Rise and fall of the Paratethys Sea during the Messinian Salinity Crisis

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1. Introduction

Major sea level fluctuations, causing dramatic paleoenvironmental changes and related mass-extinctions, form an intricate part of Earth history (Hallam and Wignall, 1997). Renowned examples are the biblical flood of Noah and the Messinian Salinity Crisis (MSC) of the Mediterranean. Geological investigations indicated that a great deluge surged the Black Sea basin roughly 8000 years ago, rapidly raising the lake level by some 100 m (Ryan et al., 1997, 2003) so that civilizations and populations inhabiting the Black Sea shores may have suddenly drowned (Ryan and Pitman, 1998). The sudden influx hypothesis is highly debated between geologists and archeologists (Aksu et al., 2002), but may also have occurred in late Messinian times (Hsiu and Giovanoli, 1979) when the Black Sea domain was part of the Eastern Paratethys (Fig. 1). During the Messinian (7.24–5.33 Ma), the Mediterranean became progressively isolated from the Atlantic Ocean, triggering widespread precipitation of gypsum (5.96–5.6 Ma), massive salt deposition (5.6–5.5 Ma), and a dramatic sea level lowering followed by brackish water environments of “Lago-Mare” (Lake Sea) facies (e.g. Hilgen et al., 2007; Krijgsman and Meijer, 2008; Roveri et al., 2008). A catastrophic re-flooding from the Atlantic at the beginning of the Pliocene (5.33 Ma) abruptly ended the salinity crisis by re-establishing open marine conditions in the Mediterranean (Hsiu et al., 1973).

The hydrological flux from Paratethys to Mediterranean is a crucial component in quantitative studies on paleocirculation patterns and precipitation models of evaporites (Meijer and Krijgsman, 2005; Flecker and Ellam, 2006), but connectivity between the two basins is controversial (Çagatay et al., 2006). Overspilling of Paratethys waters into the Mediterranean has been argued to explain the presence of brackish water fauna in the Lago-Mare sediments (Cita et al., 1978), but a lowering of Paratethys levels during the Messinian event is also suggested (Hsiu and Giovanoli, 1979). Seismic profiles of the Black Sea basin show evidence of deep canyon cutting, but the exact stratigraphic position differs; at the base of the Pontian Stage (Dinu et al., 2005) or intra-Pontian (Gillet et al., 2007). Sequence stratigraphic interpretations on a seismic transect from the western Dacian Basin also reveal significant sea level changes within the Pontian Stage (Leever et al., 2009). Seismic and borehole data from the Pannonian Basin show unconformities as well, but these are interpreted to have a regional tectonic origin and no relation to Messinian drawdown (Magyar and Sztanó, 2008). A concurrent base level drop has been proposed for the Caspian Sea (Reynolds et al., 1998; Popov et al., 2006), although numerical ages are poorly defined.

Paratethys time scales comprise regional stages (e.g. Maeotian–Pontian–Dacian or Kimmerian within the Mi–Pliocene interval) and substages (e.g. Odessian–Portaferrian–Bosphorian within the Pontian).
based on endemic ostracod and mollusc species. At present, correlations to the marine record are mainly tentatively based on rare incursions of nannofossils (e.g., Marunteanu and Papaianopol, 1998) and chronostratigraphic resolution is generally inadequate to determine causal relationships with the Mediterranean MSC events.

Here, we construct a robust biochronologic framework for the Paratethys domain by integrating paleomagnetic data with detailed paleontologic analyses of endemic Paratethys faunal (molluscs and ostracods) assemblages from sections of the Dacian and the Black Sea basin (Fig. 1). The integrated stratigraphic results of these individual domains will unfold the intrinsic paleoenvironmental evolution of the Eastern Paratethys during the Messinian Salinity Crisis with revised chronologic constraints.

2. Sections and setting

Paleomagnetic studies recently showed that excellent biochronologic control for the Paratethys can be obtained from continuous sedimentary sequences (Vasiliev et al., 2004, 2005). The Dacian Basin in particular comprises several complete and well-exposed sedimentary successions from the Pontian Stage, consisting of fossiliferous silts and sands indicative of lacustrine and fluvio-deltaic environment (Panaiotu et al., 2007). These sediments accumulated rapidly in auvio-deltaic environment and sands indicative of lacustrine and fluvio-deltaic environment.

The target section in the Black Sea Basin is on Taman Peninsula (Russia); the classic Zheleznyi Rog (Iron Cape) section is 500 m long and covers ~5 Myr of sediments (Fig. 1). The section has been extensively studied by several Russian research teams (Semenenko, 1979; Trubikhin, 1986; Filippova, 2002), but despite the presence of paleontological, paleomagnetic and (K–Ar) isotopic data, correlations to the GTS are still highly debated (Chumakov et al., 1992; Pevzner et al., 2003; Popov et al., 2006). We have focused here on the Mio–Pliocene interval of the Zheleznyi Rog section and resampled the uppermost Maotian, Pontian and the lower Kimmerian for paleomagnetic and biostratigraphic purposes to establish direct correlations to the integrated stratigraphic record in the Dacian Basin.

3. Paleomagnetic results

Standard paleomagnetic measurements have been performed to establish a new magnetostratigraphic record for the Zheleznyi Rog section (Fig. 2). Thermal (TH) demagnetization was applied with small temperature increments of 10–30 °C up to a maximum temperature of 580 °C in a magnetically shielded furnace. Alternating Field (AF) demagnetization was performed with small field increments, up to a maximum of 100 mT, using an in-house built robotized sample handler controller attached to a horizontal 2G Enterprises DC SQUID cryogenic magnetometer. Demagnetization results were analyzed using orthogonal plots and stereographic projections. The direction of the NRM components was calculated by principal-component analysis. Dual polarity components were isolated in most samples between the 270–420 °C (Fig. 2A–C) or 20–45 mT demagnetization steps (Fig. 2D,E). Several specimens were demagnetized up to 580 °C or 100 mT (Fig. 2F). We recognized three polarity intervals in the studied succession, normal polarities at the basal (upper Maotian) part, reversed polarity in the middle (Pontian) part and normal polarity in the upper (lower Kimmerian) part.

An alternating gradient magnetometer (Princeton Measurements Corporation, MicroMag Model 2900 with 2T magnet, noise...
level $2 \times 10^{-9}$ Am$^2$) was used to measure first order reversal curves (FORC) diagrams. The domain state, and particularly the amount of magnetic interaction emerges clearly from FORC diagrams. Contours closing around a single domain (SD) peak at $B_c = 40–50$ mT (Fig. 2G,H) are similar to those previously reported for greigite as magnetic carrier.

### 4. Rise in Paratethyan water level at the Maeotian/Pontian boundary

The Paratethyan ostracod distribution in Miocene–Pliocene times reflects evolutionary trends, but also the influence of paleoenvironmental changes. Changing the connectivity with the open ocean influences the bathymetry and salinity of Paratethyan basins, which is reflected in the marginal faunal assemblages of the Dacian Basin. We present here the results of a detailed micro-paleontological study, focussing mainly on ostracods and foraminifera of the Râmnicu Sărat section, which provides a high-resolution biochronology for the Eastern Paratethys (Fig. 3).

Our biostratigraphic results show that the fossil ostracod assemblages from the upper Maeotian (Moldavian substage) comprise a low number of species, of which Cyprideis pannonica is common and Paracandona albicans and Leptocythere blanda are rare (Fig. 3). These fossil assemblages are indicative of sub-littoral fresh- to brackish water environment, suggesting that the upper Maeotian sediments in the east Carpathian foredeep are associated with temporary lakes on flood plain areas. The marginal areas of the Dacian Basin thus evolved in almost freshwater conditions, while the paleoenvironment was dominated by littoral and fluvial conditions.

The Maeotian assemblages are rapidly replaced by lower Pontian (Odessian/Novorossian) associations (Fig. 3). The lower Pontian ostracod assemblages indicate relatively deep basinal environments, and a widespread rise of relative sea level. At this time, characteristic layers formed comprising monospecific Congeria novorossica molluscs (Stevanovic et al., 1989). Our detailed study of the Maeotian–Pontian transition interval, for the first time, reveals the presence of agglutinated and calcareous benthic foraminifera and planktonic foraminifera (Streptochilus and Tenuitellina species) of marine origin in the Upper Miocene of the Eastern Paratethys (Fig. 4A–J). This indicates that a major marine deluge took place by re-establishing a connection through the Mediterranean to the Atlantic, or alternatively to the Indian Ocean. Magnetostatigraphic results show that this flooding interval occurred synchronously in the Dacian and Black Sea basins near the paleomagnetic reversal C3An.2n(y), and is dated at 6.04 Ma (Fig. 4). The marine environment in the Eastern Paratethys was only a short-lived feature of maximum 10 kyr, after which micro-paleontological assemblages are again dominated by ostracods indicative of brackish water conditions. After this transgressive interval, the lower Pontian ostracod fauna reacted to the changes in bathymetry and salinity, while variations in interbasinal connectivity allowed migration of species. It generated a “bloom” of ostracod species in the Odessian at ~5.95 Ma (Fig. 3), especially in the predominantly pelitic deposits that are well-developed in lower Pontian times.

A transgression at the Maeotian/Pontian boundary has previously been documented from wells and seismics in the western Dacian Basin (Jipa, 1997; Leever, 2007; Leever et al., 2009) and is biostratigraphically marked by a migration of faunal elements from the Pannonian basin (Hungary–Austria) into the Eastern Paratethys and by migration of typical Aegean species into the Black Sea domain. This is supported by earlier observations of a short calcareous nannofossil influx at the Maeotian/Pontian boundary interval (Marunteanu and Papaianopol, 1998). Biostratigraphic data from the Caspian Basin in Azerbaijan reveal similar changes in faunal elements indicating that this event extended into western Asia (Stevanovic et al., 1989).

### 5. Fall in Paratethyan water level during the Portaferrian

A marked paleoenvironmental change occurs at the middle Pontian (Portaferrian) of the Dacian Basin. The study region in Romania shows a transition to more sandy facies, with ample presence of wave rippled...
sediments indicating deposition in shallow water, probably on the lower shore face (Panaiotu et al., 2007). The Portaferrian thus represents a regressive event where the bathymetry of the Dacian Basin decreased. In marginal settings, the rich Odessian ostracod fauna indicative of basinal conditions is replaced by littoral, fluvial and lacustrine Portaferrian species: Amplocypris dorsobrevis, C. pannonica, Fig. 3. Ostracod distribution of the Râmnicu Sărat section in the east Carpathian foredeep of the Dacian Basin. The magnetostratigraphic pattern is after Vasiliev et al. (2004) and correlates excellently to the GTS. It allows high-resolution dating of the ostracod assemblages and related stages and substages. The resulting new ages of the (sub)stage boundaries are indicated.
C. sp., Tyrrenocythere ex. gr. motasi, Candoniella sp., and Zonocypris membranae (Fig. 3).

The Portaferrian low-stand is determined magnetostratigraphically in the middle part of chron C3r, and precise ages can thus not be obtained here. Assuming constant sedimentation rates for the Râmnicu Sărat section results in interpolated ages of ~5.8 and ~5.5 Ma for the lower and upper Portaferrian boundary, respectively (Fig. 3). Seismic data from the western part of the Dacian Basin confirm a general regressive middle Pontian low-stand (Leever et al., 2009), while an erosional unconformity of regional significance has been observed between Maeotian and upper Pontian sediments at marginal regions (Stoica et al., 2007).

The section at the Black Sea margin shows a conspicuous change at the top of this interval by deep lacustrine brackish marls with Pontian fauna indicative of the photic zone (~100 m deep) abruptly changing to condensed coastal sequences of reddish sands, with some minor sedimentary hiatuses, attributed to the base of the Kimmerian (Fig. 5). This red sequence comprises oolites/pisolites plus nodular marls that suggest high-energetic coastal environments (Fig. 5E). It furthermore contains molluscs that are characteristic of the Portaferrian (Fig. 5F–H) and minerals indicative of evaporitic conditions (selenite, gypsum and jarosite), which probably formed after deposition (Fig. 5I–L). This indicates that the Black Sea experienced a sea level drop of about 50–100 m at the base of the Kimmerian (middle Portaferrian), which is coeval to the intra-Pontian unconformities observed in seismic profiles of the Romanian Black Sea margin (Gillet et al., 2007).

The Caspian Sea may have become isolated during this period, as suggested by the expansion of the deltaic systems of the ‘Productive Series’, which are Kimmerian in age. This is the main hydrocarbon reservoir unit of the South Caspian Basin, thought to represent the low-stand wedge of a dramatic sea level fall (Hinds et al., 2004). A tentative link has been made with the late Messinian eustatic sea level fall (Reynolds et al., 1998), but other studies have suggested a relation to large scale plate-tectonic processes (Allen et al., 2002). The base of the Productive Series is radiometrically dated at ~5.5 Ma and is interpreted as the sudden southward expansion of the Miocene Volga delta resulting from a major regression (Dumont, 1998).

Consequently, we conclude that all regions in the Eastern Paratethys show evidence for a marked sea level lowering of at least 50 m during the Messinian (5.6–5.5 Myr) time interval, corresponding to the Portaferrian of the Dacian Basin and the lowermost Kimmerian of the Black Sea and Caspian basins.

6. Paratethys transgression during the Bosphorian

The upper Pontian (Bosphorian) corresponds to a second transgressive event in the Dacian Basin, showing a major faunal change in the
ostracod assemblages (Fig. 3) and a lithological change to more basinal sequences (Jipa, 1997). The Portaferrian–Bosphorian transition is marked by a second bloom of ostracod fauna, and most Pontian species are well represented. Some species pass through the limit with lower Dacian (Getian substage).

Interpolation assuming constant sedimentation rates, suggests that this upper Pontian transgression started at an age of 5.5±0.1 Ma (Table 1). Detailed micropalaeontological studies have not revealed the presence of marine foraminifera here. In the western Dacian Basin, seismic profiles also show a transgressive system tract at the base of the Bosphorian (Leever et al., 2009). In the Topolog region of the south Carpathian foredeep, the Bosphorian is found transgressive on Maeotian deposits while the upper Maeotian and lower-middle Pontian are missing (Stoica et al., 2007). In addition, the bottom sets of a ‘Gilbert fan delta’ are correlated to this sea level rise (Clauzon et al., 2005), although stratigraphic data from Romanian geologists indicate that these fan deposits are of pre-Maeotian age (Savu and Ghenea, 1967; Nastaseanu and Bercia, 1968).

In the Black Sea Basin, the Miocene–Pliocene boundary is commonly placed at the Pontian/Kimmerian boundary. This is in slight disagreement with our stratigraphic results, which shows that the red level of the lowermost Kimmerian corresponds to the Portaferrian of the Dacian Basin and thus to the latest Miocene (Fig. 4). Faunal elements of Kimmerian marls, overlying the reddish interval at Zheleznyi Rog, are similar to the Bosphorian and can be largely attributed to the Pliocene. The “Productive Series” of the Caspian Basin are also biostratigraphically dated as Kimmerian in terms of Eastern Paratethyan chronostratigraphy (Neveux et al., 2002). The numerical age is still a matter of debate, because of conflicting paleomagnetic evidence on which calibration to the global record is based, and because biostratigraphic control for interregional correlation is hindered by the presence of mostly local faunas and by massive reworking (Jones and Simmons, 1996).

Our integrated stratigraphic results from the Dacian Basin show that the Pontian/Dacian boundary is younger than the Sidufjall normal chron (C3n.3n) and is magnetostratigraphically dated at 4.70±0.05 Ma (Table 1). This is significantly younger than presumed in other Paratethys time scales, where the Pontian–Dacian stage boundary is tentatively positioned at, or close to, the Miocene–Pliocene boundary (5.33 Ma) (Steininger et al., 1996; Clauzon et al., 2005; Snel et al., 2006). It is clear that different definitions have been used for the upper Pontian boundary in Romanian and Russian literature (Fig. 6; Table 1), which is especially problematic when working on the Miocene–Pliocene sedimentary successions and seismic sequences of the Black Sea domain. A formal re-definition of the Paratethys regional stages according to international stratigraphic codes is urgently required.

7. Causes and consequences for the Messinian Salinity Crisis

Our new chronological framework for the Eastern Paratethys allows high-resolution correlations with the oxygen isotope curves (Hodell et al., 2001; Hilgen et al., 2007) and the Messinian successions of the Mediterranean (Fig. 6). These are subdivided into three astronomically dated evaporite phases: M1) marine “Lower Gypsum” (5.96–5.6 Ma), M2) halite and resedimented evaporites (5.6–5.5 Ma), M3) Lago-Mare sediments with gypsum (5.5–5.3 Ma) (Krijgsman et al., 1999; Hilgen et al., 2007; Roveri et al., 2008).
7.1. The onset of “Lower Gypsum” formation in the Mediterranean

Our new data shows that the onset of the Messinian Salinity Crisis in the Mediterranean was directly preceded by the marine flooding of the Eastern Paratethys, confirming the hypothesis that the Lower Gypsum units formed during a relative high-stand of Mediterranean sea level (Flecker et al., 2002; Krijgsman and Meijer, 2008). A transgression at the onset of the Messinian evaporite formation is in serious contrast to hypotheses inferring glacio-eustatic sea level lowering (Hsü et al., 1973; Clauzon et al., 2005), but has earlier been suggested on the basis of strontium isotope models (Flecker et al., 2002; Flecker and Ellam, 2006). It is interesting to note that the bloom of Odessian ostracods (Fig. 3), indicating re-stabilization of paleoenvironmental conditions in the Paratethys, coincides with the onset of MSC evaporites at 5.96 Ma in the Mediterranean (Krijgsman et al., 1999). Consequently, the changes in Paratethys–Mediterranean connectivity at the Maeotian–Pontian transition interval probably generated a new hydrological equilibrium in both Paratethys and Mediterranean that allows gypsum to precipitate during astronomically-forced optimum (= dry) climate conditions on a precessional resolution in the Mediterranean Basin (Krijgsman et al., 2001).

A flooding of the Paratethys basin could only have happened if its water level was significantly below global ocean and Mediterranean level. This indicates that the hydrological budget for the Paratethys region in Maeotian times was slightly negative. Establishing a Mediterranean–Paratethys connection would result in an increased hydrological flux into the Paratethys and consequently an increase in water and salt flux from the Atlantic into the highly restricted evaporation-dominated Mediterranean. We speculate that creating a connection to the Paratethys will increase Mediterranean stratification and ultimately influence the hydrodynamics of the Gibraltar gateways, two crucial factors to explain the onset of widespread gypsum deposition during the MSC (Meijer and Krijgsman, 2005).

7.2. Location of Paratethys flooding

Another intriguing question is: where did the Paratethys flooding actually come from? The Aegean region of the Mediterranean Sea is the most likely source area according to the paleogeographic reconstructions of the Paratethys domain (e.g. Popov et al., 2006), although we cannot exclude the Indian Ocean on the basis of our data. A flooding event is further expected to leave marked traces of significant erosion on land and offshore the Bosporus region (e.g. Loget et al. 2005). The Karadeniz–1 borehole in the European part of the Turkish Black Sea shelf indeed shows Messinian erosional surfaces (Gillet et al., 2007), which can possibly be traced to the Karacadag region at the Black Sea margin northwest of Istanbul. We thus consider a Karacadag–Karacadag passage as potential candidate to account for the flooding event, but more detailed biostratigraphic data is necessary to confirm this hypothesis.
7.3. Down drop of the sea level during the MSC

The observed fall in Paratethyan water level at the base of the Portaferrian is estimated to have occurred at 5.8 Ma in the Dacian Basin (Fig. 3). This is remarkably close to glacial peaks TG22–20 (Fig. 6), which are suggested to have caused a significant drop in global sea level (Shackleton et al., 1995). In the Zheleznzy Rog succession this interval also shows evidence of sea level lowering, expressed by the occurrence of white shell beds of Portaferrian age (Po2; Popov et al., 2006).

The climax of the Messinian Salinity Crisis occurred during glacial peaks TG12–14, when the water exchange with the Atlantic became restricted resulting in the formation of massive halite in the deepest parts of the Mediterranean and a dramatic fall in water level (Fig. 6). The potential connection to Paratethys thus also would have become lost, lowering the water level in the Black Sea Basin immediately to the level of the paleo-Bosphorus. Our data from Zheleznzy Rog suggest that this event is clearly reflected in the sharp transition to the reddish interval at the Russian Black Sea margin of the Taman Peninsula. The ultimate lake levels in the isolated Dacian, Black Sea and Caspian basins will obviously be influenced by astronomically induced changes of regional climate. Depending on the hydrological budget of the individual Paratethys basins desiccation (negative) or overflow (positive) will take place (Fig. 6).

A marked change occurs in the oxygen isotope curves after TG12 at 5.5 Ma (Fig. 6), interpreted to result in much warmer and humid global climates (Hodell et al., 2001; Hilgen et al., 2007). This resulted in a positive hydrological change and caused widespread transgression of Lago-Mare/Upper Evaporite facies over the Messinian erosional surfaces (Loi et al., 2005; Roveri et al., 2008). Transgressional sequences are especially clear in Northern Italy where they are attributed to an increased hydrological flux from the Alps (Willet et al., 2006). The time-equivalent transgression in the Paratethys can also be explained by these regional climatic changes.

The alternative hypothesis for this transgression is the re-establishment of Paratethys–Mediterranean connectivity by the Zanclean deluge of the Mediterranean at the Miocene Pliocene boundary (5.33 Ma). This would better explain the sharp transition from littoral and fluvial Portaferrian facies to predominantly pelitic facies in the lower Bosphorian. The Bosphorian ostracod and mollusc fauna do not show evidence of significant freshening of the water conditions, although their strontium isotope ratios suggest isolation from the Mediterranean (Vasyliev, 2006). Mio–Pliocene connectivity at high sea level has earlier been suggested by Clauzון et al. (2005), but these authors based it on the nannofossil influxes in the Paratethys at the Pontian–Dacian boundary which are dated at 4.7 Ma and have thus no relation at all with the Pliocene flooding. We realize that a correlation to the Zanclean flooding cannot be excluded on the basis of our data. However, were the Paratethys transgression to be coeval with the Mediterranean flooding, substantial changes in sedimentation rate would be required, especially by a major (4×) increase in the lowermost part of the Bosphorian (below the Thvera). We have not seen any evidence for such an increase in the field, nor in the Rămnuc Sârât section (east Carpathian foredeep), nor in the Topolog region (south Carpathian foredeep). Future research should therefore aim at localizing marine influxes at the base of the Bosphorian and focus on geochemical proxies that may quantify Paratethys–Mediterranean connectivity.

8. Conclusions

Our integrated stratigraphic data results in a robust chronological framework for the Dacian and Black Sea basins of the Eastern Paratethys (Table 1), allowing high-resolution stratigraphic correlations between the individual Paratethys subbasins and with the Messinian Salinity Crisis of the Mediterranean (Fig. 6). The Maeotian/Pontian boundary is dated at 6.04 Ma and corresponds to a major faunal change triggered by a marine flooding of the Paratethys, as evidenced by the presence of planktonic foraminifera. The lowermost Pontian (Odessian/Novoros-sian) substage relates to a general high-stand in the Paratethys, possibly with interbasinal and Mediterranean connections. The onset of MSC evaporites closely coincides in age with the bloom of Odessian ostracods in the Paratethys at ~5.95 Ma. The peak of the MSC at 5.6–5.5 Ma definitely ended Mediterranean–Paratethys connectivity in the Portaferrian, causing a sudden drawdown of Paratethys water levels of at least 50–100 m and isolating the Caspian Sea and the Dacian Basin from the Black Sea domain. From 5.5 Ma onward a major change in Eurasian climate, resulting in much warmer and humid conditions changed the hydrological balance and resulted in a widespread transgression in Mediterranean and Paratethys. The Miocene/Pliocene boundary may correspond to the Portaferian/Bosphorian boundary in the Dacian Basin and to the top of the red layer in Zheleznzy Rog, i.e. within the lower Kimmerian of the Black Sea Basin, but certainly not to the Pontian/Dacian boundary in the Dacian Basin, which is dated ~600 ky younger at 4.7 Ma.

Our new stratigraphic framework has also serious consequences for the Mediterranean MSC. Ever since the discovery of widespread Messinian evaporites all over the Mediterranean seafloor, tectonic or glacio-eustatic processes restricting and closing the water exchange to the Atlantic in the west have been put forward and modeled to understand the causes of the Messinian Salinity Crisis (Hsi et al., 1973; Meijer and Krijgsman, 2005; Ryan, 2009), but conclusive answers are still lacking. Our data suggest that changing the connectivity to the Paratethys in the northeast could play an essential role in the onset of gypsum formation, which should give ample ammunition for new ideas and models concerning evaporite formation in semi-isolated basins. This will also have major implications for paleoceanographic circulation patterns, Mediterranean paleosalinity models and the internal stratification of its water column.

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References
