Use of tidal-circulation modeling in paleogeographical studies: An example from the Tertiary of the Alpine perimeter

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ABSTRACT

Tidal conditions in ancient shallow-marine basins, as revealed by preserved sedimentary deposits, reflect the strong influence of the paleobathymetry. Use of a tidal-circulation model can test existing paleobathymetric reconstructions. Meso- and macrotidal conditions are believed to have existed throughout most of the Miocene Molasse (France and Switzerland) seaway. Tidal simulations using external tidal ranges of 2 and 4 m entering from the south (Mediterranean) fail to generate mesotidal conditions in the majority of the seaway, because of a narrow constriction in the present Alpes du Dauphiné and Drôme areas. Meso–tidal conditions are simulated in the Rhône-Alp part of the seaway only after the postulated paleobathymetry is widened in the Alpes du Dauphiné area; this change allows tidal penetration from the Mediterranean. Despite this widening, the new simulations fail to generate mesotidal conditions in the Swiss part of the seaway. Mesotidal conditions are simulated in Switzerland with the addition of a second tidal input from eastern Switzerland, favoring an interpretation that the Swiss part of the seaway was connected with either the eastern Mediterranean or the Indo-Pacific Ocean. The revised paleobathymetry brackets uplift events that affected the basin margin.

INTRODUCTION

Paleogeographic reconstructions are an important component of basin analysis and are commonly based on the present-day distributions of rocks of a given age. However, structural deformation or uplift and erosion may have greatly modified their distribution. In such cases, paleogeographic reconstructions must be based on independent criteria.

In this paper we discuss the results of tidal-circulation simulations used to test paleogeographic reconstructions of the Miocene (lower Burdigalian) seaway that stretched from the French Mediterranean into Switzerland (Fig. 1). Widespread tidal Molasse deposits in this region require a major ocean connection (or connections) and basin bathymetry that would allow tides to propagate throughout the basin. Tides are quickly damped or reflected in shallow or narrow basins. Model output is constrained by well-documented, widely distributed tidal deposits, allowing reinterpretation of the paleogeography.

SETTING AND METHOD

Marine transgression into the Rhône Valley and the Alpine foreland basin of France and Switzerland occurred during late Aquitanian or early Burdigalian time (ca. 22 Ma). Contrasting fossil assemblages indicate that the transgression occurred simultaneously from Tethys via southern France and from Paratethys via eastern Switzerland (Berger, 1985, 1992), marine conditions persisting in general until the late Miocene (Fig. 2).

The Burdigalian transgressive deposits consist of widespread glauconitic sandstone and conglomerate dominated by current-generated cross-bedding. Shallow-marine fossils and the abundance of tidally related sedimentary structures such as bidirectional cross-stratification, neap-spring tidal bundle sequences, clay drapes, and large sand waves have led numerous authors to interpret these deposits as the products of either meso– or macro–tidal regimes (e.g., Homewood and Allen, 1981; Matter et al., 1980; Allen et al., 1985; Homewood et al., 1985; Lesueur et al., 1990; Allen and Bass, 1993).

The initial Burdigalian paleobathymetry was constructed from paleogeographic maps (Demarcq and Perriaux, 1984; Alabouvette et al., 1984; Allen et al., 1985) and 1:50,000 geologic maps. Water-depth estimates were derived from paleontologic and sedimentologic data of the publications and theses cited above. Confidence in the seaway boundary is high where shorelines are identified by nearshore deposits, deltas, alluvial fans, or long-lived structural highs such as the Massif Central (Fig. 3A). Confidence is moderate where the basin shape has remained relatively undeformed but where identifiable nearshore deposits or outcrops are absent. Confidence is lowest where tectonic activity or erosion has made the definition of the basin edge and shoreline impossible.

Burdigalian simulations were run by using the coastal-ocean circulation model of Leendertse et al. (1973) and Keen and Slingerland (1993). The model uses a finite-difference scheme written for a space-staggered grid to solve the set of hydrodynamic equations. The model has been tested in modern estuaries, where it has successfully simulated the existing tidal conditions (Leendertse and Liu, 1979), and has been used to

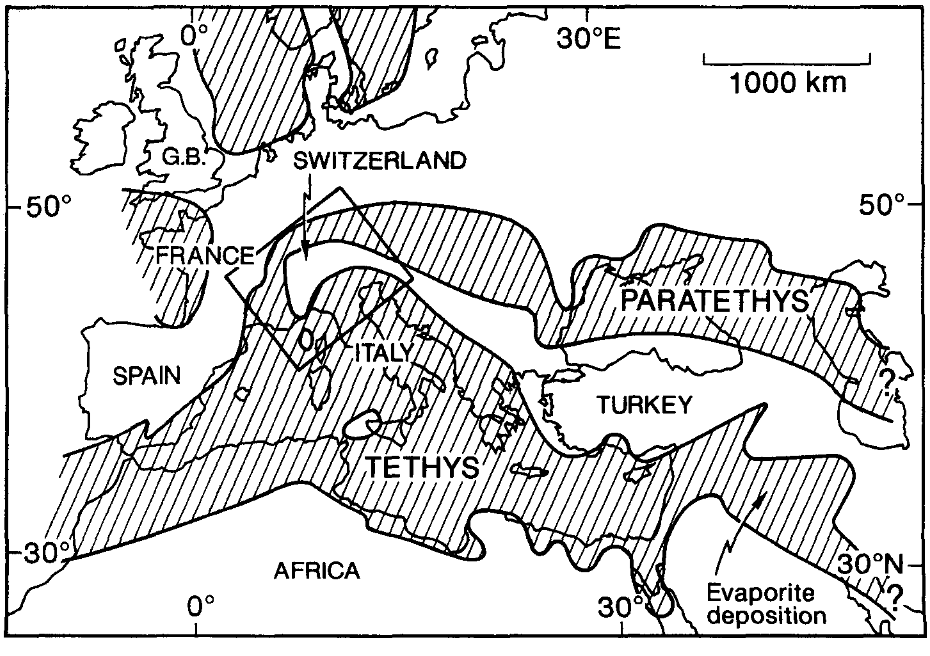
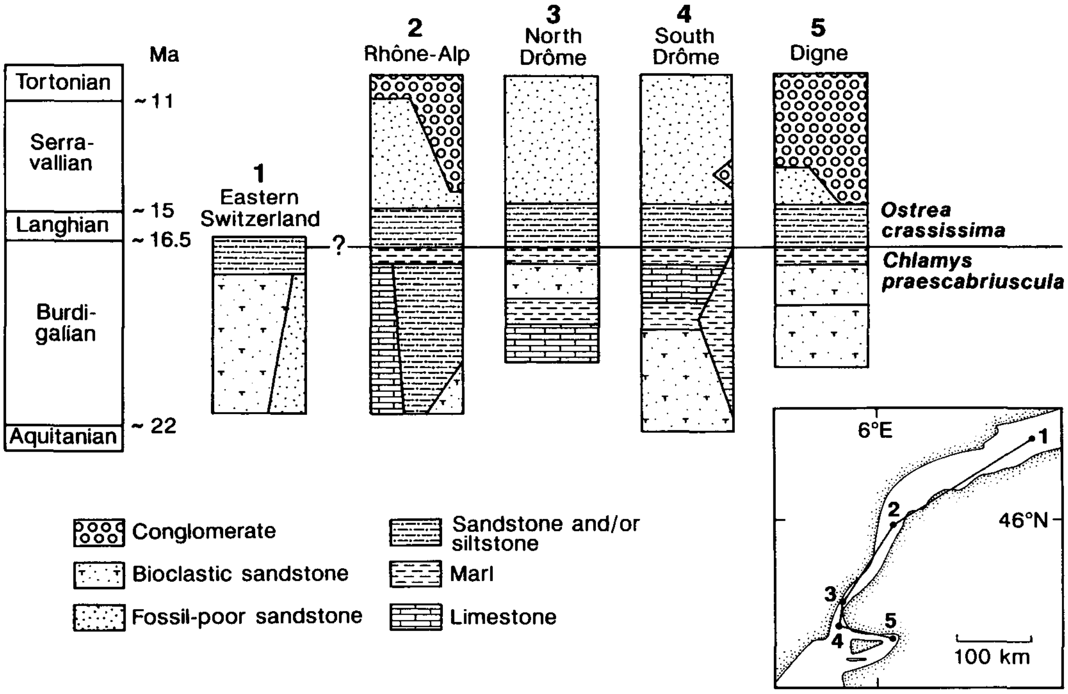


Figure 1. Reconstruction of Miocene (middle to late Burdigalian) Tethys and Paratethys seas (diagonal ruled pattern) (after Steininger and Rogl, 1984). Rectangle outlines study area.

Figure 2. Simplified Miocene stratigraphy of Molasse seaway. Sections were aligned on latest occurrences of *Chlamys praescabriuscula* and first appearance of *Ostrea crassissima*. Note that vertical scale is *time*, not thickness. See Figure 3A for detail of the inset.



simulate tides in epicontinental seas (Slingerland, 1986; Ericksen and Slingerland, 1990). Three critical model inputs are as follows. First, the paleobathymetry was entered on a grid of 46 × 60 nodes with 12 km spacing to represent the plan area and up to thirteen levels of varying thickness at each node to represent the water depths shown in Figure 3A. Second, simulations were run by using external tidal ranges at the model boundaries of 1, 2, and 4 m. The small independent tidal component, resulting from tidal forces acting directly on the seaway, was ignored. Finally, friction factors (Manning's n) of 0.016 and 0.032 were tested (Slingerland, 1986). The friction factor accounts for bottom friction as a function of water depth and influences tidal damping. Both friction factors gave similar results, but the higher friction number of 0.032 probably better reflects the greater bed roughness

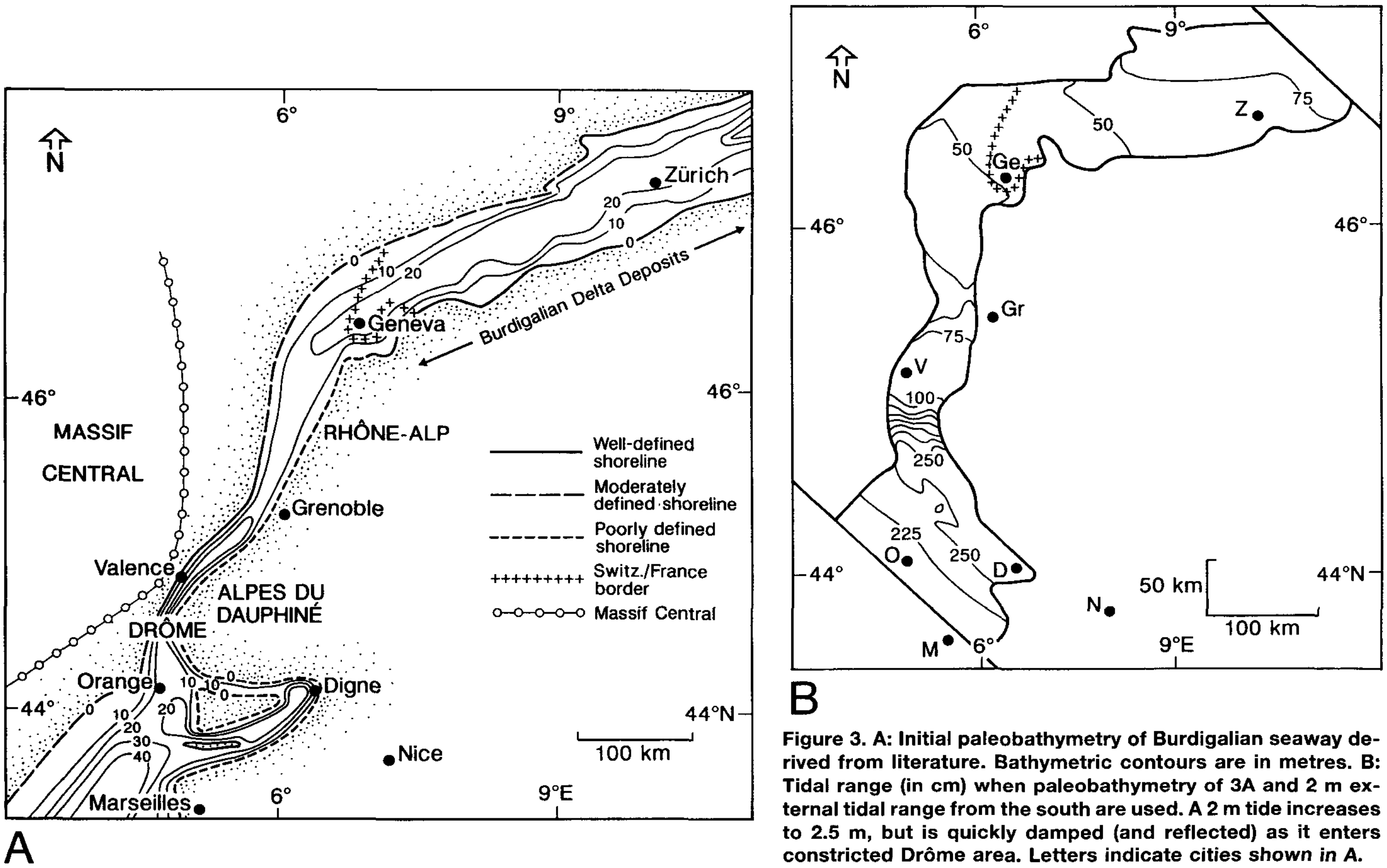


Figure 3. A: Initial paleobathymetry of Burdigalian seaway derived from literature. Bathymetric contours are in metres. B: Tidal range (in cm) when paleobathymetry of 3A and 2 m external tidal range from the south are used. A 2 m tide increases to 2.5 m, but is quickly damped (and reflected) as it enters constricted Drôme area. Letters indicate cities shown in A.

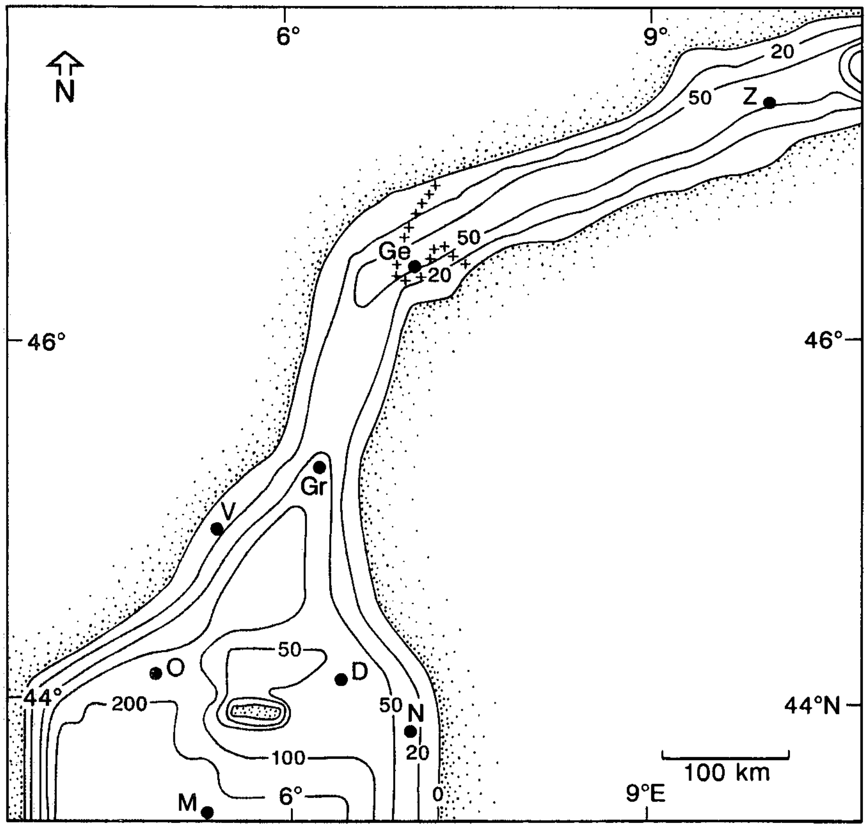


Figure 4. Expanded and deepened seaway paleobathymetry. New paleobathymetry conforms to well-defined coastlines in Figure 3A but is expanded elsewhere, as described in text. Bathymetric contours are in metres. See Figure 3A for abbreviations and symbols.

due to tidal bed forms. The model generated surface heights (tidal ranges), tidal current-velocity vectors, maximum current velocities at the bed, and residual (over an entire cycle) velocity vectors. The model results were then evaluated in light of sedimentologic information on the seaway, derived from the literature and field work.

RESULTS

Initial Paleobathymetry

Model simulations were run by using the initial paleobathymetry (Fig. 3A) with external tidal ranges of 2 and 4 m from the south alone and also in combination with 1 and 2 m ranges from the northeast. The 2 m (south only) simulation results in only low microtidal (<1 m) conditions (Fig. 3B) and maximum current velocities of <24 cm/s within much of the seaway, particularly in Switzerland and the Rhône-Alp region north of the narrow constriction in the Drôme area. Simulations were run with a higher external tide (4 m), a lower Manning's *n* (0.016), and deeper water (50 m) in the Drôme constriction. In all cases, tidal ranges (and maximum current velocities) do not significantly increase in the Rhône-Alp area and northeastward. The tides are severely reduced owing to reflection and frictional damping in the constricted area and

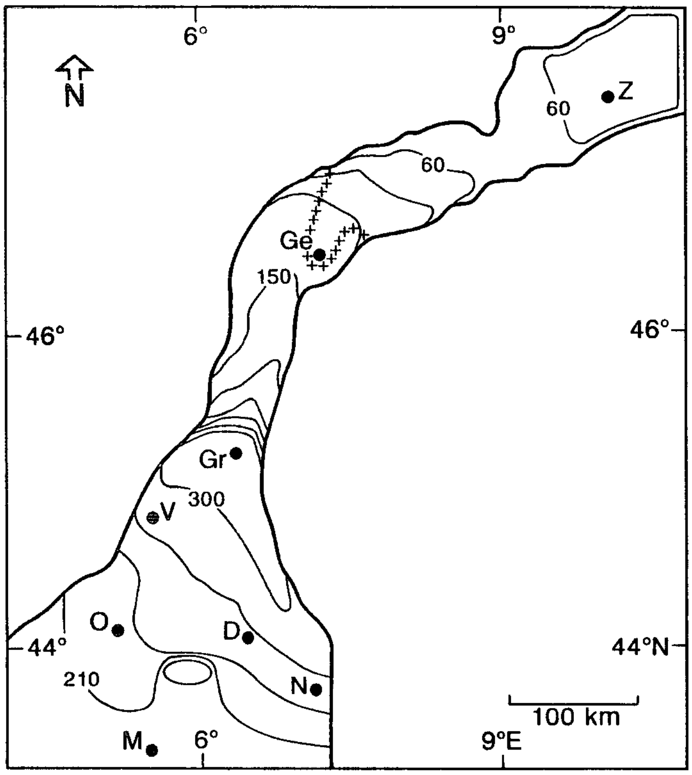


Figure 5. Tidal range (in cm) from model run using paleobathymetry of Figure 4 with initial tidal range of 2 m from south. Tide amplifies to 3 m in Rhône-Alp and Dauphiné region. See Figure 3A for abbreviations and symbols.

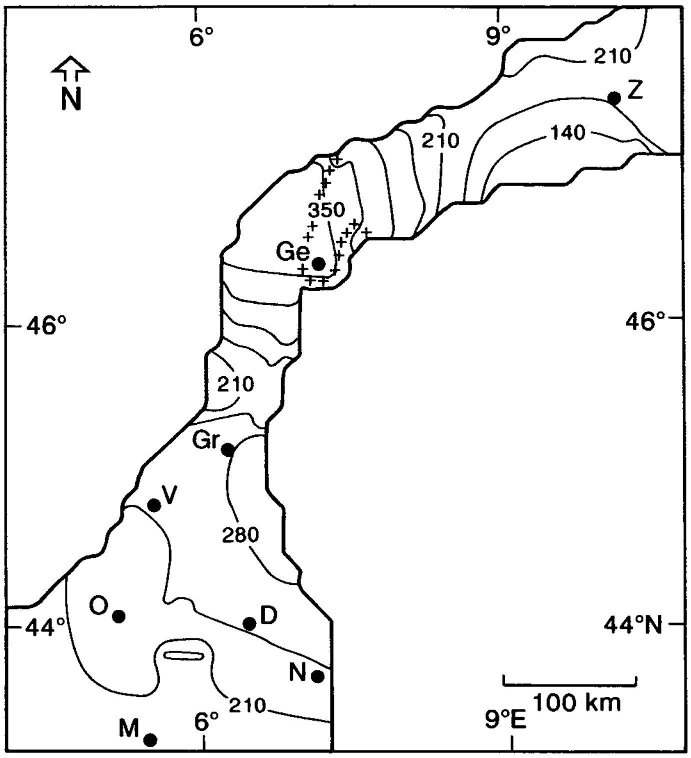


Figure 6. Tidal range (in cm) from external tidal range of 2 m from south and 2 m from northeast. Peak tides are now found in western Switzerland. Destructive and constructive interference creates lows and highs throughout seaway, locations of which vary depending on timing of external tide maxima. See Figure 3A for abbreviations and symbols.

by the remaining tidal energy being dispersed as the basin broadens to the north of the constriction. The addition of a 2 m external tide in the northeast in combination with the southern tides increases the tidal range in Switzerland, but has little effect in the Rhône-Alp area. Therefore, the interpretation of widespread meso- to macrotidal (2 to 4+ m) conditions in Burdigalian clastic deposits throughout the French and Swiss parts of the seaway requires that the initial paleobathymetry be reconsidered.

Refinement of the Paleobathymetry

To better match the interpreted tidal conditions of the seaway, a new paleobathymetry (Fig. 4) was created by investigating the moderately defined and undefined shorelines shown in Figure 3A. The modifications were based on the following lines of reasoning.

The initial paleobathymetry was widened in the Digne basin and Rhône-Alp regions by restoring the late Miocene structural shortening estimated at 30 and 40 km, respectively (Mugnier et al., 1990; M. Ford, 1993, written commun.). Scattered Miocene sedimentary rocks crop out in Provence to the east of Marseilles as far as Nice. The pelecypod fossil *Chlamys praescabriuscula* from those outcrops is also characteristic of the Burdigalian of the Rhône Valley (Drôme through the Rhône-Alp) (Gourinard et al., 1985). These scattered outcrops may be the erosional remnants of a larger Burdigalian seaway.

In the critical Drôme region, Burdigalian shoreline conglomerates and sandstones in the west pass into sandstones, marlstones, and carbonates toward the east (Demarcq and Perriaux, 1984) (Fig. 2). This lateral change is consistent with a seaway that deepened to the east of what is now the eastern limit of outcrop. The Alpine paleoshoreline and its deposits were some distance farther eastward and have subsequently been eroded.

Model Results from New Paleobathymetry

Simulations using the new paleobathymetry show that a tide with a 2 m range entering from the southern boundary is amplified to over 3 m in the Rhône-Alp region (Fig. 5). This tidal range is consistent with the tidal deposits found in the area. However, Figure 5 shows that the tidal ranges throughout Switzerland are still quite low. They remain so in the modeling despite an input tide of 4 m from the southern boundary, because in the Geneva area the new paleobathymetry is still relatively narrow and shallow and the shoreline curves eastward, reflecting the tidal wave. The tidal regime evident in the Swiss Burdigalian was therefore unlikely to have originated solely from the south. Simulations with a deep Drôme area allow greater tidal penetration into the basin; however, this configuration lowers tidal current velocities in the Drôme area to below the threshold for sand movement.

The tidal conditions interpreted from the rock record are best replicated in simulations where a 2 m tide from the south is run concurrently with a 2 m tide from the northeast. The results show tidal amplification in both the Rhône-Alp region and in much of Switzerland (Fig. 6).

DISCUSSION AND CONCLUSIONS

Tidal-circulation modeling has allowed us to test the viability of previous paleobathymetries for the Miocene Molasse seaway and has led us to conclude that the Alpes du Dauphiné area was submerged during Burdigalian times (subsequent uplift had begun by the Serravallian, ~2 m.y. later [Berger, 1992]). A widened seaway paleobathymetry allows tidal propagation into the Rhône-Alp area, but even with this modification the model requires the addition of a 2 m external tide from the northeast to create tidal effects throughout the seaway.

Consequently, tides probably propagated into the eastern Swiss foreland basin, either through another connection with the Mediterranean or, as favored by the different assemblage of fossils, from the Indo-Pacific. Paleogeographic reconstructions for the European Oligocene (Steininger and Rogl, 1984) show a connection of Paratethys with the Indo-Pacific Ocean, and a connection with the Mediterranean through the Adriatic. One (or both) of these openings may still have existed during the Burdigalian (cf. Fig. 1).

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