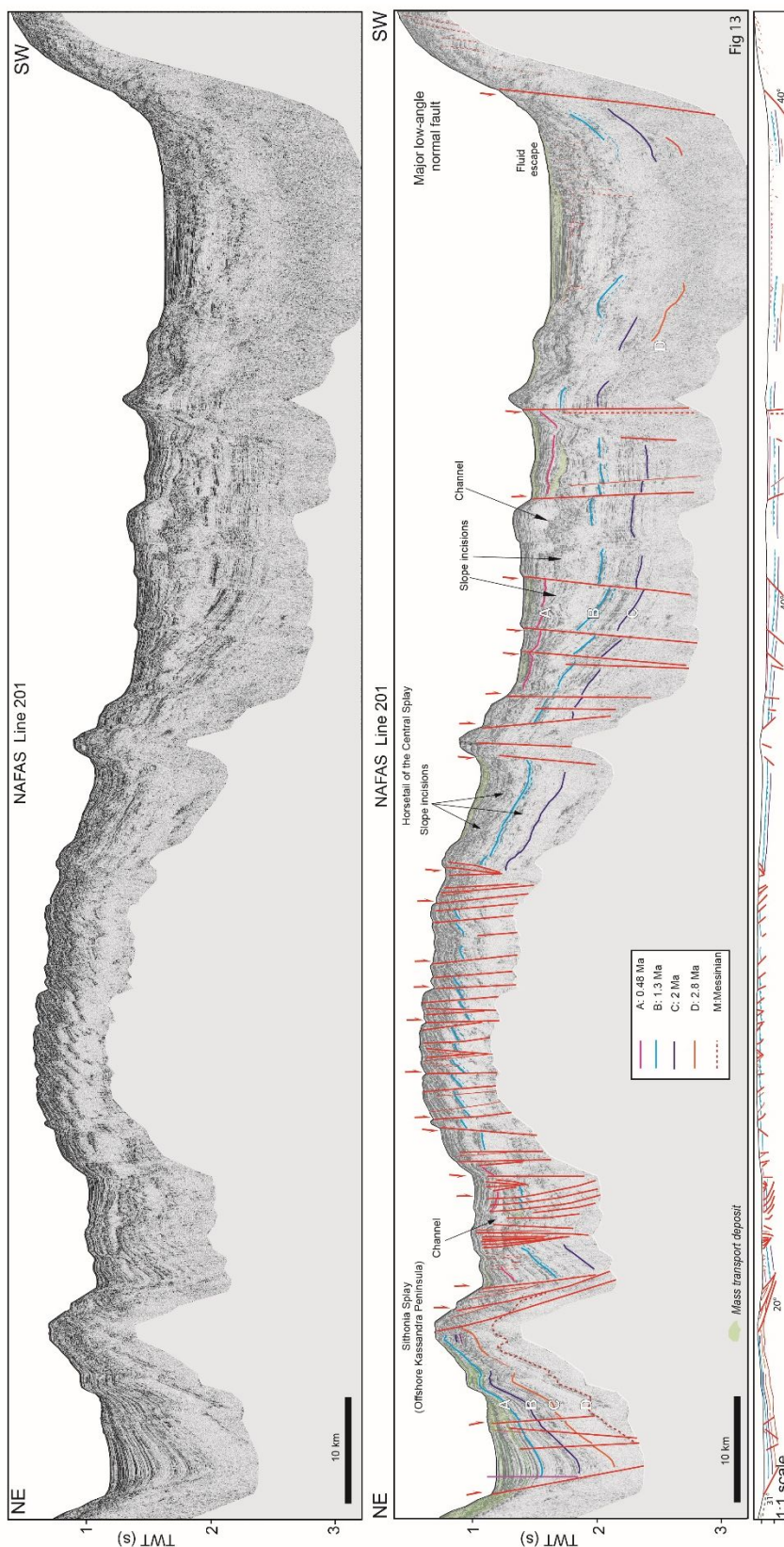
677 **Figure 11:** Seismic line 603 from the NAFAS cruise, crossing the main splay of the North Anatolian

678 Fault, the central high and the Sithonia splay within the North Aegean Trough. See figure 3 for location.

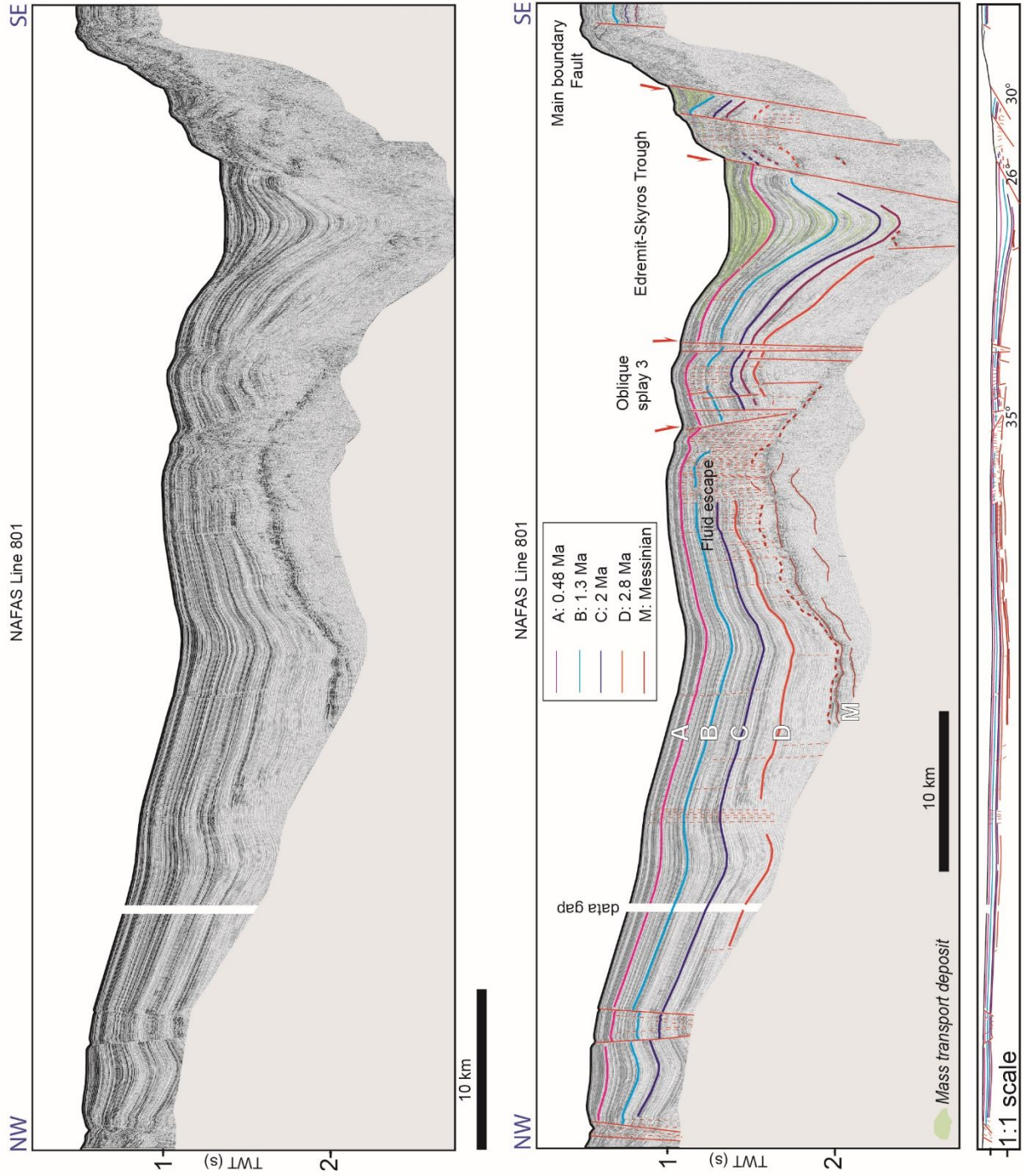


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680 **Figure 12:** Seismic line 103 from the NAFAS cruise, crossing the Main splay of the North Anatolian  
 681 Fault, the central splay and the western termination of the Sithonia Splay within the North Aegean  
 682 Trough. See figure 3 for location



683  
 684 **Figure 13:** Seismic line 201 from the NAFAS cruise, crossing the series of oblique splays dissecting  
 685 the slope at the edge of the Gulf of Thermaïkos and a field of fluid escape features. See figure 3 for  
 686 location.

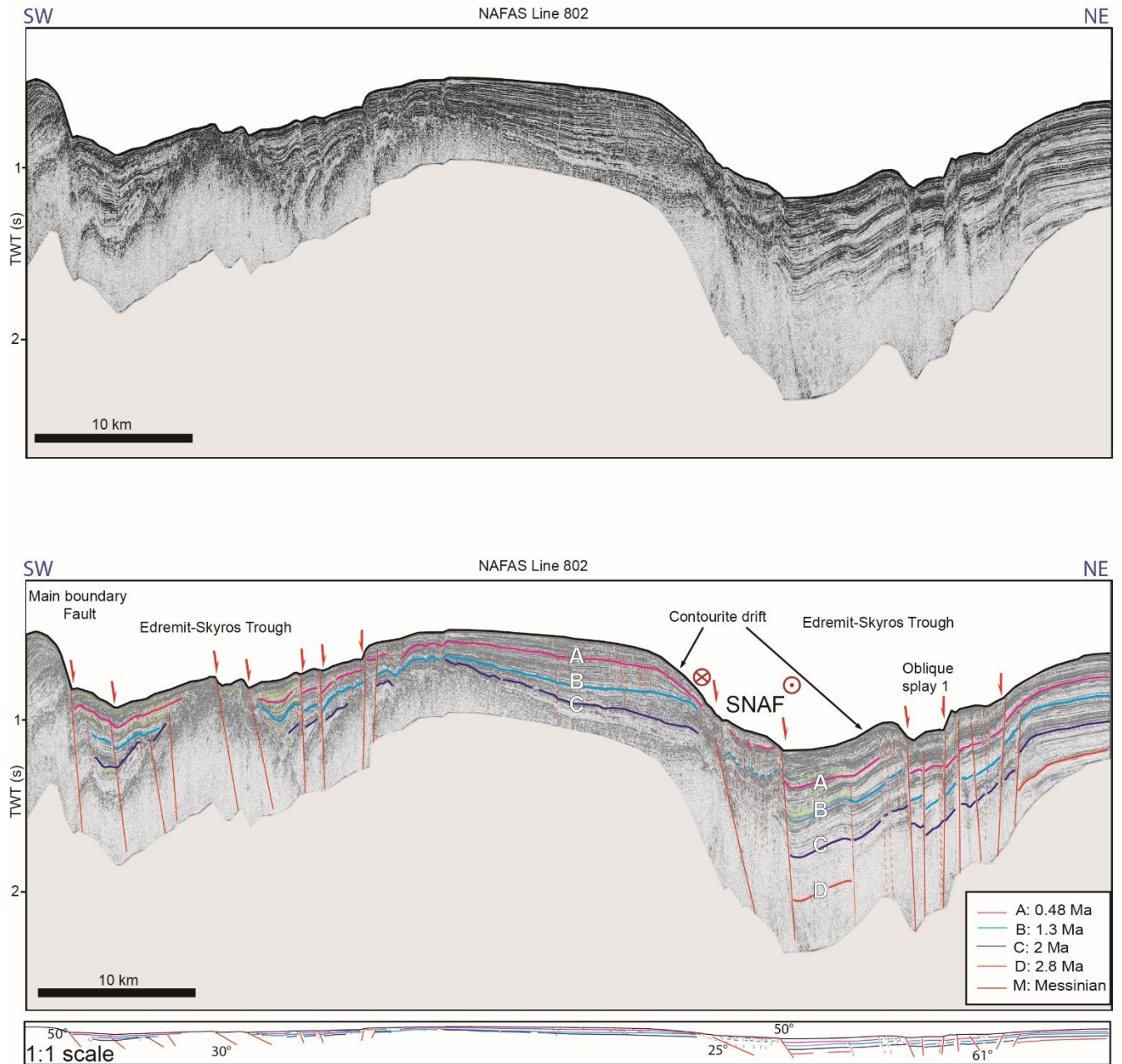


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688 **Figure 14:** Seismic line 801 from the NAFAS cruise, crossing the Edremit-Skyros Trough. See figure

689 3 for location.

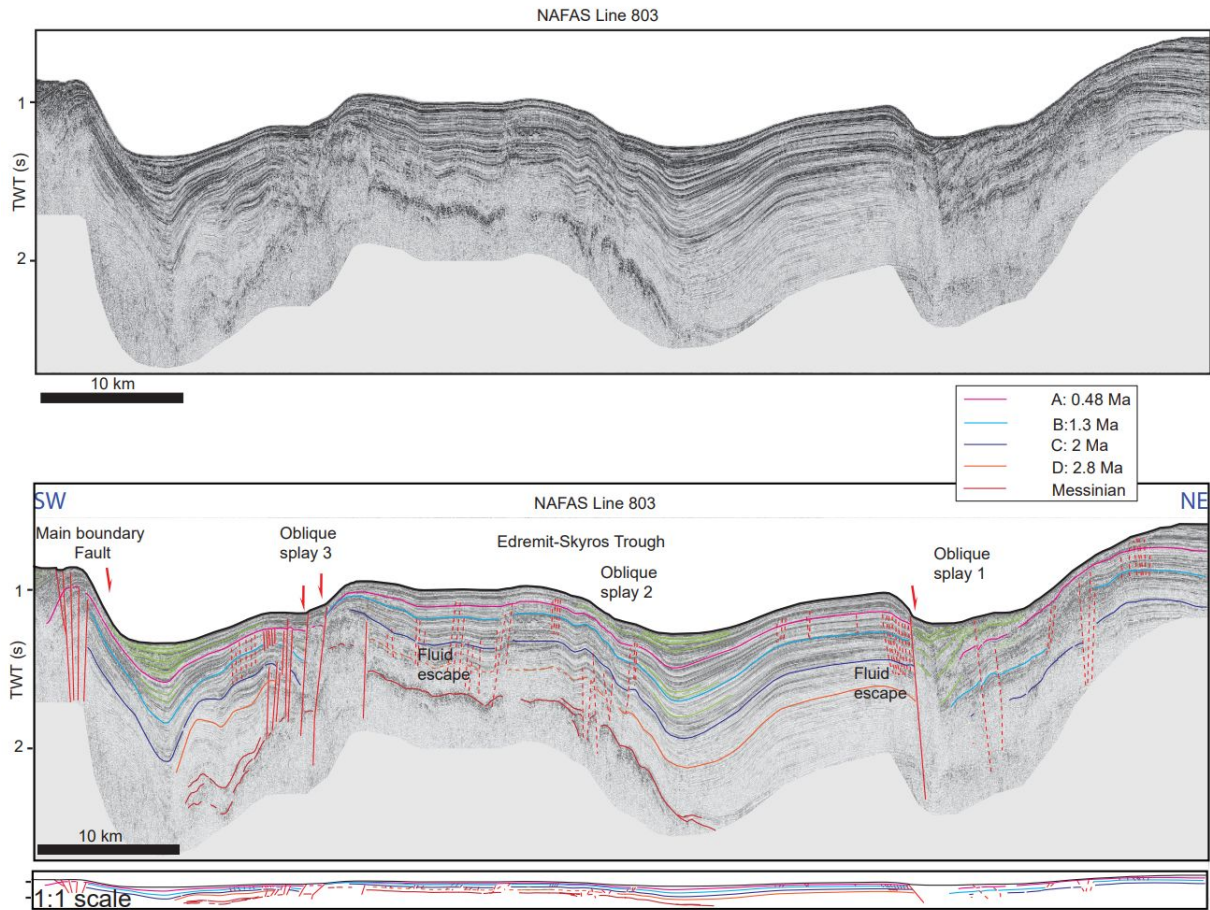




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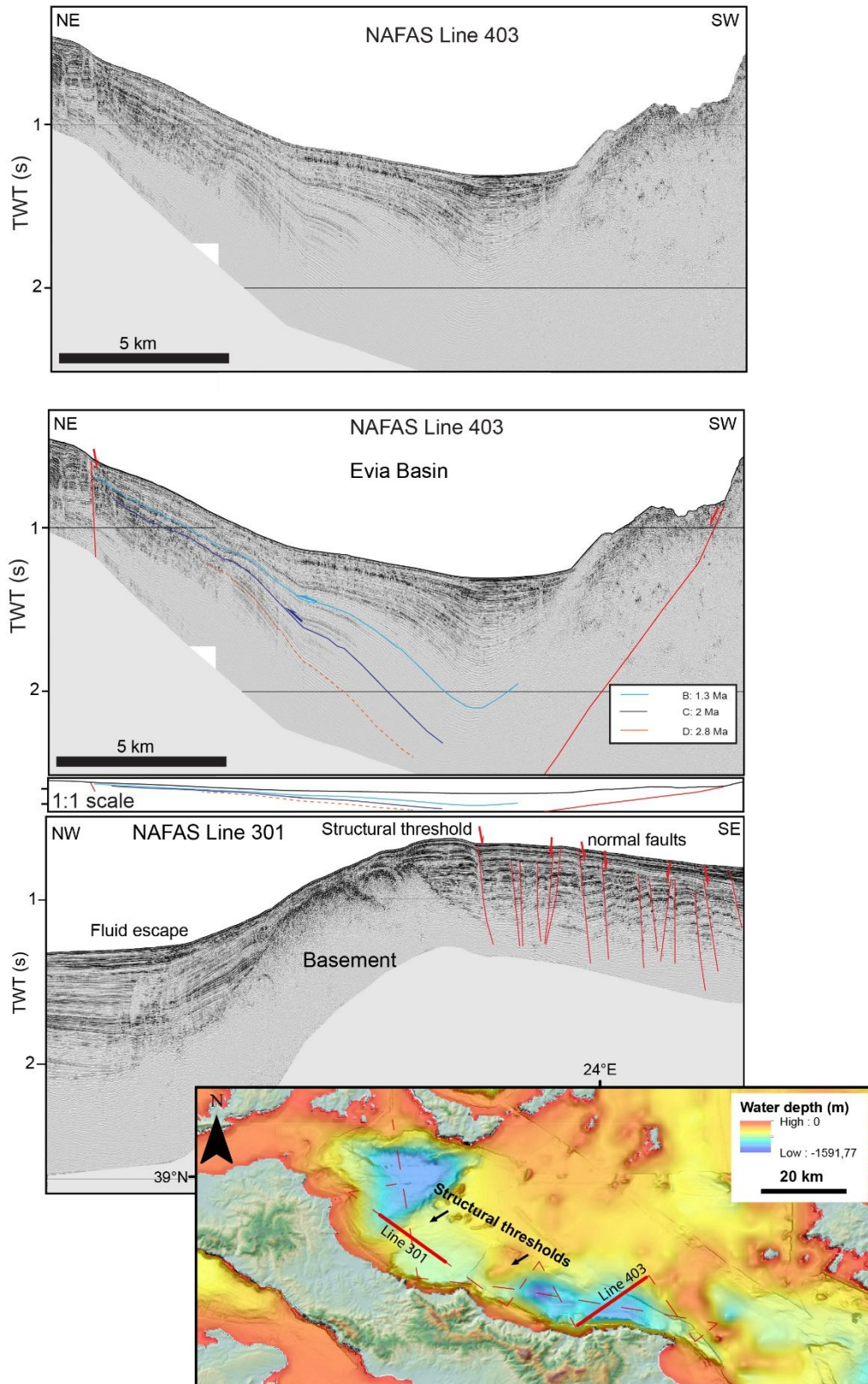
691 **Figure 15:** Seismic line 802 from the NAFAS cruise, crossing the Edremit-Skyros Trough. See figure

692 3 for location.



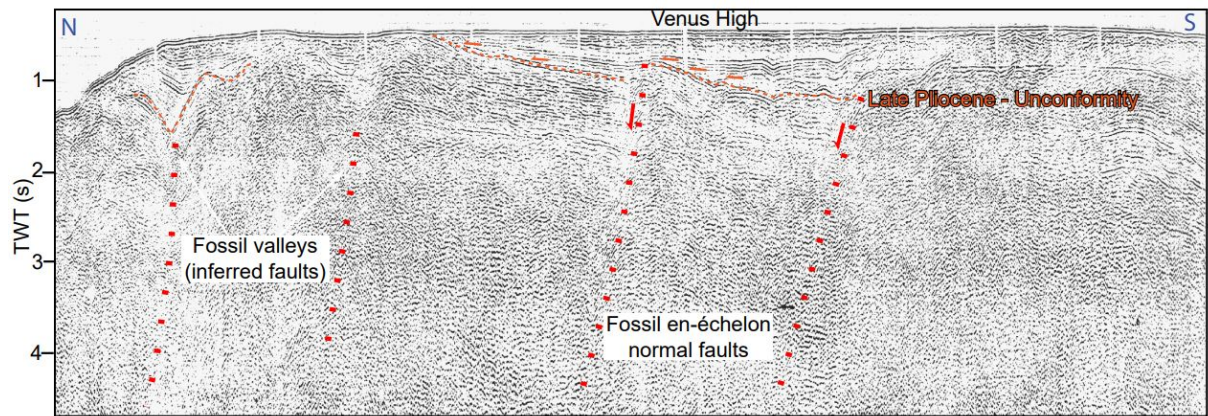
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694 **Figure 16:** Seismic line 803 from the NAFAS cruise, crossing the Edremit-Skyros Trough. See figure  
 695 3 for location.



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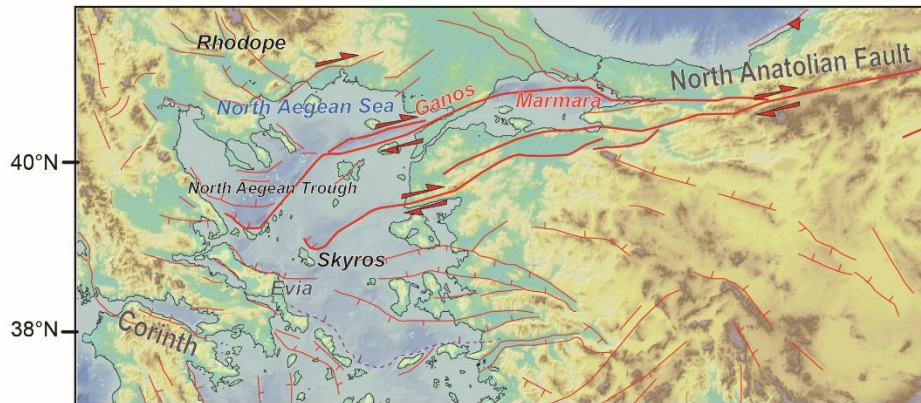
697 **Figure 17:** Seismic line 401 from the NAFAS cruise, crossing the main normal fault bounding the Evia  
 698 Basin and seismic line 301 crossing one of the structural thresholds identified within the Evia basin. See  
 699 inset and figure 3 for location.



700

701 **Figure 18:** Vintage seismic line, from Beniest et al. (2016), showing the Venus graben. See figure 3 for

702 location.

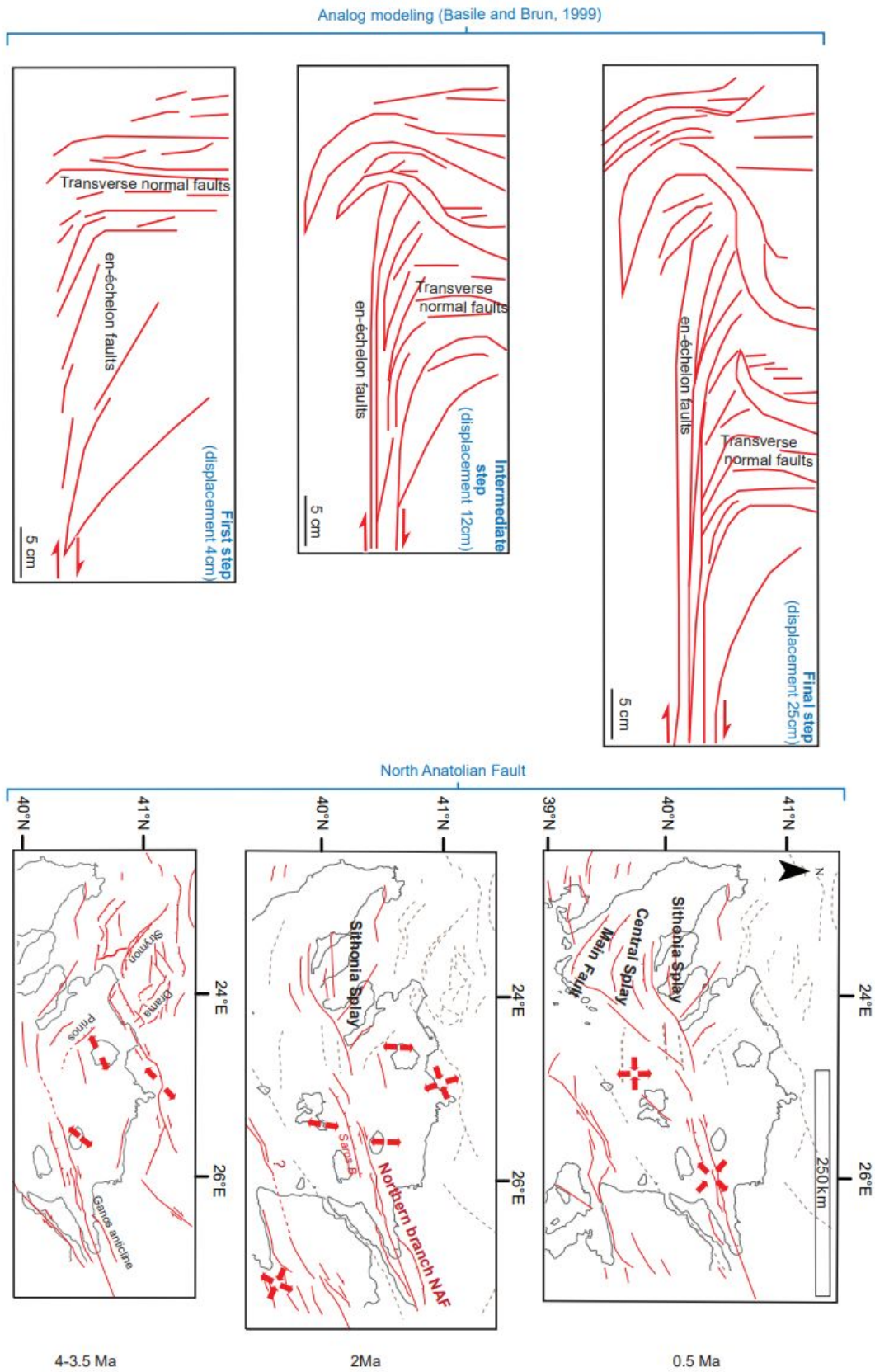


	Corinth	Rhodope & North Aegean Sea	Marmara & Ganos
Late Miocene		*Opening of Strymon, Orfanos, Mygdonia, and Drama Basins (Brun & Sokoutis, 2018)	*Diffuse strike-slip system (Thrace Basin) *First stage of the Southern branch of the NAF (Le Pichon et al., 2015)
Messinian Event			
Pliocene	*Distributed extension south of the Corinth rift -Early Pliocene (Collier & Dart, 1991)	*Opening of Prinos Basin (Proedrou & Papaconstantinou, 2004)  *Deactivation of Venus and Athos Grabens at 2.8 Ma (this study)	*Ganos Fold (Armijo et al., 1999) *South Marmara Fault & Restraining bend Early Pliocene-3.5 Ma (Le Pichon et al., 2014)
Pleistocene	*Migration of deformation within the Corinth Rift & Distributed deformation Early Pleistocene (Nixon et al., 2016)  *Migration of fault activity within the Corinth Rift between 0.6 -0.34 Ma *Strain localization since 0.34 Ma (Nixon et al., 2016)	*Sequential formation of the North Aegean Trough: *Sithonia Splay & Skyros Basin since 2-1.3 Ma (this study) *Central Splay of the North Aegean Trough since 1.3 Ma (this study) *Opening of the Evia Basin since 1.3 Ma (this study) * Main Splay of the NAF within the North Aegean Trough since 0.5 Ma (Ferentinos et al., 2018; this study) *Alonissos splay since 0.1-0.2Ma (Porkolab et al., 2023)	*Main Marmara Fault (emplacement between 0.5 & 2.5 Ma) (Grall et al., 2013; Le Pichon et al., 2015)  *Reorganization of the Southern branch of the NAF at 0.5-1.3 Ma (Demoulin et al. 2013)

703

704 **Figure 19:** Summary of the main steps of structural evolution of the North Anatolian Fault and the Gulf

705 of Corinth in the North Aegean Domain.

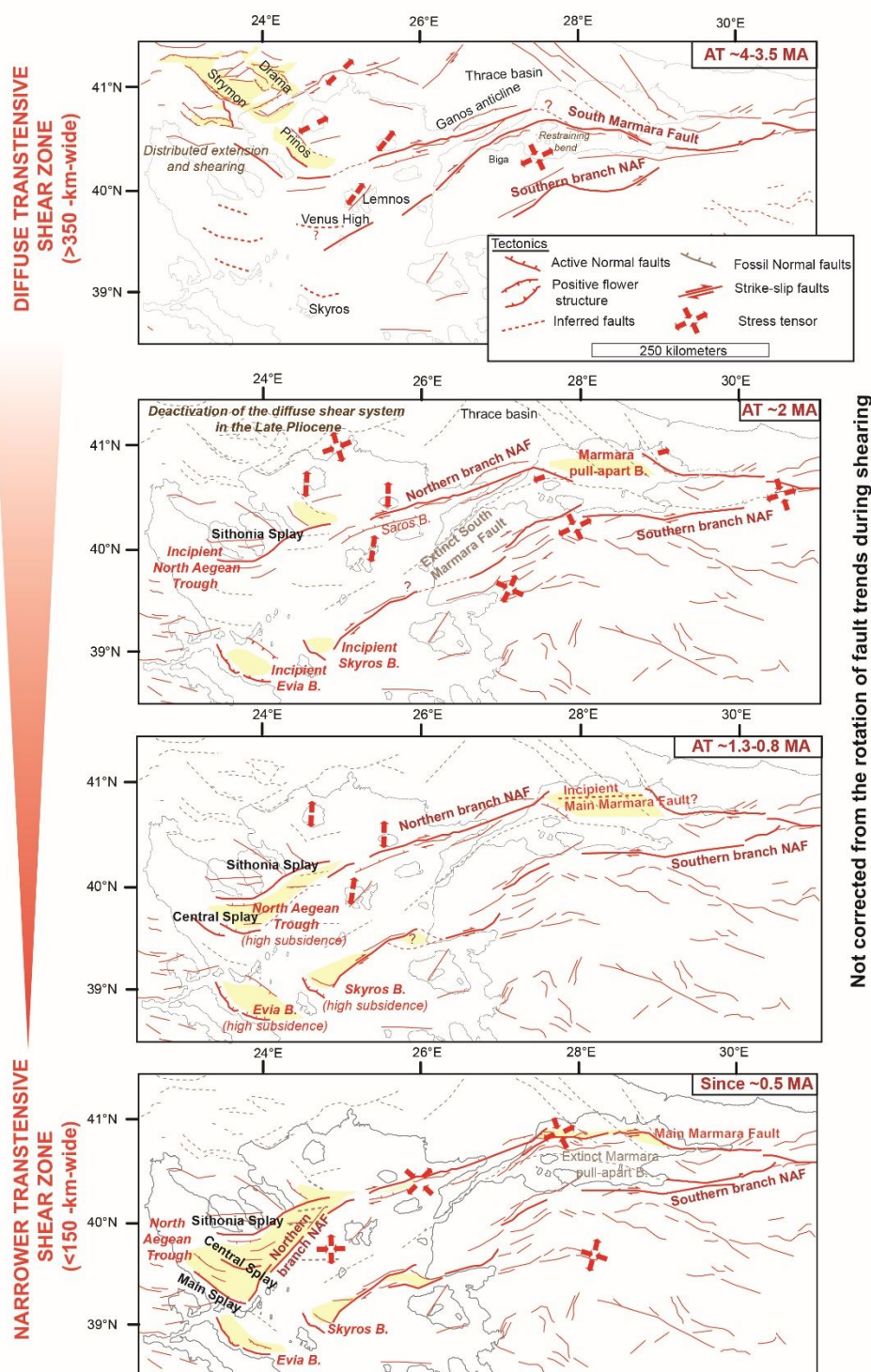


706

707 **Figure 20:** Analog (sandbox) models for the evolution of horsetail termination, from Basile and Brun

708 (1999), compared with the evolution of the North Aegean Trough horsetail (this study).

709



710

711 **Figure 21:** Structural evolution of the North Anatolian Fault in the North Aegean Domain, compiling  
 712 field and offshore observations. This series of maps represents the present-day location of the faults that  
 713 used to be active at 4-3.5 Ma, 2 Ma, 1.3-0.8 Ma, 0.5 Ma. The past shorelines are not reconstructed.  
 714 Paleo-stress tensors from Sümer et al. (2018) and Lybéris (1984).

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