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Modeling tides and tsunami propagation in the former Gulf of Tartessos, as a tool for Archaeological Science

José-María Abril [a,*], Raúl Periáñez [a], José-Luis Escacena [b]

[a] Departamento de Física Aplicada I, ETSIA, Universidad de Sevilla, Carretera de Utrera km 1, D.P. 41013 Seville, Spain
[b] Departamento de Prehistoria y Arqueología, Facultad de Geografía e Historia, Universidad de Sevilla, Calle Doña María de Padilla s/n, D.P. 41004 Seville, Spain

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ABSTRACT

After the last Holocene sea level rise (about 6900 BP), the Gulf of Tartessos extended over the south-western area of the nowadays Guadalquivir Valley (Spain). With the development of some depositional littoral landforms and the progressive infill, the system evolved towards an inland lagoon. The first political system in the area emerged and collapsed from the fourth to the second millennium BC. Around the first millennium BC the culture of Tartessos flourished in this area under the Phoenician influence, but it vanished by the sixth century BC. The quest of its lost capital, the city of Tartessos, has been one of the most exciting archaeological enterprises in the past century. The former coastline and the bathymetry of the gulf can be reasonably reconstructed from geo-archaeological studies, and it can be used for the numerical modeling of tide and tsunami propagation in this water body. Models, with a spatial resolution of 30 s of arc, are based on the 2D non-linear hydrodynamic equations and have been previously validated under nowadays conditions. Computed tidal elevations and currents can provide some insight on the ancient trades for ship traffic and fisheries. The simulation of tsunami propagation, like the catastrophic one of 1755, allows estimating their potential hazardous effects on ancient coastal cities.

1. Introduction

When Schulten and Bonsor worked in the 1923–1925 excavations in the Doñana National Park (southwestern Spain) looking for the city of Tartessos, the geology of the Guadalquivir estuary was radically different from that described in the *Ora Maritima* by Avieno (265–306). Our insight changed after the works of the Spanish geologist Gavala (1959), who first studied the geological evolution of this area, and, among others, those by Menanteau (1984, 1982), Schubart et al. (1988) and Schulz et al. (1992). During the “Marismas Project”, Arteaga and collaborators conducted an intensive geo-archeological study with more than 600 field survey sites around the 10 m contour-level, allowing for a reliable reconstruction of the former coastline of the Gulf of Tartessos (Arteaga and Roos, 1995; Arteaga et al., 1995). A review on the recent coastal evolution of Doñana can be found in the work by Rodríguez-Ramírez et al. (1996). More recently, Ruiz et al. (2004) conducted a multidisciplinary analysis of sediments present in drill cores, distinguishing four phases in the late Holocene evolution of the southwestern area of the Guadalquivir estuary.

As a summary, with the last Holocene sea level rise, about 6900 BP, a large marine gulf (the Gulf of Tartessos) extended over the south-western area of the nowadays Guadalquivir Valley. Since then, a series of depositional littoral landforms were progressively generated; meanwhile the infill of the lagoon progressed. This way, 2000 years BP, the area was an inland lagoon (the so-called *Lacus Ligustinus*) with a double outlet to the sea, as described by Estrabo in his *Geographica*.

The first known political system in the Guadalquivir Basin emerged at the beginning of the third millennium BC and consisted in a regional inter-settlement hierarchical system centered on the south-western Pyrite Belt and the Lower Guadalquivir Basin (Nocete et al., 2005, 2010). For the latter, the site of Valencina, over 300 ha in size, and close to the former outlet of the Guadalquivir River in the northeast area of the Gulf of Tartessos, was its main human settlement and the head of a primary territorial network. Located near the marine exit, Valencina also became an important trade center for raw materials and products from regional to transcontinental scales (Nocete et al., 2010). Between ca. 2500 and ca. 2300 BC this political system collapsed.

It had been thought that the kingdom of Tartessos flourished in this area, based upon its mineral resources and the early trade with the Phoenician sailors. Since the discovery in 1958 of the

* Corresponding author. Tel.: +34 954486473; fax: +34 954486436.
E-mail address: jmabril@us.es (J.-M. Abril).

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Carambolo Treasure, in the vicinity of Seville, it had been considered as the best exponent of the Tartessian culture, but recent findings are now ascribing it to a Phoenician settlement (Escacena and García-Fernández, 2012). However, the detailed description by Avieno of the topography of the former coastline and the location of the city of Tartessos, the capital of this kingdom, when it still existed in the sixth century BC, along with the influence of the Schulten's work, *Tartessos*, turned the quest of this legendary city in one of the most exciting archaeological enterprises in the past century (see Table 1 for some proposed locations; an extensive historical review can be found in Mederos, 2008). Whatever it was the degree of the autochthonous contribution versus the Phoenician one in the Tartessian culture, it vanished by the sixth century BC, perhaps due to the loss of the eastern markets, or may be because a catastrophic natural hazard. Thus, it has been speculated about the possibility that a tsunami could have destroyed the city of Tartessos.

The identification of the city of Tartessos (if ever existed) with the mythic Atlantis of Plato, already handled by Schulten and others, was recently reinforced by Kühne (2004); and the idea has been popularized in a recent (2011) documentary film, *Finding Atlantis*, by National Geographic.

In all this time the water body of the Tartessian Gulf allowed for an important boat traffic carrying regional and transcontinental trade, for fisheries and other human activities; and it could have also been the mean through which catastrophic tsunamis arrived.

The transoceanic tsunami generated by the Lisbon earthquake (November 1st, 1755 AD) is well documented in historical accounts. The recorded run-up in Cádiz (Spain) was 15 m. The location of the earthquake epicenter has been extensively studied (Baptista et al., 2003; Barkan et al., 2009), but it still remains as an open problem. Five active faults of tsunamigenic potential have been identified in the Africa–Eurasia plate boundary, west of the Strait of Gibraltar (Zitellini et al., 2009). The last relevant tsunami event in the area (Mw 8.0) occurred in 1969 AD (Guesmia et al., 1998), being originated in one of these faults (the Horseshoe fault). Campos (1991) documented sixteen tsunami events, affecting with different intensity the southwestern Spanish coasts, for the time-period between 218 BC and AD 1900. More recently, Lario et al. (2011) have identified at least five catastrophic tsunami events generated by strong earthquakes affecting this area during the last 7000 years, with a recurrence interval between 1200 and 1500 years.

The oldest catastrophic tsunami is recorded in the Valdelagrana spit-barrier system, and dated at ca.7000–6800 BP. Other event, also recorded in the Punta Umbria spit barrier and in Doñana marshlands, took place at ca. 5700–5600 BP. Between ca. 4500–4100 BP, a large extreme wave event was recorded in the Doñana marshlands as an interbedded marine layer within the inner marsh deposits of the Guadalquivir river estuary. It caused major geomorphological changes (Lario et al., 2011) and seems to be isochrone with the collapse of the Valencina emporium, which is not a demonstration of causality.

Table 1
Some proposed locations for the lost city of Tartessos.

Code	Proposed site	Latitude	Longitude
T1	Isle of Saltés, Huelva (Jiménez-Vialás, 2009)	37°12.43′ N	6°57.42 W
T2	Cádiz (Alvar, 1989)	36°31.95′ N	6°17.98 W
T3	Cerro del Trigo, Almonte (Schulten, 1924)	37°53.40′ N	6°23.53 W
T4	Marismas de Hinojos (Kühne, 2004)	37°57.42′ N	6°22.97 W
T5	La Algaida (Barbadillo-Delgado, 1951)	37°51.33′ N	6°18.41 W
T6	Mesas de Asta (Chocomeli, 1940; Pemán, 1969)	37°47.28′ N	6°10.35 W
T7	*Carteia* (Jiménez-Vialás, 2009)	36°10.96′ N	5°24.76 W
T8	*Caura*, Coria-Aljarafe (Caruz-Arenas, 1969)	37°17.24′ N	6°02.96 W

Codes are used for depicting sites in Figures. The list is not exhaustive. These locations will be used in this paper as reference sites to study processes of marine dynamics.

A younger event (ca. 3900–3700 BP) has also been described and interpreted as a tsunami by Ruiz et al. (2005) and Caceres et al. (2006). Evidences of a widespread catastrophic tsunami have been reported with a radiocarbon data range from 2700 to 2200 cal BP (Luque, 2008; Lario et al., 2011). Thus, it is not clear if they correspond to the same historical documented tsunami of 218–209 BC, or to two distinct events. Particularly, this range includes the collapse of the Tartessian culture around the sixth century BC.

The knowledge on tidal dynamics in this relatively shallow and semi-enclosed marine system could be of interest for reconstructing the living environment of these former cultures. Particularly, the navigation days cited in the Avieno's poem have usually been interpreted as standard sailing distances of some 90–100 km (Caruz-Arenas, 1969), but the occurrence of strong tidal currents could have delayed the trip. Moreover, large tidal amplitudes could have limited the navigation in shallower areas during low tide.

The numerical modeling of tsunami propagation is a relatively well stated methodology which has been validated against recorded data from historical events over the world (Ma and Lee, 1997; Choi et al., 2003; Alasset et al., 2006; Ioualalen et al., 2010). Particularly, the tsunami generated by the 1755 Lisbon earthquake has been modeled, among others, by Baptista et al. (1998), Barkan et al. (2009), and Periáñez and Abril (2013). Similarly, the numerical modeling of tidal dynamics in marine systems is a well-established discipline (Pugh, 1987; Kowalik and Murty, 1993; Periáñez, 2007). Applications of this kind of models for the Gulf of Cadiz, the Strait of Gibraltar and the Alboran Sea have been conducted, among others, by Tejedor et al. (1999), Periáñez (2007) and by Quaresma and Pichon (2013).

The aim of the present work is the application of numerical models for tides and tsunami propagation in the Iberia-Africa plate boundary area, which after independent validation can include the bathymetry of the former Gulf of Tartessos as it was at ca. 4000 BP and 2200 BP. This way, a reliable reconstruction of this marine palaeo-environment can improve our insight on how it could have influenced the human activities of ancient cultures settled around it, and to which extent catastrophic tsunamis could be behind their collapse.

2. Materials and methods

2.1. Bathymetric map of the former Gulf of Tartessos

The computational domain used for the numerical modeling of tsunami propagation comprises from 13° W to 6° E in longitude and from 33° N to 40.5° N in latitude (Fig. 1). Water depths have been obtained from the GEBCO08 digital atlas, available on-line, with a resolution of 30 s of arc both in longitude and latitude. Thus, the domain is covered by a total number of 2,052,000 grid cells. The emerged lands appear with a minimum elevation of 1 m, the minimum water depth is 1 m. Data are provided with a resolution of 1 m.

Little is known about the bathymetry of the former Gulf of Tartessos at 2200–4000 years BP, but it was a rather shallow water body. From a set of dated cores collected in the marshland area, as reported by Ruiz et al. (2004) and Rodríguez-Vidal et al. (2011), accretion over the last two millennia roughly accounted for 1 m of sediments, while the accretion of the Doñana spit-barrier was higher by one order of magnitude.

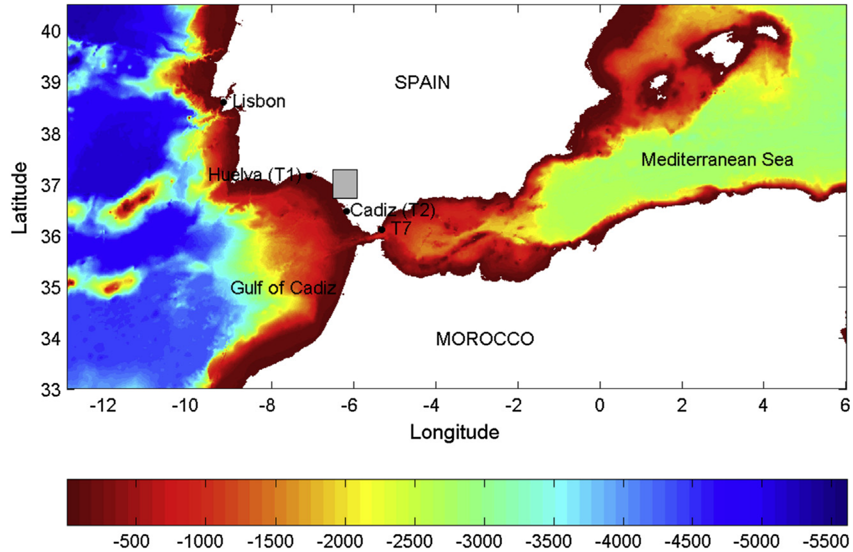

Fig. 1. Model domain used for the tide and tsunami propagation models. Water depths (GEBCO08 bathymetry, 30 s of arc resolution) are given in meters. Some reference cities and other places mentioned in Table 1 are located in the map. The gray box indicates the area of the former Gulf of Tartessos.

The former Gulf of Tartessos has been first re-created at it was at 2200 BP, following the methodology presented by Periáñez and Abril (2013). In the 30-s GEBCO mesh we defined a window containing the nowadays Guadalquivir marshland area. The contour-level of 3 m was then selected as the former coastline, and for the inner cells their original depths/elevations were diminished by 3.5 m. Finally, the details of the Doñana and the Algaiba spits prior to the 218–209 BC tsunami have been introduced by digitizing the paleographical reconstruction by Rodríguez-Vidal et al. (2011) (their Fig. 6A).

A similar methodology has been applied for the re-creation of the former Gulf of Tartessos as it was at ca. 4000 BP, but using the contour-level of 7 m (based upon the results of the Marismas Project by Arteaga and collaborators), and applying a correction of 7.5 m to depth/elevations within the gulf. At that time the Doñana spit-barrier was less developed, taking into account the accretion rates estimated by Rodríguez-Vidal et al. (2011). In our model the southern extent of the spit barrier has been limited to 36° 57.5′ N, in reasonable agreement with the paleographical study by Gavala (1959). A uniform water depth of 7.8 m has been initially ascribed to the grid cells nowadays occupied by this spit, and the surrounding water depths were diminished by 3 m. A filter was finally applied to smooth the bathymetry using mean values between adjacent grid-cells.

The studies on sea-level rise for the SW Iberian Atlantic margin (Boski et al., 2002; Delgado et al., 2012) provide mean values of 7.3–8.5 m ky^{-1} for the period 13 ky–7.5 ky BP. After a second phase of slower rise, the mean sea level (MSL) close to the present was attained at ca. 5 ky BP (Boski et al., 2002). Thus, and taking into account the involved vertical resolution in GEBC008 database, corrections due to changes in MSL have not been explicitly considered in this work. Nevertheless, results from both configurations (two chronologies) can also provide some insight on model sensitivity to small-scale bathymetric settings.

2.2. Numerical model for tsunami propagation

The numerical model has been presented in detail elsewhere (Periáñez and Abril, 2013). It is based on the two-dimensional hydrodynamic equations (Appendix A) and allows calculating maximum wave amplitude, arrival times and tsunami run-ups. This is achieved by means of a flood-drying algorithm. 2D modeling is justified by the size and complexity of the studied system and because tides and tsunamis involve barotropic waves; but it is worth noting that 3D models are being increasingly used in relation to systems of smaller-scale (Alasset et al., 2006; Kowalik et al., 2007; Bøe et al., 2007; Choi et al., 2008).

The modeled tsunami originates at a given active fault. Following the earthquake, the seafloor is displaced from its original position, which produces an almost instantaneous and equivalent deformation of the water surface. Initial deformation is estimated by the classical formulas by Okada (1985) from the known position, length, and width of the fault, along with its slip, strike and dip angles, as well as seismic moment and rigidity. This also allows the estimation of the total potential energy (Kowalik et al., 2007). Thus, the Lisbon tsunami (1755) released the energy of 835 kilotons, which propagated as a gravity wave over the Atlantic. The propagation of the gravity wave is computed by solving the depth-averaged equations for the conservation of mass and the two Cartesian components of the momentum in a rotating Earth (Appendix A). This way, Periáñez and Abril (2013) simulated the historical tsunamis of Lisbon (1755) and Algeria (1856 and 2003). Their results reliably accounted for the recorded data on run-ups and arrival times, which can be considered as a model validation. After that, the model can be used as a predictive tool. Here it is applied to simulate the propagation of tsunamis in the computational domain which contains the former Gulf of Tartessos as it has been reconstructed at ca. 2200 BP and 4000 BP.

2.3. Numerical model for tide propagation

Tides are described by the same 2D depth-averaged equations in Appendix A. The main difference is that water surface elevations are prescribed along open boundaries from information in Schwiderski (1980a,b). Prescribed tides then propagate into the model domain. Once that stable oscillations are achieved, standard tidal analysis is carried out (Pugh, 1987) to obtain tidal constants (amplitudes and phases of water elevations and currents over the domain). These tidal constants are required to plot the model results described below. Tidal computations, using the present topography (i.e., without the former Gulf of Tartessos), have been carefully tested through comparisons of calculated tidal constants with those obtained from observations (Periáñez, 2007, 2009). Moreover, these tidal computations were used as the basis for pollutant transport models developed for southern Iberia waters (Periáñez, 2007, 2009). Details may be seen in these references.

3. Results and discussion

3.1. Bathymetries

The reconstructed bathymetries for the former Gulf of Tartessos at ca. 2200 BP and 4000 BP are depicted in Fig. 2. Besides the details for the mouth of the Gulf, already commented above, the inner coastline remains essentially the same, except in its upper reaches in the northeast area, for both bathymetries. The coastline for 4000 BP reasonably fits to the one reconstructed for the early Holocene from geological studies by Gavala (1959), who placed the Guadalquivir outlet near Coria. He also depicted the reference cities in Fig. 2 in the same relative position with respect to the shoreline. Results are also consistent with the geoarchaeological studies carried out in the area of Seville by Barral (2009).

Nevertheless, both bathymetries are only tentative. Although the work by Rodríguez-Vidal et al. (2011) provides some insight on the accretion rates in its western area, there is a lack of data for the northeastern part and around the main riverine inlets, which most likely suffered higher sediment accumulation rates. Consequently, water depths in these areas should have been somewhat larger than our estimations. The uniform correction of 3.5 and 7.5 m applied, respectively, for the 2200 BP and 4000 BP chronologies then have to be understood as a compromise between simplicity and a rough estimation of mean accretion rates. Anyhow we found a rather shallow marine system which would have been navigable in its inner central part for the ancient Phoenician transport boats, with typical drafts of 1.5 m. The approach to the shoreline should have been problematic in many places, particularly when the system evolved towards the situation of 2200 BP. This is consistent with some Phoenician tales accounting for these shallow waters (Caruz-Arenas, 1969). Nevertheless, most of the places in the shoreline could have been accessible for the smaller Phoenician flotsam, as those found in Mazarrón (Spain), with 8.2 m length, 2.2 m beam, and a maximum strut of 0.9 m, and dated from the second half of the VII century BC (Martínez-Alcalde et al., 2009).

Concerning the proposed locations for the city of Tartessos, location T8 (*Caura*, nowadays Coria) was in the shoreline at 4000 BP, and at 2200 BP it could be reachable by boat overcoming the Guadalquivir River, as during present (it must be noted that the course of the river is not depicted because of the low resolution of Fig. 2). The same can be said for the ancient settlement of Valencina (in the vicinity of Seville). Location T6 was at the close end of a small bight, where a marine harbor has been documented (Esteve, 1969). The place T5 (La Algaida) occupied a small island at 4000 BP, which was later connected to the Sanlucar area by a spit barrier. According to the work by Rodríguez-Vidal et al. (2011), location T4 was at most a flooded marshland at 2200 BP and it should have been submerged before; thus it can be discharged for any human settlement within this chronological range. Finally site T3 occupies a place of recent geological formation (between 4000 BP and 2200 BP). Shulten and Bonsor found some Roman salt-works there. The location of these settlements beside the former coastline suggests an important role of this inner marine system, either as a source of food supply and/or as an appropriate mean for transportation of goods at regional and transcontinental scale.

3.2. Tsunamis

The speed of gravity waves in the ocean is proportional to the square root of the water depth. Thus the tsunami wave travels at high velocity in the deep ocean, but when it approaches the shallower shoreline an amplification phenomenon takes place: the velocity decreases but, to preserve the total energy, the wave increases its height. Consequently, tsunamis can produce primary catastrophic effects through strong water currents and waves of large amplitude which break on the coastline, being able to flood large flat areas.

Periáñez and Abril (2013) studied the potential hazardous impacts in the coasts of the Gulf of Cádiz due to tsunamis generated in the five known active faults around the Atlantic area of the Iberia-Africa plate boundary. Concerning the nowadays coastline lying between Huelva and Cádiz, the highest impacts would be linked to the Cádiz Wedge fault (34.833°N 9.329°W). But the 1755-Lisbon tsunami (with its proposed source at 36.042° N 10.753° W, adapted from Barkan et al., 2009) produced even higher run-ups. Thus, this last source has been selected in this work as being

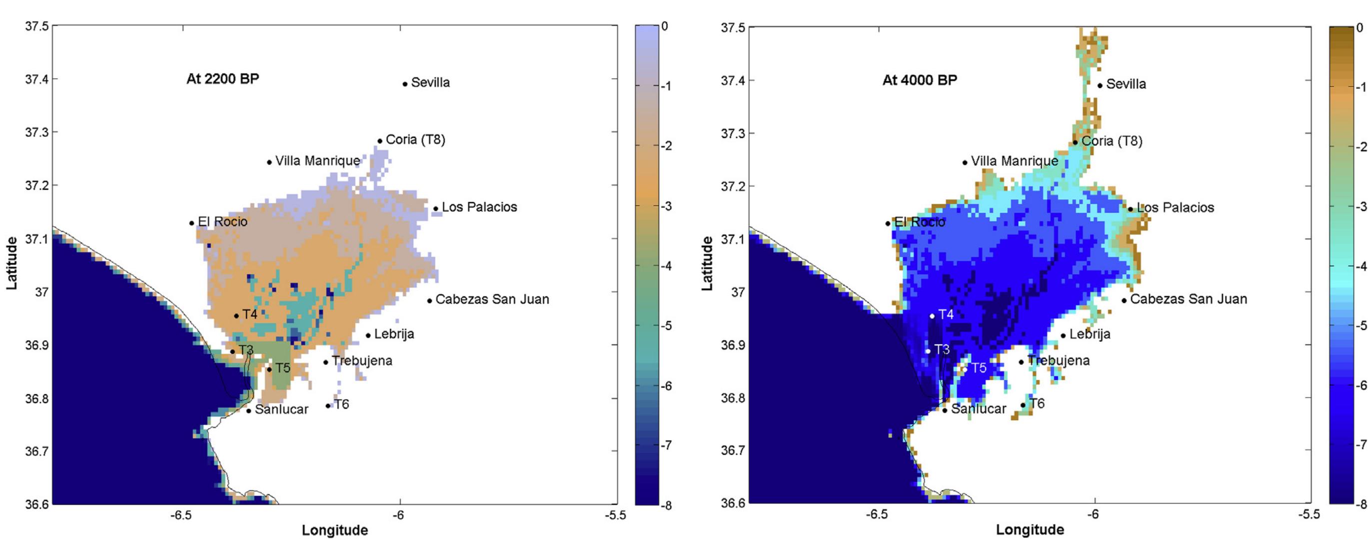

Fig. 2. Bathymetric maps of the former Gulf of Tartessos as reconstructed for ca. 2200 BP and 4000 BP. Color scale is provided in meters. Nowadays cities are depicted as reference. T3 to T8 correspond to some proposed locations for the lost city of Tartessos, as listed in Table 1. The continuous line is the nowadays coastline. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

representative of the worst case of a tsunami affecting the former Gulf of Tartessos. This is also consistent with the estimated epicenter of the 218–209 BC tsunami which affected this area with run-ups of ∼5 m, and being likely located near Cape San Vicente (Rodríguez-Vidal et al., 2011).

Fig. 3 shows the sequence of the propagation, at 15 min intervals, of a 1755-Lisbon like tsunami in which the amplification phenomenon can be observed. It may also be seen that a depression in the sea surface appears after the passage of the wave front. Inline Supplementary Figs. S1 and S2 show some snapshots with the arrival of the tsunami wave to the Cádiz-Huelva coastline, and its propagation within the former Gulf of Tartessos (2200 years BP). The computed time series of water elevations in the vicinity of the proposed locations for the city of Tartessos (Table 1) are depicted in Fig. 4. The effect of the gulf bathymetry on the propagation of a tsunami in locations outside it, as T1 (Isle Saltés, Huelva), T2 (Cádiz) and T7 (*Carteia*), is negligible. A wave of 9.3 m reaches Cádiz 70 min after the earthquake originating the tsunami, then waters recede and the sea level depresses about 4 m under its equilibrium level. Later, a series of minor perturbations hit the coast for several hours. In Huelva, a first wave of 4.0 m arrives two minutes later than in Cádiz, but replications are stronger, with a third wave of about 3 m arriving after 80 min. The tsunami hardly penetrates the Mediterranean due to the presence of the narrow Strait of Gibraltar. But in

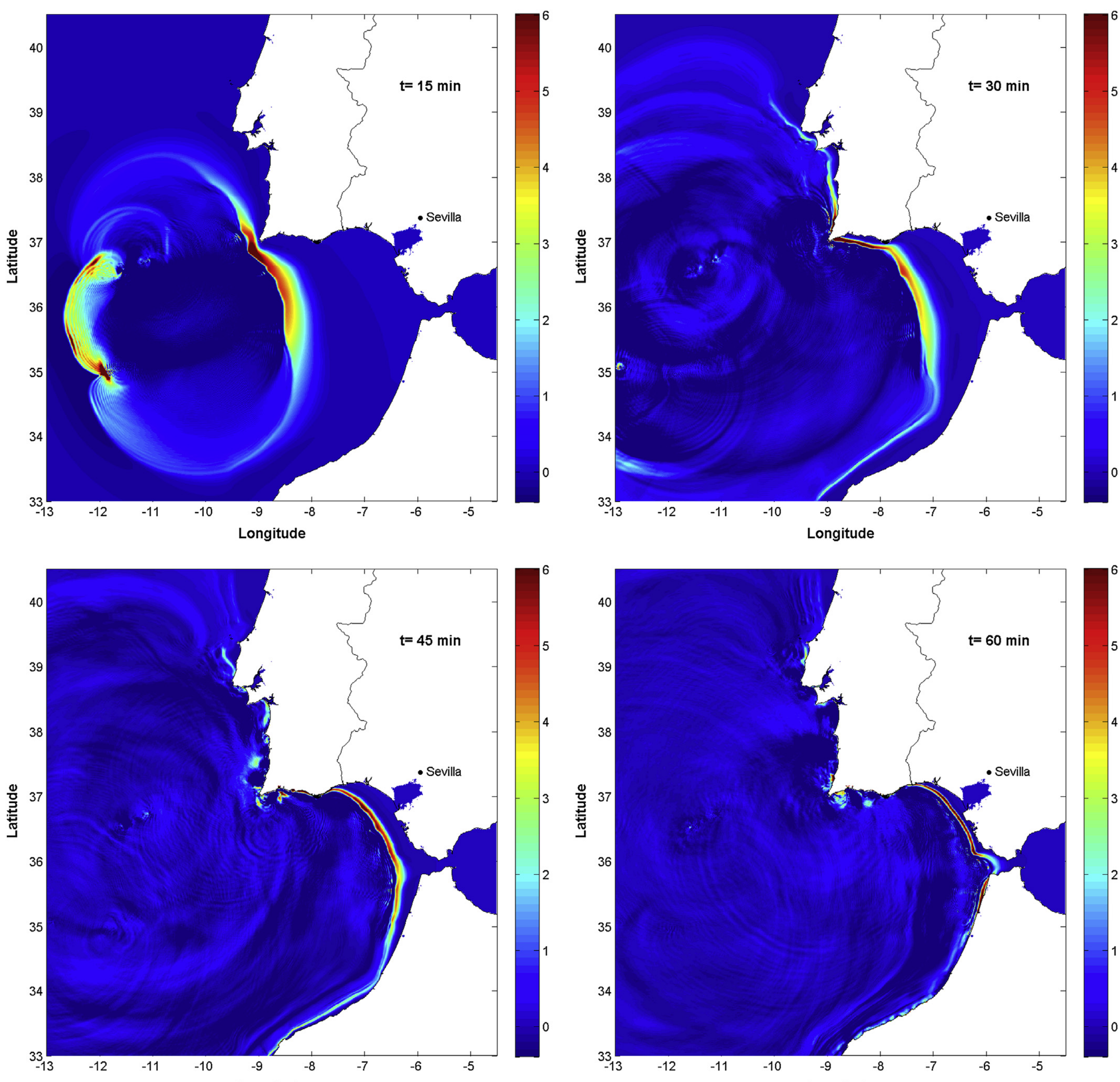

Fig. 3. Propagation of a 1755-Lisbon like tsunami. Computed water elevations (m) above mean sea level at 15 min intervals. The source has been prescribed as in Periáñez and Abril (2013). The domain includes the former Gulf of Tartessos (at ca. 2200 BP).

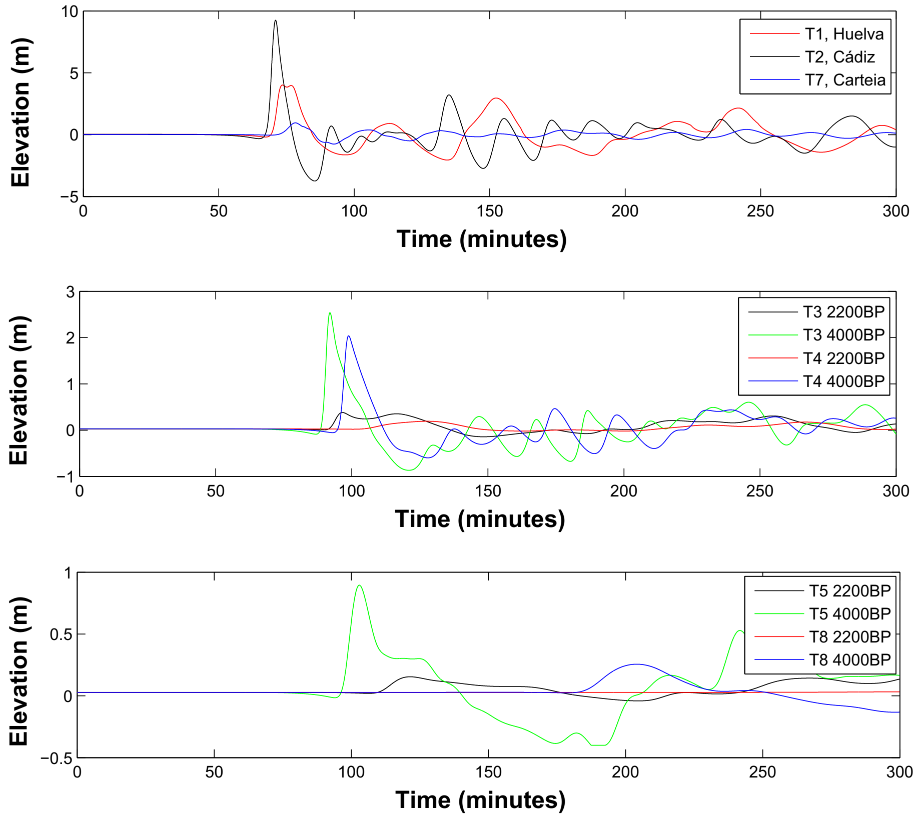

Fig. 4. Computed time series of water elevations at several proposed locations for the lost city of Tartessos (Table 1) for the tsunami of Fig. 3 using the reconstructed bathymetries for 2200 BP and 4000 BP. For locations T1 (Isle Santé, Huelva), T2 (Cádiz) and T7 (Carteia) the effect of different bathymetries is negligible.

Carteia, located in Algeciras Bay, with an eigenmode being excited by this tsunami (see Periáñez and Abril, 2013), the maximum height of the wave is about 1 m.

Inline Supplementary Fig. S1 can be found online at http://dx.doi.org/10.1016/j.jas.2013.06.030.

Inline Supplementary Fig. S2 can be found online at http://dx.doi.org/10.1016/j.jas.2013.06.030.

In the inner shoreline of the former Gulf of Tartessos, the effects of the tsunami strongly depend on the bathymetry and on the width of its entrance (Fig. 4). Thus, for the shallower and semi-enclosed gulf at 2200 BP, the western vicinity of location T3 is flooded, but the inner area remains almost unaffected. In the configuration for 4000 BP, waves over 2 m height hit locations T3 and T4, and the tsunami could be noticed at Caura, in the most inner part of the gulf.

Fig. 5 provides a general view of the spatial distribution of maximum wave amplitude and water currents within the former Gulf of Tartessos after a 1755-Lisbon like tsunami, and for the two bathymetries. It can be seen that in the surrounding waters outside the gulf the wave amplitude easily exceeds 6 m, but it quickly drops at the entrance of the gulf (its inner extent being higher for the 4000 BP configuration). Nevertheless, this energy dissipation is linked to other harmful effects of the tsunami through the morphological changes resulting from the associated strong water currents. Thus, the computed maximum water current amplitude exceeds 5.0 m s^{-1} in most of the Atlantic coast, and it is over 3.0 m s^{-1} in the mouth of the gulf itself. Thus, from these figures, the expected morphological impacts of a 1755-like tsunami would consist of the erosion of the coastal sediments and their subsequent spreading on the western area of the former Gulf of Tartessos, according to the work by Rodríguez-Vidal et al. (2011), which describes the effects of the historical tsunami in 218–209 BC.

From these results it can be concluded that a catastrophic tsunami could have hardly affected the site of Valencina at the end of the third millennium BC. Following Nocete et al. (2010), their associated settlements extended over the low Guadalquivir valley and over the northwestern area of the former Gulf of Tartessos. Although there are evidences for transcontinental trade (e.g. ivory), at present there is not any empirical support for the existence of a hypothetical harbor of capital and strategic importance located in the outer area of the gulf which could have been destroyed by an isochronic catastrophic tsunami. In any case, the ports of Southern Iberia at the Copper Age were not permanent buildings, as the boats directly beached on the shore.

The situation for the VI–VII century BC tsunami is slightly different. Firstly, and although there are some geological evidences which have been dated at that time and interpreted as the effects of a tsunami (Lario et al., 2011), its spatial extent is not so well documented as for the other major events. On the other hand, its potential hazardous effects have to be interpreted as an intermediate situation between the two configurations for the former gulf, 4000 BP and 2200 BP, although closer to this latter. The inner ports around *Caura* and the Carambolo (close to Seville) remain in the safe side. Locations T3 and T5 could have suffered moderate to severe damage, but hardly being extreme enough as to justify the collapse of the Tartessian world. Finally, a 1755-Lisbon like tsunami should have had drastic effects in the Phoenician settlement in Cádiz (T2) and, in some lesser extent, in Huelva (T1). Gómez-Toscano (2002) noticed a crisis in the Phoenician influence in the area of Huelva at the end of the VII century BC, and also new trade relationships with Greek sailors. Beyond isochronisms, the modeled tsunami only represents a proxy to the worst case, and archeological evidences are needed to support any hypotheses involving the catastrophic impact of a tsunami in these settlements.

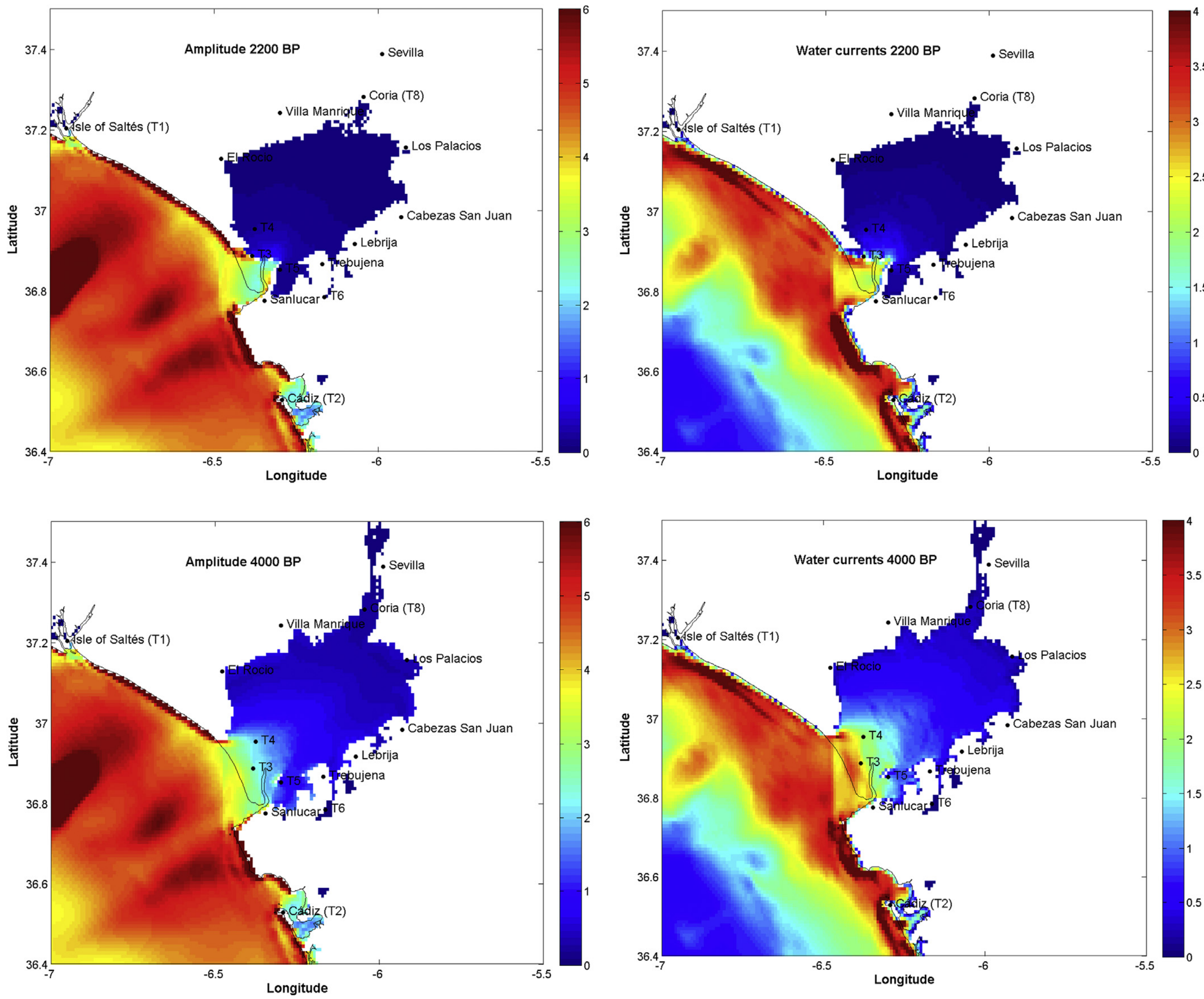

Fig. 5. Computed maximum amplitude of waves (m) and currents (m s^{-1}) after a 1755-Lisbon like tsunami in the former Gulf of Tartessos as reconstructed for 2200 BP and 4000 BP. Simulation time 5 h. Labels are as in Fig. 2.

Understanding the extent of the potential impact of a tsunami on the boat-fleet, harbors and other infrastructures supporting navigation through these waters requires a better knowledge on former environmental conditions, and, particularly, on tidal dynamics. This will be studied in the next section.

3.3. *Tidal dynamics*

From Fig. 6 it can be seen that the tide amplitude within the former Gulf of Tartessos due to the main M_2 constituent remains below 20 and 50 cm, respectively, for bathymetric configurations of ca. 2200 BP and 4000 BP. The amplitude of the S_2 constituent, the second in importance in the area, is roughly 50% of the one of M_2. Thus, and despite of the non-linear effects, their superposition, which produces the neap-spring cycle, would result in combined tide amplitudes below 30 and 75 cm, respectively – these being relatively small values when compared with the mean water depths. Consequently, the navigation through the inner and shallow gulf would have not been affected by significant changes in water levels.

Concerning the computed water currents for the M_2 constituent (Fig. 6), their amplitudes remain below 0.2 and 0.4 m s^{-1} in most of the inner part of the gulf for the configurations of 2200 BP and 4000 BP, respectively, but they exceed 0.5 m s^{-1} in the mouth of the gulf. The combined effect with the S_2 constituent would increase these later values up to roughly 0.7 m s^{-1}. At some times, and under strong wind conditions, these values could have been significantly higher, making the passage difficult for the ancient Phoenician boats, particularly through the narrow channels between the Algaida spit-barrier and the two small islands existing at ca. 2200 BP in the entrance of the gulf. Thus, Fig. 7 shows for this place beside the Algaida, the time series of computed water currents and elevations over a half neap-spring cycle, resulting from the superposition of M_2 and S_2 constituents (being both explicitly solved for the two configurations of the former Gulf of Tartessos). Consequently, it is possible that boats had to be anchored at a safe place, waiting for more appropriated conditions. In this sense, some guidance from the Algaida and/or from the other islands could have been helpful for navigation. It is worth noting that La Algaida records a pre-Roman settlement (with a sanctuary) documented in

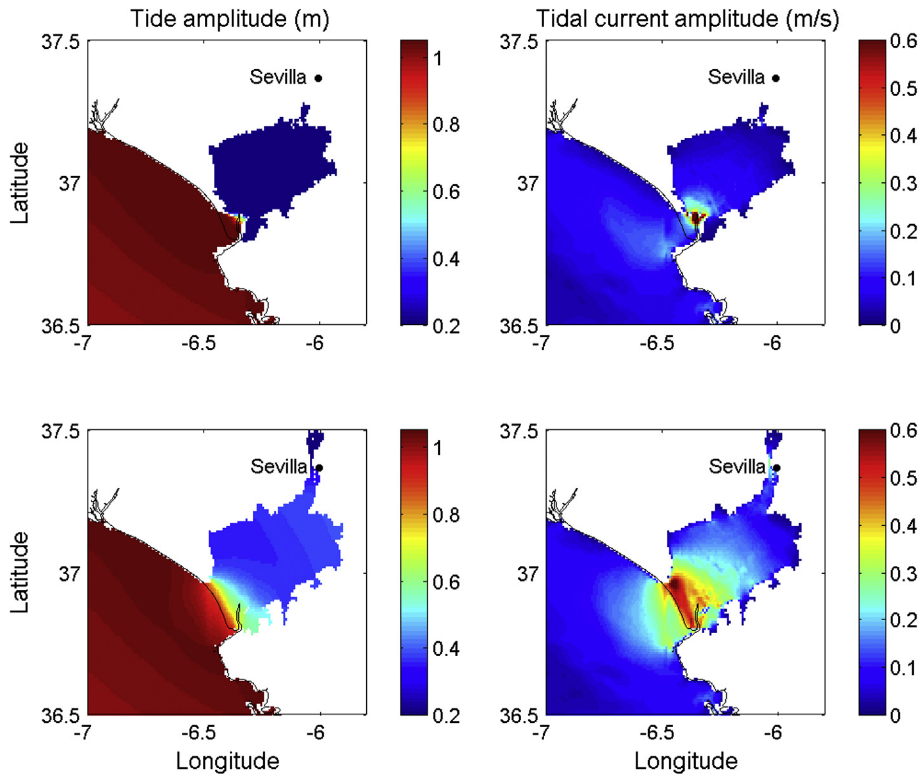

Fig. 6. Computed tidal amplitude for elevations (m) and water currents (m s^{-1}) for the M_2 main constituent, using the bathymetries for 2200 BP and 4000 BP for the former Gulf of Tartessos.

this coastal area and dated from the VI to the III/II century BC (Blanco and Corzo, 1983; Belén, 2000). Following Rodríguez-Ramírez et al. (1996), this settlement was abandoned approximately at the date of the 218–209 BC tsunami. This tsunami destroyed the spit-barrier connecting the Algaida with the Sanlucar area and it produced enough erosion to remove the two small islands previously developed as an extension of the Doñana spit-barrier, according to the geological studies by Rodríguez-Vidal

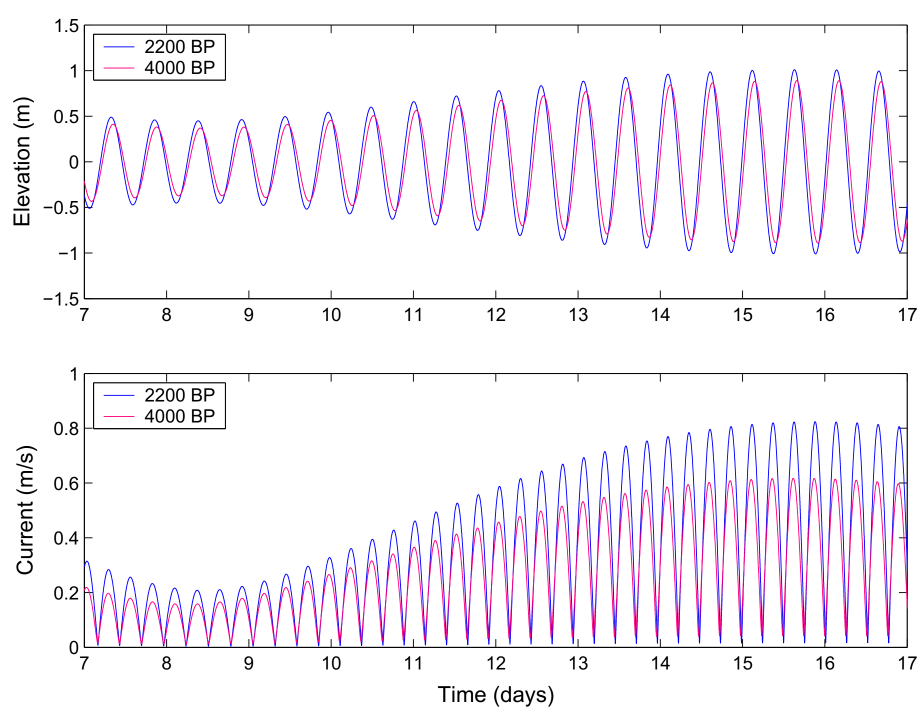

Fig. 7. Computed time series of tidal elevations (m) and water currents (m s^{-1}) beside the Algaida site (T5) resulting from the superposition of M_2 and S_s constituents, using the bathymetries for 2200 BP and 4000 BP for the former Gulf of Tartessos (time in days, with arbitrary origin).

et al. (2011). Once the danger of the straits is overcome, sailing through the inner gulf would be peaceful, with no other risk than entering areas of shallow draft. Finally, the comeback of the Guadalquivir should be somewhat easier with the help of the tidal current.

4. Conclusions

The former Gulf of Tartessos has been reconstructed as it was at ca. 2200 BP and 4000 BP from the contour-levels of 3.0 and 7.0 m, respectively, using the GEBCO08 database with resolution 30 s of arc, and introducing details for the gulf entrance from geological studies (Rodríguez-Vidal et al., 2011). The resulting configurations are in reasonably agreement with other geo-archeological studies.

Numerical models for tide and tsunami propagation, based on the 2D non-linear hydrodynamic equations, have been previously developed and validated for the Iberia-Africa plateau boundary area, and here they have been adapted to include the former configurations of the Gulf of Tartessos.

Catastrophic tsunamis have been registered in this area since 7000 BP, two of them being isochrones with the collapse of the Valencina emporium and the Tartessian culture. Present results reveal negligible impacts for the inner shoreline of the Gulf of Tartessos, but severe damage could have been produced along the Atlantic coasts of SW Spain, from Cádiz to Huelva.

The reconstructed tidal dynamics for the former Gulf of Tartessos results in a relatively quiet inner lagoon, with sea level oscillations of about 10% of the mean water depths, and water currents being of some importance (over 0.5–0.7 m s^{-1}) only in the entrance of the gulf.

These main conclusions, being valid for both configurations, will remain unaffected by small refinements in the used bathymetric data.

Appendix A

The 2D depth-averaged barotropic hydrodynamic equations, which describe the propagation of surface shallow water gravity waves, are (see for instance Kowalik and Murty, 1993):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} - \Omega v + \frac{\tau_u}{\rho H} = A\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + \Omega u + \frac{\tau_v}{\rho H} = A\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

where u and v are the depth averaged water velocities along the x and y axes, h is the depth of water below the mean sea level, ζ is the displacement of the water surface above the mean sea level measured upwards, $H = h + \zeta$ is the total water depth, Ω is the Coriolis parameter ($\Omega = 2w \sin \lambda$, where w is the Earth rotational angular velocity and λ is latitude), g is acceleration due to gravity, ρ is a mean value of water density and A is the horizontal eddy viscosity. τ_u and τ_v are friction stresses which have been written in terms of a quadratic law:

$$\tau_u = k\rho u\sqrt{u^2 + v^2}; \quad \tau_v = k\rho v\sqrt{u^2 + v^2}, \quad (4)$$

where k is the bed friction coefficient. Essentially, these equations express mass and momentum conservation. They have been written in Cartesian coordinates given the relatively small model domain.

All the equations are solved using explicit finite difference schemes (Kowalik and Murty, 1993) with second order accuracy. In particular, the MSOU (Monotonic Second Order Upstream) is used for the advective non-linear terms in the momentum equations.

Still waters are used as initial conditions for tides and tsunami propagation. In the case of tsunamis, the sea-level deformation computed from the classical Okada's formulas is imposed. As boundary conditions, water flow towards a dry grid cell is not allowed. Time series of water surface elevations are prescribed along the open boundaries for tidal simulations. A gravity wave radiation condition (Herzfeld et al., 2011) is imposed along open boundaries for tsunamis. Due to the CFL stability condition (Kowalik and Murty, 1993) time step for model integration was fixed as $\Delta t = 1$ s.

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