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COASTAL GEOMORPHOLOGY AND TSUNAMI VULNERABILITY. THE CASE-STUDY OF APULIA REGION (ITALY)

ABSTRACT: MASTRONUZZI G. & SANSÒ P., *Coastal geomorphology and Tsunami vulnerability. The case-study of Apulia region (Italy)*. (IT ISSN 1724-4757, 2006).

The growing urbanization of the coastal area rises the risk linked to low frequency - high magnitude events, like tsunamis, which are rarely taken into account by planners. Present-day research focuses mainly on the tsunami hazard assessment, linked to the frequency and intensity of these catastrophic events. However, tsunamis can have very different effects in response to different morphological types of coasts. Aiming to define the vulnerability of the Apulian coast (southern Italy), the effects of tsunamis on different types of coast have been inferred from the available post-report events integrated by information gathered form the geological research on deposits and forms which have been related to tsunami action. This analysis allows the vulnerability of different type of coasts occurring in Apulia region to be assessed.

The study reveals that that more than half of the Apulian coast is marked by a very low or low vulnerability to tsunami action (57%) whereas about a quarter (21%) shows a high or very high vulnerability.

KEY WORDS: Tsunami, Coastal morphology, Vulnerability, Apulia (Italy).

RIASSUNTO: MASTRONUZZI G. & SANSÒ P., *Morfologia costiera e vulnerabilità connessa a tsunami: l'esempio della Puglia (Italia)*. (IT ISSN 1724-4757, 2006).

La crescente urbanizzazione della fascia costiera comporta un aumento del grado di rischio legato ad eventi caratterizzati da bassa frequenza ed alta magnitudo, come i maremoti. Ciò nonostante tali eventi sono raramente presi in considerazione dai pianificatori.

Le ricerche attuali si concentrano principalmente sulla valutazione della pericolosità connessa ad eventi di maremoto, funzione della frequenza ed intensità di tali eventi catastrofici. Comunque, gli effetti di un maremoto possono essere molto differenti in funzione dei differenti tipi morfologici di costa.

Allo scopo di valutare la vulnerabilità delle coste pugliesi in relazione ad eventi di maremoto, sono stati desunti gli effetti di tali eventi su differenti tipi di costa sulla base dei dati provenienti dalle campagne di rilevamento post-evento, integrati da informazioni ottenute mediante indagini di tipo geologico su depositi e forme legate all'azione di maremoti. Questo metodo ha consentito di ottenere una valutazione del differente grado di vulnerabilità dei morfotipi costieri presenti in Puglia.

Lo studio rivela che più della metà (57%) della costa pugliese è marcata da un grado di vulnerabilità molto basso o basso in relazione all'azione di onde di maremoto mentre circa un quarto (21%) mostra grado di vulnerabilità alto o molto alto.

TERMINI CHIAVE: Maremoto, Morfologia costiera, Vulnerabilità, Puglia (Italia).

INTRODUCTION

The increasing development of coastal areas makes them particularly prone to low frequency - high magnitude events, such as tsunamis. These phenomena are rarely taken into account by planners, with the exception of particular high-developed areas where the high frequency and intensity of these phenomena have imposed the realization of structures and procedures for the mitigation of tsunami risk.

During the past years, worldwide catalogues of tsunami events occurred in different regions of the world have been compiled (e.g. for the Mediterranean area: Ambrasey, 1965; Antonopoulos, 1979; Tinti & Maramai, 1996; Soloviev, 1990); they comprise far more than 2000 events during the past 4000 years (Sheffers & Kelletat, 2003).

Present-day researchers focused their studies mainly on tsunami generating mechanisms, on the origin, propagation and deformation of tsunami waves, or on the physics of tsunami run-up and inundation. In contrast, there are still few geological research about field evidence of tsuna-

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mi occurred in the late Holocene or earlier. Most of these efforts are justified by the importance to assess the hazard along the coast of the world due to the action of tsunamis, which is directly linked to the frequency and intensity of events occurred in a particular area.

However, a crucial information for the tsunamis risk assessment along a coastal area is the definition of its vulnerability to such phenomena.

The aim of this paper is to define the main effects of tsunamis on different morphological types of coast as inferred from post-events reports, available for different regions of the world since 1992 (e.g., Baptista & *alii*, 1993; Yeh & *alii*, 1993; Shimamoto & *alii*, 1995; Tsuji & *alii*, 1995; Yeh & *alii*, 1995; Imamura & *alii*, 1995; Shuto & Matsutomi, 1995; Pelinovski & *alii*, 1997; Maramai &Tinti, 1997). Since the information about the modifications of coastal landscape due to tsunamis reported in these surveys are not generally very detailed, they have been integrated by data gained by the geological record. This procedure allows the definition of the vulnerability of different types of coast occurring along Apulia region (southern Italy) to tsunami events (fig. 1).

THE EFFECTS OF TSUNAMIS ON COASTS

The effects of a tsunami on coasts can be greatly influenced by coastal morphology. Since tsunami wave celerity is a function of water depth, sea bottom bathymetry and morphology can determine different values of run-up and inundation along different coastal tracts. Several numerical

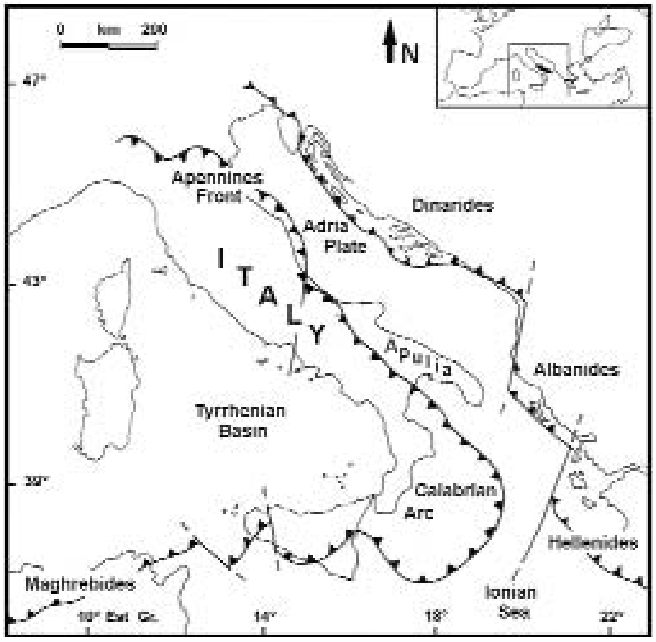

FIG. 1 - Geographical position of Apulia region and main geodynamic features of surrounding areas.

models able to forecast these values along coast have been developed and validated.

In this paper we will neglect this particular aspect, focusing only on effects of tsunami on different morphological types of coast. An evaluation of these effects has been carried out by means of the detailed analysis of available post-event reports, integrated by geological data on deposits and forms linked to recent and past tsunamis.

a - Cliffs and convex rocky coasts

Cliffs are subvertical slopes due to rockfalls promoted by an effective wave erosion at the cliff foot. Convex rocky coasts correspond to subaerial slopes shaped on resistant rocks which have been reached by sea level; coastal erosion is mainly due to biochemical processes. Post-event reports generally lack of a description of tsunami effects on cliffs and convex rocky coasts, mainly due to the difficulty to survey them.

Some effects of a tsunami wave impacting on a cliff face can be inferred from geomorphological studies. According to Young & Bryant (1993) tsunami would be responsible for some of the cliff morphology occurring along the coast of south-eastern Australia. In extreme cases tsunami waves swamped clifflines ripping slabs of bedrock up to 6 m in diameter from cliff face as high as 40-50 m above sea level. Young & *alii* (1996) identified at Mermaid's Inlet (Australia) a boulder measuring up to 4.0x2.3x.0.4 m which was ripped from the cliff face and trown upwards onto the sandstone topcliff surface. Catastrophic waves would have swept the entire cliff face, about 32 m high, overtopped it and produced extensive erosion on the cliff top surface.

No data exist on the effects of a tsunami wave against limestone or sandstone cliffs studded by large caves open to the sea. It would be expected that in case of a rapid run-up, the incoming wave could induce diffuse rockfalls due to piston effect (fig. 2).

b - Rocky low-sloping coasts

Low sloping rocky coasts are made of low elevated platforms shaped on resistant rocks which reach sea level without abrupt change of slope. Main morphological effects of tsunamis on low sloping rocky coasts are represented by the detachment of large boulders in the nearshore zone and their deposition farther inland (Dawson, 1994; 2000), and by the sculpturing of bedrock resulting in the production of both smooth, small scale forms and large scale features as well (Bryant & Young, 1996; Bryant, 2001). However, very few observations are dedicated in the post-event reports about the effects of tsunami waves on this type of coast so that information are mostly inferred by geomorphological studies.

Bryant (2001) refers the shaping on the bedrock of small-scale landforms such as impact marks, drill holes, comma marks, sinous grooves, throughs or cavettos and flutes to high velocity flows produced by tsunamis. Landforms greater than 1 m are vortex, whirlpools, canyons, drumlin-like and keel-like features.

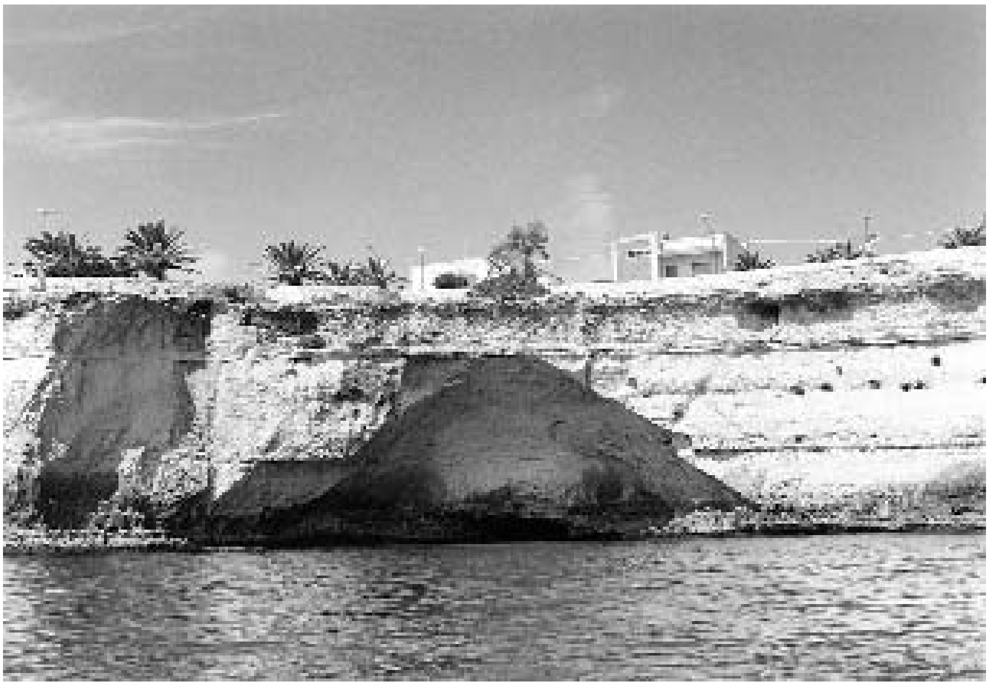

FIG. 2 - The cliff of Torre dell'Orso locality (Adriatic coast) is affected by the development of numerous sea caves. No report exist on the effects of a tsunami wave on sandstone cliffs studded by large caves open to the sea.

Large boulders deposition has been observed along numerous coastal tracts all over the world: Rangiroa, Tuamotum SE Pacific (Bourrouilh - Le Jean & Talandier, 1985), Hawaii (Moore & Moore, 1984; 1988), Ryukyu Islands in Japan (Nakata & Kawana, 1993), New South Wales in Australia (Young & *alii*, 1996), Bahamas (Hearty, 1997; 1998), Southern Caribbean Islands (Scheffers, 2002). Along the Mediterranean coast, large boulders are reported at Messina strait (Heck, 1947), southern Apulia (Mastronuzzi & Sansò, 2000; 2004) (fig. 3), Cyprus (Kelletat & Schellmann, 2002) and Lebanon coasts (Pirazzoli & Morhange, pers. comm., 2001).

c.1 - Beaches

Beaches are the most vulnerable area due to their low slope and elevation and are those that underwent major damage because they usually border very populated areas. Post-event reports point out generally the development of

FIG. 3 - A view of the characteristic shape of a low sloping rocky coast (Torre Santa Sabina locality, Adriatic coast). Note the sparse boulders carved and transported by the 6th April, 1667 and the 20th February, 1743 tsunami events.

an erosional scarp into beach or foredune deposits; the eroded material is transported and deposited as a sheet of sand farther inland.

Beach and foredune are the main source of sediments transported by tsunamis (Sato & *alii*, 1995) well above extreme storm wave limits. These sediments can reach a thickness of about 30 m, can be transported up to 10 km inland and reach 130 m of altitude (Scheffers & Kelletat, 2003).

According to Minuora & Nakaya (1990) during the 1983 tsunami of the Japan Sea Earthquake incoming tsunami waves rapidly transported materials landward from beaches and dunes, together with man-made structures. Outgoing waves in turn carried land materials seaward. Removed materials accumulated in the shoreface region forming submarine bars. Pelinovski & *alii* (1997) report that the 1996 Sulawesi tsunami waves eroded beach ridges higher than 70 cm by 30-50 cm.

The erosional scarps due to three different tsunamis occurred during the last 2500 years have been recognized on the Lesina Lake coastal barrier, along the northen coast of Puglia by Gravina & *alii* (2005). According to Nichol & *alii* (2003), a tsunami occurred during the late Holocene at Great Barrier Island (New Zealand) was responsible for the deposition of a gravel sheet extending from the toe of the foredune to 14.3 m above m.s.l. and 200 m landward from the beach.

c.2 - Pocket beach

The most vulnerable coast are represented by pocket beaches, which are placed inside small bays bordered by high cliff. In this case, cliffs determine the development of a reflected wave producing huge run-up values, up to 31.7 m during the 1993 Hokkaido Nansei-Oki tsunami according to Shuto & *alii* (1995). Moreover, rockfalls from cliffs behind prevent people to evacuate safely are often reported (Tsuji & *alii*, 1995)

c.3 - Beach/lagoon system

A beach/lagoon system is linked to the formation of a coastal barrier which closes a more or less wide sound of sea from the open sea. Narrow and low coastal barriers are particular vulnerable coastal landforms since they can be totally overwashed by tsunami waves. Tsunami waves can break a spit closing seaward a coastal lagoon or lake, whose fresh water became salty due to the inundation (Tsuji & *alii*, 1995). The rise of water level in the lagoon can impede the escape of people inland.

Minoura & Nakaya (1990) point out that the 1983 tsunami of the Japan Sea Earthquake invaded intertidal lagoonal lakes and deeply eroded subsurface deposits. Molluscs and their shells were sorted out from the deposits by sediment agitation and were then transported to shallower environments. Moreover, seismic shock cracked beaches and dunes separating some ponds from the Japan Sea. Tsunami wave rushed into ponds through these cracks depositing a thin sand layer eroded by beaches and dunes. Sea water remained for a long period at a deeper layer of the pond.

A similar process produced most likely four wide wash-over fans recognized along the sandy coastal barrier which divides the Lesina Lake from the Adriatic sea (northern Apulia, Italy) (Gianfreda & *alii*, 2001) (fig. 4).

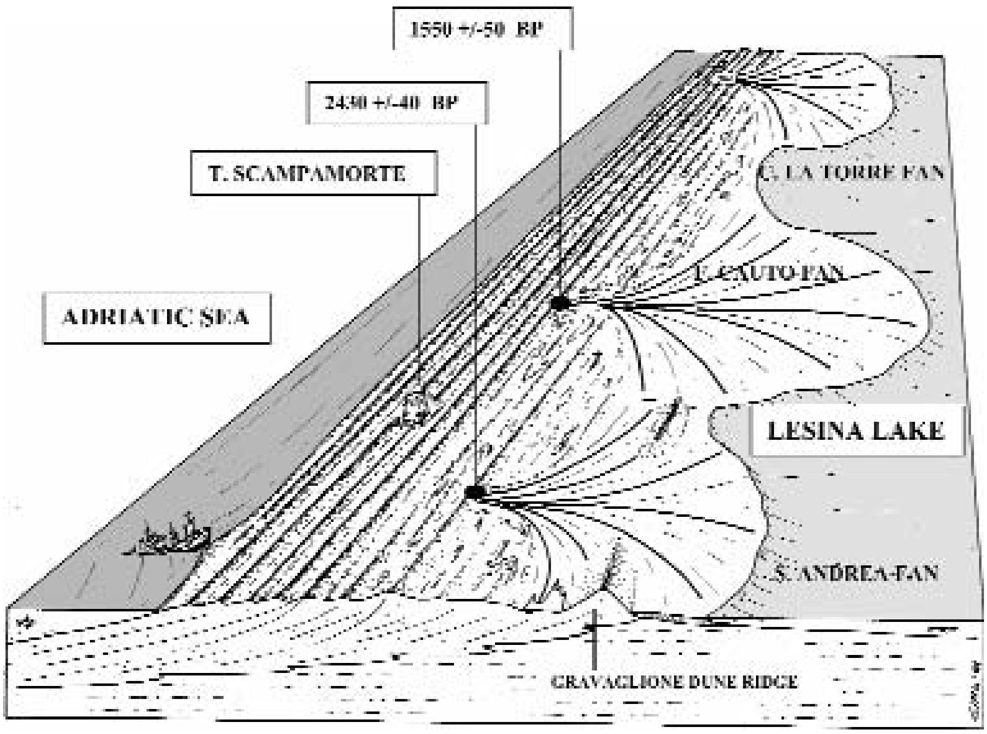

FIG. 4 - A scheme of the particular morphology of the Lesina Lake coastal barrier marked by wash-over fans which have been related to the impact of three tsunamis which stuck the coastal barrier about 2500 years BP, 493 AD and 1627 AD (from Gianfreda & *alii*, 2001).

These landforms would be formed by three tsunamis which struck the coastal barrier at 2500 years BP, 493 AD and 1627 AD.

Andrade (1992) studied some overwash features which mark the barrier islands located in front of the Algarve in southern Portugal and attributed them to the Lisboa Tsunami of 1755.

Goff & *alii* (2000) studied catastrophic saltwater inundations recorded in the sediments of the Okupe Lagoon (New Zealand). Some of these events have been correlated to the action of strong tsunamis which struck this coastal lagoon during the last 5000 years. Chagué-Goff & *alii* (2002) identify a short-lived catastrophic saltwater inundation at northen Hawke's Bay (New Zealand) which may suggest the occurrence of a tsunami at about 6300 years BP.

McSaveney & *alii* (2000) surveyed along the spit fronting the Sissano Lagoon (Papua New Guinea) struck by the 17 July 1998 tsunami the occurrence of sand deposition exceeding 1 m on the seaward beach ridges along with scour holes up to 2 m deep.

d - River mouth

Another coastal area of high vulnerability is represented by river mouths and river banks (Shiramoto & *alii*, 1995). If a tsunami hits the mouth mainly parallel to the coast, much of the tsunami would run-up along the river. But if it hits the mouth of a river at an angle to the coast, tsunami will invade from the mouth and deluge the river bank. Also in this case, the flooding of backshore area can impede people from escaping inland (Tsuji & *alii*, 1995).

Erosion at river mouth has been reported by Tsuji & *alii* (1995) during the 1992 Flores Island tsunami. On the other hand, the 1994 Miraduro Island Tsunami (Philippine) produced the closing of a river mouth due to the deposition of marine sands.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING OF APULIA REGION

Apulia region stretches for 350 km in the southern part of Italy, between the Adriatic and the Ionian Seas (fig. 1). The Apulia region represents the emerged part of the foreland domain of both Apenninic and Dinaric orogens. It is constituted by a Variscan basement covered by a Mesozoic carbonate sequence 3 to 5 km thick and is overlain by thin deposits of Tertiary and Quaternary age (Ricchetti & *alii*, 1988). The Apulian foreland is slightly deformed and it is affected by Apenninic and anti-Apenninic trending faults. In particular, Apulia is a low seismic region surrounded by highly seismic zones: the coast of Albania and Ionian Islands (western Greece) to the east, the Calabrian arc and southern Apennines to the west, the Gargano promontory to the north. Seismic activity has been responsible for the recording of numerous earthquakes in this region during the last millennium and can explain the historical tsunamis which have struck the southern Adriatic and Ionian coasts (Antonopoulos, 1979; Soloviev, 1990; Tinti & Maramai, 1996; Mastronuzzi & Sansò, 2000; Gianfreda & *alii*, 2001) (fig. 5).

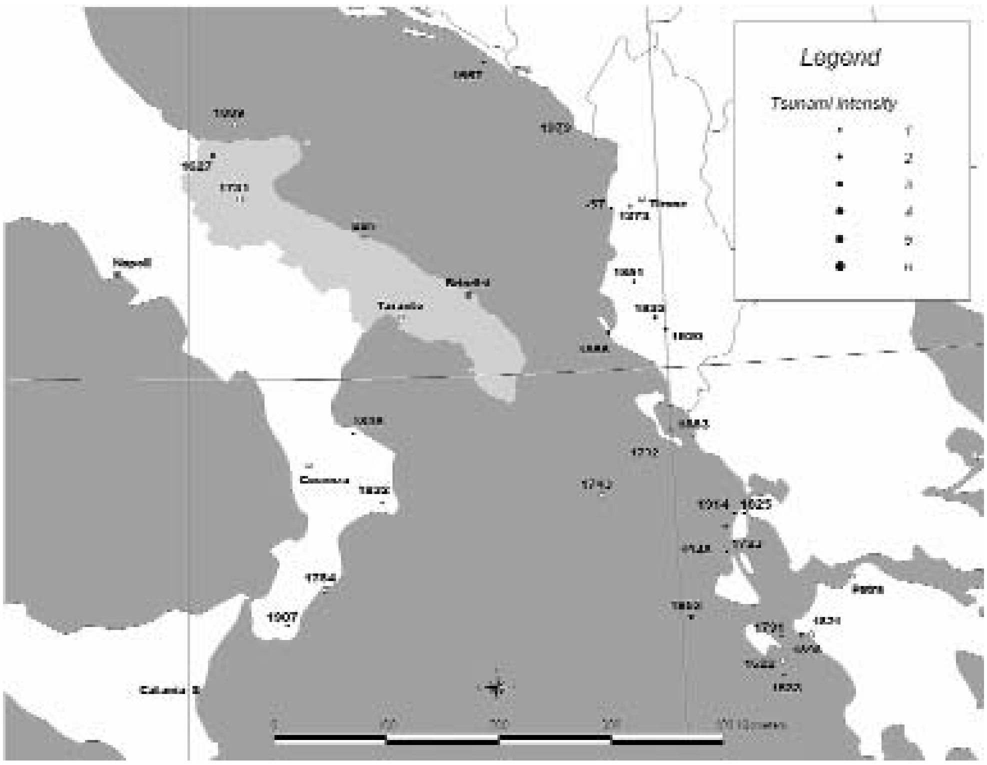

FIG. 5 - Geographical distribution of tsunami-generative earthquake epicenters in southern Adriatic and Ionian seas occurred during the last two millennia. Legend: Tsunami intensity: 1 - very light, 2 - light, 3 - rather strong, 4 - strong, 5 - very strong, 6 - disastrous. White dots mark the epicentres of earthquakes which produced tsunamis of unknown intensity; labels indicate earthquake dates.

The Italian Adriatic coasts have been struck by several tsunamis during the last 500 years. In particular, Tinti & *alii* (1995) detected 4 historical tsunamis along the Apulian coasts of Gargano and Tavoliere. The 30th of July, 1627 tsunami was particularly violent along the northern coast of Gargano; chronicles report the withdrawal of shoreline for about 3.5 km followed by seismic waves with catastrophic effects. Recent geomorphological research (Gianfreda & *alii*, 2001) on the Lesina coastal barrier point out the effects of three tsunamis occurred during the last 2500 years.

The presence of large boulders transported and deposited above the limit of storm waves marks out other catastrophic events along the coast of Apulia. One of these events was most likely triggered by the 5th of December, 1456 earthquake and struck the Ionian coast of Salento peninsula (Mastronuzzi & Sansò, 2000). A detailed geomorphological study of boulder accumulations occurring along the coast from Bari to Brindisi individuates two other distinct tsunamis triggered most likely by the strong earthquakes occurred at Ragusa (present day Dubrovnik) the 6th April, 1667 and at the Ionian Sea the 20th February, 1743 (Mastronuzzi & Sansò, 2004).

Soloviev (1990) reports along the Albanian and Greek coasts several tsunamis of great intensity, II-V grade of Sieberg-Ambrasey scale. These events cluster in correspondence of the Ionian islands (Zante, Giacintos, Corfù) and of the Corinth Gulf. The available data point out for the eastern coasts of Italy a recurrence period of tsunamis of about 50 years and maximum intensity of III-VI grade of Sieberg-Ambraseys scale. On the eastern Adriatic coast, tsunamis show similar intensity and recurrence period of 25 years.

The coast of Apulia region is composed by four principle morphological types: beaches, low sloping rocky coasts, convex rocky coasts, cliffs. Beaches are generally less than 40 m wide and 8 km long, and are generally bordered by a dune belt, often covering a former mid-Holocene cemented dune, and by reclaimed and urbanised swamps (Caldara & *alii*, 1998; Mastronuzzi & *alii*, 2002). Beaches are separated by long tracts made of low sloping rocky coasts. These last ones are constituted by an even plain sloping gently seaward cut through well-cemented Plio-Pleistocene calcareous sandstones (fig. 3). Convex rocky coast are mostly subaerial slopes shaped on limestones which have been partly submerged by sea; wave action has produced more or less high cliffs at sea level. Cliffs developed along coastal tracts composed either of clays, or calcareous sandstones, or intensely dissected and karstified limestones which are greatly affected by wave erosion; they are usually backed by a tabular landscape (fig. 2).

DISCUSSION

Vulnerability is defined as being an estimate of the degree of loss resulting from a potentially damaging phenomenon (UN-DHA, 1992). The analysis of available post-event surveys as well as the geological data on recent and past tsunami points out that the vulnerability of a coastal area to tsunami can vary greatly in function of coastal morphology (table 1).

TABLE 1 - Vulnerability class of different types of coasts

Morphological type of coast	*Post-event reports*	*Geomorphological record*	*Vulnerability Class*
Convex rocky coast	–	Detatchment of boulders	I
Retreating cliff	–	–	II
Gently sloping rocky coast	–	Detachment of boulders Deposition of sandy sheets	II
Beach	Erosional scarp	Erosional scarp Marine sand layers into foredune	III
Beach/lagoon system	Washover fan Salt water inundation Sand sheet	Washover fan Salt water inundation Sand sheet	IV
Beach at river mouth	Erosion Deposition Inundation	Erosional scarp Marine sand layers into lagune/swamp	III
Pocket beach	Highest run-up values Rockfall from the backing cliff	Marine sand layers into foredune	V

The most vulnerable are pocket beaches bordered landward by high cliffs which produce very high run-up values; rockfalls from the cliff face impede people to move inland. Beaches are effectively overwashed by tsunami waves, with intense erosion of beach and dune materials which are brought farther inland; erosional scarps form on beaches and foredunes and some distinct sandy layers can be deposited. Where a coastal barrier divides a lagoon by the open sea, washover fans can form at its landward border; the lagoon is inundated by salt water preventing people to escape inland. River mouths represent a fairly large entrance for tsunamis; extensive damage on river banks is produced by tsunami hitting at an angle to the coast. Finally, rocky platforms placed close to sea level are strongly affected by tsunamis which determine the reshaping of these landforms, with extensive carving and deposition of large boulders. Tsunami effects on unstable cliffs have not been investigated, even if some retreat due to mass movements could be expected.

This data set allows the vulnerability of Apulian coasts to tsunamis to be assessed (fig. 6). The most vulnerable coasts *(Vulnerability Class: Very high)* are those made of a narrow beach bordered inland by high cliffs. They characterize about 6% of the coast and are placed mainly at the Gargano Promontory-Foce Romandato, Baia delle Zagare (fig. 7), Mattinatella, etc. and in Salento Peninsula Torre S. Gennaro, Torre dell'Orso, etc. Very vulnerable coastal tracts *(Vulnerability Class: High)* are those made of a beach/dune/lagoon system such as Lesina and Varano lakes, Siponto-Margherita di Savoia, Cesine, etc. along the Adriatic coast of Apulia. The Ionian coast is studded by small beach/dune/backdune swamp systems which are

FIG. 6 - The vulnerability of the Apulian coasts to tsunami action.

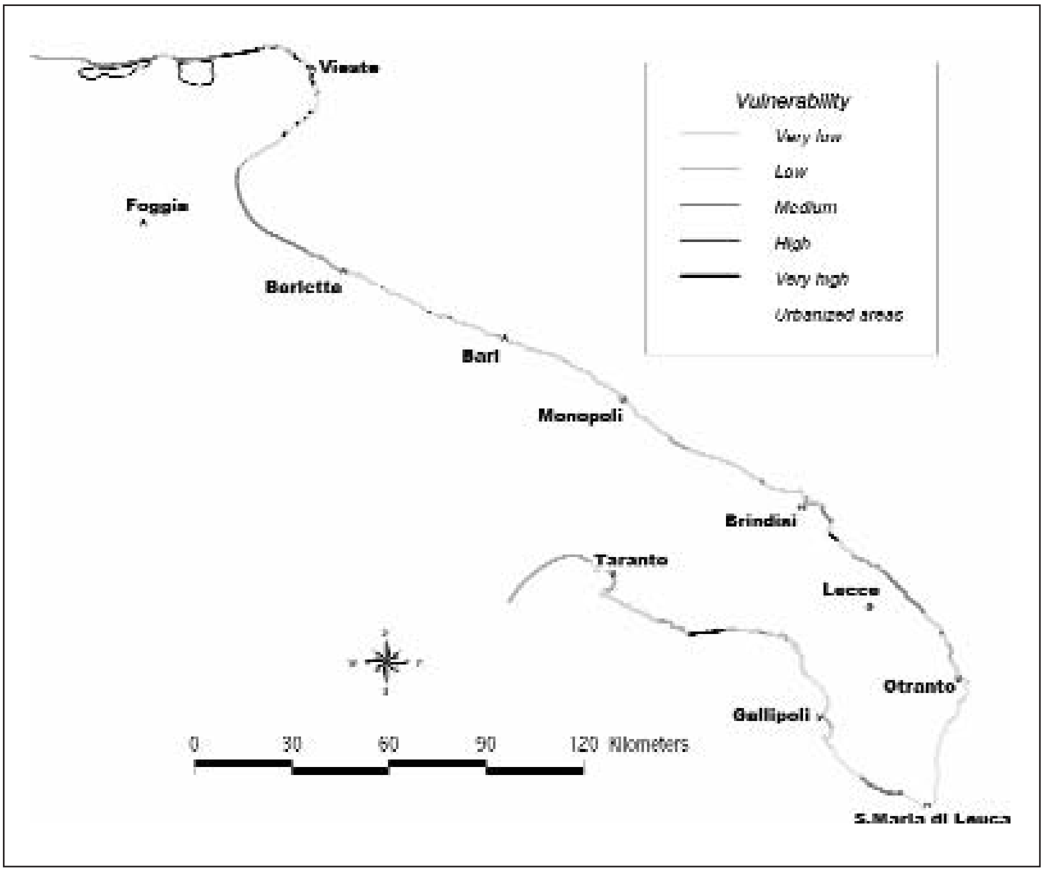

FIG. 7 - A view of Baia delle Zagare pocket beach (Gargano Promontory). This beach is backed by a high cliff whose presence renders this coastal tract the most vulnerable to tsunami action.

also very vulnerable to tsunamis. High vulnerable coasts represent about 15% of the entire coastal perimeter.

Coastal area prone to the effects of tsunamis *(Vulnerability Class: Medium)* are represented by the mouths of main rivers, i.e. Fortore River, at the north westernmost part of the region, and the Ofanto River. However, a number of relict valleys showing at the present their mouth below present sea level and at present constituting small inlets must be also taken into account (Brindisi inlet, Otranto inlet). This class comprises also main beaches attached directly to mainland; it covers about 16% of the Apulian coastal perimeter.

Furthermore, coastal tracts made by low gentle platforms sensible to tsunami action *(Vulnerability Class: Low)* are very diffuse along the Adriatic coast of Apulia, from Barletta to Otranto, and on the Ionian one, from Leuca to Taranto. In the same vulnerability class are retreating cliffs which mark some spots of Gargano Promontory, Bari province and Salento Peninsula. This class of vulnerability is the most diffuse since it covers about 42% of the Apulian coast. Finally, convex rocky coasts, potentially prone to tsunami action *(Vulnerability Class: Very low)*, are diffuse along the coast of Gargano Promontory and in the Salento Peninsula for about 15% of the Apulian coastal perimeter.

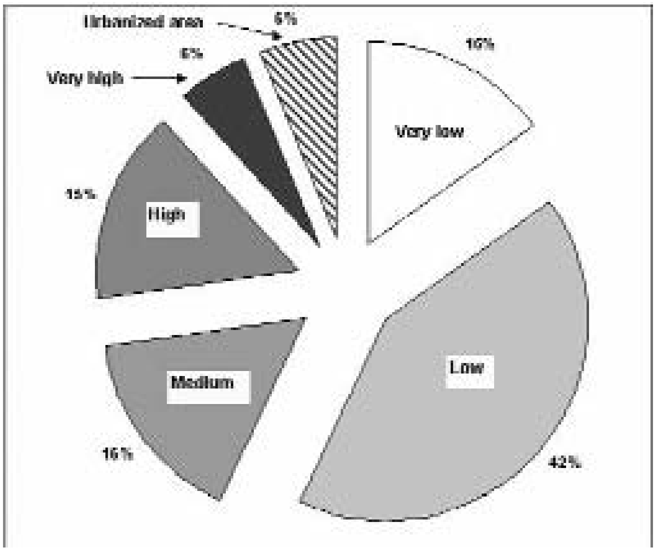

FIG. 8 - The frequency distribution of tsunami vulnerability classes along the Apulian coast.

CONCLUSION

The definition of the tsunami risk along a coast prone to this low frequency-high magnitude events is based on the assessment of hazard, linked to the frequency and intensity of tsunami events, of coastal vulnerability to tsunami and of demographic and land value distribution as well. Most of research is at present focused on the definition of tsunami hazard whereas study about the vulnerability are still very few.

In this paper, an attempt to define the vulnerability of different coastal morphological types which compound the Apulian coastal landscape is reported. It is based on the analysis of available post-event reports integrated with the geological data about the modifications produced by recent and past tsunami in the coastal landscape. Furthermore, taking into account the main morphological coastal types occurring along the Apulian coast, the vulnerability of the Apulian coast to tsunami has been assessed.

In summary, the analysis of vulnerability class distribution along the Apulian coast (fig. 8) shows that more than half of the Apulian coastal perimeter is marked by a very low or low vulnerability to tsunami action (57%) whereas about a quarter (21%) shows a high or very high vulnerability.

This study should represent a step towards the risk assessment of the Apulian coast which is not negligible. In fact, notwithstanding this region has been struck several times by destructive tsunamis in historical times, it is extensively urbanized and densely populated.

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