1. Introduction

The purpose of this work is to start up a thorough investigation of earthquake-related tsunamis in the Mediterranean area and a systematic assessment of the associated hazards. We focused on strictly earthquake-generated tsunamis, i.e., tsunamis generated by sudden tectonic dislocation of the sea-floor.

We specifically focused on the impact of tsunami waves on the coasts of Central-Southern Italy, that through history have suffered from tsunamis generated by sources located at widely different distance (from a few to a few hundred km). The method we present is proposed as a general scheme to be applied to the coasts of the entire Mediterranean basin. The impact of tsunami waves onto the coastlines is calculated through numerical simulations of tsunami wave propagation.

A compelling issue in the development of realistic tsunami scenarios is the identification and characterization of their potential sources. Here we present an attempt to identify the principal tsunamigenic structures in the Mediterranean area by combining geological and tectonic data on the one hand with historical and instrumental records on the other hand. We benefit from the expertise developed during the DPC-S2 project, and particularly of UR 1.1 Basili (with which we worked in tight collaboration) in the preparation of the most recent version of the Database of Individual Seismogenic Sources (www.ingv.it/DISS). Our approach is a novelty in the assessment of tsunami hazard as it allows preliminary tsunami scenarios to be supplied to their potential end-users while they are being progressively updated at the same pace as the advances in source mapping.

2. Method

In this pilot study we focused on six major tsunamigenic structures, hereinafter referred to as Source Zones (SZs): the southern Tyrrhenian Sea thrust system, the Tell system in the Algeria-Tunisia offshore, the Hellenic Arc, the Montenegro offshore, the Greece-Albania Ionian offshore and the Kefallonia-Lefkada fault system (Fig. 1). For each of these potential source zones we first defined the geometrical parameters of seismogenic faults on the basis of geological and seismological evidence and constraints and assessed the size of the expected earthquakes.

A Source Zone includes an active tectonic structure at regional scale. The geometric and kinematic properties of the structure are assumed to exhibit only small variations inside the SZ; similarly, the rheological and dynamic properties of the tectonic structure are assumed to allow equally large earthquakes to be released all throughout the SZ. We then assume a SZ
is made up of a number of individual fault segments, each of them capable of releasing an earthquake.

For each SZ we identified a Maximum Credible Earthquake (MCE) and an associated Typical Fault (TF). We let the TF float along the entire SZ and computed a tsunami scenario at regular intervals. This procedure allows a number of potential scenarios to be explored based on the information that is more robust - the location and geometry of the fault(s) - without having to worry about the exact location of the ends of the coseismic rupture. The full procedure is summarized below in schematic pseudo-code form.

```
define SOURCE ZONES
choose COASTLINES
for each SOURCE ZONE
define MAX CREDIBLE EARTHQUAKE and TYPICAL FAULT (Mw, rake, dip, length, width, depth, slip)
define SIMULATION PARAMETERS (domain size, spatial resolution, time step)
for each TYPICAL FAULT
    move TYPICAL FAULT along the SOURCE ZONE
    and define discrete TSUNAMIGENIC SOURCES (lat, lon, strike)
calculate Maximum Water Elevation (HMAXs)
End
for each COASTLINE
Calculate MAXIMUM, AVERAGE and STANDARD DEVIATION of HMAXs
End
End
```

To assess the MCE for each SZ we selected the largest earthquake that has ever occurred in that zone and for which there exists, or is possible to obtain, a reliable estimation of the magnitude. We therefore took into account historical and instrumental catalogues, such as the CFTI catalogue [Boschi et al., 2000], the CPTI04 catalogue [Gruppo di lavoro CPTI, 2004], the ISC On-line Bulletin (http://www.isc.ac.uk/), the Global CMT catalogue (http://www.globalcmt.org/), the EMMA database [Vannucci and Gasperini, 2004], and recent literature on the seismotectonics of the study regions. We assumed that such an earthquake may repeat anywhere within its parent SZ at any time in the future, and used its moment magnitude to constrain the size of the TF.

The TF is defined by parameters that must comply with both the seismological properties of the MCE and the tectonic properties of its parent SZ. The TF was let floating at regular steps along the strike of the SZ. At each new position of the TF, strike, dip and rake were adjusted for the internal geometric variations of the SZ. Steps were taken at one fault length. In the case of the Hellenic Arc and of the Kefallonia-Lefkada SZs, shifting was taken at half and 2/3 fault length respectively, to guarantee a sufficient spatial sampling of the tsunamigenic structure. At each new position the TF was made to release its MCE by uniform slip over the entire fault plane. Rupture
was assumed to be instantaneous, because the typical timescale of a tsunami wave is usually much larger than the rupture timescale.

In established simulation practice, tsunami waves are considered as long shallow-water gravity waves because their wavelength is usually much larger than the sea depth. In this study we used the nonlinear shallow water equations, we solved numerically by means of a finite difference method on a staggered grid.

We performed a distinct numerical experiment for each fault position in each SZ for a total of 104 runs. During each simulation we calculated and stored for subsequent analyses the absolute maximum values of water height (HMAX) reached during tsunami propagation at each node of the computational domain. From each simulation and for each of the three target areas (coastlines of Sicily, Sardinia and peninsular Central-Southern Italy; Fig. 2) we extracted three HMAX profiles. For each point along these coastlines the HMAX values produced by each single potential source were grouped according to the source zone. Finally, we calculated the absolute maximum, the average, and the standard deviation of all coastal HMAX values and for each source zone.

3. Selected tsunamigenic source zones and corresponding MCE

Algeria-Tunisia offshore Source Zone. This zone is widely known as the Tell-Atlas thrust system, which accommodates a significant portion of the Africa-Europe convergence in the western Mediterranean. Reverse faulting dominates along most of the Tell-Atlas, whereas strike-slip earthquakes are more frequent at the very western end of the belt. We adopted the 1980 El Asnam earthquake as the MCE. We sized the TF after the moment magnitude of this earthquake as taken from the Global CMT catalog (Mw 7.1). Conversely, strike and dip of the TF were defined on the basis of published tectonic maps of key areas and extended along the trace of the entire SZ (see Tab.1).

Southern Tyrrhenian Source Zone. An E-W narrow contraction belt runs from the Sicily Channel to the Eolian Islands, about 50 km off the northern Sicily coast. The MCE for this SZ was based on the 5 March 1823 earthquake, the largest event reported in current catalogues [Boschi et al., 2000; Gruppo di lavoro CPTI, 2004]. This event is located on the northern coast of Sicily, but, due to inherent difficulties in locating earthquakes in coastal areas, we assume it belongs to the offshore seismic belt and adopted as reference earthquake. Its reported magnitude based on a large set of macroseismic data is Mw 5.9. However, as a consequence of its off-shore location, we believe this value is likely underestimated. We therefore arbitrarily increased it by 0.3 units up to Mw 6.2, still below the maximum potential of M≥6.5 estimated for this tectonic region by Jenny et al. [2006] (see Tab.1).

Hellenic Arc Source Zone. The Hellenic Arc has historically proven to be capable of frequent and occasionally very large earthquakes (M>8) related to the subduction of the Ionian oceanic crust under the Aegean. We considered the 365 AD earthquake as the MCE for this area. The
characteristics of its source are based on a good set of data on raised shorelines (up to 9 m in SW Crete) that have long been interpreted as the effect of coseismic uplift. We used this coastal uplift dataset and fault dislocation modeling to estimate the magnitude (Mw 8.4) that fits best the vertical displacement field (see Tab.1).

Montenegro offshore Source Zone. This source zone belongs to the Dinarides Periadriatic thrust belt, which is characterized by a MCE of Mw 7.2 (1667 Montenegro earthquake) (see Tab.1).

Albania-Greece Ionian offshore Source Zone. As the Montenegro offshore, this source zone belongs to the Periadriatic thrust belt of the Albanides and Ellenides. The MCE is the 1786 Kerkira earthquake, Mw 7.0 (see Tab.1).

Kefallonia-Lefkada Source Zone. This source zone is characterized by a right-lateral strike-slip fault system, which separates the Ellenides from the Hellenic Arc. The MCE adopted is the Mw 7.2, 1953 Kefallonia earthquake (see Tab.1).

4. Results

This section illustrates the results obtained for all simulations in each SZ. The HMAX maps (upper-right panels in Figs. 3, 4, 5, 6, 7 and 8), the are all related to a single sample TF for each SZ. Conversely, the total number of simulations we performed yielded 104 HMAX maps: all these maps will be given in the corresponding deliverables). As this paper is essentially concerned with tsunami threats to the Italian coasts, bottom panels of Figs. 3, 4, 5, 6, 7 and 8 show the tsunami impact along the coastlines of Sicily, peninsular Southern Italy and Sardinia of all the simulations performed for each SZ, respectively. The impact of the tsunami wave is shown as a profile of the aggregated HMAXs maximum, average and standard deviation at each point of all selected coastline stretches. Distances along the coastlines (in km) are taken from an arbitrary starting point and increase counter-clockwise (Fig. 2). They are not intended to be accurate distance measurements but rather to be a practical way to identify positions along the coastlines. Also note that the selected coastline stretches may vary depending on the source zone.

Algeria-Tunisia offshore Source Zone. Upper-right panel of Fig. 3 shows the HMAX values reached during propagation of a tsunami generated by the TF releasing the MCE of this SZ (Fig. 3 upper-left panel). Most of the tsunami energy (roughly corresponding with the area where the wave height exceeds 0.5 m) focuses mainly into two branches orthogonal to fault strike. Fig. 3, bottom panels shows the effects of the Algeria-Tunisia SZ, aggregated for all floating faults. The strongest impact is seen on the coast of Sardinia, where the maximum wave height is frequently higher than 0.5 m, sometimes higher than 1 m, and is negligible only in the North-western part of the island (between 1,000 and 1,200 km). Although the average wave heights rarely exceed 0.5 m, the standard deviations are quite large indicating that the effects on a given location may change significantly depending on the position of the source fault. The maximum wave height generated by any
fault belonging to this SZ on the coasts of Sicily and peninsular Southern Italy is generally less than half of that calculated for Sardinia.

**Southern Tyrrhenian Source Zone.** The TF of this SZ (Fig. 4, upper-left panel) produces very low energy tsunamis (Fig. 4, upper-right panel). Significant waves on the northern Sicily coasts are predicted only in the case of north-dipping faults. Relatively high waves, however, may reach scattered localities on the western coast of peninsular Southern Italy. Fig. 4, bottom panels, shows the aggregated results for all the floating faults of the Southern Tyrrhenian SZ. In general, predicted tsunami waves, even their maxima (black lines), do not exceed 0.2 m. Significantly higher waves (>0.5 m) affect only few localities, scattered on the coast of northern Sicily, such as Palermo itself and Trapani (in the distance ranges 0-300 km) and particularly around Milazzo and the coast west of it (1,100-1,300 km).

**Hellenic Arc Source Zone.** The TF of this SZ (Fig. 5, upper-left panel) focuses its energy along a SW-NE direction (Fig. 5, upper-right panel). Waves higher than 1 m (more than 5 m at some places) are predicted along the coasts of northern Africa, mainly in Libya, the Aegean islands and the coasts all around the source. Fig. 5, bottom panels, shows the aggregated effects of all floating faults of this SZ. The average values are often higher than 2 m and are sometimes not very different from the maximum values. Extreme values exceeding 4 m are common all along the southeastern coast of peninsular Southern Italy. The Adriatic coast of Apulia beyond 2,000 km shows comparatively low wave heights of less than 1 m. Sardinia seems to be rather well shielded by the landmass of Tunisia and Sicily for it experiences waves of less than 0.5 m.

**Montenegro offshore Source Zone.** Upper-right panel of Fig. 6 shows the HMAX values reached during propagation of a tsunami generated by the TF releasing the MCE of this SZ (Fig. 6 upper-left panel). Most of the tsunami energy (roughly corresponding with the area where the wave height exceeds 0.4 m) is trapped by the shallow water of the source region and refracted back toward northern coast of Albania. Fig. 6, bottom panels, shows the aggregated results for all the floating faults of the Montenegro offshore SZ. Predicted tsunami waves do not exceed 5 cm all along the coast of Sicily, revealing a negligible hazard. Differently, the Adriatic coast of Apulia, from 1,700 to 2,600 km shows maximum wave heights of 0.4-0.6 m, especially along the coast of the Gulf of Manfredonia.

**Albania-Greece Ionian offshore Source Zone.** The tsunami generated by TF of this source zone radiates most of the energy toward the southern coast of Apulia (Fig. 7). The average wave heights along the coast of Apulia rarely exceed 0.4 m, though the standard deviations are quite large indicating that the effects on a given location may change significantly depending on the position of the source fault. As for the Montenegro SZ, the tsunami impact against the Sicily coast is very low, with wave heights generally not exceeding 10 cm.

**Kefallonia-Lefkada Source Zone.** All the tsunamis generated by the MCE released on the TFs, floating along this source zone, reveal a peculiar
radiation pattern, characterized by a strong energy focusing toward the southern coast of Apulia (Fig. 8, upper-right panel). This phenomenon, mostly due to wave refraction induced by bathymetric features, produces two distinct peaks along the coastlines of southern Italy: the larger, between 1,700 and 1,900 km (southern Apulia) reaching 0.7 m and a smaller, between 1,000 and 1,300 km (Calabria) exceeding 0.2 m. The wave heights along Sicily are small, not exceeding 10 cm.

5. Conclusions

The Italian peninsula and Sicily are exposed to tsunamis generated both in the western and in the eastern Mediterranean. Our results show that the Sicily Channel and the Messina Strait separate the Mediterranean basin into two sub-basins and effectively act as barriers for E-W tsunami propagation. Our analysis also suggests that, given the relatively small size of the Mediterranean basin compared to the Pacific or Indian Oceans, the identification of all possible sources of earthquake-generated tsunamis is indeed feasible, and that our method can be extended and replicated for different target coastlines (e.g. Spain, southern France, Greece, north Africa). A complete assessment of tsunami hazard, however, would involve the production of inundation maps of selected coastal sections, for example densely populated coastal areas and/or around the main harbors (e.g. the U.S. Tsunami Inundation Mapping Effort, http://nctr.pmel.noaa.gov/time/index.html).

A step beyond. Though not planned nor required for the present project, we conducted a pilot experiment for the production of an inundation map on a small area located south of Catania (Sicily). In Fig. 9 we present the preliminary inundation map of the Lentini Agnone Bagni computed for one of the TF of the Hellenic Arc SZ. The computations have been conducted with a recently developed numerical model which solves the nonlinear shallow water equations with a finite-volume technique and adaptative mesh refinement (George and Leveque, 2006).

6. Deliverables

- Maps of Maximum Height of Wave for each fault and for each source zone (104 maps as jpeg images).
- Maximum Height of Wave along selected coastlines aggregated for each source zone. These data will be put and visualized in a GIS (GoogleEarth).

7. Related Publications

The research conducted and the work done during this project have been presented at international meetings and submitted for publication.


Lorito, S.; Piatanesi, A.; Tiberti, M.; Basili, R. Earthquake-induced tsunamis in the


**References**


**Table 1.** Summary of parameters of the TFs shown in Figs. 3, 4, 5, 6, 7 and 8. L: length; W: down-dip width; D: depth of top edge of fault below sea level.

<table>
<thead>
<tr>
<th>Region</th>
<th>L (km)</th>
<th>W (km)</th>
<th>D (km)</th>
<th>Slip (m)</th>
<th>Strike (deg)</th>
<th>Dip (deg)</th>
<th>Rake (deg)</th>
<th>MCE (Mw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria-Tunisia</td>
<td>35</td>
<td>13.5</td>
<td>1</td>
<td>4</td>
<td>72</td>
<td>30</td>
<td>90</td>
<td>7.1</td>
</tr>
<tr>
<td>Southern Tyrhenian</td>
<td>12</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>273 (93)</td>
<td>45</td>
<td>90</td>
<td>6.2</td>
</tr>
<tr>
<td>Hellenic Arc</td>
<td>130</td>
<td>86</td>
<td>5</td>
<td>17.5</td>
<td>314</td>
<td>35</td>
<td>90</td>
<td>8.4</td>
</tr>
<tr>
<td>Montenegro</td>
<td>50</td>
<td>20</td>
<td>1</td>
<td>2.5</td>
<td>312</td>
<td>35</td>
<td>82</td>
<td>7.2</td>
</tr>
<tr>
<td>Albania-Greece</td>
<td>36</td>
<td>16</td>
<td>1</td>
<td>2</td>
<td>330</td>
<td>35</td>
<td>90</td>
<td>7.0</td>
</tr>
<tr>
<td>Kefallonia-Lefkada</td>
<td>110</td>
<td>18</td>
<td>3</td>
<td>2</td>
<td>27</td>
<td>60</td>
<td>162</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Figure 1. Tectonic sketch map of the Mediterranean basin. Instrumental seismicity (yellow dots; M> 4; depth 0-50 km) is taken from the ISC Catalogue (ISC, 2004). Color-shaded ribbons highlight the main structures capable of generating tsunamis that pose significant hazard to Mediterranean shore-facing settlements (shown in blue. Those shown in red have been investigated in this work).
Figure 2. Map showing distance (km) along target coastlines where the tsunami impact was estimated. This map is intended for use in conjunction with Figs. 3, 4, 5, 6, 7 and 8.
Figure 3. Algeria-Tunisia offshore source zone. Upper-left panel) Map of the source zone. The double-headed arrow indicates the floating path of the Typical Fault (see Tab. 1 for its parameters). Upper-right panel) Map of the maximum wave height in the simulation domain for the tsunami generated by the selected Typical Fault. Bottom panels) Diagram of tsunami impact along the coastlines of Sicily, peninsular Southern Italy, and Sardinia, shown as aggregated HMAX of the wave generated by all the faults let floating along the SZ. Horizontal scales are distances in kilometers: see Fig. 2 for locating the diagram relative to the coastline.
Figure 4. Southern Tyrrhenian source zone. Upper-left panel) Map of the source zone. The double-headed arrow indicates the floating path of the Typical Fault (see Tab. 1 for its parameters). Upper-right panel) Map of the maximum wave height in the simulation domain for the tsunami generated by the selected Typical Fault. Bottom panels) Diagram of tsunami impact along the coastlines of Sicily, peninsular Southern Italy, and Sardinia, shown as aggregated HMAX of the wave generated by all the faults let floating along the SZ. Horizontal scales are distances in kilometers: see Fig. 2 for locating the diagram relative to the coastline.
Figure 5. Hellenic Arc source zone. Upper-left panel) Map of the source zone. The double-headed arrow indicates the floating path of the Typical Fault (see Tab. 1 for its parameters). Upper-right panel) Map of the maximum wave height in the simulation domain for the tsunami generated by the selected Typical Fault. Bottom panels) Diagram of tsunami impact along the coastlines of Sicily, peninsular Southern Italy, and Sardinia, shown as aggregated HMAX of the wave generated by all the faults let floating along the SZ. Horizontal scales are distances in kilometers: see Fig. 2 for locating the diagram relative to the coastline.
Figure 6. Montenegro offshore source zone. Upper-left panel) Map of the source zone. The double-headed arrow indicates the floating path of the Typical Fault (see Tab. 1 for its parameters). Upper-right panel) Map of the maximum wave height in the simulation domain for the tsunami generated by the selected Typical Fault. Bottom panels) Diagram of tsunami impact along the coastlines of Sicily and peninsular Southern Italy, shown as aggregated HMAX of the wave generated by all the faults let floating along the SZ. Horizontal scales are distances in kilometers: see Fig. 2 for locating the diagram relative to the coastline.
Figure 7. Albania-Greece offshore source zone. Upper-left panel) Map of the source zone. The double-headed arrow indicates the floating path of the Typical Fault (see Tab. 1 for its parameters). Upper-right panel) Map of the maximum wave height in the simulation domain for the tsunami generated by the selected Typical Fault. Bottom panels) Diagram of tsunami impact along the coastlines of Sicily and peninsular Southern Italy, shown as aggregated HMAX of the wave generated by all the faults let floating along the SZ. Horizontal scales are distances in kilometers: see Fig. 2 for locating the diagram relative to the coastline.
Figure 8. Kefallonia-Lefkada source zone. Upper-left panel) Map of the source zone. The double-headed arrow indicates the floating path of the Typical Fault (see Tab. 1 for its parameters). Upper-right panel) Map of the maximum wave height in the simulation domain for the tsunami generated by the selected Typical Fault. Bottom panels) Diagram of tsunami impact along the coastlines of Sicily and peninsular Southern Italy, shown as aggregated HMAX of the wave generated by all the faults let floating along the SZ. Horizontal scales are distances in kilometers: see Fig. 2 for locating the diagram relative to the coastline.
**Figure 9.** Inundation at Lentini Agnone Bagni (eastern coast of Sicily) induced by a Mw 8.4 earthquake in the Hellenic Arc. Dashed and solid lines represent sea depth and topographic elevation (in meter), respectively. Red line indicates the coastline before inundation. White and blue colours represent dry and wet areas, respectively.