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APPRAISAL OF THE 1790 ALBORAN TSUNAMI SOURCE IN THE WEST MEDITERRANEAN SEA AS INFERRED FROM NUMERICAL MODELLING: INSIGHTS FOR THE TSUNAMI HAZARD IN ALGERIA

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ABSTRACT

Compressional active deformation due to the African-Eurasian tectonic convergence is responsible for damaging earthquakes in the Ibero-Maghreb region. On October 1790, a destructive earthquake occurred near Oran city in the western part of Algeria (MSK: X). It generated a tsunami that inundated the Spanish and North Africa coasts. On June 2008, a moderate earthquake (Mw=5.5) with epicentre in the offshore region was felt again near Oran. Although no damage from this earthquake was reported and no tsunami warning information was sent out, some of the coastal inhabitants panicked, fearing a potential tsunami. It became apparent that in order to mitigate risks from loss of life and potential damage, it is necessary to improve on the understanding of potential tsunami sources in this region and to organize a strategy for public education and preparedness.

The present tsunami numerical modelling study is based on the source mechanism of the 1790 Oran earthquake. According to Spanish historic records, following this earthquake, the sea rose by nearly 1.80 meters in height in the harbour of Carthagena, in Spain, and the tsunami inundation was nearly 50 meters inland in Almeria (Lopez Marinas and Salord, 1990). This data helped establish the geometry of the active fault plane that is used in the present study. The dimensions of the tsunami source is estimated from classical empirical seismological relationships. The sea bottom displacement field is calculated from the Okada formalism (1992). Finally, the tsunami's propagation is simulated with the SWAN code that solves the 2-Dimensional non-linear Eulerian shallow water equations (Mader, 2004).

The Oran region is located in the north of the Murdjajo anticline in the southeast Alboran basin. The regional tectonics includes NW-SE compressional stress in Algeria and NE-SW strike-slip structures in the Alboran basin. From field investigations, Bouhadad (2001) identified reverse faulting in the southeastern flank of the Murdjajo anticline. In this work, several scenario are tested to fit the reported tsunami observations. From the results, the identified tsunami source is a 7.5 magnitude earthquake at the entrance of the Oran harbour, with a pure reverse faulting. The tsunami wave height profile obtained for the city of Oran shows an initial withdrawal of the sea that is followed by tsunami run ups of 2 meters in height. The results obtained in Spain agree with the run ups reported in the literature (2 meters in height). The tsunami

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travel time to the Spanish coast was less than twenty minutes. Furthermore the study did not incorporate slides that may be triggered by an earthquake. Offshore seismic surveys have revealed the existence of numerous canyons, slope failures, slide scars and debris avalanches in the Alboran basin and along the Algerian margin (Lastras et al., 2004; Deverchere et al., 2005; Domzig et al., 2009) . This modeling could be improved by including the slide component as a part of the tsunami source.

Introduction

The convergence between the African and the Eurasian tectonic plates results in the occurrence of earthquakes that sometimes generate tsunami in Western Mediterranean. Table 1 lists the major tsunamis reported for the Ibero-Maghreb region.

On October 1790, a devastating earthquake hit Oran city in North Western of Algeria (Io= IX-X, MSK Scale). From historical Spanish documents, Marinas and Salord (1990) reported the extent of damages. In North Africa, castles and fortifications were seriously damaged. Some of them were in ruins (Fig. 1). Two thousands people died. The earthquake was felt until Almeria and Carthagena in south of Spain. The seismic crisis consisted of a series of foreshocks reported during September and beginning of October 1790. The main shock occurred at 01:15 AM on the 9th of October and aftershocks were reported until February 1790. The earthquake was felt as far as 200 km from Oran to Spain.

A tsunami was generated just a few minutes after the main shock. In the Algerian coast, the sea withdrawal was about 200 meters. In Spain, the sea penetrated inland by 50 meters nearby Almeria. In the harbour of Carthagena, the ship “Marie- Salope-la Chata” broke its moorings and the sea rose by 1.8 meters (Marinas and Salord, 1990).

Table 1: Tsunami events in the Ibero-Maghreb (Spanish tsunami catalog, http://www.fomento.es)

Year	Source location	Year	Source location
-218	Cádiz	1856 (08.21)	Algeria
-210	Cádiz	1856 (08.22)	Algeria
-60	SW Portugal	1885	Algeria
881	Cádiz	1891	Algeria
1706	Canary Islands	1954	Alborán Sea
1755 (11.01)	SW Portugal	1969	Gorringe Bank
1755 (11.02)	SW Portugal	1975	AGFZ (Acores Gibraltar Fault)
1755 (11.16)	Coruña	1978	Cádiz
1756	Baleares	1980	Algeria
1790	Alborán Sea	2003 (05.21)	Algeria
1804	Alborán Sea	2003 (05.27)	Algeria

Because of lack of information, the 1790 Oran earthquake is poorly constrained. As regards to the importance of damages, Marinas and Salord (1990) suggested the epicenter was inland. But they also proposed to reevaluate it offshore since a tsunami was reported. In 2001, Bouhadad suggested the earthquake was associated to the Murdjajo active thrust fault identified through field investigations. He also considered the epicenter was inland.

In this work, the 1790 earthquake source is studied from a tsunami modeling approach. The run ups observed and reported in North Africa and Spanish coasts help to constrain the tsunami source. Series of tests are considered to fit reported historical observations from Marinas and Salord (1990).

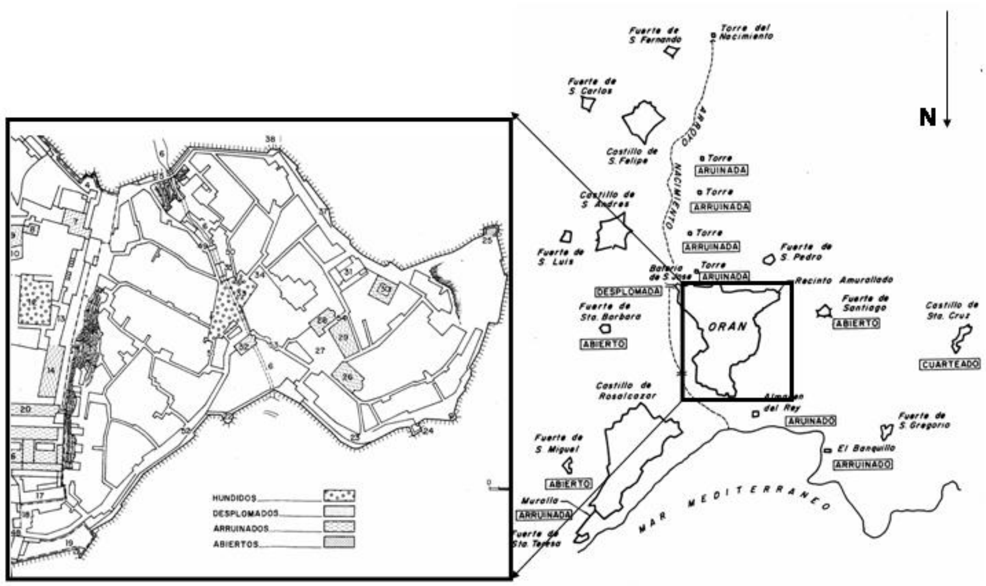


Figure 1: Damages reported in the fortified city of Oran (Western Algeria) (Marinas and Salord, 1990).

Structural Geology and Seismicity of the Alboran Region

The Alboran Sea is narrow and located between the African and the Eurasian convergent tectonic plates (< 1cm.yr^{-1}). It is surrounded by the Betic and the Rif Cordilleras and connects the West offshore Mediterranean to the Iberian Peninsula (Fig. 2a). The geological structure of the region is complex (Ammar et al., 2007; Gracia et al., 2006). Offshore geophysical surveys reveal thrust active fault along the margin and numerous strike-slip accidents that mark the Alboran Ridge. Potential destructive active fault are identified in Iberia and in North Africa. In the South East of Spain, Gracia et al. (2006) reported the existence of a NE-SW offshore continuation of the Carboneras active strike-slip fault system. They suggested it may generate a potential destructive 7.2 magnitude (Mw) earthquake.

The West Mediterranean Margin is marked by numerous escarpments and related active fault (Ex: Arzew, North West of Algeria) (Fig. 2b). Inland, in the nearby of Oran, Bouhadad (2001) identified an active thrust fault related to the Murdjajo Anticline. He estimated the Murdjajo anticline is a N050 assymetric geological structure of about 32 km in length. Geological field and historical investigations revealed the total length of the reverse fault is about 60 km and the fault dips at 60° to the NW. The seismicity recorded in the Ibero-Maghreb area is mostly associated to strike-slip and thrust mechanisms. In the Tell Atlas, the seismicity is shallow. According to Bouhadad et al. (2002), a strong earthquake in the Oran region may be induced by accidents dipping 40° to 60° NW. Finally, the

Arzew escarpment and the related active fault (offshore western Algeria) were well imaged from swath bathymetry (Mauffret, 2007). This structure could be a candidate for a destructive earthquake triggering water waves.

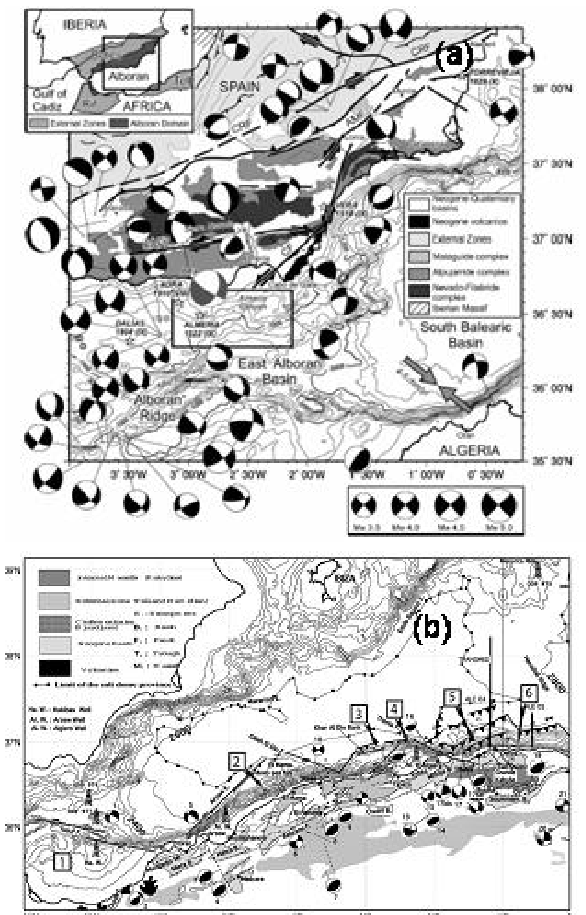


Figure 2: Seismotectonic of the Alboran (2a) and the West Algerian Margin (2b) (Gracia et al., 2006; Mauffret, 2007).

The tsunami modelling

The method

The modelling is performed with the SWAN code (Mader, 2004). This program is a shallow water model that solves the 2D- non linear Eulerian equations with a finite difference scheme. Simulations are computed with the ETOPO 1 Minute Global Relief database (Amante and Eakins, 2009). The grid extends from 34°N to 42°N and 6°W to 2°E (Fig. 3).

The bottom motion due to the earthquake is calculated within the topographic grid using the Okada formalism (1992). The grid resolution for the earthquake and tsunami modelling is 1853 meters in the (Ox) and (Oy) direction.

The seismic moment Mo is converted to the moment magnitude Mw from the Kanamori law (Kanamori and Anderson, 1975). Finally, the empirical seismological relationships from Wells and Coppersmith (1994) help to evaluate the geometry of the fault plane (length, width, dislocation).

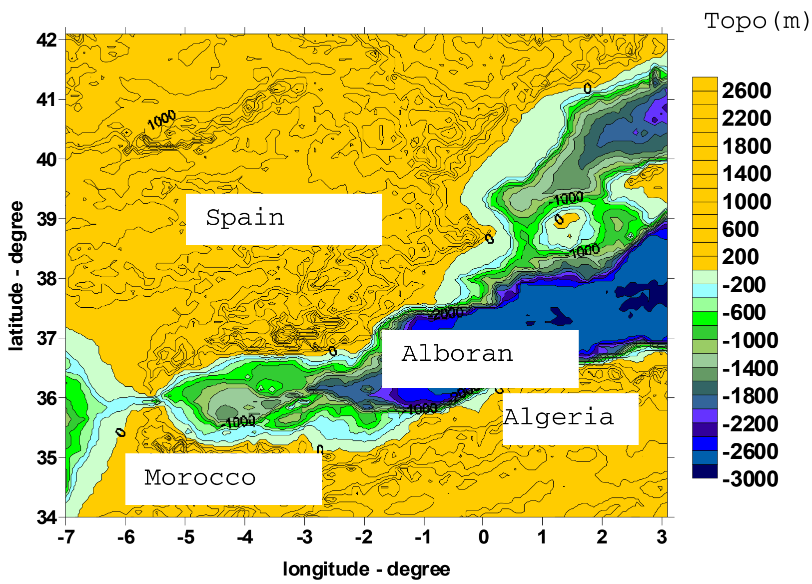


Figure 3: Bathymetry of the Alboran Sea (from ETOPO 1' Global Relief database)

The Tsunami Scenario parameters

In this work, we suggest the 1790 earthquake epicenter is located offshore the Oran bay. The tsunami scenario parameters are selected as regards to the important damages reported by Marinas and Salord (1990), the tectonic sketch of the Alboran and the Tell Atlas (Ammar et al., 2007, Mauffret, 2007) and the field investigations carried out by Bouhadad (2001) on the Murdjajo related fold.

Different tests are computed with a pure thrust fault mechanism (rake is 90°). The earthquake moment magnitudes vary from 7 to 7.5. Fault strike ranges between 40 to 65° NE-SW. The dips tested are between 20 to 45 degrees and the focal depths vary from 5 to 15 km.

Results

The choice of the strike and the dip parameters helped to constrain the seismic source. In fact, the more the strike and the dip are, the greater the South East Spanish coast is affected. From the results obtained, we found the best scenario was a 7.5 magnitude (Mw) earthquake with a pure thrust mechanism at the entrance of Oran harbour (lat, long). The fault strike is 65°N and dips 45° SE.The focal depth is 5 km. The length and width of the fault is 73 km by 29 km. The slip is 3.5 meters.

The figure 4 shows the results obtained for the tsunami propagation through the Alboran Sea. On the whole, the Oran bay is immediately affected by the tsunami waves that reach the Spanish coasts less than 20 minutes after the seismic shock (Fig. 4b&c). The Almeria gulf is the first affected by the waves. The Balearic Islands are also affected by the tsunami waves from 40 minutes (Fig. 4d). In

North Africa, the tsunami largely propagated through Morocco coast and East of Algeria one hour after the earthquake occurrence (Fig. 4e).

Results obtained in the Oran, Arzew (about 20 km W of Oran) and Almeria Bay show the waves were trapped along the coasts for a long time (up to 50 minutes).

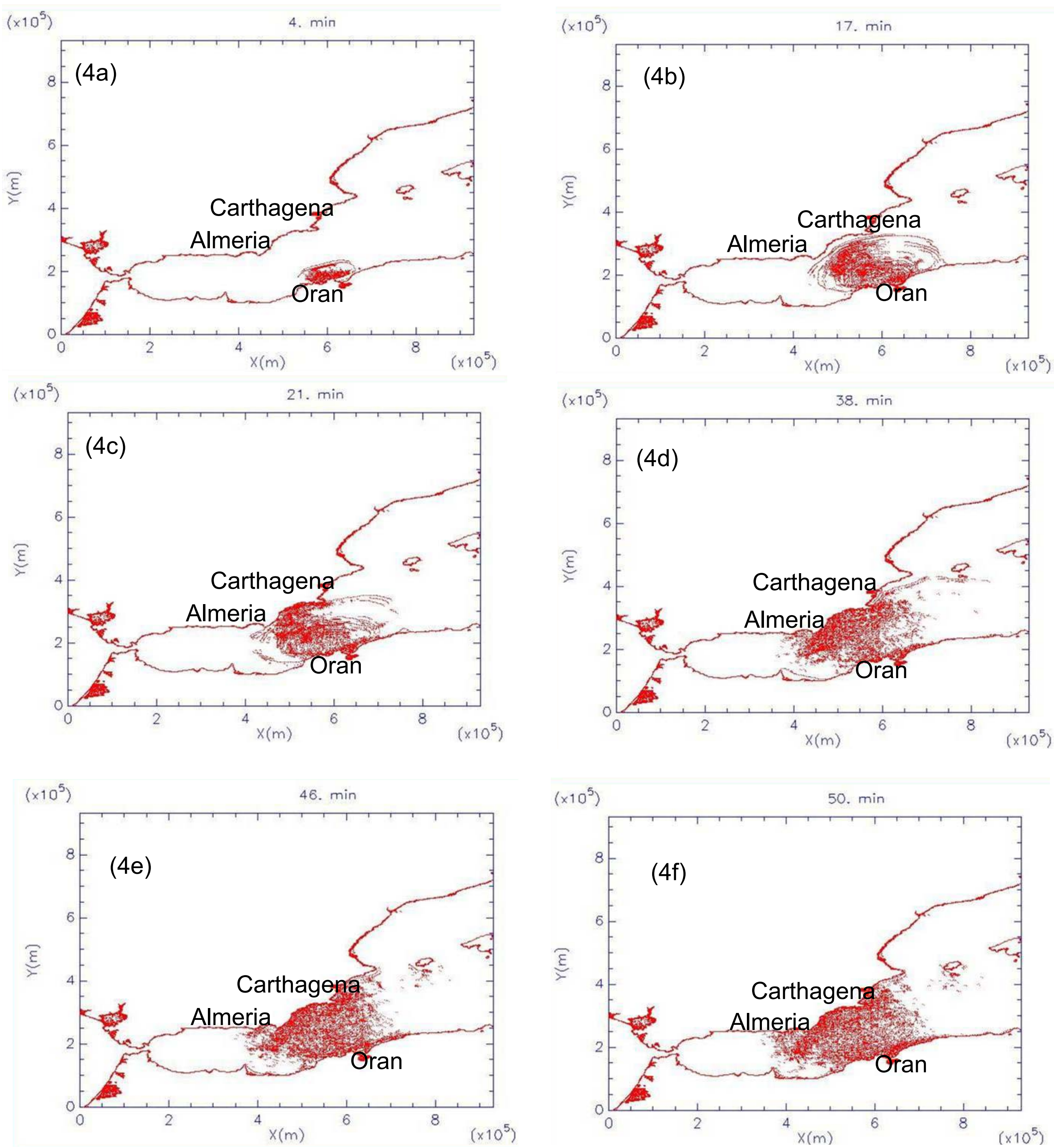
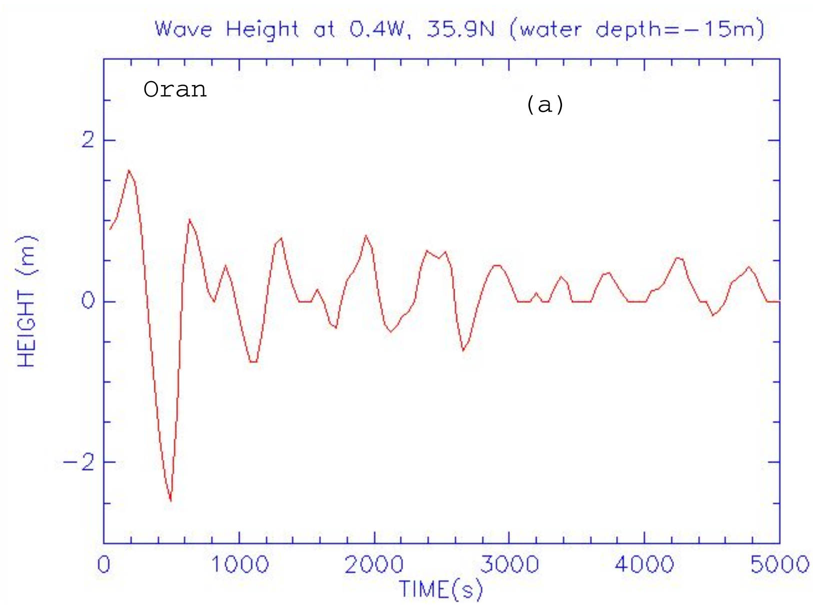


Fig. 4: Snapshots for the tsunami propagation in the Alboran Sea, Mw =7.5.

The figures 5a&b show the water wave profile computed in Oran (0.4W, 35.9N) and Carthagena (0.98W, 37.58N) for a moment magnitude Mw 7.5. Results show run ups are estimated up to 2 meters and 1.5 meters in height in Oran and Carthagena respectively.

In Oran, the first crest is rapidly followed by a trough of 2 meters. Then, the results show the sea level disturbance with several waves of 1 meter in height. In Carthagena, the first crest appears 20 minutes later. It is followed by a trough of 1 meter and water waves ranging between 0.5 and 1 meter in height.



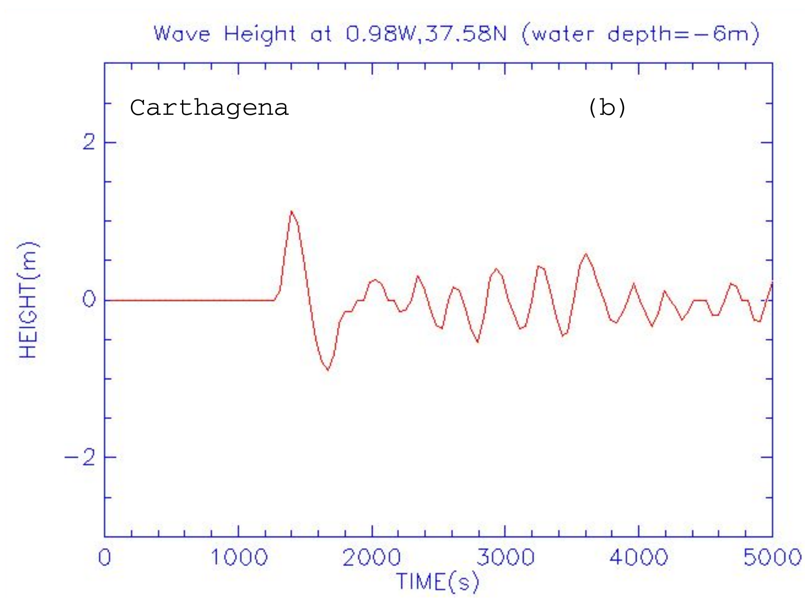


Figure 5: Water wave profile computed in Oran (0.4W, 35.9N) and Carthagena (0.98W, 37.58N) with

the swan code Mader (2004). The water height is in meters and the time is in seconds.

Discussion and Conclusions

From the tsunami modelling, we found the 1790 Alboran Tsunami Source was a 7.5 (Mw) magnitude earthquake with a thrust active fault marked by a strike of 65°N and dipping 45°SE . The epicentre is located offshore at the entrance of the Oran harbour. The fault length is 73 km and its width is 29 km. The numerical results agree with the historical observations reported in Marinas and Salord (1990).

This fault model corresponds to the global trend offshore of the Algerian Margin. In 2003, a magnitude Mw=6.8 earthquake in Boumerdes-Zemmouri triggered a tsunami in the West Mediterranean (Bounif et al., 2004, Alasset et al., 2006).
The Spanish tide gauge in the Balearic recorded run ups around 2 to 3 meters in height. Several fault models are proposed for the 2003 tsunami source to fit the wave amplitude recorded by the tide gauges (Wang and Liu, 2005; Sahal et al., 2009). Hence, we found the resulting fault strike and dip and the focal depth for the tsunami induced by the 2003 Zemmouri earthquake are in the range of order of the 1790 alboran tsunami source.

Offshore Geophysical surveys confirmed the existence of such active thrust fault in the Algerian Margin (Deverchere et al., 2005; Mauffret, 2007). Moreover, swath bathymetry and seismic surveys in the West Mediterranean highlighted evidences of turbidites currents and imaged headwall scarp on submarine canyons suggesting slides and debris flow probably associated to earthquakes events (Lastras et al., 2004; Gracia et al., 2006; Domzig et al., 2009).

In this study, we do not integrate the slide component in the tsunami source. Finally, further modelling should also include a combination of coupled grid with distinct resolution (coarse and thin)to better reproduce offshore coastal geometries and complexity of the small bays (Oran, Arzew, Almeria, …).

The tsunami hazard in Northern Algeria is related to damaging earthquakes with magnitudes greater than 6.5. Because of the combination between the high level of potential damages in case of a destructive earthquake and the short time propagation of triggered water waves, there is a necessity to develop tsunami preparadeness policies in the Mediterranean. In Algeria, the issues related to coastal urbanism also should also be considered in the development of a Mediterranean Tsunami Alert Program (Amir, 2009).

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