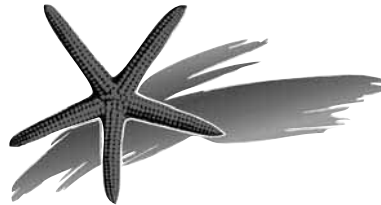

CIESM Workshop Monographs



Marine geo-hazards in the Mediterranean

Nicosia, 2 - 5 February 2011

CIESM Workshop Monographs ◊ 42.

To be cited as: CIESM, 2011. Marine geo-hazards in the Mediterranean. N° 42 *in CIESM Workshop Monographs* [F. Briand Ed.], 192 pages, Monaco.

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A collection founded and edited by Frédéric Briand.
Publisher : CIESM, 16 bd de Suisse, MC-98000, Monaco.

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I - EXECUTIVE SUMMARY

This synthesis, initiated during the meeting, was developed and coordinated thereafter by inputs received from all participants, under the coordination of Gert de Lange. Frédéric Briand, the Monograph Series Editor, reviewed and edited the entire volume, whose physical production was carried out by Valérie Gollino.

1. INTRODUCTION

Amongst the most devastating marine catastrophes that can occur in areas prone to seismic and volcanic activity, are earthquakes, volcanic eruptions and submarine slides, all of which can lead to tsunamis and/or additional hazards which may seriously endanger human society. Many such events are known and have been reported for the Mediterranean, a region where high-frequency occurrence of seismic and volcanic activity coincides with some of the most densely populated coastal areas in the world.

Acutely conscious of these potential marine geohazards, CIESM invited a selected group of scientists, covering the broad aspects mentioned above, at its 42nd International Workshop from 2-5 February 2011, at Nicosia, Cyprus. Following introductions by Frédéric Briand, Director General, and Gert de Lange, Chair of the CIESM Committee on Marine Geosciences, the group discussed not only past seismic, volcanic, and submarine slide generation, but also past tsunami activity, and potential present and future areas for tsunami origin and fate, based on field observations, historical records, and modeling studies. In addition, mitigation was considered for risk reduction purposes. The outcome of the workshop includes a state of the art review, conclusions, and recommendations for actions and for further research activities. These are synthesized in this Executive Summary and are presented with specific details in the full papers prepared by each of the workshop participants.

Note from the Editor:

On 11 March 2011, just a few weeks past the conclusion of this workshop, a major earthquake and a subsequent catastrophic tsunami hit the northeastern coastal region of Japan, taking thousands of lives and leaving hundreds of thousand survivors homeless and desperate. The dramatic observations made in Japan (Kyoto University Team, 2011; Tokyo Earthquake Research Institute, 2011; Group on Earth Observations, 2011; Parashar *et al.*, 2011) served as a powerful reminder, if necessary, of the destructive nature of such events. They signaled the rapid and devastating impact in areas close enough to be struck within half an hour ... as would be the case for most locations of any such event in the closed Mediterranean Sea. Added to the lessons previously learned from the Indian Ocean tsunami of 26 December 2004, such observations are of much relevance to the Mediterranean setting and were therefore constantly in the mind of the group who drafted this synthesis thereafter. These two recent catastrophes have demonstrated the reality and plausibility of worst case scenarios, that tended to be previously considered as a hypothetical upper boundary. In addition, the magnitude and severity of the impact call for our urgent re-consideration of assessment of magnitude for geohazard events where recurrence rates now exceed several millennia.

Most marine hazardous events in general and in the Mediterranean in particular can be related to geological processes associated with plate boundaries and to active faulting or slope failure resulting in major slumps at continental margin areas. In the present-day Mediterranean configuration, it is the subduction of the African plate underneath the EurAsian plate (for details, see Mascle, this volume) that initiates the former and the shallow margin and steep unstable continental slopes (Fig. 1) that contribute to the latter event generation (for details, see Sallarès *et al.*, this volume; Ceramicola *et al.*, this volume; and Migeon *et al.*, this volume). The former large-scale geological processes not only lead to distinct volcanic arc activity (Sakellariou, this volume) but also to enhanced seismicity in discrete areas (see below, and Papadopoulos, this volume). Volcanoes and Earthquakes are two near-surface expressions of these deep geological processes that may lead on the one hand to catastrophic events directly and on the other hand to tsunami-related damage, indirectly. Massive slides may be triggered by an earthquake (Salamon, this volume) or by progressive *in situ* destabilizing processes.

Each of these generalized processes will be outlined in the next sections, followed by others on tsunami activity and detection, mitigation, and recommendations.

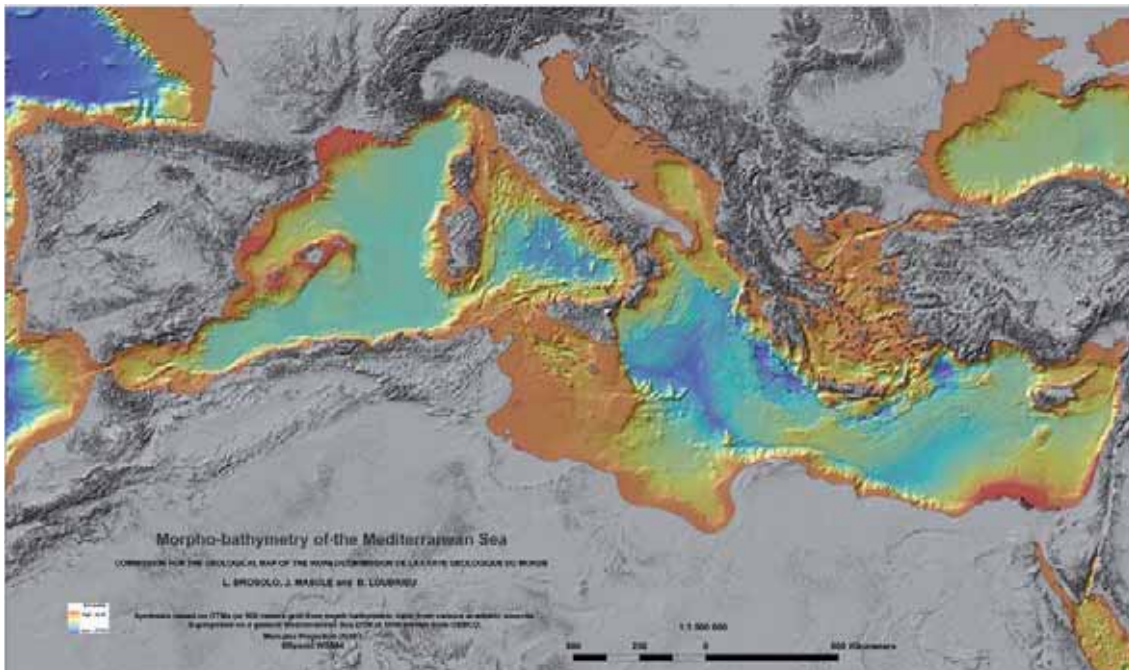


Figure 1. General morpho-bathymetry of the Mediterranean Sea DTM at 500 m.

2. VOLCANOES

Mediterranean subduction-related volcanism occurs in the Tyrrhenian and the Aegean Seas with respectively the Aeolian and Hellenic volcanic arcs. Volcanic activity along these arcs has been known since prehistoric time and is still going on. Approximately 5% of the known tsunamis worldwide have been generated by processes connected with volcanoes. In general, volcanic activity-related tsunami triggering mechanisms may relate to the caldera formation, to the volcanic edifice collapse, to pyroclastic flows, to hot surges generated during eruption, and even to failure of volcanic deposits soon after their deposition on the seafloor (Gamberi and Marani, this volume; Sakellariou, this volume).

Caldera formation – submarine eruptions

Large volcanic eruptions may lead to collapse of the entire volcanic edifice and consequently to the formation of a caldera. Caldera formation has repeatedly occurred during the long eruptive history of Thera (Santorini) volcano, including the Minoan eruption in the 17th century BC. If such caldera formation is below sealevel, then huge quantities of seawater rush in to fill the new

cavity. The tsunami generated in that way spreads radially, like the tsunami triggered by the explosion of Krakatoa volcano in 1883, or of Sumiso volcano, Japan (Tani *et al.*, 2008). The same process is thought to have occurred during the Minoan eruption and subsequent caldera formation (Yokoyama, 1978; Goodman-Tchernov *et al.*, 2009; McCoy and Heiken, 2000; De Martini *et al.*, this volume; Sakellariou, this volume). Shallow-water submarine eruptions, like the AD 1650 Columbo eruption, just north of Santorini, are known to be able to cause hazardous phenomena like gas explosions, pyroclastic flows and tsunamis (Dominey-Howes *et al.*, 2000). Deep submarine eruptions probably do not constitute a major hazard since the pressure of the water column causes the material to be ejected mainly in the form of lava flows.

Pyroclastic flows

Pyroclastic flows are tightly associated with and constitute one of the most devastating phenomena of volcanic eruptions. They are hot surges, composed of hot gas and volcanic tephra, which travel down the volcanic slopes and spread laterally at velocities of hundreds of kilometres per hour. Recent studies have shown that pyroclastic flows, depending on their density and velocity, when entering the ocean are capable of triggering tsunamis. Very thick pyroclastic flow deposits of the Minoan eruption have been mapped on the seafloor at distances up to 30 km around Santorini (Sigurdsson *et al.*, 2006; Sakellariou, this volume), and may have triggered tsunami waves (McCoy and Heiken, 2000).

Volcanic edifice gravitational collapse / slope failure

An additional geohazard associated with most of the volcanoes in the Mediterranean is the process of structural failure and gravity collapse of the volcanic edifices. This hazard is inherent to the history of volcano growth that evolves through constructional phases to gravitational instability. This inevitably leads to an increase of the steepness of the edifice's flanks, of overloading and of potential instability. When the volcanic dynamics results in an excess critical instability, destructional phases punctuate the constructional processes, leading to structural collapses, often catastrophic, of the volcano's flank.

2.1 Tyrrhenian Sea

In the Tyrrhenian Sea, the Aeolian volcanic arc includes seven islands and several volcanic seamounts that do not reach the sea surface. Some of the Aeolian Island volcanoes are known to be active, as for example the well known Stromboli volcano that due to its continuing intermittent eruptions was known in the antiquity as "the lighthouse of the Mediterranean". Besides many accounts of past potential hazards from eruptions of these active volcanoes, their period of 'unrest' in 2002 has shown that the submarine portions of these islands can be hazardous. This can be exemplified for Stromboli where after a period of intense activity, with lava flows emission, a large amount of pyroclastic material and lava had accumulated on the northern side of the volcano. Due to the weight of this new material and the steep gradient of the flank, huge downslope mass movements occurred on 30 December 2002. A first massive submarine landslide occurred just under the sea level followed by a subaerial landslide; both landslides produced tsunami waves. The tsunami had a run-up of about 10 m (Maramai *et al.*, 2005a), and the fact that there were no casualties was due to the low touristic season. Another example comes from Panarea Island. On 3 November 2002, three large whitish plumes suddenly appeared at the sea surface about 3 km eastward of Panarea. Submarine craters opened at the top of a 2.3 km² shallow rise of the seafloor, between -2 and -30 m below sea level. This event highlighted the unexpected revival of volcanic activity offshore Panarea Island a volcano generally considered to be extinct (Esposito *et al.*, 2006). In addition to Island arc volcanism, large volcanic seamounts are present in the Tyrrhenian back arc domain that have been possibly affected by large collapse and by explosive submarine eruptions at a depth of 500 m.

A further active volcanic region is located in the Sicily Strait where crustal extension in front of the Apenninic-Maghrebic chain is accompanied by magma ascent and volcanic activity. Here, historical reports on submarine volcanic activity are frequent. The most recent and well described ones correspond with the eruptions that lead to the formation of the ephemeral Ferdinandea Island in 1831 and the Foerstener submarine eruption of 1891 (Corti *et al.*, 2006). The case of the Ferdinandea Island has shown that in the area submarine eruptions can be hazardous associated with phreatomagmatic eruptions that also can generate local tsunamis.

2.2 Aegean Sea

The Hellenic Volcanic Arc has developed as a consequence of the active subduction and melting of the African lithosphere beneath the Aegean Sea. The trace of the volcanic arc is parallel to and about 150 km north of the Hellenic Trench, and is delineated by four main volcanic fields in the South Aegean Sea, namely Poros-Methana-Egina, Milos, Santorini-Columbo, and Nisyros-Kos. Major historically recorded eruptions took place mainly in the Santorini-Columbo volcanic field. The most recent major explosive eruption, the Minoan eruption of the Santorini volcano, took place in the 17th century BC (about 3600 years B.P.) and has been considered to be a main reason for the decline of the Minoan civilization on Crete (e.g. Marinatos, 1939), an hypothesis that is no longer generally accepted. Recent studies have shown that the Minoan eruption is the second largest one worldwide, after the Tambora 1815 eruption in Indonesia, and much greater than the 1883 eruption of Krakatau also in Indonesia (Sigurdsson *et al.*, 2006). It is widely believed and there is evidence proving this, that huge tsunami waves were generated as a consequence of the various eruptive phases, which inundated the coasts of the Central and Eastern Mediterranean (Marinatos, 1939; Yokoyama, 1978; Minoura *et al.*, 2000; Pareschi *et al.*, 2006a; Bruins *et al.*, 2008; Papadopoulos, 2009; Novikova *et al.*, 2011; De Martini *et al.*, this volume). A more recent, submarine eruption took place in September 1650, associated with the submarine Columbo volcano that is located a few miles northeast of Santorini. Tens of casualties were reported from the volcanic gases and the tsunami which followed this eruption (Dominey-Howes *et al.*, 2000). The Columbo volcanic field is comprised of about 20 small, submarine volcanic cones. Recent studies suggest that these cones may be younger than the main Columbo edifice and may thus constitute potential centers of future submarine eruptions.

2.3 Gaps of knowledge related to volcanic activity

Monitoring of hydrothermal activity, geochemical composition of emitted gas, seismicity and ground motion is well established on volcanoes located on land in the Mediterranean Region. In contrast, submarine volcanoes in the Mediterranean (such as in Columbo-field, or submarine cones in the Tyrrhenian Sea) are not being monitored by any means. Consequently, no risk assessment or prevision can be done for the marine domain.

3. EARTHQUAKES

3.1 Geodynamics and seismo-tectonics

Earthquakes represent the most frequent hazardous events in the Mediterranean region. The main geodynamic process, which controls seismicity on Earth, is the continuous motion of rigid lithospheric plates. This mechanism is quite active in the region where complex interactions between the African and Eurasian plates, and several microplates (see Fig. 1 in Mascle, this volume), are associated with a variety of seismo-tectonic styles: *compression* due to lithospheric convergence in SW Iberian Peninsula, North Algeria, Calabria Arc in Italy, Hellenic Arc in Greece, Cyprus Arc in Levantine basin; *extension* in back-arc basins (e.g. Alboran Sea, Tyrrhenian Sea, Aegean Sea), as well as in more complicated areas such as the Apennines and the Messina Strait in Italy, and the Corinth Rift in Central Greece; *shear* associated with horizontal *strike-slip motion* of adjacent lithospheric blocks, for example along the North Anatolian Fault, in Eastern Ionian Sea (Cephalonia), and along the Dead Sea Fault; *oblique-slip* where compression, or extension, are combined with strike-slip motion, like *transpression* along the Eastern Hellenic arc, or *transtension* along the southern part of the Dead Sea Fault, and along the western segment of the North Anatolian Fault Zone. Most of this seismicity is relatively shallow and occurs in the upper 30 or 40 km of the lithosphere. Deeper earthquakes have however been recorded in Spain (up to about 660 km) as well as in the subduction zones of the Calabria (up to ~350 km), Hellenic (up to ~180 km), and Cyprus Arcs (up to ~120 km). Earthquakes associated coastal uplifts such as at Rhodes and Crete (Stiros and Pirazzoli, 2009; Stiros, 2010) are signatures of the convergence between Africa and Eurasian plates along the Mediterranean Arc Systems.

3.2 Distribution – short history

Although the seismicity, that is the level of earthquake activity, is not uniformly distributed in space and time, there is in fact no area in the Mediterranean Sea region which is free of earthquake epicentres (see Fig. 2 in Mascle, this volume) or its influence. The highest seismicity, however, is

concentrated in the eastern basin of the Mediterranean Sea. This is mainly due to a higher rate of tectonic deformation varying from 7 mm/yr, near the western Peloponnesis, to 15 mm/yr around SW Crete (Hollenstein *et al.*, 2008) compared to the western Mediterranean. In the eastern Mediterranean the kinematics is dominated by a general motion towards the Hellenic trench, where the oceanic lithosphere is subducted beneath the Aegean continental crust at about 35 mm/yr while the North Anatolian Fault is taking up the westward motion of Anatolia relative to Eurasia which amounts on the order of 25 mm/yr (Reilinger *et al.*, 2006). The seismo-tectonic styles, as well as the distribution of the focal depth of earthquakes, are also different from one place to another. The Hellenic subduction zone is particularly capable of producing large earthquakes and large events may obviously be expected to occur in the future. Such large events would accordingly impact the coastline bounding the Aegean Sea and the Marmara Sea.

The occurrence of strong, usually disastrous, earthquakes is well known from the antiquity up to now. Some large earthquakes caused destructive or damaging tsunamis, including the events of 373 BC in Corinth Gulf (Sakellariou and Lykousis, 2003), of AD 365 and 1303 in the Hellenic Arc (Yolsal *et al.*, 2007; Fokaefs and Papadopoulos, 2007), of 1402 in the Corinth Gulf, of 1481 in Rhodes island, of 1956 in Amorgos in southern Aegean Sea (Okal *et al.*, 2009), of 551 and 1202 in the Levantine Sea (Salamon *et al.*, 2007), of 1222 in Cyprus, of 1627 at Gargano off the Adriatic coast (De Martini *et al.*, 2003), Italy, 1755 in Portugal, 1822 in Antiochia (Soloviev *et al.*, 2000), 1856 in Algeria, of 1783 and 1908 in the Messina Strait; of 479 BC, 330, 1859 in Thessaloniki and Imroz, of 1893 in Samothraki, 1983 at Lemnos in the northern Aegean (Soloviev *et al.*, 2000; Papadopoulos, 2009; Okay, this volume), of 447 and 1509 in Istanbul and Marmara Sea. Recent catastrophic earthquakes occurred in Izmit (Turkey) and Athens (Greece) in 1999 (Görür *et al.*, 2002; Tinti *et al.*, 2006a; Altınok *et al.*, 2011), in North Algeria in 2003 (which also triggered a tsunami), in L'Aquila (Italy, 2009) and in Lorca (Spain, 2011).

Most earthquake sources are located close to coastal zones. This is of particular importance from the point of view of tsunami hazard. Since the geodynamic processes that cause earthquakes continue for millions of years and are still ongoing, there is no doubt that large earthquakes will repeatedly occur in this area.

3.3 Seismic parameter determination – data bases

Information about the main source parameters of earthquake events, being the time of initiation, the epicentre, the focal depth and the magnitude, are available in catalogues usually arranged in chronological order. Furthermore, additional earthquake information is organized in data bases compiling other parameters related to seismic events such as driving mechanism, surface rupture and associated natural effects such as the resulting intensities and damage, etc.

The instrumental record of earthquakes started to develop about 100 years ago. Thanks to this instrumental monitoring, it progressively became possible to produce catalogues of seismicity for the instrumental period of seismology. The recorded and calculated parameters are improving with time due to gradual enhancements of monitoring and processing capabilities through seismograph networks. The catalogues thus become more and more complete, homogeneous and accurate. This yields important insight for the improved identification and characterisation of seismogenic fault, for the understanding of their geometry and kinematics, and for reconstructing the overall seismo-tectonic framework (e.g. Sallarès *et al.*, this volume). However, the identification of earthquake events that occurred prior to the instrumental era, is based only on historical and archaeological documentation, as well as on a variety of geological observations and methods. Palaeoseismology, for example, is one of the main geological methods which could be applied, but this has, so far, been done mainly on land (see Sallarès *et al.*, this volume). The data provided by these methods is less -complete, -homogeneous and -accurate as compared with the instrumental records. Nonetheless, the pre-instrumental information is invaluable since it provides evidence for at least some of the events, both on land and offshore, which otherwise would have remained unknown. In addition, the historical and geological methods also allow to extend the seismic catalogues far into the past. This is especially important for seismogenic structures for which the frequency of earthquake production is longer than a century. This not only improves the earthquake statistics, but even more importantly it is vital for hazard assessment of events with lower frequency (and often more catastrophic consequences). There is a clear need for information on past earthquakes

so as to permit a better evaluation of (1) the general irregularities of the time-space patterns of large earthquakes, (2) the common discrepancy between long-term plate boundary slip rates versus rates inferred from seismicity, (3) archaeological evidence for clustering of destructive earthquakes that is associated with the recurrence time.

The geological identification of tsunami sediment deposits in coastal areas is a newly developing discipline which provides useful and important information about palaeo-tsunamis and their causative earthquakes. In parallel, several geophysical methods that were developed to investigate the offshore environment, greatly contribute in the identification and characterization of submarine seismic faults and slumps.

3.4 Associated marine hazards

Large earthquakes ($M > 6.0$) are usually damaging and can be destructive. The impact of earthquakes on human communities generally decreases with distance of populated areas to the epicentres. A characteristic deviation from this general rule can be found in cases of large ($M > 6.5$) intermediate-depth earthquakes in the Hellenic Arc and possibly in the Cypriot Arc, which may cause serious damage at large distances towards remote Mediterranean Sea localities. However, strong submarine earthquakes *per se* do not constitute a direct hazard of marine origin, as it is the secondary effects which induce the hazard. Examples of the latter are tsunamis directly related to co-seismic fault displacement and strong ground motion at the sea floor or indirectly to submarine and coastal landslides, all of them being triggered by strong ground motion (Fig. 2). Submarine slumps and coastal landslides may also result in the generation of local or regional tsunami waves. However, the majority of the basin-wide tsunamis are produced by shallow earthquake activity in the Mediterranean basins. Overall, the main tsunamigenic zones in the Mediterranean are associated with the main seismogenic zones and nearby continental slopes (Fig. 3). The triggering of tsunami waves by co-seismic processes and its impact on the communities along the coast of the Mediterranean Sea, is evaluated in Okay (this volume).

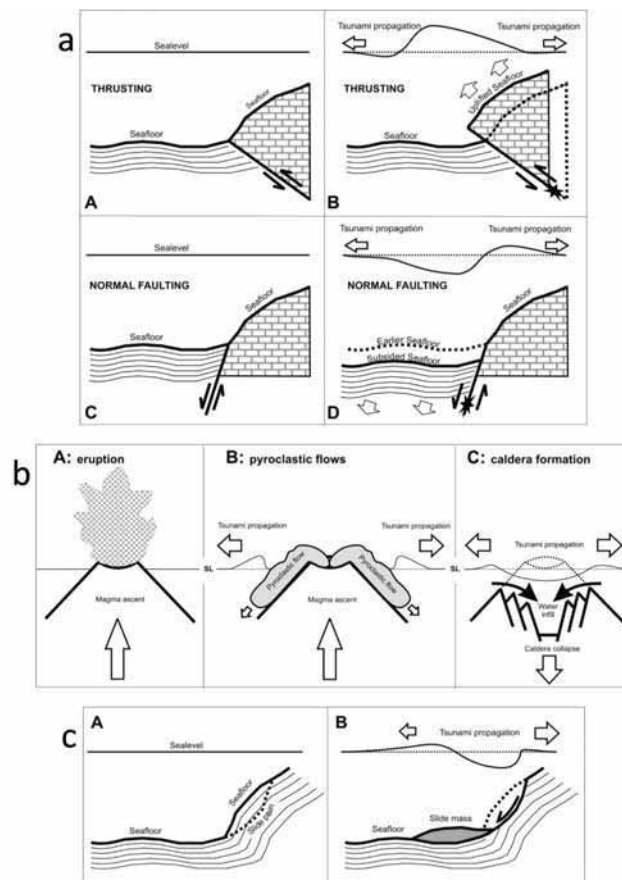


Figure 2. Sketches illustrating the origin of tsunami generated by: (a) faulting (ground displacement), (b) volcanic activities and, (c) submarine landslide.

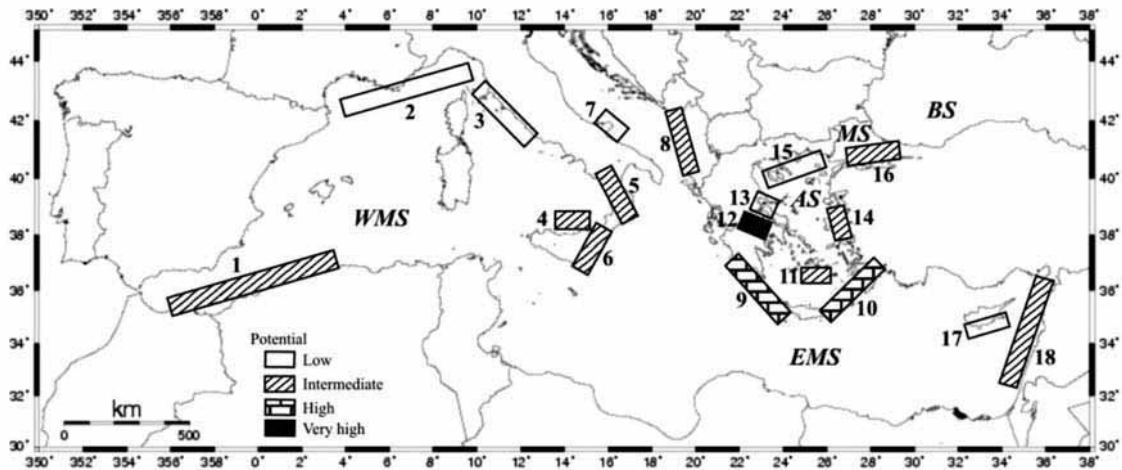


Figure 3. Tsunamigenic zones defined from documentary sources and their relative tsunami potential classification (Papadopoulos and Fokaefs, 2005; Papadopoulos, 2009): WMS=Western Mediterranean Sea, EMS=Eastern Mediterranean Sea, AS=Aegean Sea MS=Marmara Sea. Black Sea (BS) is not included in this study. Zonation key; 1 = Alboran Sea, 2= Liguria and Côte d' Azur, 3 = Tuscany, 4=Aeolian Islands, 5=Tyrrhenian Calabria, 6= Eastern Sicily and Messina Straits, 7=Gargano, 8=east Adriatic Sea, 9=west Hellenic arc, 10=east Hellenic arc, 11=Cyclades, 12=Corinth Gulf, 13=Maliakos Gulf, 14=east Aegean Sea, 15=north Aegean Sea, 16=Marmara Sea, 17=Cyprus, 18=Levantine Sea.

4. SUBMARINE LANDSLIDES

In the Mediterranean Sea, the steep and narrow continental margins, tectonically active in majority, and fed by small mountain-supplied rivers, are highly affected by several slope failure processes (Figs. 2-4). Until now, about 600 scars related to submarine landslides and almost the same number of mass-failure deposits have been reported in the literature from specific studies realized around the whole Mediterranean basin (Camerlenghi *et al.*, 2010). These events are located in both tectonically active and quiet areas and have usually been triggered from shallow (about 50-100 m) to up to 2 km water depth. They involve remobilization of continental-slope deposits with volumes ranging from less than 0.001 km³ to more than 1,000 km³. Only few submarine landslides have been accurately dated so far, with ages ranging from within the last 100,000 years to very recent

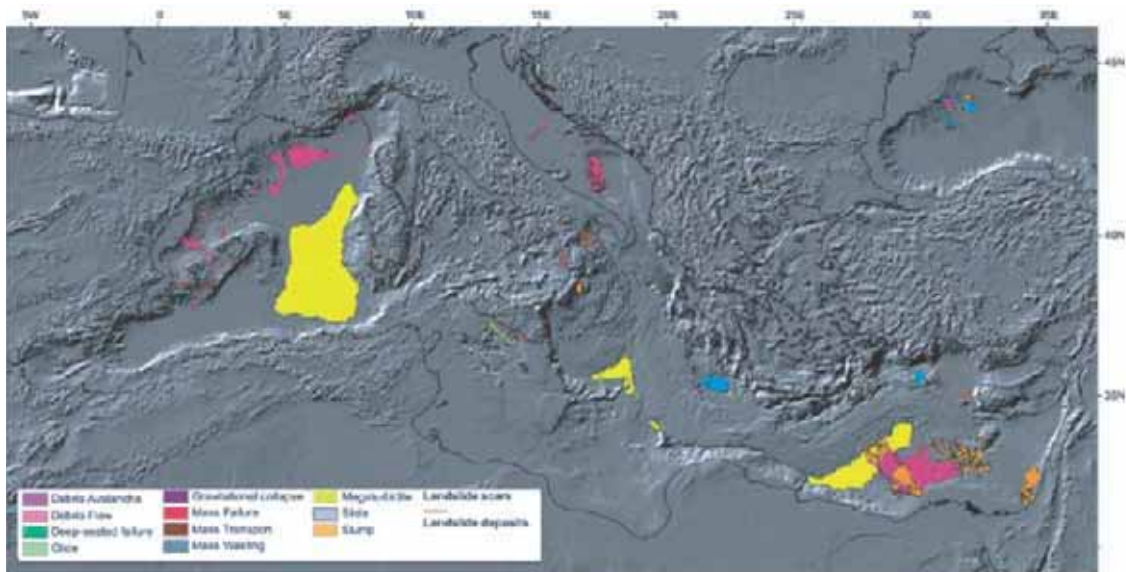


Figure 4. Location of the main submarine-landslide events reported around the Mediterranean margins and basins. Modified from Camerlenghi *et al.* (2010).

times. Therefore, the frequency of triggering and relationship with potential punctual events such as earthquakes are still a matter of debate. Moreover, there is still a lack of information for modern, “active”, failures (i.e. the land reclamation failure into the sea at the Nice airport that affected the shelf edge in 1976 (Sultan *et al.*, this volume) or the Calabria failures that affected the Ionian margin (Ceramicola *et al.*, 2010a;b; Planinsek *et al.*, 2011), from which we could extract valuable parameters that will help to better understand past failures.

Depending on the volume of deposits mobilized by the failure event, the depth at which failure occurs, and the acceleration history of the failed mass, submarine landslides can generate tsunami waves at the sea surface that are known to have a local and damaging effect along the coastline, a few tens of kilometers around the location of the source of the landslide by comparison with earthquake-induced tsunamis that can affect a whole basin (Papadopoulos *et al.*, 2007a; Ioualalen *et al.*, 2010). However, simulations of landslide generated tsunami for the coast of Israel (Rosen, this volume) showed that also regional effects (beyond 150 km) can be encountered in some cases.

4.1 Slope movement stages and physical mechanisms

To evaluate the failure potential of a submarine slope, a clear understanding is needed of underlying physical processes associated to both predisposition and triggering factors. Examples of the latter are: slope gradients, high sedimentation rates, fluid seepages, lithological discontinuities, loose sand and liquefaction, leaching and high sensitivity clay, hydrates occurrence and free gas generation, etc. Three main types of triggering mechanisms can act in time and space to produce failure of submarine slopes: (1) tectonic factors related to the Mediterranean plate-tectonic reorganization (in the last 5 Ma) such as the Calabrian Arc and the Mediterranean Ridge subduction (i.e. vertical uplift of Calabria offshore shelf areas) and fore-arc extension (i.e. Crotono Spartivento Basins); (2) eustatic changes in sea level such as during the Messinian salinity crisis (6 Ma ago) and changes due to glacial-interglacial periods (such as the LGM, 20 Ka) where sea level drops were in the orders of hundred meters; (3) high storm waves inducing overloading on shallow underconsolidated sediments. An additional potential landslide mechanism (Rosen, this volume) may occur due to scouring of the lower part of the eastern flank of the Nile delta (consisting of huge unconsolidated sediment volumes) resulting from the increased bottom flow of much saltier and warmer waters coming from the Suez Canal, since its widening and deepening after the 1990s. A main initial slope failure event may be accompanied by subsequent mass movement processes at different stages (post-failure; retrogressive failure, and slope failure reactivation; Hampton *et al.*, 1996).

4.2 Observation, detection and precursory evidence

Great technological improvement in geophysical tools (multibeam bathymetry, AUV, ROV, side-scan sonar) during the last two decades has allowed to map seabed morphologies with a resolution never achieved before - up to cm resolution even at great water depths. This has allowed marine geoscientists to identify new features (cold water coral reefs, fluid vents, mud volcanoes provinces) as well as to characterize structures such as submarine failures at a higher resolution, and to assess their spatial distribution. Seabed mapping has hence shown to be an important tool not only to identify recent morphologies and active faults at the seabed, but also to integrate information from the morpho-bathymetric data (sea-bottom surface) with data coming from shallow to deep sediments (sub-bottom data, multichannel seismic reflection; see Ceramicola *et al.*, this volume; Migeon *et al.*, this volume). Tsunami-genic recent morphologies caused by deformation, erosion and depositional events that are observed at the seafloor can now be related to deep-seated structures that may represent the trigger (i.e. seismogenic faults, fluid/gas, rapid sediment loading). Slope failure processes are at first local, with formation of plastic and weak zones, then become more general (Leroueil, 2001). Therefore, sediments submitted to active deformation are characterized by specific litho-facies and typical geotechnical properties (weak zones). Collecting sediment cores is thus a necessary step to identify processes that usually start at the scale of the grains, i.e. at a millimetre scale. In addition, laboratory and *in situ* geotechnical measurements may constrain changes in physical properties characterizing the presence of weakness layers within the sedimentary column (see Nice airport case study, Sultan *et al.*, this volume).

Identification of potential precursory evidences of submarine landslides requires continuous temporal physical data acquisition and high spatial resolution imaging of the seafloor and sub-seafloor deformation features. High resolution morphological data and changes in geotechnical properties may give an indication on a deformation mechanism affecting progressively the superficial continental-slope sediment (i.e. creeping). The easiest recognizable/detectable precursor for submarine failures should be the formation of trains of small-scale low-elevation escarpments, few tens of cm high.

4.3 Gaps of knowledge associated with sedimentary mass movements

4.3.1 Submarine slides

Little is known about the early phases of submarine landslide initiation, the steady-state or transient conditions under which early deformation and subsequent slope failure may evolve. Also, the sediments from which slope failure originates have rarely been sampled, nor their physical properties determined. Moreover there is a lack of understanding on the early post-failure evolution of submarine slope failures, which is critical for assessing tsunami hazard from submarine landslides. Finally, a major gap in knowledge concerns the timing of failure processes and the precise age of failed sediment accumulations, i.e. recurrence rate.

4.3.2 Submarine faults and paleoseismic parameters

In submarine fault characterization (i.e. slip rate, segmentation and kinematics), large difficulties appear when dealing with slow-moving and reactivated faults located in low sedimentation rate areas. An important gap of knowledge concerns the identification of earthquake single ruptures and the occurrence of vertical and strike-slip components per event (i.e. co-seismic slip). This is based on the ability to recognize and date individual event horizons, as is done in trench techniques on land. Regarding the off-fault paleo-seismic studies, the use of turbidites as paleo-seismic indicators requires demonstrating that earthquakes are their most plausible triggering mechanism. Other gaps of knowledge are related to: the selection of sediment coring sites, as events may be missing or under-represented depending on the depositional location; the link between the turbidite thickness and the magnitude of an earthquake, the relation of which is not straightforward; and the limitations to obtain accurate ages using radiocarbon, due to the spatial and temporal variability of the ^{14}C reservoir age essential for date calibration.

5. TSUNAMIS

The word tsunami is a Japanese term derived from the characters “tsu” meaning harbor and “nami” meaning wave. It is generally accepted by the international scientific community to describe a series of travelling waves in water produced by the rapid displacement of a large amount of seawater such as can be associated with submarine earthquakes, volcanic eruptions, or landslides. The length of tsunami waves (i.e. the distance between two consecutive crests or troughs) ranges from 10-300 km and is much larger than that of waves generated by winds or by big storms. As for all ocean waves, their wave-period is proportional to the wave-length, and is typically comprised between 5 minutes and 1 hour. This is much larger than the period of wind waves, typically confined to the 1-15 sec band.

As discussed above, tsunamis are most frequently generated by large submarine earthquakes (about 75% of the cases according to tsunami catalogues), and less frequently by volcanic activity and by landslides (~5 and 10% respectively) (Tinti *et al.*, this volume). However, not every submarine disturbance generates a tsunami. Wiegel (1964) quotes Leet who stated that a catalog made in 1861 reported only 124 tsunamis during the interval that 15,000 earthquakes were observed along coastlines. According to Smid (1970), the Greek historian Thucydides was the first to relate tsunamis to submarine earthquakes, but the understanding of a tsunami's nature remained low until the 20th century.

In addition to tsunami, in recent years (see Vilibic´ and Šepic´, 2009; Tinti *et al.*, 2004; Rabinovich and Monserrat, 1996) a new term appeared, “meteo-tsunami”, attributed to long water waves of similar periods and behavior (including coastal flooding), but being generated by meteorological factors such as by a travelling atmospheric disturbance. Since the meteo-tsunamis are not due to

geo-hazards, they will not be addressed in this summary. Their flooding risks and early detection and warning aspects, however, are similar to those due to geohazards.

As mentioned above, a tsunami is generated when the sea water is displaced within a very short time over a large region by a disturbance involving the sea bottom or the sea surface (Fig. 2a). An earthquake, which may be explained as the effect of the movement (slip) of two crustal blocks slipping one with respect to the other along a contact surface that is called seismic fault or rupture surface, causes a deformation of the sea floor even if the fault is buried and does not reach the surface. The shallower the earthquake, the greater is its impact; the larger the deformation, the larger is the extent of the area involved. When a large sector of the sea bottom is displaced vertically (upheaval or subsidence) in a very short time, then the ocean water mass experiences the same displacement as the ocean-floor and consequently, the sea surface also deforms and is forced out of the equilibrium. In this way initial crests (or troughs) form in correspondence to zones of sea bottom upward (or downward) movement and then propagate as tsunami waves. The initial amplitude of tsunamis in a source region ranges from a few cm for small earthquakes ($M = 5.5$) to a few meters for large magnitude earthquakes ($M > 7.5$).

Mass movements (e.g. coastal and submarine landslides, pyroclastic flows) generate tsunami waves when they involve a large volume of material over an extensive area (Fig. 2b,c). A mass sliding along the ocean floor with a sufficient speed displaces water in the front and draws or sucks water in at the rear. If the slide front is wide enough, then the water cannot escape laterally but is pushed upward. So in general, crests and troughs are continuously formed during the motion of the sliding mass, and then propagate across the ocean. The larger the thickness of the landslide, the larger is the amplitude of crests and troughs. The tsunami is the result of complex interactions between all such waves. Dense pyroclastic flows can be interpreted as masses moving along the sea bottom and therefore their tsunami generation mechanism is the same as for landslides. Lighter components of pyroclastic flows with a density less than that of water are not able to penetrate, and float at the sea surface. Their quick motion determines tangential stresses and overpressures, that are larger than the ones produced by winds and that are capable to produce tsunami waves at the surface, usually however of small amplitude.

Volcanic slope collapses can be assimilated to mass movements (submarine or coastal), while the collapse of a volcanic caldera can be schematically seen as a sudden downward displacement of a sector of land that goes underwater: the rapid extension of the sea domain causes the seawater to flow in and fill the caldera, and starts the tsunami (Fig. 2c). Both events can involve volumes up to $1-10 \text{ km}^3$ and have the potential to generate large amplitude tsunamis. Explosions of submarine volcanoes can also initiate water waves, but usually most of the energy is dispersed in turbulent motions and only small amplitude waves are formed.

Tsunami waves propagate across the ocean with a speed that increases with the water depth h and that, when the wavelength is much larger than h , is proportional to the square root of h . It ranges from 700 km/h in the deep ocean to a few km/h in shallow water close to the coast. Consequently, tsunami wave propagation is strongly influenced by the ocean topography, with two main effects: 1) they slow down when they approach the coast, and their wavelength diminishes since crests offshore travel faster than crests nearshore; 2) their fronts tend to deform and bend due to wave shoaling and refraction.

The amplitude of the tsunami waves strongly depends upon their origin. Tsunamis induced by earthquakes have initial amplitudes at most up to a few meters in the source region, but they can be much larger when they are generated by large landslides. Tsunami amplitude increases when they approach the coast, the amplification factor depending mainly on the sea floor slope, sea-bottom roughness, the tsunami wavelength and the configuration of the coastline. Because of their large wave periods and corresponding large wave lengths, tsunamis may amplify 2-10 times when they impact a coast and therefore their potential of flooding is quite large. For a low-lying coast, they can penetrate for hundreds of meters inland reaching run-up heights (that is the maximum topographical altitude touched by the wave onshore) of some tens of meters above sea level. For example, the recent earthquake-related tsunami event in Japan (11-March-2011) had an initial height of $\sim 6\text{ m}$ but the run-up waves have in many places reached heights of 15-18 m (even upto

37.9 m; Kyodo News, 2011), and in some cases, moved more than 4 to even 10 km in-land (e.g. Kyoto University Team, 2011; Parashar *et al.*, 2011; EOS, 2011).

According to the available tsunami catalogues, 10-15% of the known tsunamis did occur in the Mediterranean. The presence of coastal and submarine seismic zones, of coastal, island and submarine volcanoes, and of unstable ocean margins ensures that all the causative processes are active. In the Mediterranean and in the NE Atlantic there is a potential for the generation of very large tsunamis that can travel across the ocean over very great distances. The 1755 M=8.5 earthquake in the Gulf of Cadiz produced a tsunami that penetrated along the river Tagus estuary with catastrophic effects in Lisbon and that was observed as far as the British Islands in the north and as far as the Caribbean Islands to the west. In the Mediterranean, basin-wide tsunamis are expected to be generated by seismic sources north of Algeria, by earthquakes in the Calabrian Arc and along the Hellenic Arc. On the western segment of the Hellenic Arc, a 365 AD earthquake is believed to have occurred in western Crete producing a tsunami that, according to historical records and to recent geological findings, propagated in the whole eastern Mediterranean and reached Greek coastal zones, Israel, Gaza, Egypt, Libya, eastern Sicily and the Adriatic Sea. The large 1303 tsunami, caused by a M~8 earthquake that ruptured the eastern segment of the Hellenic Arc, had a similar propagation. (Fokaefs and Papadopoulos, 2007). Basin-wide tsunamis can be produced also by the Mediterranean volcanoes. The tsunami produced by the Santorini Minoan eruption has been well studied and seems to have affected most of the eastern Mediterranean and the Ionian Sea (McCoy and Heiken, 2000; Goodman-Tchernov *et al.*, 2009; Bruins *et al.*, 2008; Papadopoulos, 2009; De Martini *et al.*, this volume). Holocene slope collapses of Stromboli and Ischia volcanoes (Maramai *et al.*, 2005a) are speculated to have produced tsunamis affecting the whole Tyrrhenian Sea. Moreover, along most of the margin of the Mediterranean Sea very large, mostly Pleistocene, landslide deposits have been identified that had the potential for basin-wide tsunami generation (Salamon, this volume).

Since most of the tsunamigenic sources are found close to the coast in the Mediterranean region, the minimum tsunami lead-time is quite short. The highest waves can reach the nearest coast in only a few minutes. The 2002 Stromboli tsunami that was caused by a 15 million cubic meter submarine landslide sliding along the Sciara del Fuoco, took less than three minutes to attack the entire coast of the island, and five minutes to strike the Panarea coasts 20 km away from the source. For the 1908 Messina catastrophic tsunami, most of the witnesses reported that the tsunami reached the shore of the Messina Strait less than 5 minutes after they felt the earthquake. The large 1956 South Aegean Sea tsunami arrived in nearby islands within less than 10 minutes. The Mediterranean is a small basin compared to the large oceans, consequently tsunamis generated near one coast can reach the opposing shore of the basin in about 1-2 hours. Observed and computed travel times confirm that the 2003 tsunami generated in north Algeria took 70-80 minutes to reach the coast of southern France. Less than one hour is taken by tsunamis generated in Italy to reach Greek Ionian coasts and *vice versa*, and about one hour for tsunamis generated in the eastern Hellenic Arc to reach the Egyptian coast. Propagation time is of course even shorter for tsunamis that occur in smaller basins like the Marmara Sea or in narrow gulfs like the Gulf of Corinth and Patras, or the Gulf of Izmit. Short tsunami travel times pose very severe and demanding constraints to tsunami early warning systems (TEWSs) in the region. This is one of the main concerns of the IOC-UNESCO Intergovernmental Oceanographic Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS in short) since its establishment in November 2005. This activity is strongly supported by CIESM, in particular through the upgrade of the MedGLOSS sea level stations to real time sea level data transmission.

6. RISK REDUCTION: PREPAREDNESS AND MITIGATION

Due to the increasing coastal developments and population, potential economic and social impacts of natural disasters continue to increase. Preparedness and mitigation against geohazards involve a series of risk reduction actions. Such actions include the establishment of TEWSs, of evacuation and emergency systems, as well as developing short- medium- and long-term strategies and sectorial plans (UNESCO, 2008; Murata *et al.*, 2010; Okay, this volume).

Until 2004, only the Pacific Ocean was covered by a TEWS which has been operating since the 1960s under the supervision of the IOC-UNESCO. More recently, other systems were also developed there. The national delegations participating at the General Assembly of IOC in June 2005 took decisions for the development of TEWSs in the North East Atlantic and the Mediterranean Sea, in the Indian Ocean, as well as in the Caribbean Sea. The three systems are under construction and still in the pre-operational stage.

The systems mentioned above are designed for issuing warnings only in the regional and transoceanic domain (coastal zones threatened by tsunami waves that may arrive more than one hour after its generation). They will report only to the national authorities in each country, whereas only national authorities will decide upon dissemination of warnings to their countries inhabitants. This is the case of tsunamis generated by fault displacements induced by major earthquakes. However, the most common tsunami sources around the world are situated very close to the coasts, which is in the near-field domain (coastal zones threatened by tsunami waves within a few minutes and certainly less than one hour after their generation). The afore-mentioned systems are inadequate in providing timely warnings for the near-field domain and in addition, such warnings remain the sole responsibility of the national authorities in each country.

Global statistics shows that more than 80% of tsunamis victims are caused during the first hour of tsunami wave propagation (Gusiakov, 2009). Hence the issue of near-field early warning of tsunamis is today a hot topic (e.g. Murata *et al.*, 2010). Following the 2004 Indian Ocean catastrophe, the German Indonesian Tsunami Early Warning System (GITEWS) was initiated in conjunction with the Indonesian TEWS (InaTEWS) (Lauterjung *et al.*, 2010; Behrens *et al.*, 2010), and designed for both regional and near-field tsunamis.

In the Mediterranean region nearly all coastal zones are threatened by near-field tsunamis (Fig. 2 in Mascle, this volume; and Fig. 3) and until now no answer has been given on how to issue a warning message within the first 5 - 30 minutes, which is the most common time window for the arrival of the first tsunami wave. So far, only a simple local tsunami device has been installed at Stromboli, intended only for the needs of this island. In addition, the national French project RATCOM develops a demonstrator, pre-operational local TEWS in the area of Ligurian coast and Corsica Island. The development of such TEWS's for near-field tsunamis is a realistic goal in the Mediterranean region that can be achieved by utilizing traditional and modern technologies such as sea-bottom seismometers, near-field tide-gauges, tsunameters, CGPS, GPS buoys, fast wave simulation tools and others (Rosen, this volume). The improvement of reliable and accurate earthquake catalogues, as well as the understanding of the tsunamigenic sources and mechanisms, are also crucial for modelling earthquake sources and tsunami generation and propagation, and are expected to contribute substantially for early-warning operations.

Effective early warning systems require a strong commitment of national and local authorities. Risk mitigation plans increase the capacity of local communities with the development and implication of risk reduction strategies and measurements (UNESCO, 2008; Murata *et al.*, 2010). Tsunami warning and evacuation systems, public awareness, risk mitigation measurements are the ultimate goal to build coastal disaster resilient communities around the Mediterranean (Okay, this volume). There is a need for identifying and monitoring marine geo-hazards and risks and improving early warnings as a priority. Series of continuous multiple risk reduction and mitigation efforts, such as short- to long-term actions, must be taken to reduce the structural and social vulnerabilities and to build up the capacities of communities (Okay, this volume).

For the short-term actions, strengthening of evacuation systems including evacuation plans for early warning are essential and should be linked with coastal inundation and evacuation maps. Particular attention should be given to the continuous improvement and upgrading of the evacuation exercise, emergency communication and response systems. Preparedness and public awareness will be enhanced through such education and training for geohazards and risk.

For the medium to long-term actions, the reduction of structural vulnerabilities and strengthening of coastal infrastructures as well as designing codes for coastal infrastructure and buildings, and inspecting coastal roads, railways and airports against tsunami heights, and protecting hazardous facilities such as nuclear power plants from tsunamis, and implementing structural mitigation

measurements including constructing seawalls, tsunami towers, vertical evacuation structures as well as educating for good constructing practices are important components of an overall structural risk mitigation action plan.

For the long-term actions, the increase of institutional capacity by improving communication, coordination, cooperation among the governmental offices plays a significant role. In addition, attention needs to be given to non-structural mitigation actions including risk transfer strategies (e.g. insurance, financial tools), investment in disaster prevention, focusing on policy development, legislation and organizational development of partnership (local authorities, business sector, media and volunteer organizations), targeting at land-use best practices (restricted coastal buffer zones) as well as networking of local knowledge centres along coast zones.

7. RECOMMENDATIONS

In the last seven years the world has suffered three major devastating tsunamis: 2011 in Japan, 2010 in Chile, and 2004 in Sumatra, with many thousands of casualties. Still, there are large areas where geo-hazard identification, and risk reduction systems are under-developed or even non-existent. Hazard identification and risk analysis provide the first step for the development of risk reduction and disaster resilient capacities.

As detailed above, several types of marine geohazards exist in the Mediterranean Sea, the most important of which are earthquakes, landslides, tsunamis and volcanism. Although some of them occur infrequently, their potential impact cannot be underestimated. For example, nuclear power plants are often located in coastal areas because of the nearby source of cooling water. Therefore, marine geohazards should be studied in depth and be taken into account in hazard analysis, risk assessment, and mitigation plans, by utilizing all available instrumental, historical, geological and other data. In order to reduce risks this information is the key for building policies and prevention measurements (mitigation). Hazard and risk identification involve series of scientific investigations and research through understanding hazard, vulnerabilities and risk elements. Current scientific knowledge on the main sources and generation mechanisms of marine geohazards in the Mediterranean region is still incomplete and uncertain (see above). Therefore, there is a need to acquire geophysical, geological and geotechnical data in order to better determine the location, size and kinematics and average frequency of occurrence for the potential sources of marine geohazards.

The purpose of improving and extending the coverage of high-resolution sea-floor mapping, coastal bathymetry (including river estuaries and inlets) and local beach and land topography, is of great importance in simulating better realistic generation, propagation and inundation of tsunami waves. These are all essential tools to support hazard mapping and early warning.

Considering that the regional Tsunami Early Warning System (TEWS), now under construction within the coordination of IOC-UNESCO, is meant to cover basin-wide and regional tsunamis, the need to develop specific near-field TEWS is of the highest priority. Priority should also be given to the densification of already existing instrumental networks in potential tsunamigenic areas, and the improvement of the capabilities for real-time data transmission and processing. There is also a need for further development and implementation of offshore monitoring systems of earthquake activity, volcanoes, unstable submarine masses and sea level changes. As travel time from source to coast is short, improved knowledge of the seafloor coupled with realistic simulations of potential hazard scenarios, and inundation maps besides TEWS, is needed to guide the preparation and mitigation of tsunami hazards. Risk mitigation actions should include proper planning and design of building codes to account for these geohazards in the design and construction standards, public education, preparedness and evacuation plans, and legislation for risk mitigation practices.

Time is an important variable in risk management, especially when it concerns extreme events (Beer and Ismail-Zadeh, 2003). The success of risk reduction actions is dependent on risk communication between scientists and local authorities as well as operational people. The Geoscience community has a responsibility to educate the engineers, and urban planners, authorities, media and public to build disaster resilience (Okay, this volume). In parallel, similar consistency should be established between early warning and evacuation systems. For a timely

evacuation, tsunami warning should be linked with the magnitude of earthquakes. Local authorities must prepare communities to understand warnings and to respond adequately. Coastal infrastructure, roads, railroads, airports, industrial facilities and plants such as shore-based power plants based on seawater cooling, need to be sufficiently protected from potential tsunamis impacts.

SUGGESTED ROADMAP

Identification, characterization, and potential generation mechanisms of main sources for marine geohazards have been summarized in Table 1. In addition, actions and tools as well as mitigation of risks are recapitulated.

Table 1. Summary of marine geohazards in the Mediterranean and suggested potential mitigation actions. (*): EQ = earthquake; F = fault; L = landslide; V = volcano; VP=Volcanic Processes; T = tsunami.

| AIMS | OBJECTIVES | ACTIONS | TOOLS |
|----------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| UNDERSTAND PHENOMENA | Identify and characterize the main sources of marine geo-hazards: EQ/F, L, VP, T (*) | Identify hazardous submarine geological features (F, L, V, T) Define source models including structure, geometry, size and age (F, L, V) Quantify sediment/rock properties, composition and pore pressures (F, L) Infer their likely evolution and kinematic patterns (F, L) | Seabed mapping Sub-seafloor imaging and modeling Seafloor and sub-seafloor sampling (analysis and dating) Seafloor and sub-seafloor geotechnical measurements Seafloor seismological monitoring |
| | Understand the mechanisms of generation | Improve understanding of the generation mechanism of EQ, L, VP Improve understanding of energy transmission from seafloor to water to generate tsunamis depending on source mechanism Simulate the generation mechanisms and energy transmission including observations | Seafloor and sub-seafloor stress and strain monitoring Seafloor seismological monitoring Numerical models of rupture dynamics, failure, sliding, collapse Numerical and empirical models of energy transmission at the solid/liquid interface Analog models |
| REDUCE THEIR EFFECTS | Assess the associated hazards | Simulate the process of tsunami generation, propagation and inundation and compare with observations (T) Produce detailed tsunami hazard maps (arrival time, run-up, inland penetration distance) (T) Evaluate time evolution of key active faults, volcanoes, and unstable slopes including estimation of recurrence intervals (EQ, L, VP) Develop and implement probabilistic methods for hazard analysis and integrate with on land hazard models (EQ, L, VP) Identify and recognize possible precursory signals (EQ, L, VP) | Numerical models of wave propagation including near-shore effects Include source kinematics and energy transmission models Include near-shore bathymetry and coastal DEM (*) data Paleo-seismic tsunami records (on-/off-shore) High-resolution bathymetry and DEM Long-term seafloor and sub-seafloor monitoring of key active faults, volcanoes, and unstable slopes Compile historical and instrumental catalogs with information on location, magnitude and timing of the hazards (EQ, L, VP) |
| | Mitigate the risk | Design and implement near-field tsunami warning systems Assess vulnerability and risk for T, EQ, L, and VP Develop improved tsunami design codes for marine and coastal infrastructures and constructions Integrate systematic education and training Improve communication strategies | Real-time access to data from seafloor monitoring instrumentation Tsunami impact scenarios for the main sources Hazard maps Data bases of socio-economic, infrastructure and building attributes |