Insights on the origin of multiple tsunami events affected the archaeological site of Ognina (South-eastern Sicily, Italy)

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Abstract

South-eastern Sicily is among the most seismically active areas of the Mediterranean basin. It is marked by a high-level of crustal seismicity producing major earthquakes (up to Mw ~7) and, as consequence, by several earthquake-generated tsunami events, which have affected the Ionian coast of Sicily in historical times. These tsunami events left geomorphic imprints such as large boulders or high-energy deposits along the coasts. In Ognina, a small residential arealocated 20 km south of Siracusa, high-energy deposit has been detected in the inner part of a narrow coastal channel and correlated with three tsunami events that struck the Ionian coast on 21 July 365 Common Era (CE), 4 February 1169 CE, and 11 January 1693 CE.

In this work, numerical models have been performed to simulate the tsunami impacts considering the most probable tsunamogenic sources described in the literature and integrating them with the reconstruction of past sea-level positions and ancient landscapes. To this end, we used geological and historical information to reconstruct the past topography of Ognina coast and high-performance software (Delft Dashboard, Delft 3d-FLOW and XBeach) to model the tsunami wave propagation in the ancient landscapes.

Modelling results indicate that the 1693 tsunami event was stronger than others impacting the Ognina area, determining significant inland flooding in the narrow channel that is thought to have funnelled the tsunami flow energy. Moreover, simulations show that the most probable tsunamogenic source of 1693 and 1169 tsunami events could be attributed to the Western Fault dislocations occurred off-shore of Siracusa area, rather than other tsunamogenic sources described in the literature and located off-shore of Catania and Augusta. Regarding the 365 event, model results show a long tsunami wave period determining the sedimentation on the lower units in the outcrop. The results of this last event allow presuming that a river channel was present in the Ognina area at least since the IV century and therefore provide a useful element for a reliable reconstruction of the ancient coastal landscape.

The results of this study demonstrate that the use of advanced modelling tools, combined with *in situ* geological evidence, enables both the attribution of coastal geomorphic imprints to specific tsunami events and the identification of the most likely tsunamogenic sources. This last aspect plays a fundamental role in providing more reliable characteristics of the tsunami propagation phenomenon as well as in the assessing of potential tsunami hazard and related coastal impacts.

Keywords: tsunami; tsunamogenic sources; earthquake; faults; coastal flooding; sea-level.

Introduction

Tsunami impacts are testified by many geological evidence that can be detected both off-shore and on-shore in several coastal sites worldwide (Bryant and Nott, 2001; Kelletat et al., 2005; Mastronuzzi, 2010; Mastronuzzi et al., 2010; Papadopoulos et al., 2014; Chagué et al., 2018; Abad et al., 2020). Due to their energetic features, tsunami waves determine flows able to transport high-energy deposits, to which out-of-size and out-of-layer sediment deposition can be attributed.

The analysis of these deposits allows to increment the knowledge about the characteristics of past tsunami events (in terms of wave energy and inland propagation) and to integrate the lack of information about their occurrence at a time-scale longer than instrumental and historical records, leading to the definition of detailed local and regional catalogues (*List of Tsunamis - International Tsunami Information Center*, n.d.; *USGS Earthquake Hazards Program*, n.d.; Soloviev, 1990; Soloviev et al., 2000; Tinti et al., 2004; Guidoboni and Comastri, 2005; Center, 2020; NGDC, 2020).

During the last decades, different approaches have been proposed to recognize tsunami deposits (Dawson and Stewart, 2007; Morton et al., 2008; Shiki et al., 2008; Goff et al., 2012; Costa et al., 2015; Moreira et al., 2017) and several criteria, which include morphological, stratigraphic and sedimentary aspects, have been defined to distinguish them from storm deposits (Nanayama et al., 2000; Kortekaas and Dawson, 2007; Morton et al., 2008; Regnauld et al., 2010). Sedimentological criteria used to recognize tsunami deposits are based on the identification of peculiar transport and sedimentary structures that reflect the energy of the events and the associated wave-height (Shiki and Cita, 2021), as highlighted for example in Scicchitano et al. (2007) where stratal units forming a lithological succession were interpreted and associated with different energy phases of the coastal flooding process induced by a tsunami event. By considering palaeontological criteria, tsunami signatures are characterized by the increase in shells alteration and fragmentation favoured by the high energy of the event (Quintela et al., 2016). Furthermore, due to the dynamic characteristics of the high-energy events, tsunami deposits might contain deeper-water foraminifera assemblages (Hawkes, 2020; Pilarczyk et al., 2020)that are uncommon in the shallow water environment, as find out in Nanayama and Shigeno (2006) where the comparison between different sedimentary deposits related to high-energy events showed that tsunami deposits are mainly derived from the offshore area, suggesting that benthonic foraminifera included in the onshore deposits are entrained from the deep seabed during the tsunami run-up. Nevertheless, when available, archaeological, historical and instrumental data represent suitable resources to improve the reliability of the final attribution of a geological fingerprint to a tsunami event (Mastronuzzi et al., 2007b; Scicchitano et al., 2007; Mastronuzzi and Pignatelli, 2012; Fago et al., 2014; Scardino et al., 2020).

In recent years, several geological evidence related to high-energy waves has been identified over the Mediterranean coasts (Scardino et al., 2020 and reference therein), confirming that this area is strongly exposed to the impact of exceptional marine storms as well as tsunami. These deposits are mainly represented by high-energy sedimentary layers interbedded in coastal plain and shelf deposits (De Martini et al., 2003; 2012; Gerardi et al., 2012), coastal mega-boulders (Mastronuzzi et al., 2006; 2007a; Scicchitano et al., 2007; 2007; 2012; Maouche et al., 2009; Mastronuzzi and Pignatelli, 2012; Abad et al., 2020; Evelpidou et al., 2020), and wash-over fans (Gianfreda et al., 2001; Mastronuzzi and Sansò, 2002; 2012; Vött et al., 2008; 2009; May et al., 2012; Obrocki et al., 2020).

In particular, several tsunami events (Soloviev, 1990; El-Sayed et al., 2000; 2004; Tinti et al., 2004; 2005; Sørensen et al., 2012; Papadopoulos et al., 2014) have been triggered by the major earthquakes occurred in the historical time in the Eastern Mediterranean area that, due to its geo-tectonic setting due to the clash between the Eurasian Plate and the African Plate, is a very seismically active area. The evidence of these events has been detected along the coasts of Greece (Pirazzoli et al., 1999; Scheffers and Scheffers, 2007; Scheffers et al., 2008; Werner et al., 2018; 2019), Southern Italy (Mastronuzzi and Sansò, 2000; Gianfreda et al., 2001; Scicchitano et al., 2007; De Martini et al., 2012; Gerardi et al., 2012), Cyprus (Kelletat and Schellmann, 2002; Whelan and Kelletat, 2002), Turkey (Öğretmen et al., 2015), Lebanon (Marriner and Pirazzoli, 2006), and Aegean coasts (Perissoratis and Papadopoulos, 1999; Vacchi et al., 2012).

With particular reference to the Italian coastal territory, the South-eastern part of Sicily is considered one of the most exposed Mediterranean coastal areas to tsunami impact (Samaras et al., 2015; Lo Re et al., 2020) being marked by a high level of crustal activity (Monaco and Tortorici, 2007) that caused high magnitude earthquakes (Postpischl, 1985; Boschi et al., 1997) as well as landslides and volcanic eruptions. As consequence, devastating tsunami have affected the Ionian coast of Sicily in historical times (365, 1169, 1329, 1542, 1693, 1783, 1818, 1908, 1990 (data from Boschi et al., 2000; Tinti et al., 2004; Gerardi et al., 2008; Barbano et al., 2010) and references therein) whose geomorphic imprints have been detected in many coastal localities (Torre degli Inglesi, Augusta, Priolo, Ognina, Vendicari, Maddalena Peninsula, Morghella) situated along the Sicilian Ionian coast in the municipalities of Messina and Siracusa (Scicchitano et al., 2007; De Martini et al., 2012 and reference therein)

In this study, we focused on the analysis of a well-known deposit detected in a coastal outcrop located in Ognina, a small town 20 km south of Siracusa, whose landform is characterized by a coastal embayment constituting the relict shape of an ancient river mouth, as showed in historical documents (Spannocchi, 1578). Archaeological observations and sediments dating (Scicchitano et al., 2010) allowed correlating these deposits with three past tsunami events that struck the Sicilian Ionian coast on 21 July 365 Common Era (CE), 4 February 1169 CE, and 11 January 1693 CE. By modelling the hydrodynamic of these tsunami events, this paper aims to assess the maximum inland flooding and subsequent deposition of high-energy sediments and to identify the most probable tsunamogenic sources of the studied events.

In order to reconstruct the past landforms that probably influenced the dynamic of the accounted tsunami events, the paleo-landscapes of the investigated area were reconstructed by means of ancient topographies and evaluating the past sea-level positions.

In line with the most recent methodological approaches proposed to investigate past tsunami events (Dourado et al., 2019; and Bosnic et al., 2021), the numerical analysis performed in this study was carried out by defying a high-performing model-chain (obtained by integrating Delft Dashboard, Delft 3d-FLOW and XBeach models) that allows simulating: i) the off-shore tsunami wave propagation; ìi) the on-shore tsunami wave propagation; iii) the inland extent of the flooded area; iv) the cumulative sediment budget. The high-resolution topographic and bathymetric features performed for defying the present-day topography of the investigated area were elaborated by means of GIS tools.

The comparison between the position of the *in situ* geological evidence and the numerical model results, which depend on the benchmark fault location and displacement scenarios, allowed attributing the studied deposits to a specific earthquake-generated tsunami event.

The results of the proposed multidisciplinary approach provide new insights on the origin and characteristics of past tsunami events and define more reliable information about on-shore wave propagation. Furthermore, by identifying the most probable tsunamogenic sources, this study represents a step forward to the identification of the areas where similar earthquake-generated tsunami could occur in the future and therefore it provides preliminary information for the identification of the coastal area potentially affected by tsunami impacts.

2. Study area

2.1 Geological settings

The Sicily region is one of the Mediterranean areas affected by a lot of tsunami evidence along the coasts.

Since the Early-Middle Pleistocene, active faulting has contributed to extensional deformation along the coastal sector of south-eastern Sicily, where NNW-SSE trending normal faults control the Ionian shoreline (Bianca et al., 1999; Monaco and Tortorici, 2000; Monaco et al., 2002). These structures are mostly located off-shore and their Quaternary activity is probably associated with the recent reactivation of the Malta Escarpment system (Gambino et al., 2020). This area is marked by a high level of crustal seismicity that released earthquakes with Magnitude of about 7, such as the destructive events occurred in 1169, 1542 and 1693. The seismogenic sources of these historical events are still debated but they are likely located in the Malta Escarpment, between Catania and Siracusa (Postpischl, 1985; Bianca et al., 1999; Azzaro and Barbano, 2000; Monaco and Tortorici, 2000; Valensise and Pantosti, 2001; Tinti and Armigliato, 2003; Mastrolembo Ventura et al., 2014; Gambino et al., 2020).

During the Late Quaternary, this area has been affected by regional uplifting. Uplift progressively decreases from the southern Calabria to north-eastern Sicily, as shown by flights of marine terraces developed along the coasts (Ferranti et al., 2010; Spampinato et al., 2011; 2012; Meschis et al., 2020). In the northern sector

of SE Sicily, the long-term uplift has been estimated at rates of 0.2-0.7 mm/y from Middle-Upper Quaternary marine terraces and paleo-shorelines (Di Grande and Raimondo, 1982; Monaco et al., 2002; Dutton et al., 2009), gradually decreasing to zero toward the stable areas of the south-eastern corner of Sicily (Antonioli et al., 2006). Toward the south-eastern corner of Sicily, the observed uplift decreases also during the Holocene. In fact, archaeological and borehole evidence show vertical land stability or weak uplift during the late Holocene (Scicchitano et al., 2008; 2016; 2018; Spampinato et al., 2011; 2012).
The studied coastal area has been affected by several marine extreme events in historical times. Effects of several tsunamis have been reconstructed from the analyses of boulder accumulation (Scicchitano et al., 2007; 2012; Barbano et al., 2010), high-energy deposits (Smedile et al., 2011; De Martini et al., 2012) and cores performed inside lagoons (De Martini et al., 2010). This is particularly important considering that in a SLR scenario, the effects of the extreme marine events will probably impact on the coastal landscapes currently emerged. Particularly, the peculiar geodynamic of the area showed that the occurrence of tsunami could be connected not only to off-shore structures but also to the seismic-induced submarine landslide(Paparo et al., 2017).
From Capo Asparano to Capo Ognina, a coastal embayment incised within Miocene limestones owns an outcrop with high-energy deposits (Fig.1, Scicchitano et al., 2010). In this area, a fossilized Holocene beach-barrier system lying unconformably onto the Miocene calcareous bedrock in the inner part of a natural channel. The outermost edge of the narrow channel hosts a little harbour quay and some high-energy deposits were detected and attributed to tsunami events (Scicchitanto et al., 2010).

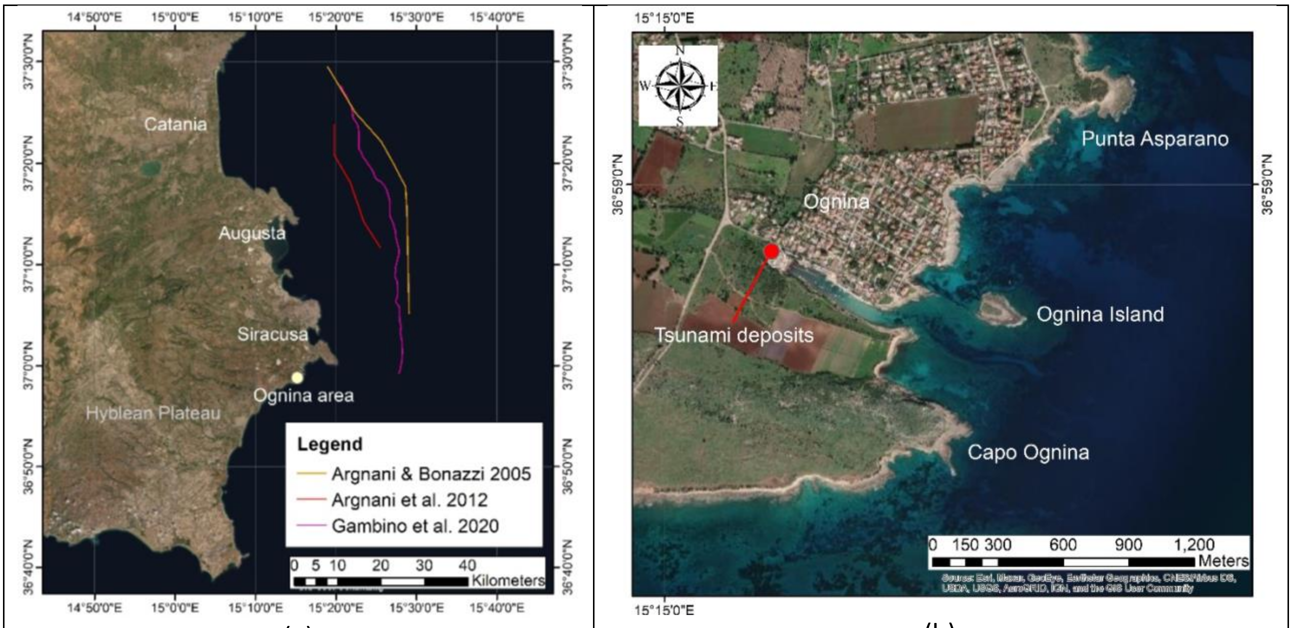


Fig.1 - Geographic setting of the South-eastern Sicily; a) – Geographic framework of the study area and annexed faults-generated tsunami that impacted the South-eastern Sicily; b) – coastal area of Ognina.

2.2 Interpretation of the tsunami geological evidence in the Ognina area

In the area of Ognina, a high-energy deposit located in a natural section on the edge of the coastal embayment were surveyed by Scicchitano et al. (2010). The outcrop is oriented ENE-WSW and it is 20 m long and 0.3-1.8 m thick (Fig. 2). It presents three stratal units bounded by disconformity surfaces and with different amount of shell fragments and archaeological remains. Detailed sedimentological and paleoecological analyses were performed by Scicchitano et al. (2010), through the employ of photomosaic to reconstruct the geometrical features of the strata and the analysis of the fossil assemblages. Radiometric dating of marine organism and age of archaeological remains in the surveyed stratal units were performed to constrain the depositional timing. Furthermore, the analysis performed by Scicchitano et al. (2010) allowed to discriminate the geometry of the stratal units recognized in the Ognina outcrop () and to constrain their deposition timing.

In detail, three different stratal units were recognized and two of them were attributed to two different tsunami events, as showed in Fig. 2. The deposits of the lower stratal unit were attributed to the 365 CE and 1169 CE events and are located in the outermost part of Ognina channel. These units showed foresets and well-sorted sand deposits attributed to landward-directed pulsatory flow (Dawson and Stewart, 2007; Morton et al., 2008; Scicchitano et al., 2010). Sediments were constituted by marine shell fragments of *Cerastoderma spp*. with the presence of terrestrial deposits, probably transported by the uprush of tsunami wave. The intermediate stratal unit is made by finer sediments compatible with low-energy environment with the flat-laminated levels that passed upward to thinner clay-rich intervals interbedded with shell/pebble layer of high-energy processes. Such kind of unit was attributed to storm waves or lower energy tsunami events that determined the breaching of the beach-barrier system with deposition of high-energy layer(Kortekaas and Dawson, 2007; Regnauld et al., 2010). The upper stratal unit showed different deposits from underlying strata, highlighting a basal erosive surface and different size-clastic sediments with pottery fragments encrusted by *Serpulidae* and transported landward. The basal bounding surface locally showed deep erosion suggesting very high-energy processes and very rapid propagation of landward wave flow. The granulometry presented a high-variable grain size typical of no-gravitative mass flow, such as violent dynamic events (Nardin et al., 1979). The encrustation of Serpulidae on the pottery fragments suggests a period of permanence in subacqueos conditions with subsequent scattering landward in response to high-energy wave flow. This stratal unit was interpreted by Scicchitano et al. (2010) as the results of high-energy deposition due to 1693 CE tsunami event.

Fig. 2 Correlation between stratal units detected in the Ognina section.

3. Material and Methods

In order to correlate *in situ* geological evidence with past tsunami impacted the Ognina area, three events (21 July 365 CE; 4 February 1169 CE; 11 January 1693 CE) were numerically modelled for defining the hydrodynamic features of tsunami waves and evaluating the cumulative sediment deposition in different paleo-geographic phases (c.f. flowchart in Fig. 3).

To this aim, the following steps were carried out:

1) Definition of the current coastal landscape;
2) Reconstruction of the paleo-geographic landscapes, representative of paleo-geographic scenarios during the impact of past tsunami waves;
3) Numerical modelling of the tsunami hydro-dynamic features, considering different tsunamogenic sources.

In the following paragraphs (3.1-3.3), each step of the analysis is described in detail.

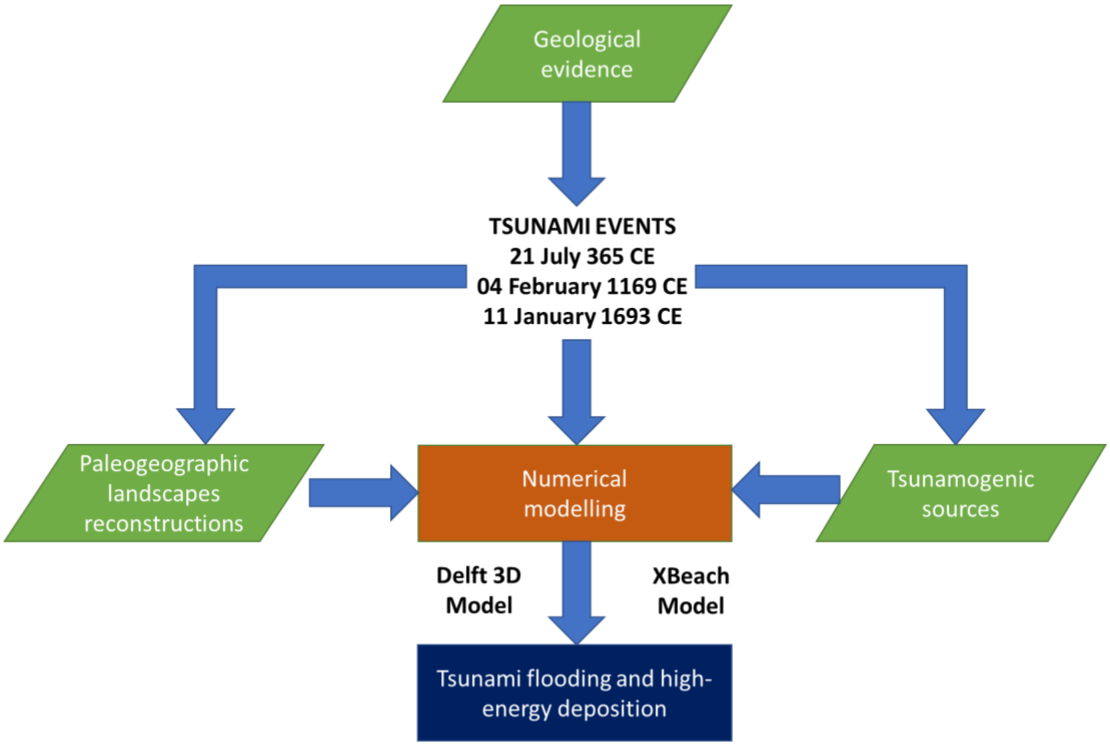


Fig. 3 - Flow chart of the sequential steps employed in this work to model the tsunami propagation and related flooding and high-energy deposition processes.

3.1 Definition of the current coastal landscape of the Ognina area

In order to obtain the Digital Terrain Model (DTM) representative of the current coastal landscape of the Ognina area, topographic and bathymetric surveys performed by Scicchitano et al. (2016) were used. In detail, the topographic features were derived by an aerial-photogrammetric survey performed in 2018 (resolution 30cm) and integrated with LiDAR data of 2008 (property of Regione Sicilia) obtaining a DTM with 2x2 m grid cell resolution. To characterize the bathymetry, a Multibeam survey was performed using a shallow-water vessel and an Autonomous Underwater Vehicle (AUV). The AUV system was adapted to cover the area where the vessel cannot move for safety reasons and allowed to make a better connection between terrestrial topography and marine bathymetry. Resulting data were corrected for tides using the software WX Tide and gridded with GIS to create a DTM of the bathymetry with a cell size of 1 m.

3.2 Reconstruction of the ancient landscape scenarios of the Ognina area

In order to depict an immersive scenario during the impact of past tsunami events, the ancient landscapes characterizing the Ognina area at the time of the occurrence of the accounted tsunami (365 CE, 1169 CE, 1693 CE) were reconstructed considering the past embayment configurations and the past coastline positions. In particular, in order to define the ancient *thalweg* and river mouth, the reconstruction of the old river was obtained from archival documents (Spannocchi, 1578) where the presence of a river was highlighted up to the XVI century, in correspondence of the current harbour (Fig. 4). The ancient river path was reconstructed in GIS environment by analysing the DTM representative of the past landscapes. To this aim, topographical and bathymetric features were digitally reconstructed for the time of occurrence of each tsunami event .

Fig. 4 - The Ognina area as drawn by Tribucio Spannocchi (Spannocchi 1578).

In order to define the ancient coastlines, past Relative Sea-Level (RSL) positions were assessed considering: i) the eustatic contribution; ii) the tectonic movement contribution, and iii) the coastal erosion contribution. Specifically, the sea level positions provided by the eustatic curve of Lambeck et al. (2011) were corrected accounting for the local vertical movements and coastal erosion rates. In particular, the vertical tectonic movements were assessed by means of the Late Quaternary paleo-shoreline elevations that, for Ognina area, revealed an uplift rate of about 0.2 mm/yr (Dutton et al., 2009; Meschis et al., 2020) while, for the coastal erosion contribution, the rate value of 0.14 mm/yr (suitable for the limestone) was considered (Furlani and Cucchi, 2013).

3.3 Numerical modelling of the tsunami hydro-dynamic features

The off-shore tsunami generation was modelled by means of DelftDashboard-Delft3D Flow model (Le Quéré et al., 2020). Delft3D is a three-dimensional coupled hydrodynamic numerical model, which solves the nonlinear shallow water equations (NLSWEs) on a three-dimensional staggered grid using a finite difference scheme. The Delft3D Flow requires the definition of fault parameters and magnitude of the seismic event to generate the initial wave conditions and to model wave propagation toward the coast. Fault parameters of the 21 July 365 event were derived by Stiros (2010) and Ohsumi et al. (2018), while for the events of the 4 February 1169 and 11 January 1693, the Western Fault parameters of Gambino et al. (2020) were considered (Table 1).

Table 1- Fault parameters of tsunami events impacting the South-eastern Sicily in 365 CE, 1169 CE, and 1694 CE.

Date of tsunami	Geological structure	Focal Depth (km)	Fault length (km)	Strike (°)	Dip (°)	Rake (°)	Width (km)	Slip (m)	Mw
21 July 365	Hellenic Fault	45	100	330/50	30	45	70	20	8.3
04 February 1169	Western Fault	20	30	179	28	270	16.5	3	6.8
11 January 1694	Western Fault	20	30	179	28	270	16.5	3	7.3

The characteristics of tsunami propagation, from deep to shallow waters, are very different for each event and the modelling process implies the use of different grid resolutions to represent the wave dynamics at different spatial scales. For this reason, the simulation of the tsunami propagation from its source region (coarse grid in off-shore) to the coastal area (finer grid in Ognina area) needed the nesting of the various resolution grids. The coarser grid was built with 80x80 m cell width in off-shore of SE Sicily and in the Hellenic area, while the finer grid was built with 4x4 m cell width in Ognina coast (Fig. 5). The Delft3D model computed the tsunami generation on the coarser grid for the larger region on the Hellenic Fault and on the Western Fault and then used the simulation results along the boundaries of the finer grid of Ognina area. The wave propagation on the finer grid was made by means of XBeach model, to assess the inland flooding and the sedimentary movements in the narrow channel. For each event, XBeach model requires the spectra parameters of the waves, which were assessed using a JONSWAP Spectra characterized by root-mean square wave height (Hrms) and common peak period (Tp) defined from Delft 3D Flow results.

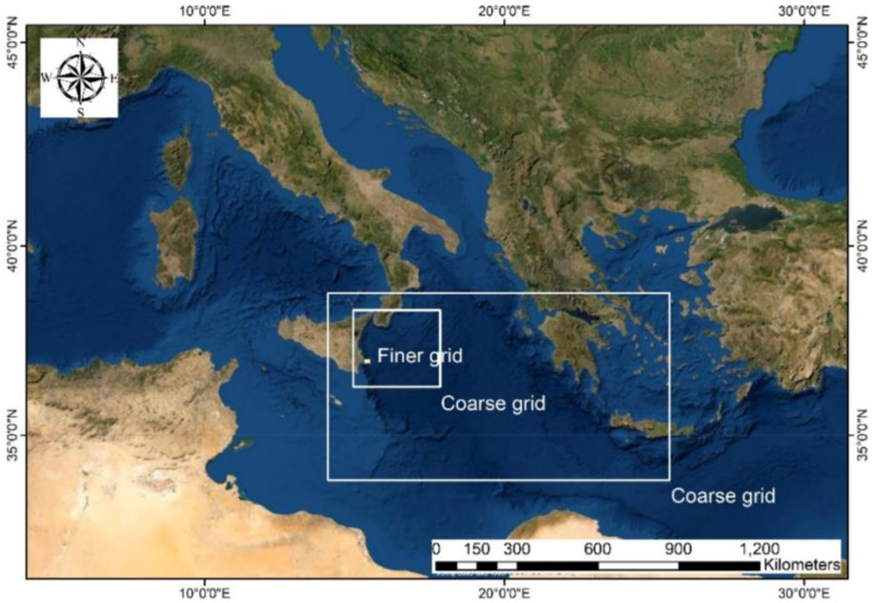


Fig. 5 - Coarse grids for Hellenic and the South-eastern Sicily areas (80x80 m cell width) employed in Delf3D-Flow simulation and finer grid (4x4 m cell width) employed in XBeach modelling.

4. Results

4.1 Current coastal landscape of the Ognina area

By integrating the DTM of the topography (2x2 m grid cell resolution) with the DTM of the bathymetry (1x1 m grid cell resolution) (c.f. section 3.1), the DTM representative of the current coastal landscape of the Ognina area was obtained (1x1 m grid cell resolution – Fig. 6).

The analysis of the topography allowed identifying the main landforms connected to the beach-barrier system of the Ognina embayment and the present-day harbour located in the inner part of the narrow channel. The high-energy deposits are presently located in the inner part of the channel at an elevation of 5 m above sea-level (a.s.l.). By analysing the DTM of the bathymetry, an incised-valley surface presently submerged up to -30 m depth is clearly detected. The overall topographic reconstruction suggests that this relict valley crossed the entire area.

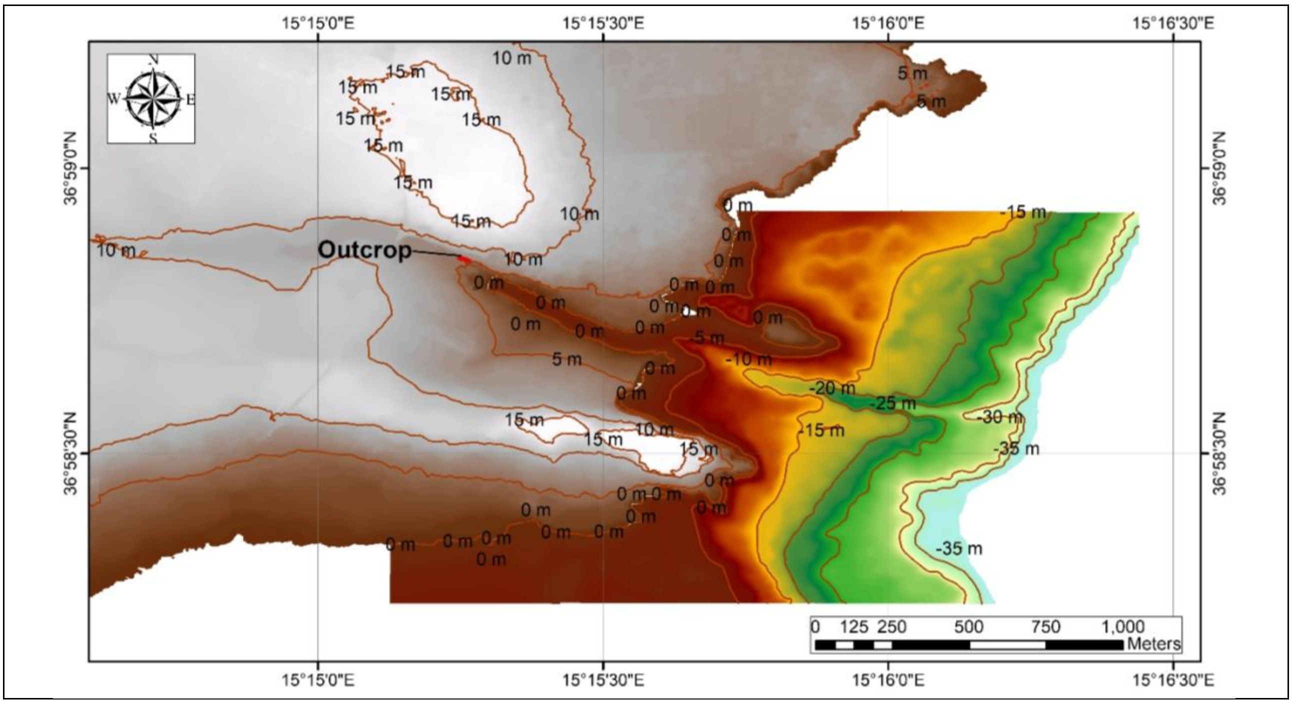


Fig. 6 - DTM of the Ognina area with the high-energy deposits located in outcrop in the inner part of the channel.

4.2 Reconstruction of the ancient landscape scenarios of the Ognina area

In Table 2 are reported the RSL positions (in mm) at the time of tsunami events occurrence, which were evaluated by adding the tectonic and erosive contributions to the sea-level positions provided by Lambeck et al. (2011) (c.f. section 3.2).

Table 2 – RSL positions (E) as function of the eustatic (B), tectonic (C) and erosive (D) contributions.

A	B	C	D	E
Time CE	Sea Level Lambeck et al 2011 (mm)	Tectonic (mm)	Erosion (mm)	RSL (mm)
365	-1160	331	231.7	-1060.7
1169	-554	170.2	119.14	-502.94
1693	-269	65.4	45.78	-249.38

Considering the past RSL positions and the changes in the paleogeographic, three different DTM were obtained representative of the ancient landscapes of the Ognina area in 365 CE (Fig. 7a), 1169 CE (Fig. 7b) and 1693 CE (Fig. 7c). The integrated analysis of the different paleo-geographic phases shows that:

- in 365 CE, the Ognina area was characterized by a RSL of 1.06 m lower than in the present, determining a narrow isthmus with Ognina Island and a river flow up to the current coastline position;
- in 1169 CE, the Ognina area was characterized by a RSL of 0.5 m lower than in the present. In this case, the connection with Ognina Island was partially eroded and submerged;
- in 1693 CE, the Ognina area was characterized by a RSL of 0.25 m lower than the present-day sea level. In this case, Ognina Island was divided by mainland and a back-barrier system filled the river mouth.

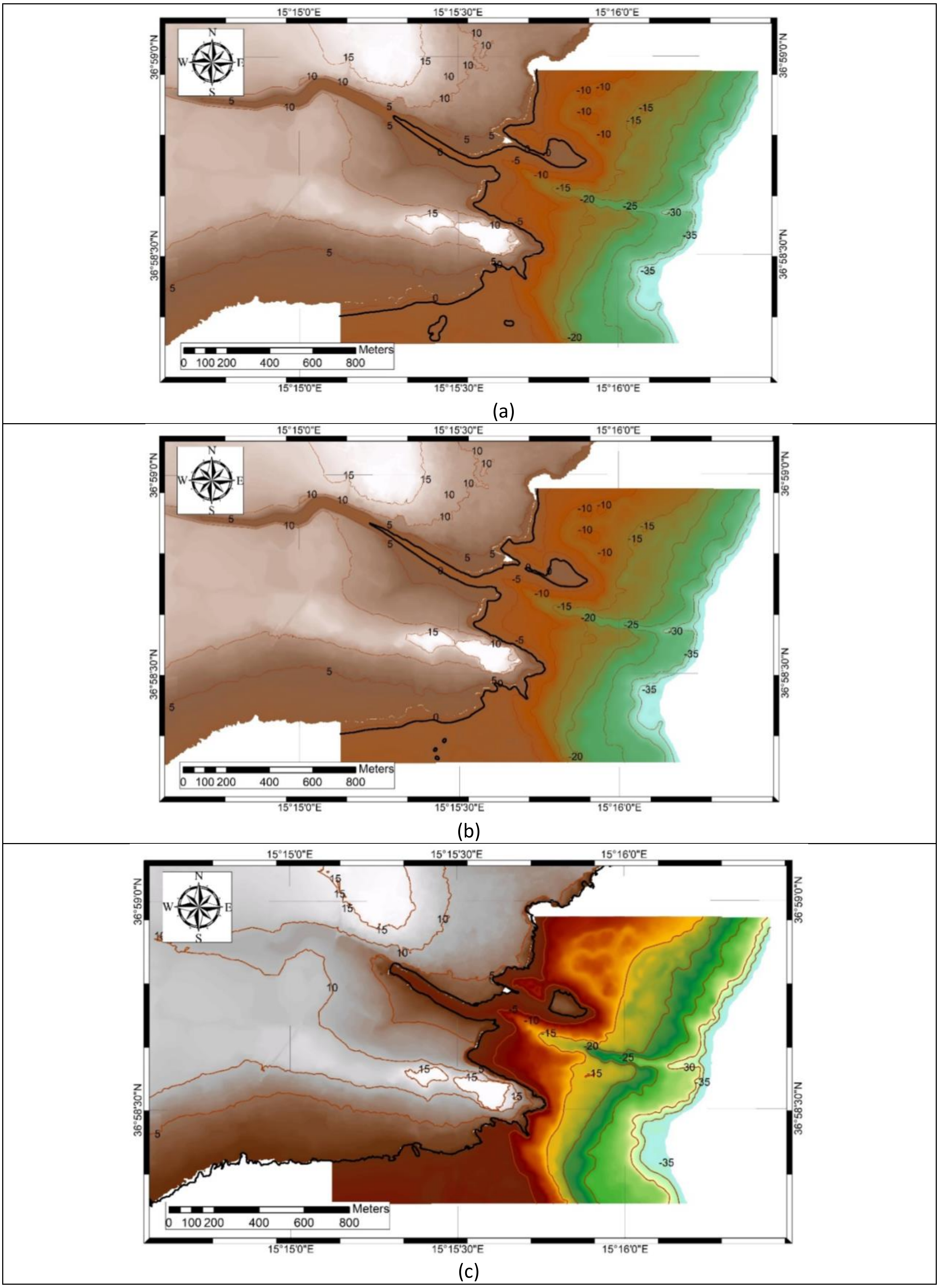


Fig. 7 - Reconstruction of Ognina landscapes as a function of past topography and RSL. DTM of Ognina area for the year a) 365 CE; b) 1169 CE; c) 1693 CE.

4.3 Assessment of the modelled tsunami hydro-dynamic features

Due to the different characteristics of each seismic event (c.f. section 3.3), the tsunami events modelled in Delft3D Flow showed a different water level perturbation (Fig. 8). In detail, the following duration time and wave heights were obtained:

- 21 July 365 event – a duration of about 2 hours with a maximum wave height of 0.72 m;
- 04 February 1169 event – a duration of about 55 min with a maximum wave height of 0.41 m;
- 11 January 1693 event – a duration of about 47 min with a maximum wave height of 2.93 m.

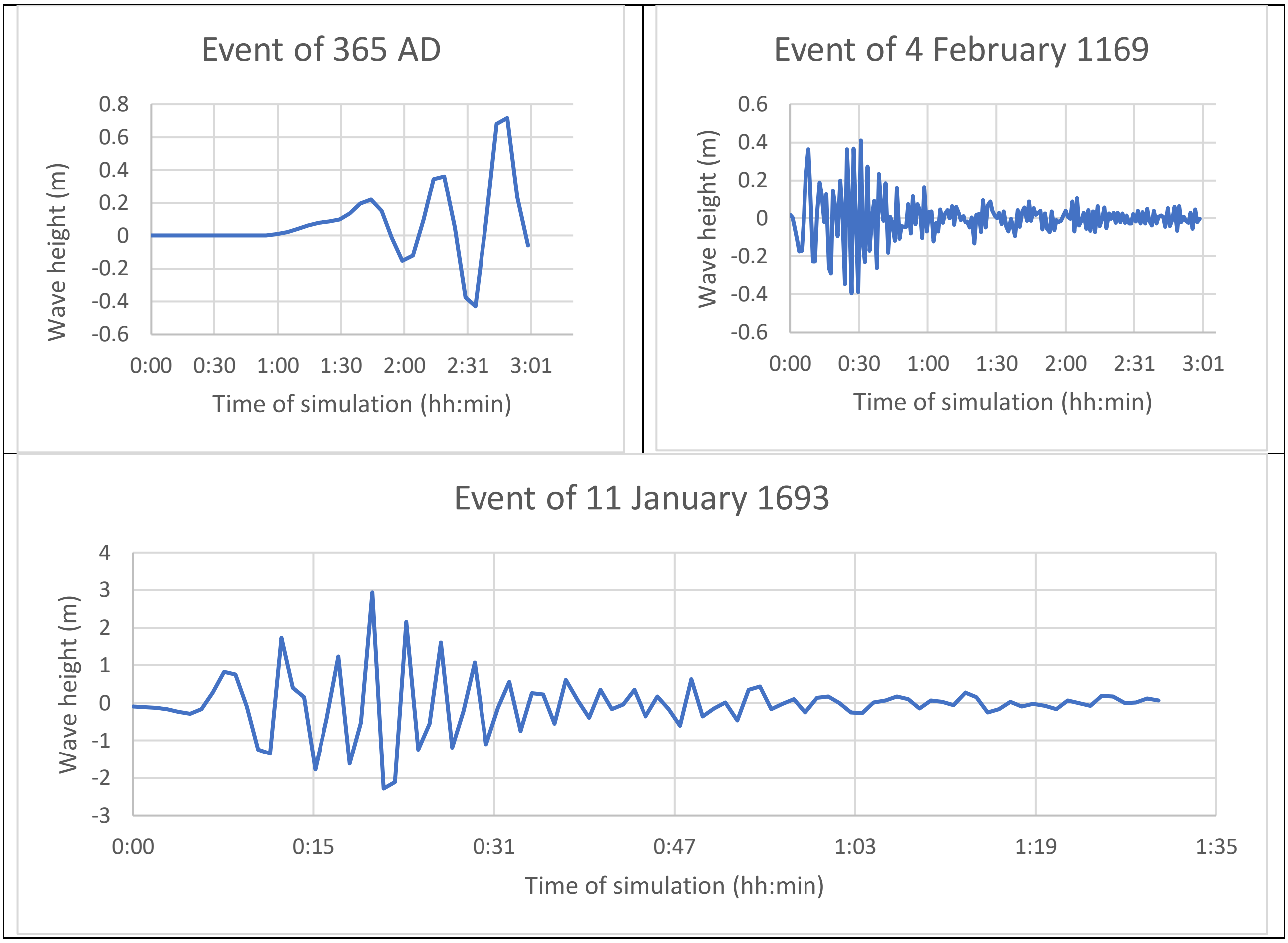
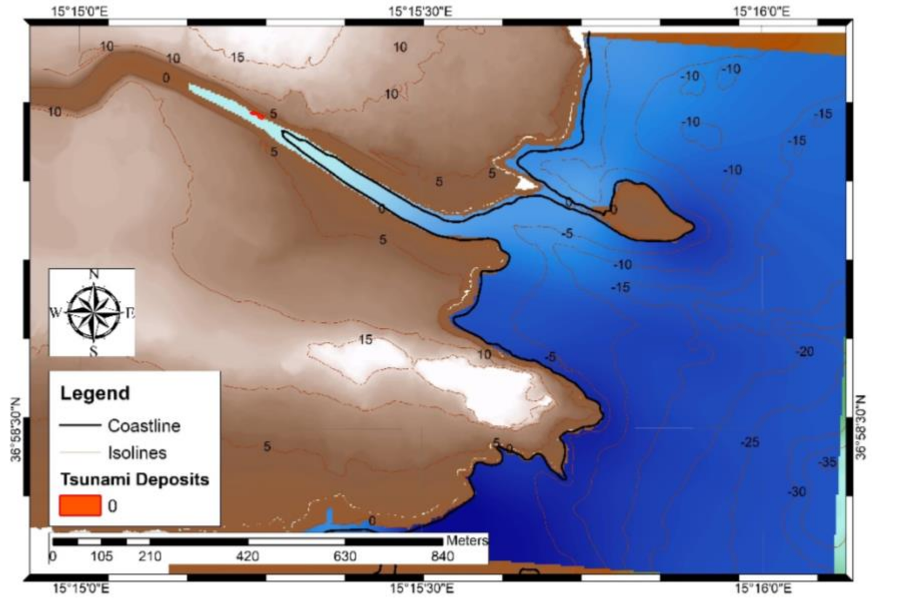


Fig. 8 - Wave height modelled in Delft3D-Flow for different tsunami event impacted the Ognina area in the past.

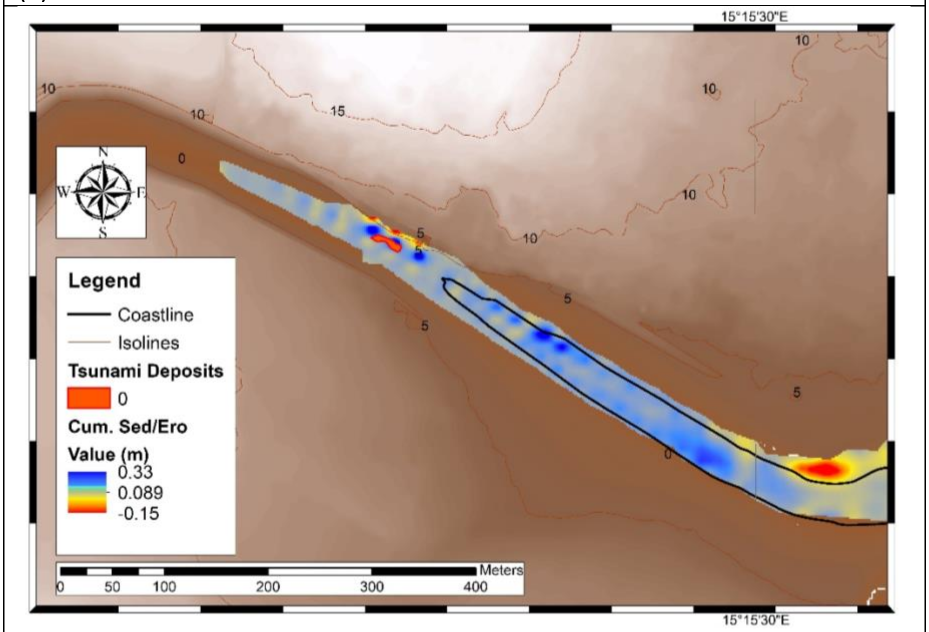
Results of Delft3D Flow were nested in the finer grid of Ognina area to assess the inland flooding and sedimentary movements through XBeach model. The flooding surfaces associated with each tsunami event showed different extensions as a function of the past landscapes configurations (Figg. 9-11).

For the 365 CE event, wave propagation was modelled by means of XBeach, using a JONSWAP Spectra characterized by root-mean square wave height (Hrms) of 0.36 m and 0.72 m, respectively and with a common peak period (Tp) of 1 hour. For the 1169 CE event, three subsequent waves were modelled with Hrms of 0.36 m, 0.37 m, 0.41 m respectively and with a common Tp of 10 min. For the 1693 CE event, three subsequent waves were modelled with Hrms of 1.3 m, 1.21 m, 2.93 m respectively and with a common Tp of 5 min. During the occurrence of tsunami in 365 CE, the tsunami wave impacted the Ognina Island with temporary flooding on the isthmus and inland flooding of about 200 m from the coastline (Fig.9a). The wave flow modelled in XBeach showed significant erosion in the outer part of the channel with an annexed amplification of the wave height. Along the river path, wave flow determined a rhythmic marine sand deposition (Fig. 9b). In the inner part of the river, the dissipation energy of the wave determined the riverbank erosion with annexed debris deposition mixed to marine sands, reaching a thickness of about 0.33±0.02 m.

For the event of 1169 CE, the tsunami wave propagated on the river channel, determining an inland flooding of about 100 m from the coastline (Fig. 10a). The wave flow determined a riverbank erosion with a chaotic deposition of marine sediments and terrestrial debris, reaching a thickness of about 0.44±0.02 m thick (Fig. 10b). The model of 1693 CE event showed a strong tsunami impact with transportation of a great number of debris landward into a back-barrier system. Particularly, the propagation model in XBeach showed wave height amplifications from the outer part to the inner part of the narrow channel, with a coastal flooding of about 110 m from the coastline reconstructed for the 1693 (Fig. 11a). These amplifications determined a series of rhythmic sediments movements along the channel, and a chaotic deposition was highlighted in the inner part with a thickness of 0.42±0.02 m (Fig. 11b).



(a)



(b)

Fig. 9 - Tsunami modelling in XBeach for the 365 CE event: a) Tsunami flooded surface is marked in blue while the ancient coastline is marked in black; in this case, the inland flooding is resulted of about 200 m from the coastline; b) Cumulative sedimentation/erosion in the channel with the position of tsunami deposit surveyed in the field (red polygon).

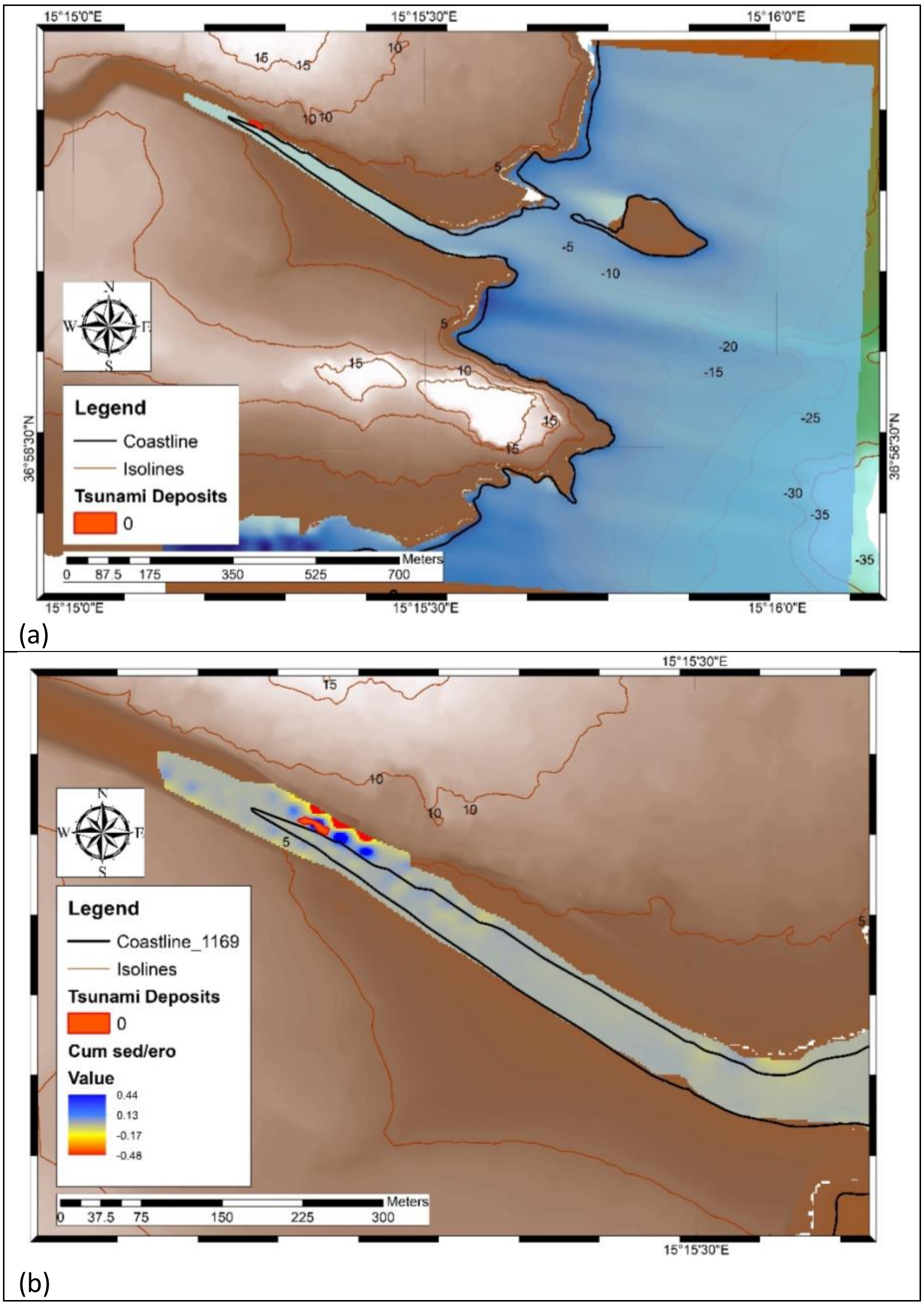


Fig. 10 – Tsunami modelling in XBeach for the 1169 CE event: a) Tsunami flooded surface is marked in blue while the ancient coastline is marked in black; in this case, the inland flooding is resulted of about 100 m from the coastline; b) Cumulative sedimentation/erosion in the channel with the position of tsunami deposit surveyed in the field (red polygon).

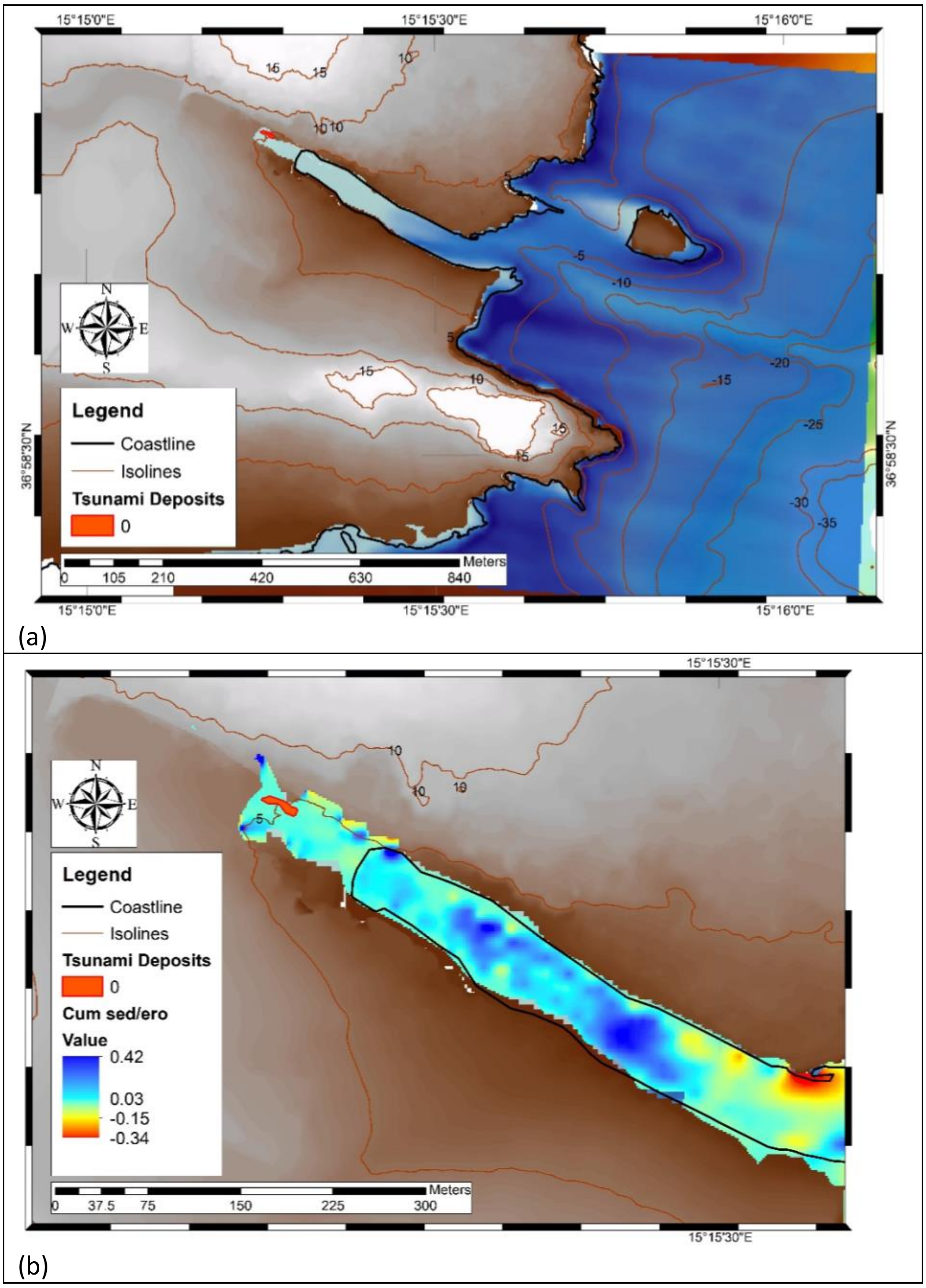


Fig. 11 – Tsunami modelling in XBeach for the 1693 CE event: a) Tsunami flooded is marked in blue while the ancient coastline is marked in black; in this case, the inland flooding is resulted of about 110 m from the coastline; b) Cumulative sedimentation/erosion in the channel with the position of tsunami deposit surveyed in the field (red polygon).

5. Discussions

The interpretation of the geological evidence detect in the Ognina coastal area, coupled with the reconstruction of the ancient landscape scenarios of the area, allows attributing the morphological setting of the investigated area to a *ria,* where a fossilized Holocene beach-barrier system was preserved by marine erosion thanks to an artificial harbour in the inner part of the channel. Furthermore, the correlation between the numerical results with the geological in situ evidence allowed demonstrating that high-energy coastal deposits detected in the Ognina area were transported and accumulated during the different earthquake-generated tsunami that impacted the Ionian coast of Sicily in the historical time.

High-performing model analysis carried out in this study enabled the evaluation of the tsunami waves height impacting the Ognina area as a function of different tsunamogenic source location, leading the identification of the maximum extension of the flooded surface during the tsunami occurrence. Based on these results, it was possible to state that the earthquake-generated tsunami of 1169 CE and 1693 CE were related to the tsunamogenic sources of the Western Fault (South-eastern Sicily). In fact, the modelling results showed that the focal depth and dimensional fault features described by Argnani and Bonazzi (2005), Monaco and Tortorici (2007), Argnani et al. (2012) can generate tsunami waves potentially impacting the northern part of Ognina area but the diffraction due to Peninsula Maddalena does not allow a significant wave impacting on the Ognina coast. On the other hand, the recent studies performed by Gambino et al. (2020) described in detail the fault parameters of the Western Fault, highlighting coesismic displacements also in front of Peninsula Maddalena, which, based on the results of this study, could generate significant wave height impacting the Ognina coasts. This aspect allows defying that the Western Fault can be considered the most probable tsunamogenic source whose southward extension could be even longer than that described in Gambino et al. (2020).

Moreover, the earthquake event occurred in 1169 CE was less in magnitude than 1693 CE event (Tinti et al., 2004; Monaco and Tortorici, 2007; Gambino et al., 2020), therefore the tsunami wave was reasonably lower in height than the wave caused by the 1693 CE event, as also demonstrated by Delft3D model outputs (Fig. 8). Accounting for the 365 CE event, it was generated by a strong earthquake, which caused several damages on the Hellenic Islands and determined a coesismic uplift in Crete Island (Stiros, 2010; Ohsumi et al., 2018; Werner et al., 2018; 2019). According to Stiros (2010), the tsunami wave impacted the Sicilian coasts 70 min after the seismic event, with long waves impacting the Ognina area. Also in this case, the inland sedimentary movements modelled in XBeach show a good match between the sedimentation outputs and *in situ* position of the lower stratal unit attributed to the 365 CE event. Considering the extension of the inland flooding surface, the higher magnitude of the 365 CE event caused long waves that determined a flooding up to 200 m from the coastline. Model results allow stating that the high inland water penetration of this event was favoured by the presence of a coastal channel that caused the hydraulic amplification of the tsunami waves. This aspect represents a useful element for a reliable reconstruction of the ancient coastal landscape allowing to presume that a river channel was present in the Ognina area at least since the IV century.

For both 365 CE and 1169 CE events, model results show riverbank erosion with concomitant deposition of marine and terrestrial sediments. Such features were also detected in the field by Scicchitano et al. (2010; 2016). The peculiar results obtained for the 1693 CE event show a chaotic sedimentation in the inner part of the channel, which conditioned the beach-barrier system. In this case, model results show sediment thickness of about 0.4 m in the outermost edge of the channel, suggesting mechanism flow without the organization of depositional structures and allowing the attribution of the upper stratal unit of the Ognina deposits to a multiple waves impact occurring during the 1693 CE event, as previously assumed in Scicchitano et al. (2010).

The methodological approach applied in this work can be considered in line with the analysis proposed in several studies that analysed historical and recent tsunami impacts by integrating high-performing models with sedimentological, chronological and stratigraphic analysis. In Chagué et al. (2018), a numerical approach was proposed to find out if geological evidence of two tsunami events occurred in Hawaii in 1946 and 1960 had been preserved in the local sedimentary record. Also in this case, sediment transport modelling was performed to estimate the origin of the sediment deposits and areas of deposition on land; numerical results were compared with in situ geological evidence and confirmed their sedimentological interpretation. The inundation and sediment transport associated with an event similar in magnitude to the 26 December 2004 Indian Ocean tsunami was simulated in Apotsos et al. (2011). In this case, the model predictions match with the observed flow depths and inundation distance, as well as with the general characteristics of the sediment erosion and deposition. Nevertheless, despite a large number of studies focused on the analysis and interpretation of tsunami coastal evidence as well as on the identification of the inland wave propagation, few studies are aimed at numerically identifying the precise location of the seismic source generating the

tsunami events. Reference works addressing this last topic were published by Dourado et al. (2019) and Bosnic et al. (2021), where sedimentary records were used to test and validate seismic sources of the Great Lisbon Earthquake (1755 CE earthquake). In this case, tsunami propagation from seven different seismic source-areas was modelled and compared with the main features of the tsunami coastal deposits in order to constrain the most likely tectonic sources of the 1755 event.
This brief overview of international studies highlights that the multi-disciplinary approach proposed in our study, based on the corroborating of numerical simulations with observed geological evidence, allows addressing all the aspects related to the identification and quantification of the physical processes (generation, propagation, inundation, erosion, and deposition) that dominate during a tsunami event. It, therefore, represents a suitable way to characterize similar earthquake-generated tsunami that can occur in tectonic active coastal areas that can be, for this reason, considered vulnerable to the potential impact of future tsunami events.

6. Conclusions

In this work, a combined approach based on the comparison between *in situ* geological evidence and numerical models allowed to attribute high-energy deposits detected in the Ognina coastal area (South-eastern Sicily) to specific tsunami events occurred in the historical times in the Eastern Mediterranean area.
The main focus of this work was to define a high-performing model-chain in order to simulate three earthquake-generated tsunami (21 July 365 CE, 4 February 1169 CE, 11 January 1693 CE) and to obtain their hydro-dynamic features for the evaluation of the maximum flooding extension and cumulative sedimentation/erosion budget in the Ognina channel.
The numerical simulations were carried out by considering the ancient landscapes of Ognina area reconstructed by means of geological evidence, historical documents and field surveys. Furthermore, past relative sea levels were defined in order to provide the coastline position at the time that tsunami events took place.
The reconstruction of past configurations of the Ognina coast highlighted that:

- From the IV to XVI century the coastal landscape was conditioned by a well-preserved river system that nourished the sedimentary budget of the coast; furthermore, Ognina Island was partially connected to the mainland by a rocky causeway;
- On the XVI-XVII century, the sea-level rise and marine erosion determined the submergence of rocky causeway separating the Ognina Island from the mainland and a new beach-barrier system was developed, filling the ancient river mouth.

On the other hand, the correlation between model results with *in situ* geological evidence highlighted that:

- Sedimentary transport due to the 365 CE and 1169 CE tsunami events determined the combined marine deposition and riverbank erosion, causing the deposition of lower strata units;
- 1693 CE tsunami event was particularly destructive; in this case, tsunami waves detached and transported the beach-barrier sediments for several meters landward determining a chaotic deposition.

Furthermore, the numerical results performed in Delft showed that the highest wave heights of the 1169 CE and 1693 CE tsunami events were annexed to tsunamogenic sources located in front of Peninsula Maddalena, always attributed to the Western Fault displacements. Instead, the 365 CE tsunami event showed a long wave propagation from the Hellenic Fault tsunamogenic source to the South-eastern Sicily that caused a wider flooding surface, as demonstrated by numerical results performed in XBeach model.
In conclusion, this study demonstrates that the peculiar morphological configuration of the Ognina area enhanced the hydraulic amplification of the tsunami waves. This last aspect allows considering the Ognina site highly vulnerable to the potential impact of future tsunami events.
Finally, the results of the study highlight that high-performing tsunami models combined with geological evidence could be a suitable tool for the analysis of the hydrodynamic features of earthquake-generated tsunami allowing the identification of the most likely tsunamogenic sources in the Mediterranean area as

well as worldwide and contributing therefore to the definition of a reliable procedure for the tsunami hazard assessment.

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