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The sensitivity of middle Miocene paleoenvironments to changing marine gateways in Central Europe

Dirk Simon, Dan Palcu, Paul Meijer, and Wout Krijgsman
Department of Earth Sciences, Utrecht University, 3584 CD Utrecht, Netherlands

ABSTRACT

During the middle Miocene (15–12 Ma), the paleoenvironmental conditions in the Paratethys Sea of Central Europe changed from normal marine to hypersaline and from normal marine to brackish-marine conditions. These paleoenvironmental changes do not consistently correlate to global sea-level curves, indicating other driving mechanisms. Water circulation in the Paratethys strongly depended on two shallow and narrow gateways that were located in tectonically active regions. Here we combine the conservation of water and salt mass with strait-exchange theory to quantitatively link freshwater surface forcing and gateway dimensions to the observed environments. Our model confirms that the proposed sea-level drop of 50–70 m at 13.8 Ma could have restricted the western gateway to the Mediterranean to such an extent that halite formed in the Central Paratethys. Subsequently, the progressive opening of the eastern gateway to the Black Sea led to a decrease in lake level, exposure of the shallow margins, and a reduced surface area in the Eastern Paratethys. This entailed a reduction in water loss to the atmosphere, which, combined with constant river influx, resulted in a positive freshwater budget for the Paratethys proper, and reduced the salinity in the Central Paratethys. This provides a novel physics-based explanation for the change from evaporitic to marine to brackish-marine water conditions in a marginal basin.

INTRODUCTION

Interpreting the effects of opening or closure of marine gateways on paleoenvironmental change has a long history. Famous examples are the opening of the Drake Passage between South America and Antarctica at ca. 41 Ma (Scher and Martin, 2006), the closure of the Tethys Seaway between Arabia and Eurasia at ca. 17 Ma (Harzhauser and Piller, 2007), the isolation of the Mediterranean during the Messinian between 8 Ma and 5 Ma (Flecker et al., 2015), and the establishment of the Panama Isthmus between North and South America at ca. 3.0 Ma (Bartoli et al., 2005). Such changes in marine gateway configuration have profound influence on water circulation and consequently on regional, or even global, climate and environment.

Marginal marine basins linked to the open ocean by narrow, shallow gateways are the most sensitive domains to experience extreme environmental change. The ancient Paratethys Sea, covering large parts of Europe and Asia during the Oligocene–Miocene, is exceptionally suited to study of such changes as it was connected via only relatively small straits to the proto-Mediterranean and thus to the global ocean (Fig. 1). Recent paleogeographic reconstructions have shown that two gateways were of crucial importance for interbasinal connectivity (Fig. 1): the Trans-Tethyan Strait through Slovenia (Bartol et al., 2014) connecting the Central Paratethys with the Mediterranean, and the Bârlad Strait in eastern Romania connecting the Central and

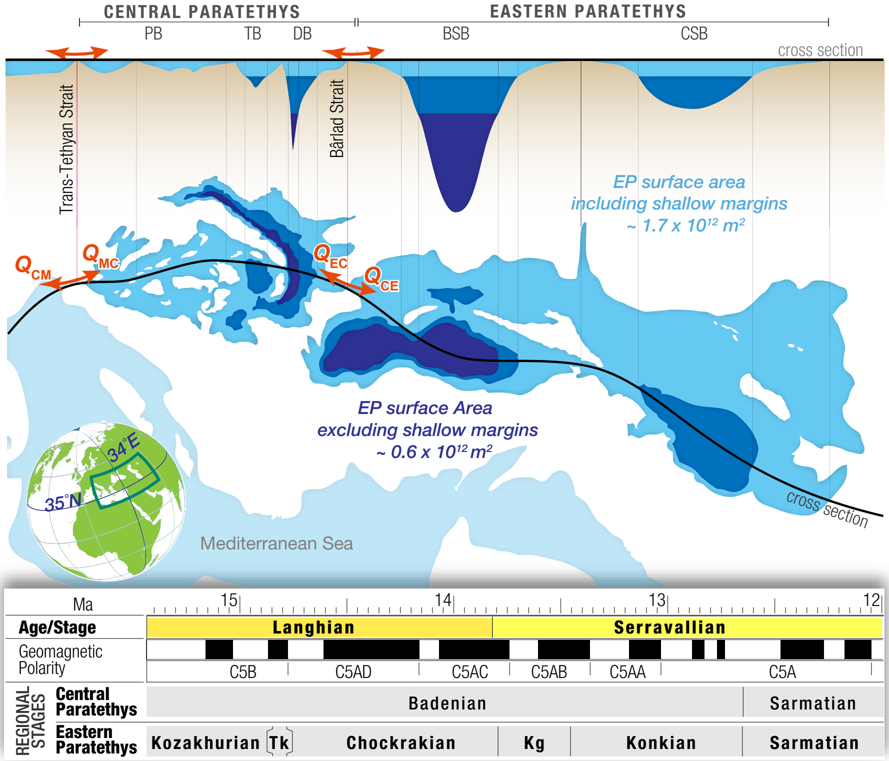

Figure 1. Regional setting of Paratethys during middle Miocene, and cross section showing bathymetry. Indicated are the two relevant gateways, Trans-Tethyan Strait (present-day Slovenia) and Bârlad Strait (present-day Romania) and their exchange fluxes (*Q*). Subbasins illustrate large shallow marginal areas (PB—Pannonian Basin; TB—Transylvanian Basin; DB—Dacian Basin; BSB—Black Sea basin; CSB—Caspian Sea basin). EP—Eastern Paratethys. Regional stages: Tk—Tarkhanian; Kg—Karaganian.

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Eastern Paratethys (Palcu et al., 2017). During the middle Miocene, the Central Paratethys experienced a period of hypersaline conditions (with halite deposition) during the so-called Badenian Salinity Crisis (BSC, 13.8–13.4 Ma; de Leeuw et al., 2010), open marine conditions during the late Badenian regional stage (13.4–12.6 Ma; Kováč et al., 2007), and brackish-marine conditions during the Sarmatian (12.6–11.6 Ma; Piller and Harzhauser, 2005). These paleoenvironmental changes were previously all correlated to seismic sequence boundaries, commonly interpreted as sea-level lowstands (Haq et al., 1988; Piller and Harzhauser, 2005), but recently it became clear that they were mainly controlled by tectonic phases (Palcu et al., 2015; Sant et al., 2017). Consequently, it was proposed that the opening, restriction, and closure of the Paratethys gateways could have been key factors controlling the recorded paleoenvironmental changes in these basins, although the exact mechanisms are still poorly understood (Palcu et al., 2017).

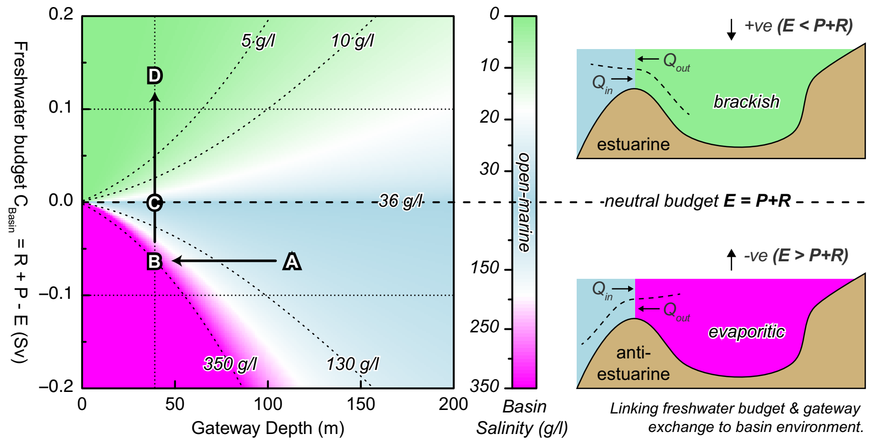

Figure 2. Left side: Results of theoretical analysis, showing how basin salinity changes for various freshwater budgets (C_{Basin}) and gateway depths (k = 8.5 × 10³; see text). R—runoff; P—precipitation; E—evaporation. Letters A–D link middle Miocene Paratethyan environments (i.e., salinity) shown in Figure 5 to central basin freshwater budget and depth of Trans-Tethyan Strait. Right side: Top cartoon shows river-dominated basin; it is low in salinity (brackish environment) and is therefore low in density, which drives estuarine exchange with connected ocean. *Q*—water flux. Bottom cartoon shows evaporation-dominated basin; it is enhanced in salinity (evaporitic) and is therefore greater in density, which drives anti-estuarine exchange with connected ocean.

Given that the various interpreted environments are associated with different water salinities, it would help to have insight from physics as to what salinity is most likely at any one point in time. Here, for the first time, we apply theoretical insights to the middle Miocene Paratethys in order to quantify whether and how changes in the marine gateways and the regional freshwater forcing can indeed explain the extreme paleoenvironmental changes in the Paratethys domain.

METHODS

In modern seaways that connect an enclosed sea to a large ocean, a two-way exchange is observed (e.g., Strait of Gibraltar: Bryden and Kinder, 1991; Bosphorus: Lane-Serff et al., 1997). It is driven by the density difference between the two water bodies, established by the surface forcing of the enclosed sea. Whereas the large evaporation rate at the surface of the Mediterranean Sea forces its salinity (i.e., density) to be greater than that of the Atlantic Ocean (e.g., Bryden and Kinder, 1991; Fig. 2), the runoff-dominated Black Sea sustains lower salinities than the Mediterranean (e.g., Lane-Serff et al., 1997; Fig. 2). Although the salinity record is well established for the middle Miocene Central Paratethys, neither the gateway sizes nor the climatic forcing are well constrained. Therefore, we consider a generalized box model of a semi-enclosed sea (righthand side of Fig. 2). Together, the conservation of water and salt yield:

$$Q_{\text{BO}} = Q_{\text{OB}} + C_{\text{Basin}} = Q_{\text{OB}} \times S_{\text{Ocean}} / S_{\text{Basin}}, \quad (1)$$

where Q_{BO} and Q_{OB} are the water flux from the semi-enclosed basin (B) to the ocean (O) and vice versa, respectively, C_{Basin} is the freshwater budget, and S_{Basin} and S_{Ocean} are the salinities. When Equation 1 is combined with hydraulic control theory for the behavior of the gateway:

$$Q_{\text{OB}}^2 + Q_{\text{BO}}^2 = \text{k} \times h^3 \times (S_{\text{Basin}} - S_{\text{Ocean}}), \quad (2)$$

the gateway exchange fluxes can be factored:

$$(S_{Ocean}^2 + S_{Basin}^2) \times \left| S_{\text{Basin}} - S_{\text{Ocean}} \right|^{-3} = \text{k} \times h^3 \times C_{\text{Basin}}^{-2}. \quad (3)$$

This allows us to link the freshwater budget (C_{Basin}) of an enclosed sea and the gateway depth (h) to the corresponding basin salinity (S_{Basin}), as plotted in Figure 2. The constant k (in Equations 2 and 3) is dependent on other gateway-related parameters, such as width or inflow-outflow interface position. We ignore the effect of temperature on the water density, because the ranges of observed salinity (0–350 g/l) imply that salinity will play the dominant role (see the GSA Data Repository[1] for additional discussion).

In our double-gateway setting, the conservation of water of the Central Paratethys is:

$$Q_{\text{CM}} = Q_{\text{MC}} + C_{\text{C}} + Q_{\text{EC}} - Q_{\text{CE}} = Q_{\text{MC}} + C_{\text{C}} + C_{\text{E}}. \quad (4)$$

The subscripts C and E refer to the central and eastern basin, respectively, and M refers to the Mediterranean Sea. Equation 4 shows that the exchange at the Trans-Tethyan Strait is independent of the individual in/outflow of the Bârlad Strait. It only depends on the net exchange at the Bârlad Strait, which is equal to the freshwater forcing across the eastern Paratethys (C_{E}). Likewise, the salinity of the Central Paratethys (S_{C}) can be expressed in terms of only the Trans-Tethyan influx (Q_{MC}) and outflux (Q_{CM}) and the Mediterranean salinity (S_{M}):

$$S_{\text{C}} = S_{\text{M}} \times Q_{\text{MC}} / Q_{\text{CM}}. \quad (5)$$

This justifies applying our theoretical insights of Figure 2 to the Central Paratethys. The geometry of the Trans-Tethyan Strait was probably more complex than a simple, hydraulic-controlled sill (used to calculate the depth in Fig. 2). Figure 2 may still be applicable to the Trans-Tethyan Strait if we assume that somewhere along the strait a constriction existed that controlled the water exchange.

RESULTS AND ANALYSIS

For any constant gateway size (e.g., vertical dotted line in Fig. 2), basin salinity can change drastically with freshwater budget. If the freshwater budget of the basin is neutral (i.e., evaporation is in balance with precipitation and river input), the salt concentration is close to that of open marine conditions and the inflow is comparable to the outflow. If the freshwater budget is positive (i.e., precipitation and river input dominate over evaporation; top half of Fig. 2), the environment is brackish; this setting is sustained by an estuarine exchange regime. The weaker the marine influx is relative to the basin outflux, the fresher the water conditions. For a negative freshwater budget (i.e., evaporation dominates over precipitation and river input; bottom half of Fig. 2), the environment is hypersaline; here an anti-estuarine exchange is active. The stronger the marine influx is relative to the basin outflux, the saltier the water conditions; if exchange is heavily reduced, evaporites may be deposited (e.g., halite at ~350 g/l; Warren, 2016).

The relative importance of influx and outflux depends on the gateway dimensions (e.g., Simon

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[1] GSA Data Repository item 2019008, information on relating strait depth to exchange rate and salinity, is available online at http://www.geosociety.org/datarepository/2019/ or on request from editing@geosociety.org.

and Meijer, 2015). A constant negative freshwater budget (e.g., horizontal dotted line at −0.1 Sv in Fig. 2) in combination with a deep gateway sustains environments close to open marine conditions. For shallower gateways, the outflux decreases relative to the influx, which leads to a greater basin salinity. Similarly, a constant positive freshwater budget (horizontal dotted line at 0.1 Sv in Fig. 2) sustains open marine conditions for a deep gateway and brackish conditions for a shallow one.

It is important to realize that a transition from evaporitic to brackish environments or vice versa cannot purely be explained by a different gateway size; the freshwater budget has to switch sign in order to make such an extreme change.

DISCUSSION

We can infer that in order for the central basin to have changed from marine conditions to halite saturation during the BSC (ca. 13.8 Ma), the overall Paratethys freshwater budget must have been negative, even though with our current knowledge of the region we cannot say how negative. If this negative budget was approximately constant during this transition, the Trans-Tethyan Strait must have become restricted, e.g., by a global sea-level drop (e.g., de Leeuw et al., 2010; 50–70 m, Fig. 2, labels A and B). The evolution from evaporitic to marine to brackish conditions in the central basin (ca. 13.4–11.6 Ma) suggests that the overall freshwater budget controlling the Trans-Tethyan exchange switched from negative to positive (Fig. 2).

What Mechanism Would Switch the Environment from Evaporitic to Brackish?

Precipitation over land will be partly absorbed by the soil of the catchment area and partly fed into rivers that flow downstream into oceans or lakes. For a constant river runoff (*R*), the relative strength of precipitation (*P*) and evaporation (*E*) occurring across the sea surface (A_s) will determine the sign of the freshwater budget:

$$C_{\text{Basin}} = R + A_s \times (P - E)_{\text{per unit area}}. \qquad (6)$$

Consider a basin in which *E* is stronger than *P* across its surface. If the surface area increases, C_{Basin} will decrease (more negative freshwater budget); if surface area decreases, the C_{Basin} will increase (more positive freshwater budget). This concept has been applied to late Miocene basin desiccations in the Mediterranean and the Black Sea (e.g., Meijer and Krijgsman, 2005; de la Vara et al., 2016).

There are no direct constraints on the magnitude of the middle Miocene freshwater budget of the wider Paratethys region. Therefore, we use the present-day Black Sea as an example of how a change in surface area of a marginal basin relates to the balance between freshwater input (e.g., from rivers) and evaporative loss. Today's runoff into the Black Sea is ~0.35 × 10^{12} m^3/yr, and evaporation per unit area exceeds precipitation per unit area by ~0.1 m/yr (de la Vara et al., 2016). For the present-day Black Sea surface area, this equates to an overall positive freshwater budget (Esin et al., 2010). If the surface area were increased (Fig. 3), the budget of the Black Sea would become more negative and the water therefore saltier (less brackish). If the surface area were reduced, the freshwater budget would increase (Fig. 3), which would reverse the effect. The latter demonstrates what might have occurred during the middle Miocene in the Paratethys.

Considering the hypsometry (Fig. 1) of the Eastern Paratethys during the middle Miocene, it becomes evident that shallow marginal areas took up a large amount of the surface area (following Popov et al., 2010, their figure 1). If the sea level dropped substantially, the margins of the basin would have been subaerially exposed. This would have drastically reduced the surface area of the Eastern Paratethys; e.g., a drop of ~70 m would have reduced the surface area by ~25% (Fig. 4). This would have upset the balance between sea-surface net evaporation (*E* – *P*) and runoff and therefore triggered an extreme change to more positive hydrological budgets. Such a drastic sea-level drop in the Eastern Paratethys might have been triggered by the opening of the Bârlad Strait (Fig. 1).

A Physics-Justified Scenario for the Paratethys throughout the Middle Miocene

The combination of a relatively deep Trans-Tethyan gateway (>70 m) and strong evaporation across the central basin made it possible for normal marine conditions to be recorded in the Central Paratethys during the Badenian (e.g., Kováč et al., 2007; Fig. 5A). At the same time, the shallow Bârlad Strait plus a positive freshwater budget caused brackish conditions in the Eastern Paratethys (regional Chokrakian stage; Popov et al., 2010).

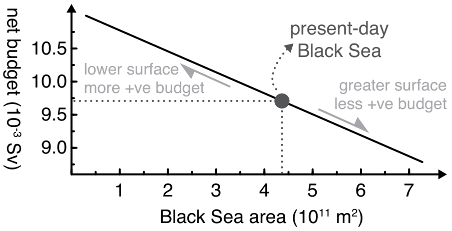

Figure 3. Impact of changes in sea-surface area on freshwater budget of present-day Black Sea.

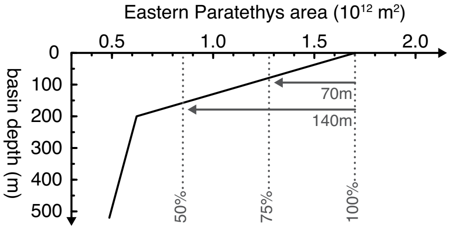

Figure 4. Middle Miocene hypsometry of Eastern Paratethys basin (following Popov et al., 2010). Characteristic is large surface area of shallow marginal areas. Dotted lines indicate basin sizes relative to sea-level drops of 70 m and 140 m.

At 13.8 Ma, the global climate cooled, triggering a glaciation, which led to a global sea-level fall of ~50–70 m (John et al., 2011; Figs. 5A and 5B). This drastically reduced the Trans-Tethyan Strait to a very shallow depth (Figs. 2A and 2B) and disconnected the two Paratethyan basins. The Bârlad Strait may now be considered as "closed" from the eastern basin point of view, which turned the eastern basin into a lake that overspilled into the central basin (Karaganian regional stage; Peryt et al., 2004). In the Central Paratethys, the persistent negative budget together with the now strongly restricted Trans-Tethyan Strait was capable of creating evaporite deposition during the BSC. It is important to note that a 50–70 m sea-level drop also lowered the central basin surface area, which decreased its evaporative loss; however, it still must have remained negative to trigger evaporite deposition.

After the BSC, global isotope records indicate stable high δ^{18}O values (Zachos et al., 2001),

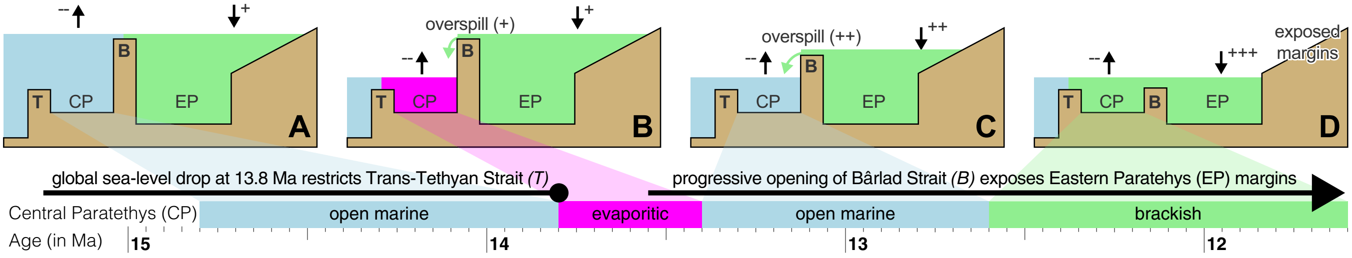

Figure 5. Middle Miocene (14.8–11.6 Ma) evolution of Paratethys. Plus (+) and minus (–) signs indicate relative strength of freshwater budget. Different environments of central Paratethys (A–D) are also shown in Figure 2.

which hints to an ongoing icehouse state and persistent low eustatic sea level. At 13.36 Ma, however, the evaporite stage ended and a new wave of marine fauna invaded Central Paratethys (Fig. 5C). The Central Paratethys returned to open marine conditions, and the eastern Paratethys remained more brackish. This was followed (at 12.65 Ma; Fig. 5D) by a sudden change to brackish-marine conditions in the Central Paratethys that triggered the Badenian-Sarmatian Extinction Event (BSEE; Harzhauser and Piller, 2007; Palcu et al., 2015). The paleoenvironmental expression of the BSC termination and the BSEE may be explained by a progressive opening of the Bârlad Strait during the Konkian, which lowered the water level of the Eastern Paratethys, reduced its surface area (Fig. 4), and increased the importance of rivers relative to evaporative loss. This excess in freshwater fed into the central basin and turned the entire Paratethys freshwater budget from a negative (Figs. 2B and 5B) to a neutral (Figs. 2C and 5C) to a positive budget (Figs. 2D and 5D). This progressive opening of the Bârlad Strait was likely due to a combination of long-term tectonic subsidence (due to subduction in the nearby East Carpathian foredeep; Tărăpoancă et al., 2003) and an oscillating global sea level (Palcu et al., 2015; 2017, and references therein). These oscillations may explain the short marine influxes recorded in the eastern basin, because they temporarily contributed to an increase in the eastward flow of Central Paratethys water across the Bârlad Strait.

CONCLUSIONS

We quantitatively show that the BSC evaporites of the Central Paratethys could have been triggered by a global sea-level drop. During the middle Miocene, the overall Paratethys freshwater budget must have switched from negative to positive to cause the Central Paratethys environment to change via marine to brackish conditions. We suggest that this switch was caused by the opening of the Bârlad Strait (ca. 13.4–11.6 Ma), which lowered the Eastern Paratethys lake level, reduced its surface area, and led to less water loss by evaporation. From a general point of view, this novel mechanism could be a plausible explanation for other events. For example, the Mediterranean halite deposition during the Messinian salinity crisis (e.g., Roveri et al., 2014; Gorini et al., 2015) could have been terminated by an increased freshwater flux from the Paratethys Sea, which became significantly contracted by the MSC sea-level lowering, thereby increasing its hydrological budget (e.g., Marzocchi et al., 2016). Moreover, the mechanism proposed here has the potential to play a dominant role, not solitarily in past events, but more importantly when considering the possibility of fast-rising sea level in the near future.

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