Review Article

Changing seas in the late Miocene Northern Aegean: A Paratethyan approach to Mediterranean basin evolution

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ABSTRACT

The Northern Aegean region evolved during the Miocene as a restricted land-locked basin with small ephemeral connections to both the Eastern Paratethys (former Black Sea) and Mediterranean. Its biostratigraphic data show mixed Paratethys-Mediterranean components, but the Paratethys fauna has generally been neglected for chronologic reconstructions. Here, we review this biostratigraphic data from a Paratethyan perspective and present revised paleogeographic reconstructions of the Northern Aegean throughout the late Miocene. In the Tortonian, all sub-basins show mainly fluvio-deltaic terrestrial environments with a series of scattered lakes that are predominantly fed by local rivers and short-lived Paratethys connections. The first persisting marine conditions, still alternating with brackish Paratethyan environments, indicate a middle Messinian (late Maeotian) age (6.9–6.1 Ma), when the region formed a semi-isolated (Egemar) sea with multiple marine influxes. The termination of marine conditions is very well documented by a marked palaeoenvironmental change to the brackish water environments that correlate to the Maeotian/Pontian boundary (6.1 Ma) in Eastern Paratethys. During the Messinian Salinity crisis (5.97–5.33 Ma), the Northern Aegean was a brackish water system (Lake Egemar) that formed a passageway for Paratethyan overspill waters towards the Mediterranean. We conclude that the thick evaporites of the Northern Aegean domain do not reflect the classic Mediterranean MSC sequences, but are more likely related to older (Badenian or Maeotian) salinity incursions.

1. Introduction

In late Miocene times, Central Eurasia was strongly influenced by two major water masses, the Mediterranean in the south and the Eastern Paratethys (the Black Sea-Caspian Sea precursor) in the more central parts (Fig. 1). The evolution of Paratethys-Mediterranean connectivity is still poorly understood, but has severely affected the development of aquatic fauna, the migration of terrestrial fauna (including hominins) and has changed the hydrological, palaeoenvironmental and palaeoecological conditions in both domains. Two-way Mediterranean-Paratethys exchange is documented by the influx of Mediterranean fauna in the Paratethys during the middle Messinian (upper Maeotian in regional stages; ~6.8–6.7 Ma) and late Messinian (lowermost Pontian; ~6.1–6.0 Ma) (Krijgsman et al., 2010; Radionova and Golovina, 2011; Radionova et al., 2012; Stoica et al., 2013; Popov et al., 2016; Golovina et al., 2019) and by the migration of

Paratethyan fauna all over the Mediterranean during the final stage of the Messinian Salinity Crisis (5.4–5.3 Ma) (Gliozzi et al., 2007; Guerra-Merchán et al., 2010; Stoica et al., 2016; Grothe et al., 2018). Geochemical records of strontium ratios and organic molecules (alkenones) confirm the existence of Mediterranean-Paratethys water exchange, but quantitative understanding of the hydrological fluxes remains uncertain (Vasiliev et al., 2013, 2015; Grothe et al., 2020).

The development of the North Aegean sea, located in a transitional position between the Black Sea and Mediterranean, forms a crucial piece of this connectivity puzzle. The Northern Aegean initially evolved as a restricted land-locked basin, and late Miocene marine connections to both the Eastern Paratethys and Mediterranean were probably only possible via shallow and narrow sea straits (Van Baak et al., 2016; Karakitsios et al., 2017). Two Aegean-Paratethys gateways have been proposed (Fig. 1); the "proto-Bosphorus hypothesis" through the Dardanelles-Marmara-Bosporus region (Steininger and Rögl, 1984; Sakinç
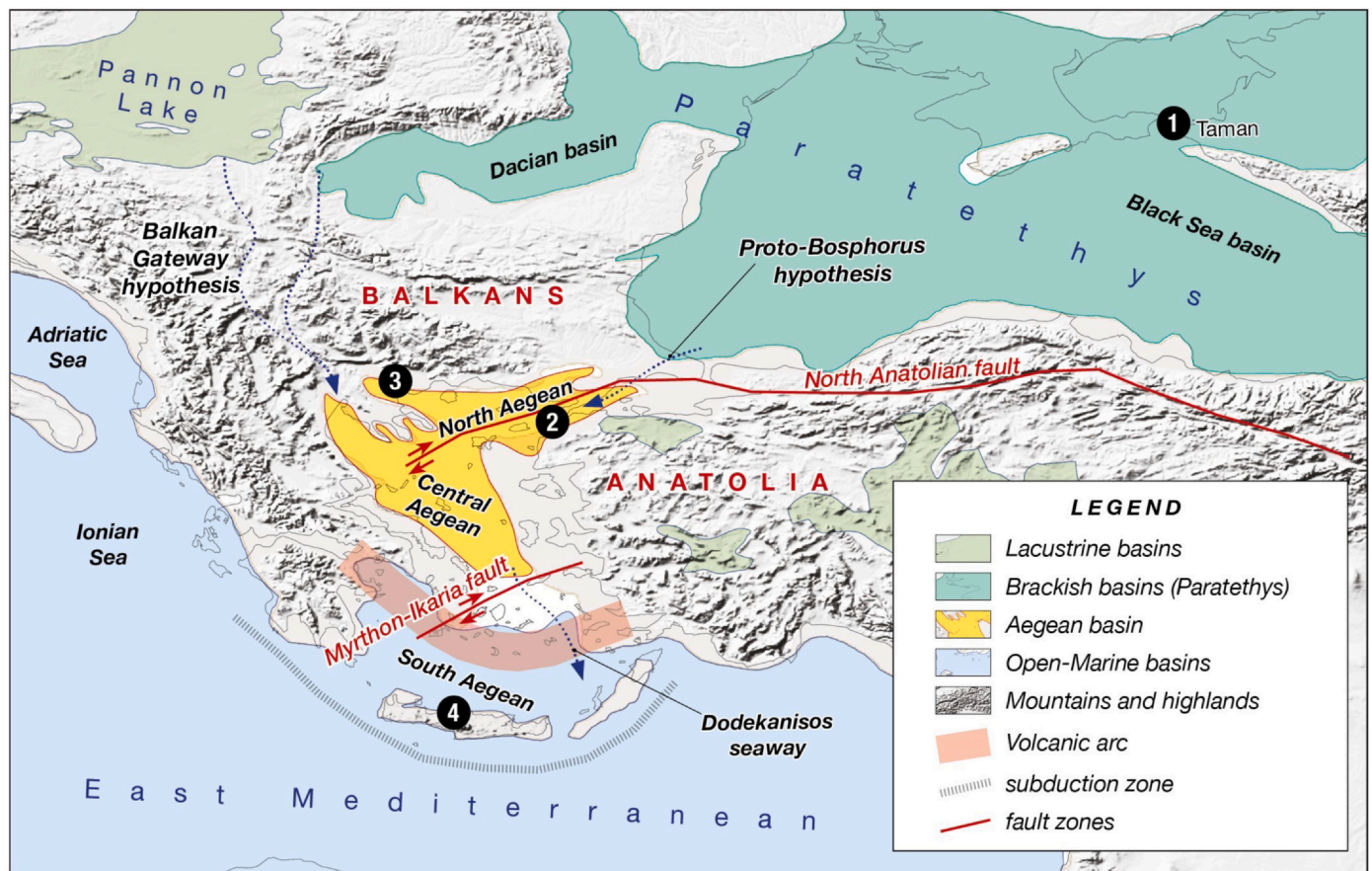
Fig. 1. Schematic location map of the North Aegean basin during the late Miocene in an intermittent position between the Paratethys and Mediterranean. Key study areas are (1) Taman region of the Paratethys domain; (2) Dardanelles region in western Turkey; (3) Strymon-Serres Basin in northern Greece; (4) Crete of the Mediterranean domain.

and Yaltirak, 2005; Popov et al., 2006), and the alternative "Balkan Gateway hypothesis" through Bulgaria (Stevanovic et al., 1989; Suc et al., 2015). The location of the Aegean-Mediterranean connection is generally envisaged via a Dodekanisos seaway (Fig. 1; van Hinsbergen and Schmid, 2012; Poulakakis et al., 2015). Evidence of connectivity to both domains is expressed in the Miocene to Pleistocene faunal record of the Northern Aegean, showing mixed Paratethyan and Mediterranean species, complicating stratigraphic correlations and robust age determinations (Gramann and Kockel, 1969; Popov and Nevesskaya, 2000).

Biostratigraphic attempts to shed light on the palaeogeographic evolution of the North Aegean basin mostly focused on rare marine Mediterranean nannofossils (foraminiferal marker species are absent) and commonly neglected the Paratethys fauna, because these species were not considered age diagnostic (Snel et al., 2006; Melinte-Dobrinescu et al., 2009; Suc et al., 2015; Karakitsios et al., 2017). Recently, however, several integrated magneto-biostratigraphic investigations in the Dacian Basin and the Black Sea domain have resulted in a comprehensive late Miocene biochronology for the Paratethys domain (Vasiliev et al., 2004, 2011; Stoica et al., 2013; Stoica et al., 2016; Palcu et al., 2017, 2019; Lazarev et al., 2020). The fast sequence of late Miocene faunal turnovers in the endemic Paratethys groups (e.g. mollusks, ostracods and dinoflagellates) provides a clear and detailed succession of biozones that are very helpful in correlations to global chronology. Here, we apply the Paratethys time scale to the enigmatic faunal evolution of the Northern Aegean domain, and expect this to result in a different, and more robust, chronology for the dominantly anomalohaline/brackish environments of the Northern Aegean region than previously presented in studies using only marine Mediterranean

biozonations (e.g. Krijgsman et al., 2020). Subsequently, we investigate the connectivity history and basin evolution of the Northern Aegean from a Paratethyan perspective. We will present new palaeogeographic reconstructions of this intermittent Mediterranean-Paratethys basin, with special focus on the hydrological changes that significantly changed the environmental conditions in the Northern Aegean domain.

2. Geological setting of the North Aegean basin

The Northern Aegean basins formed during the middle-late Miocene as back-arc basins on the overriding Eurasian plate (Jolivet and Brun, 2010; Philippon et al., 2014). The pervasive extension resulted from the combined effects of the southwestward retreat of the subducting African plate and the westward escape of Anatolia along the North Anatolian Fault (NAF) (e.g., Şengör et al., 2005). NE-SW extension occurred since 25 Ma, leading to a ~ 400 km width increase of the central Aegean zone, while slightly less displacement took place in the northwestern and eastern peripheries (van Hinsbergen and Schmid, 2012). Most of the extension occurred after 15 Ma and accumulated in symmetrical opposite rotations of the western and eastern parts of the Aegean domain (Duermeijer et al., 2000; van Hinsbergen et al., 2005). A transition from arc-parallel structures that accommodated regional upper plate extension to arc-disrupting and cross-cutting structures, occurred from late Miocene to early Pliocene (Papanikolaou and Royden, 2007). The extension migrated southwards through time and gave rise to the exhumation of the Cycladic and Menderes core complexes (Hejl et al., 2008; van Hinsbergen and Schmid, 2012) that may have formed an important land bridge allowing Asia-Europe mammal migration (Fig. 1). The presence of Middle Pleistocene hominin
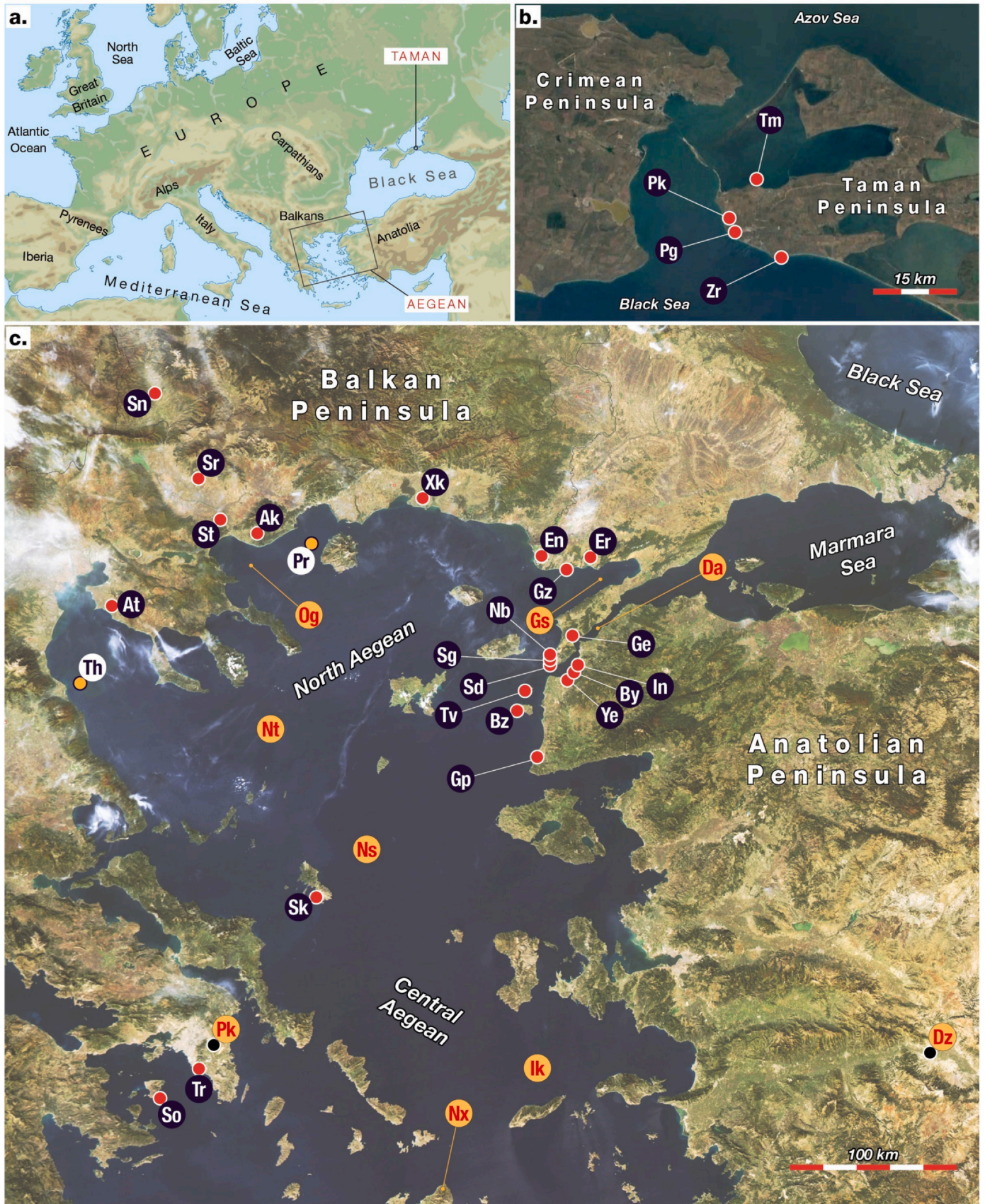
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Fig. 2. a. General location map of the study area. b. Paratethyan key sites from the Taman Peninsula (Pg - Panagia, Pk - Popov Kamen, Tm - Taman, Zr - Zhelezniy Rog). c. Aegean sites from: Northern Greece and Southern Bulgaria (Ak - Akropotamos, At - Axios-Thermaikos, Sn - Sandanski, Sr - Serres, St - Strymon, Xk - Xanthi-Komotini); drilled wells from the Aegean Sea (Pr - Prinos, Th - Thermaikos); sites from the Dardanelles region in Turkey (Bk - Bayırköy, By - Bayraktepe, Bz - Bozcaada, En - Enez, Er - Erikli, Ge - Gelibolu, Gp - Gülpınar, Gz - Göztepe, In - İntepe, Nb - Nebisuyu, Sd – Seddülbahir, Sg - Sığındere, Tv - Tavşan, Ye - Yenimahalle); SW Aegean region (Sk - Skyros, So - Souvalia, Tr - Tracones), and other sites of interest (Da - Dardanelles, Dz - Denizli, Gs - Gulf of Saros, Ik - Ikaria Basin, Ns - North Skyros Basin, Nt - North Aegean Through, Nx - Naxos, Og - Orphanic Gulf, Pk - Pikermi). See Table 1 for literature references. Map and satellite imagery sources: a - IAEA topography of Europe, b - Google Earth, c - NASA.

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artefacts on Naxos Island (Nx in Fig. 2) indicates that terrestrial crossing over this terrestrial passageway may have continued until 200 ka ago (Carter et al., 2019).

Late Miocene sedimentary successions in the central Northern Aegean are relatively scarce and scattered, because the area has since the middle Miocene been affected by large scale subsidence (Brun and Sokoutis, 2010; Philippon et al., 2014; Brun et al., 2016). Data from seismics and boreholes of the three deepest basins (North Aegean Trough; North Skyros Basin and Ikaria Basin (Nt, Ns, Ik in Fig. 2) reveal 2–3 km thick successions of mainly fluvial-lacustrine and continental deposits (Beniest et al., 2016). The Prinos-Nestos (Pr) basin also contains remarkably thick (~300 m) evaporitic sequences (gypsum, anhydrite and halite) in the Prinos Oil field region (Proedrou and Sidiropoulos, 1992; Proedrou and Papaconstantinou, 2004). These evaporites have been tentatively correlated to a Maeotian transgressive phase (Kojumdgieva, 1987; Rögl et al., 1991) or to the Messinian Salinity Crisis of the Mediterranean (Meulenkamp, 1979; Snel et al., 2006; Karakitsios et al., 2017), but both without unequivocal age constraints. Supplementary biostratigraphic data are mainly derived from sections that are exposed in the Dardanelles region and the Gulf of Saros of NW Turkey (Da and Gs in Fig. 2; Sakınç et al., 1999; Sakınç and Yaltirak, 2005; Çağatay et al., 2006), the Axios-Thermaikos (At) and Strymon-Serres (St-Sr) basins of northern Greece (Gramann and Kockel, 1969; Snel et al., 2006; Karakitsios et al., 2017), and from Skyros Island (Sk) (Grekoff et al., 1967; Guernet, 2005).

3. Late Miocene Mediterranean – Paratethys stratigraphy

The late Miocene is one of the most enigmatic time intervals of the circum-Mediterranean region, where both sea-level change and tectonic activity are suggested to have contributed to the palaeogeographic and palaeoenvironmental evolution (Jolivet et al., 2006). High-resolution biostratigraphic data from both Mediterranean and Paratethys are essential to decipher the connectivity changes in the intermittent North Aegean basin. A robust chronostratigraphic framework for the late Miocene Mediterranean successions is available (Fig. 3) by astronomically tuned marine successions containing numerous planktonic foraminiferal bioevents (e.g., Hilgen et al., 1995; Sierro et al., 2001; Lirer et al., 2019). The Mediterranean biochronology forms the basis of the standard Geological Time Scale and has not experienced any significant changes over the last two decades (Lourens et al., 2004; Hilgen et al., 2012). A revised chronology for the late Miocene stratigraphic successions of the Eastern Paratethys (Fig. 2b) has been developed as well, which is mainly based on the integration of ostracod biostratigraphy and magnetostratigraphy (Fig. 3; Hilgen et al., 2012).

Late Miocene changes in marine connectivity have also affected the palaeoenvironmental conditions in both Mediterranean and Paratethyan basins. The Mediterranean experienced several hydrological crises during the late Miocene, when progressive restriction from the Atlantic Ocean resulted in i) stressed dysoxic bottom water conditions (7.16 Ma; Kouwenhoven et al., 2006), ii) rapid cooling and increased stratification (~6.8 Ma; Sierro et al., 2001; Tzanova et al., 2015), iii) the onset of gypsum precipitation (5.97 Ma; Manzi et al., 2013) followed by iv) massive halite formation (~5.6 Ma; Roveri et al., 2014), v) a gradual transition to brackish (Lago-Mare) water conditions (5.55–5.42 Ma; Gliozzi et al., 2007), changing to vi) open marine environments at the beginning of the Pliocene (< 5.33 Ma) when the

connection with the Atlantic fully re-opened (e.g., Garcia-Castellanos et al., 2009).

The Eastern Paratethys was an isolated sea-lake between 11.6 and 6.8 Ma, and its environmental conditions were strongly dependent on the regional hydrological budgets (Kojumdgieva, 1983; Popov et al., 2006; Simon et al., 2019). Pervasive dry climatic conditions in the late Tortonian (Khersonian regional stage; 9.6–7.6 Ma; Palcu et al., 2019) resulted in an extreme lowstand in the Paratethys domain where the Black Sea basin became a high saline-high alkaline lake surrounded by fresh water basins (Fig. 3.1). A significant climatic change to cooler and more humid conditions took place in the latest Tortonian (~7.6 Ma) resulting in a gradual rise of the Paratethys lake level that finally emerged about 80 m above global sea level (Popov et al., 2006; Palcu et al., 2019). A major outburst flood occurred at ~6.8 Ma during the Intra-Maeotian Event (IME; Fig. 3.1), resulting in a sudden water level drop and the ephemeral ingression of marine waters (and fauna) from the Mediterranean (Palcu, 2018). Overspilling to the Mediterranean under positive hydrological budgets desalinised the Paratethys during the Messinian (6.8–6.1 Ma) until a major salinity incursion took place at 6.1 Ma, when the entire Eastern Paratethys region became connected to Lake Pannon and the Mediterranean as exemplified by the migration of numerous faunal elements from both domains during the regional Pontian stage (6.1–5.6 Ma in Russia; 6.1–4.8 Ma in Romania) (Krijgsman et al., 2010; Van Baak et al., 2017).

4. Changing seas in the Northern Aegean

For this study, we have re-analysed the chronologic and biostratigraphic data of the Northern Aegean from a Paratethyan perspective and established the most likely correlation of the corresponding sedimentary successions to the GTS (Fig. 3). The two key areas for this reconstruction are the Dardanelles region and the Gulf of Saros in NW Turkey (Fig. 3.2) and the various sub-basins (Strymon, Serres, Orphanic Gulf) between Thessaloniki and Kavala in N Greece (Fig. 3.3). We investigated all the stratigraphic literature available to us on the late Miocene-Pliocene sedimentary successions of the Northern Aegean (Fig. 2c) and assigned ages according to their Paratethyan faunal assemblages (Table 1). The results are presented below, subdivided in four time slices representing the main Paratethyan faunal changes: 4.1) Bessarabian-Khersonian/Tortonian (~10–7.6 Ma), 4.2) Maeotian/early Messinian (7.6–6.1 Ma), 4.3) Pontian/late Messinian (6.1–5.3 Ma) and 4.4) Zanclean (< 5.3 Ma). This approach provides an alternative view on the evolution and the connectivity of the changing seas in the Northern Aegean region, that we will discuss with the help of schematic cross-sections and palaeogeographic reconstructions (Fig. 4).

4.1. Tortonian (Bessarabian-Khersonian) lakes (~10–7.6 Ma)

The Tortonian deposits in the Strymon and Serres basins of northern Greece comprise several hundreds of meters thick fluvio-lacustrine deposits of the Lefkon Formation (Fig. 3.3), predominantly terrestrial conglomerates and sandstones with rare clay and lignite intercalations (Gramann and Kockel, 1969; Armour-Brown et al., 1979). Fossils are mainly non age diagnostic and comprise fresh water ostracods and fresh water mollusks (e.g., *Planorbis*). Fossil mammal findings include the three-toed horse *Hippotherium* sp. (Gramann and Kockel, 1969), indicating an age younger than 11.2 Ma (Garcés et al., 2003) and small
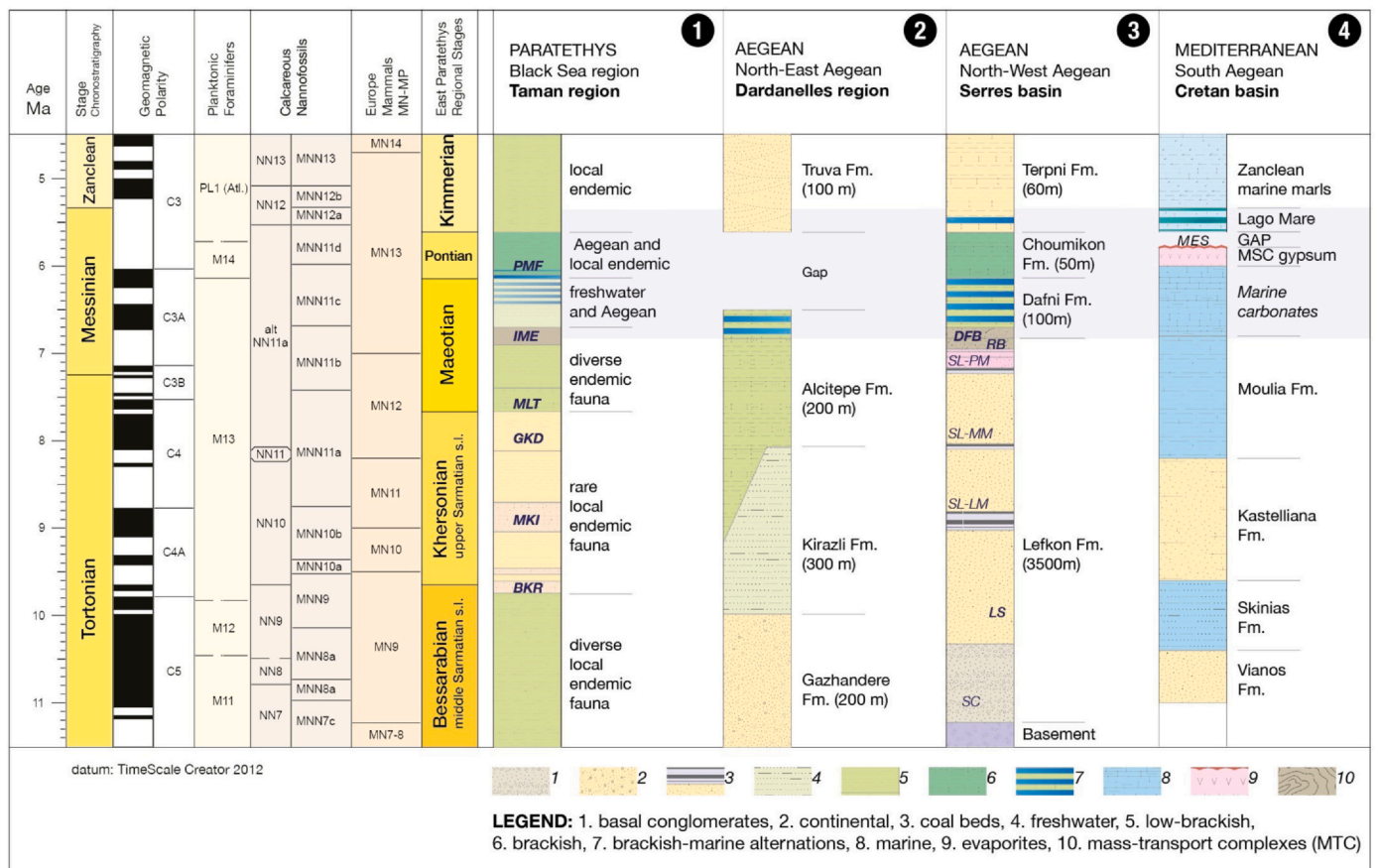
Fig. 3. Geological Time Scale with global stages, biozones and Eastern Parethys stages according to Hilgen et al. (2012), with recent updates for the Eastern Parathys after Stoica et al., 2013 and Palcu et al. (2019). Stratigraphic columns of the key regions for this study: (1) Parathys/Black Sea domain (Taman region) after Popov et al. (2016), (2) North-East Aegean (Dardanelles region) modified after Sakınç and Yaltirak (2005), (3) North-West Aegean (Strymon-Serres region) modified after Gramann and Kockel (1969), and (4) Mediterranean domain (Crete) after Zachariasse et al. (2011).

mammal fauna indicative of the middle Turolian (MN12) suggesting an age between 8 and 7 Ma (De Bruijn, 1989; Koufos, 1993, 1995, 2000; Koufos et al., 2016). Similar fossil mammal-bearing deposits are found in the fluvio-lacustrine deposits of the Sandanski Basin of southern Bulgaria (Zagorchev, 2007; Pimpirev and Beratis, 2010). Magnetostratigraphic dating placed the Sandanski fauna in the 8.2–6.85 Ma interval (Böhme et al., 2018).

The Tortonian successions in the Dardanelles region are ~1000 m thick and unconformably overlie the pre-Miocene basement rocks (Fig. 3.2). The basal parts comprise mainly terrestrial deposits consisting of reddish-brown fluvio-deltaic conglomerates, sandstones and mudstones of the Gazhanedere Formation. Bivalve-bearing mudstones contain *Unio* sp., indicating fresh water conditions (Sakınç et al., 1999). Several fossil mammal sites have reported late Astaracian-Vallesian assemblages (Umut et al., 1983; Şentürk and Karaköse, 1987; Sümengen et al., 1987; Kaya, 1989), suggesting an age of ~11 Ma. The conformably overlying Kirazlı (mainly siliciclastic) and Alçıtepe (mainly carbonaceous) formations consist of laterally and vertically transitional facies associations with *Mactra*-bearing sandstones indicative of an early Tortonian (Sarmatian s.l.) age and an open connection to the Parathys (Yaltirak et al., 2000; Çağatay et al., 2006). Intervals with *Unio*-bearing mudstones indicate temporary fresh water conditions. Some bivalve-rich sandstones (with *Ostrea edulis, Magellana. gryphoides* and *Cerastoderma edule*) at the northern margin of the Gulf of Saros indicate ephemeral influxes of marine water (Sakınç et al., 1999). The fossil mammal fauna of the region indicate a Vallesian (~11–9 Ma) age (Ünay and De Bruijn, 1984; Kaya, 1989), while ostracods and mollusks hint at the Bessarabian/Khersonian transition (~9 Ma;

Krijgsman et al., 2020). These ages are in good agreement with the absolute age control of volcanic deposits of the Kirazlı formation on Tavşan Island (Tv) which provided a radio-isotopic age of 10.1 ± 0.2 Ma (Ercan et al., 1995).

We conclude that the Northern Aegean basin in the Tortonian mainly consists of fluvio-deltaic terrestrial environments with a series of scattered lakes that are predominantly fed by local rivers and Parathyan waters, potentially with some minor short marine influxes (Fig. 4a). The basin was separated from the Mediterranean in the south by the Cyclades sill, that formed the main barrier for marine incursions into the Northern Aegean (van Hinsbergen and Schmid, 2012).

4.2. The early Messinian (Maeotian) "Egemar Sea" (7.6–6.1 Ma)

A conspicuous change to marine deposits, which are collectively named under Dafni Formation (Fig. 3.3), took place in the Strymon and Serres basins of northern Greece (e.g. Gramann and Kockel, 1969). Discontinuous levels containing nannofossil assemblages are generally attributed to zones NN11b or MNN11b–c (Popov and Nevesskaya, 2000; Snel et al., 2006; Karakitsios et al., 2017), suggesting an age between 7.4 and 5.9 Ma (Raffi et al., 2003). The euryhaline marine fauna comprises bivalves such as oysters (e,g, *Ostrea edulis)*, pectinidae (*Pecten aduncus, P. benedictus*) echinoids and corals (Gramann and Kockel, 1969; Pimpirev and Beratis, 2010). They are found alternating with brackish-water deposits that contain *Dreissenid* species (e.g. *Coelogonia. amygdaloides* and *Andrusoviconcha subcarinata*) (Popov and Nevesskaya, 2000). The marine ostracod fauna (*Hermanites haidingeri* and *Pokornyella deformis*) shows similarities with the upper Badenian of

Table 1
Late Miocene sections and sites from the Northern Aegean

Code	Site/Basin	Formation	Stage	Age (Ma)	Reference
Taman Peninsula (Paratethys)					
Pg	Panagia	–	Tortonian	10.5–7.5	Radionova et al. (2012); Popov et al. (2016)
Zr	Zhelezniy Rog	–	Tortonian-Messinian	8.5–5.5	Radionova et al. (2012); Popov et al. (2016)
Pk	Popov Kamen	–	Messinian	7.6–5.5	Radionova et al. (2012); Popov et al. (2016)
Tm	Taman	–	Messinian	7.6–5.5	Radionova et al. (2012); Popov et al. (2016)
Northern Greece and South Bulgaria					
St	Strymon	Lefkon	Tortonian	11.2–7.6	Gramann and Kockel (1969); De Bruijn (1989)
Se	Serres	Lefkon	Tortonian	11.2–7.6	Popov and Nevesskaya (2000)
Sn	Sandanski	Kalimantsi	Tortonian-Messinian	8–6.9	Zagorchev (2007); Böhme et al. (2018)
St	Strymon	Dafni	Early Messinian	7.6–6.1	Gramann and Kockel (1969); Pimpirev and Beratis (2010)
Se	Serres	Dafni	Early Messinian	7.6–6.1	Popov and Nevesskaya (2000); Snel et al. (2006)
Ak	Akropotamos	Dafni (?)	Early Messinian	7.6–6.1	Snel et al. (2006); Karakitsios et al. (2017)
St	Strymon	Choumnikon	Late Messinian	6.1–5.3	Gramann and Kockel (1969); Pimpirev and Beratis (2010)
Se	Serres	Choumnikon	Late Messinian	6.1–5.3	Popov and Nevesskaya (2000); Snel et al. (2006)
At	Axios-Thermaikos	Trilophos	Late Messinian	6.1–5.3	Syrides (1998)
Xk	Xanthi-Komotini	Trilophos	Late Messinian	6.1–5.3	Syrides (1998)
St	Strymon	Terpni	Zanclean	< 5.3	Gramann and Kockel (1969); Pimpirev and Beratis (2010)
Se	Serres	Spilia	Zanclean	< 5.3	Popov and Nevesskaya (2000)
Ak	Akropotamos	Terpni	Zanclean	< 5.3	Steffens et al., (1979); Snel et al. (2006)
At	Axios-Thermaikos	Gonia	Zanclean	< 5.3	Syrides (1998)
Aegean					
Sk	Skyros	–	Early Messinian	7.6–6.1	Grekoff et al. (1967); Guernet (2005)
So	Souvalia	Aegina	Late Messinian	6.1–5.3	Rögl et al., 1991; Popov and Nevesskaya (2000)
Tr	Tracones	–	Late Messinian	6.1–5.3	Papp and Steininger, 1979; Popov and Nevesskaya (2000)
Dardanelles (Turkey)					
Nb	Nebisuyu	Kirazlı	Serravallian	13.3–11.2	Kaya, 1982; 1989)
By	Bayraktepe	Kirazlı	Serravallian	13.3–11.2	Koufos et al., 2018; Ünay et al., 2003
En	Enez	Kirazlı	Serravallian-Tortonian	13.3–7.6	Sümengen et al. (1987); Sakinç et al. (1999)
Sg	Sığındere	Kirazlı	Tortonian	9.9–8.9	Kaya (1989); Koufos et al., 2018; Saraç, 2003
Gp	Gülpınar	Alçıtepe	Tortonian	9.9–7.6	Kaya, 1982; Sakinç and Yaltirak (2005)
Bz	Bozcaada	Alçıtepe	Tortonian	9.9–7.6	Erguvanlı (1955); Demircan, 2012
Tv	Tavşan	Alçıtepe	Tortonian	10.1 ± 0.2	Ercan et al. (1995)
In	İntepe	Alçıtepe	Tortonian	9–8	Melinte-Dobrinescu et al. (2009); Krijgsman et al. (2020)
Sd	Seddülbahir	Alçıtepe	Tortonian	9–8	Melinte-Dobrinescu et al. (2009); Krijgsman et al. (2020)
Er	Erikli	Alçıtepe	Tortonian-Messinian	13.8–11.3	Sakinç et al. (1999)
Bk	Bayırköy	Alçıtepe	Tortonian-Messinian	7.6–6.8	Ünay and De Bruijn, 1984
Ge	Gelibolu	Alçıtepe	Messinian	6.8–5.6	Sakinç and Yaltirak (2005)
Ye	Yenimahalle	Alçıtepe	Messinian	6.8–5.6	Çağatay et al. (2006)
Gz	Göztepe	Göztepe	Zanclean	5.3–4.2	Çağatay et al. (2006)

the Central Paretethys, but the anomalohaline ostracods (*Loxocorniculina hodonica*, *Cyprideis pannonica*) indicate a Maeotian age (Gramann and Kockel, 1969). These assemblages may also correlate to the *Loxocorniculina hodonica* Zone of Sissingh (1972), defined in the marine Messinian pre-evaporitic deposits on the Island of Crete. A marine ostracod fauna of supposedly early Messinian/Maeotian age is furthermore reported from Skyros Island (Sk); interpreted to form a link between the Northern Aegean and the Mediterranean (Grekoff et al., 1967; Guernet, 2005).

Indications for several marine Mediterranean influxes in the Dardanelles and Gulf of Saros region appear in the upper part of the Alçıtepe Formation, where *Ostrea* beds and some coral reefs are found (Fig. 3.2). The *Ostrea*-beds are generally alternating with *Mactra*-bearing sandstones, indicating connectivity to the Paratethys as well (Sakinç et al., 1999). A similar alternation of oyster and *Mactra*-beds is also found on Bozcaada Island (Bz) (Erguvanlı, 1955; Sakinç and Yaltirak, 2005). The ostracod fauna of the Alçıtepe Formation (e.g., *Cyprideis pannonica*, *Cyprideis torosa*, *Candona neglecta*, *C. candida*, *Loxoconcha* sp., *Heterocypris salina salina*) is ascribed to the Central Paratethys "Pannonian" age (Çağatay et al., 2006), which suggests a Khersonian-Maeotian age in Eastern Paratethys terminology. The age of the Alçıtepe Formation in the Gulf of Saros is estimated to be between Khersonian and Pontian (Sümengen et al., 1987). The Alçıtepe formation is overlain in the Dardanelles region, with an erosional unconformity, by fluvio-lacustrine sands of the Truva formation (Fig. 3.2). There appears to be a significant hiatus present, although it remains unclear how much time is missing in the geological record. Some authors claim they have found Pontian (6.1–5.6 Ma) faunas in the upper

part of the Alçıtepe formation (Taner, 1979; Çağatay et al., 2006).

We conclude that most data for these intermittent Mediterranean-Paratethyan environments point to a Maeotian age (7.6–6.1 Ma) for this marine interval (Gramann and Kockel, 1969; Popov and Nevesskaya, 2000), but that the exact age for the initiation of marine conditions remains unclear (Fig. 3.2, 3.3). The presence of alternating marine and brackish water environments indicates that the Northern Aegean formed a semi-isolated sea, with mixed influences from both Paratethys and Mediterranean, in good agreement with the reconstruction of Sakinç and Yaltirak (2005) who named this particular sea "Egemar" (Fig. 4b).

The first evidence for marine fauna entering the Eastern Paratethys basin dates back to the Maeotian (e.g., Radionova et al., 2012) and is well documented in outcrops of the marginal Black Sea setting on the Taman Peninsula (Fig. 3.1; Golovina et al., 2004; Radionova and Golovina, 2011) and in the deep DSDP records of the Black Sea basin (Golovina et al., 2019). The small size of coccoliths and the absence of zonal markers indicate that the influx of marine waters took place in stressed conditions in a restricted basin. Upper Maeotian facies show numerous laminated diatomites that contain unusual diatom and nannofossil associations. The presence of the marine diatom species *Thalassiosira convexa* and *Thalassiosira praeconvexa* in the deep Black Sea cores date between 6.6 and 6.2 Ma (Golovina et al., 2019). The first evidence of marine nannofossils (e.g. *Reticulofenestra* sp.) follows the Intra-Maeotian-Event (IME: 6.9–6.7 Ma) during which a Paratethys-Mediterranean connection was created through the proto-Bosporus and the proto- Aegean (Palcu et al., 2019).
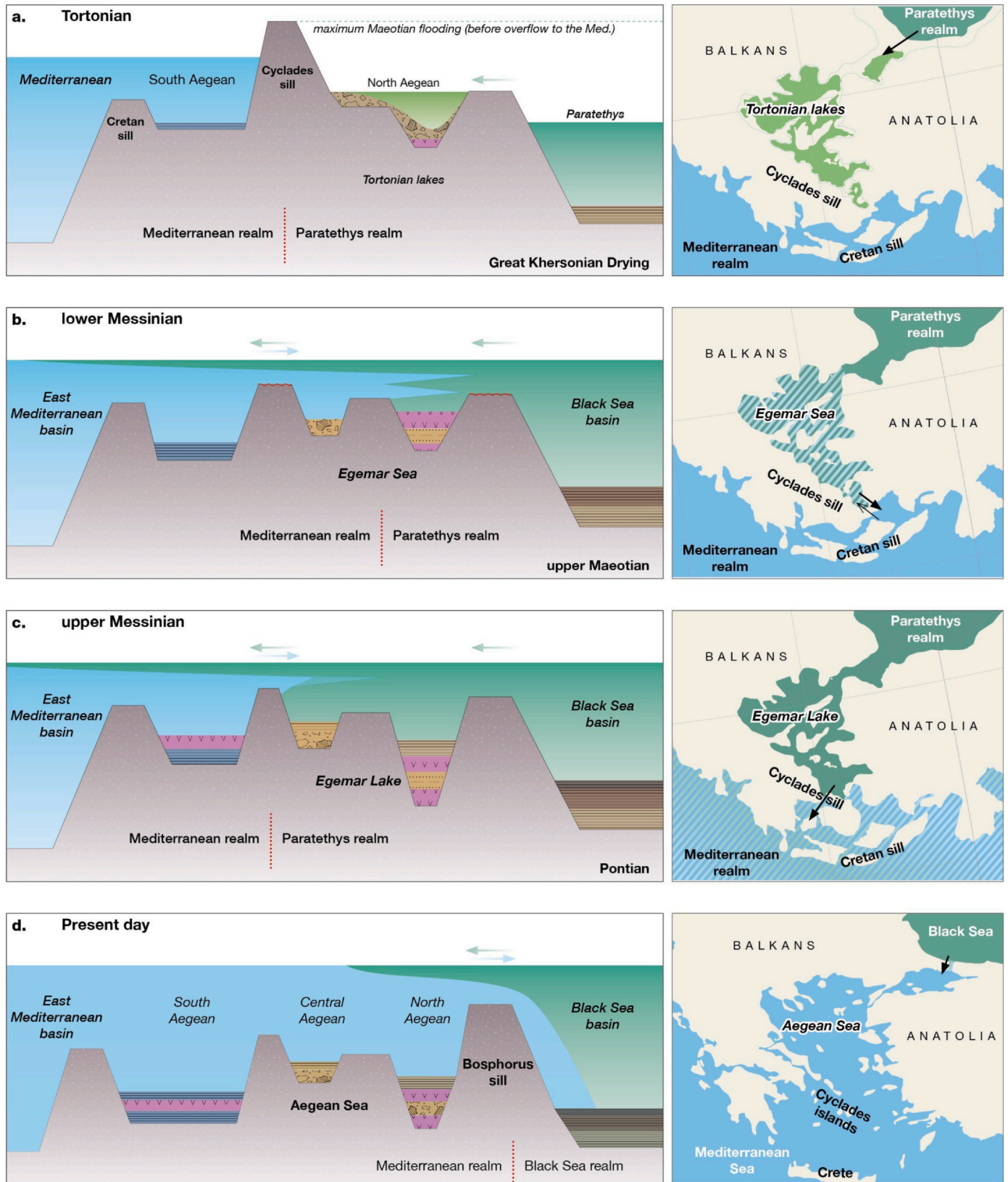
Fig. 4. Schematic cross-sections (left) and palaeogeographic reconstructions (right) of the North Aegean basins for the a. Tortonian (Bessarabian-Khersonian), b. lower Messinian (Maeotian), c. upper Messinian (Pontian; MSC) and d. the present-day configuration. Gypsum deposits are visualized with a pink colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. The late Messinian (Pontian) "Lake Egemar" (6.1–5.3 Ma)

The termination of marine conditions in the northern Aegean basins of Greece is very well documented by the marked palaeoenvironmental change that occurs at the transition from the marine Dafni Formation to the brackish water environments of the Choumnikon Formation (Fig. 3.3; Gramann and Kockel, 1969). The latter formation mainly consists of sandstones, siltstones and claystones that contain abundant mollusk and ostracod associations that have numerous genera and species in common with the Pontian of the Eastern Paratethys (Gramann and Kockel, 1969; Syrides, 1998; Popov and Nevesskaya, 2000). The basal part of this formation is marked by the abrupt first occurrence of typical brackish (oligo-mesohaline) water ostracods of the lower Pontian (e.g., *Pontioniella acuminata; Caspiolla balcanica; Leptocythere bisaltiana; Bakunella dorsoarcuata; Tyrrhenocythere ruggierri*). In addition, the brackish water mollusks show a mixture of Pontian species from Eastern Paratethys (e.g. *Paradacna abichi, Eupatorina littoralis* and *Lymnocardium* sp.) and genera unknown from the Pontian (*Mactra, Cerastoderma*) that suggest a connection to the Mediterranean (Popov and Nevesskaya, 2000). Nannofossil analysis only revealed two species (*Braarudosphaera bigelowi* and *Perfocalcinella fusiformis*) that indicate stressed (probably low salinity) environments. U-Pb geochronology on zircons from a volcaniclastic layer at the base of the Choumnikon Formation provided an age of 6.0976 ± 0.0055 Ma (Grossi et al., 2015), in good agreement with the magnetostratigraphic age of 6.1 Ma for the Maeotian-Pontian boundary (Stoica et al., 2013; Van Baak et al., 2016; Lazarev et al., 2020).

It is not clear if time-equivalent sections exist in the Dardanelles region (Fig. 3.2). After deposition of the Alçıtepe formation, the region experienced significant tectonic uplift by compressional stresses (Sakınç and Yaltirak, 2005) and we consider it likely that the entire Pontian stage is represented by the erosional unconformity between the Alçıtepe and Truva formations (Fig. 2). This strongly complicates the understanding of a Messinian Paratethys-Aegean connection through the Dardanelles-Bosporus Strait (Çağatay et al., 2006; Suc et al., 2015), which so far remains inconclusive.

Pontian deposits are furthermore reported from the Tracones Formation (Tr in Fig. 2c) south of Athens (Papp and Steininger, 1979) and Aegina Island (So) in the Southern Aegean (west of Athens: Rögl et al., 1991) showing the widespread development of brackish water facies in the Aegean domain. In addition, late Miocene lacustrine sections have been documented in the Ptolemais (Pt) region of northern Greece (Steenbrink et al., 2006) and the Denizli Basin (Dz) of SW Turkey (Wesselingh et al., 2008), although the faunal record of the Turkish basin appears difficult to interpret because of a high level of endemism (Rausch et al., 2020).

In summary, the similarity in generic composition of late Messinian brackish water ostracods and mollusks proves that the brackish Choumnikon deposits of the Northern Aegean are coeval with sediments that accumulated in the Paratethys during the Pontian (Popov and Nevesskaya, 2000). As the Pontian stage is well-established in the Black Sea basin between 6.1 and 5.6 Ma, we conclude that during Messinian Salinity Crisis times the Northern Aegean was an intermediate basin with connections both to the Eastern Paratethys and the Mediterranean (Fig. 4c). It contained a mixed Paratethys-Mediterranean fauna that is characteristic for the region. During the Pontian, Aegean fauna has been suggested to have migrated to the Black Sea basin in two events: 1) at 6.1 Ma many species appeared, together with marine foraminifera, during the Pontian flooding of the Paratethys and 2) at 5.6 Ma some marker species (*Euxinicardium nobile, Congeria rhomboidea* and *Pseudocatillus subdentatus*) are suggested to have appeared at the beginning of the uppermost Pontian/Kimmerian (Popov and Nevesskaya, 2000). The latter event, however, needs further investigation, as *C. rhomboidea* was shown to appear already at 6.9 Ma in the Dacian Basin (Stoica et al., 2013).

4.4. The Zanclean marine flooding? (< 5.3 Ma)

Marine deposits of the earliest Pliocene have been reported as sapropel-marl alternations in several section in northern Greece (Steffens et al., 1979; Snel et al., 2006). Based on their nannofossil assemblages (*Amaurolithus tricorniculatus, Ceratolithus acutus, C. larrymayeri* and *T. rugosus*), these sediments have been attributed to the basal Pliocene nannofossil zone NN 12, even though several Miocene markers are present as well (but considered as reworked by Snel et al., 2006). So far, we are not aware of additional evidence for the earliest Zanclean in the region as foraminifera are documented as rare and without marker species (Snel et al., 2006), analyses on mollusks are inconclusive (Syrides, 1998) and data on ostracods are still lacking from these deposits. We want to emphasise here that age determinations based on only some rare calcareous nannofossil marker species like *C. acutus*, without any back-up by foraminifera data, are previously shown to have resulted in erroneous interpretations due to limited knowledge of the species concept (e.g., Golovina et al., 2019), so independent confirmation of basal Zanclean marine deposits in the Northern Aegean is needed.

In the Strymon and Serres basins of Northern Greece, the brackish Choumnikon strata are discordantly overlain by poorly sorted red sandstones and conglomerates of the Terpni formation, which are in turn followed by younger marine deposits (Gramann and Kockel, 1969). According to the initial description, this marine interval corresponds to the Calabrian Stage (1.8–0.8 Ma; Hilgen et al., 2012). In the Orphanic Gulf region, similar young shallow marine successions comprise sands and gravels that are attributed to the upper Pliocene-Pleistocene (Psilovikos and Syrides, 1983).

No robust evidence for marine Zanclean deposits is available from the Dardanelles-Marmara region. A previous interpretation, based on nannofossils, that the Alçıtepe formation is Zanclean in age (Melinte-Dobrinescu et al., 2009) is in serious conflict with the presence of Khersonian Paratethys micro- and macro-fauna in that formation, which indicate a Tortonian age (Sakınç and Yaltirak, 2005; Çağatay et al., 2006; Krijgsman et al., 2020). Marine influence in the Sea of Marmara was obstructed by horsts and transpressional push-up structures generated by the NAF in the western Sea of Marmara region (Görür et al., 2000). The oldest marine deposits are attributed to the Plio-Pleistocene Özbek Formation east of Çanakkale (Görür et al., 2000), which is attributed to the Akchagilian (2.7–2.1 Ma; Lazarev et al., 2019) regional stage of the Paratethys domain, suggesting a connection all the way up to the Caspian Basin at that time.

In summary, there are several reports of the earliest Pliocene (NN12) in the Northern Aegean, which suggests that the Zanclean flooding of the Mediterranean reached the marginal basins of northern Greece. The exact age of this marine incursion remains somewhat speculative because the convincing foraminiferal marker species for the Mio-Pliocene boundary are lacking. There is no robust evidence that the Zanclean flooding reached the Dardanelles region, as basal Pliocene deposits are not preserved there. We also see no reliable evidence that the Zanclean flood entered the Parathethyan basins, as marine Pliocene conditions have not been reported from the Black Sea sediments (Van Baak et al., 2015, 2017). More data is needed to better understand the Mediterranean-Paratethys connectivity history during the Plio-Pleistocene period.

5. Consequences and future perspectives

Our literature review on the late Miocene biostratigraphic data from the Northern Aegean using a Paratethyan approach provides a paleogeographic scenario (Fig. 4) that is in reasonably good agreement with the reconstructions of Sakınç and Yaltirak (2005), but in serious conflict with studies using a Mediterranean approach (e.g. Snel et al., 2006; Melinte-Dobrinescu et al., 2009; Karakitsios et al., 2017). The latter reconstructions generally consider the Northern Aegean to be a

marginal marine basin of the Mediterranean and, relying mostly on the assumption that evaporites precipitated in the Mediterranean only during the Messinian Salinity Crisis (MSC), conclude that the Northern Aegean evaporites must correspond to this event. The faunal assemblages, however, do not corroborate such a correlation. The Akropotamos gypsum deposits in the Strymon Basin, for instance, are full of marine foraminifera, calcareous nannofossils and ostracods, in contrast to all the other gypsum units of the Mediterranean MSC that are generally strongly depleted of any in situ marine fauna (Lugli et al., 2010). In addition, the stacking pattern, the gypsum facies and the low number of cycles (2–3) in the Akropotamos gypsum unit do not reflect the classic PLG units known from Spain to Sicily, casting further doubts on the attribution to the MSC. Finally, the brackish ostracod fauna of the overlying clays does not contain any Pontian faunal elements, contrary to the sediments of the uppermost (Lago-Mare) MSC stage (Stoica et al., 2016).

The Paratethyan faunal assemblages of especially the Greek successions rather indicate that during the MSC the Northern Aegean was a brackish water lake (Fig. 4), possibly forming a passageway for Paratethyan overspill waters to the Mediterranean (Grothe et al., 2020). The marine gypsum deposits of the Northern Aegean are most likely older than the MSC and are thus related to a regional evaporitic phase (cf. Gramann and Kockel, 1969; Rögl et al., 1991), which causes and progression are largely unknown. According to the Paratethyan mollusks and ostracods, and in agreement with the marine calcareous nannofossil data (Karakitsios et al., 2017), the evaporite deposits of the Strymon-Serres basins, and probably also the ones of the offshore Prinos-Nestos basin, correspond best to a regional "Maeotian salinity crisis", although a link with the older Badenian/Serravallian (13.8–13.4 Ma; De Leeuw et al., 2018) cannot be fully excluded. In this context, it may be worthwhile to re-study the gypsum-bearing marine deposits of the Gulf of Saros that are attributed to the late Serravallian-early Tortonian according to Görür et al. (1997).

Another important consequence of our palaeogeographic reconstructions is that in Messinian times the Northern Aegean was a restricted basin with both Paratethyan and Mediterranean inflow. The Aegean faunal assemblages therefore show a poorly understood mixture of marine and anomalohaline species that warrants further multi-disciplinary studies. In addition, a future focus shift from the paleo-Bosphorus towards the Cyclades region is required to better understand Mediterranean-Paratethys connectivity during the Messinian. The southern Cyclades sill was, however, most likely emerged during the late Miocene and does not contain many remnants of past sedimentation (Hejl et al., 2008). Nevertheless, a small marine gateway must have been formed in early Messinian times to allow marine waters to enter the Northern Aegean domain (Dafni Formation) and later brackish waters to enter the Mediterranean (MSC Stage 3; Lago-Mare). The faunal composition of the Choumnikon Formation shows strong similarities with the Mediterranean Lago-Mare deposits. This fauna probably originated in Lake Egemar during the Pontian, and subsequently migrated all over the Mediterranean during the final Lago-Mare phase of the MSC, when the Mediterranean water level was high enough for this fauna to cross the intra-Mediterranean sills and reach the marginal Mediterranean basins of southern Spain, northern Italy and Cyprus (Gliozzi et al., 2007; Stoica et al., 2016).

The Aegean region is also key for deciphering the evolution of late Miocene European landscapes and it possesses a wealth of sites that are reference for the European land mammal stratigraphy. From a terrestrial perspective, the Aegean landbridges are particularly important for clarifying the migration of terrestrial mammals, particularly the dispersal hominids, and we hope this work will inspire the development of a Balkan–Anatolian mammal-based approach to complete the picture of the Aegean evolution.

Re-studying the faunal assemblages of the key localities and sites of the Dardanelles and Strymon-Serres basins is required to provide a more detailed and robust understanding of the late Miocene

hydrological variations in the Northern Aegean through time and space. Such studies also may provide useful insight in the connectivity changes between the Aegean and Black Sea that are to be foreseen in the light of future sea level rise and economic developments in the Bosphorus region.

Declaration of Competing Interest

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