

Review of the Tyrrhenian Sea seismicity: how much is still to be known? *Esame della sismicità del Mar Tirreno: quanto deve essere ancora conosciuto?*

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ABSTRACT - The Tyrrhenian basin extends in the central part of the Mediterranean sea and is of major importance in the frame of the general convergence of Eurasia and Africa plates. The southernmost sector, comprising the Aeolian Islands, the southern coast of the Italian peninsula and the northern Sicily coast, is the place of frequent, intense and, differently from the other regions of the basin, deep seismicity. This peculiarity has attracted many seismologists explaining the large amount of papers dealing with it.

We present a detailed description of the seismicity of the Tyrrhenian basin, including the Ligurian Sea, based on historical and instrumental data also dwelling on zones that are considered so far of scarce interests by most of the authors because of rare and weak activity. Large areas of the basin, generally the furthest from the coast, appear to be affected by very scarce seismicity with low energy events even in recent periods, when new conceived equipment's with high sensitivity were made available to the monitoring. The results of experiments of seafloor monitoring carried out in the Tyrrhenian and Ionian Seas in the last two decades are taken as examples of the present limits of the investigation capacity of land-based monitoring networks and, consequently, of the still persistent incompleteness of the knowledge of the basin seismicity.

KEY WORDS: historical and instrumental seismicity, Tyrrhenian Sea, Ligurian Sea, seafloor monitoring

RIASSUNTO - Il Bacino Tirrenico occupa la parte centrale del Mediterraneo e riveste grande importanza nel quadro generale della convergenza delle pacche continentali Eurasiatica e Africana. Il settore più meridionale del bacino, che comprende l'arco insulare delle Eolie, le coste meridionali dell'Italia peninsulare e le coste settentrionali della Sicilia, è luogo di sismicità intensa, frequente e, al contrario di altre regioni del bacino, profonda. Tali caratteristiche, che hanno attratto l'interesse di molti sismologi, giustificano l'abbondante letteratura al riguardo.

In questo articolo presentiamo una descrizione dettagliata della sismicità del bacino Tirrenico, includendo anche il Mar Ligure, sulla base di dati storici e strumentali, soffermandoci ad esaminare anche zone considerate di scarso interesse perché sedi di debole e sporadica attività sismica. Estese aree del bacino, generalmente le più lontane dalle coste, sono caratterizzate da sismicità scarsa e di bassa energia anche in periodi recenti, da quando nuova strumentazione con elevata sensibilità è stata messa a disposizione del monitoraggio sismologico.

I risultati di esperimenti di monitoraggio dei fondali marini del Tirreno e dello Ionio effettuati negli ultimi due decenni sono portati ad esempio dei limiti attuali del monitoraggio sismologico, basato esclusivamente su punti di osservazione a terra, e della conseguente incompletezza della conoscenza della sismicità del bacino Tirrenico.

PAROLE CHIAVE: sismicità storica e strumentale, bacino Tirrenico, Mar Ligure, monitoraggio dei fondali marini

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1. - INTRODUCTION

The Mediterranean Sea, one of the most studied regions of the world for its geodynamic and tectonic relevance, is the site of a complex system of continental blocks, oceanic basins and orogenic belts marking the boundary of the stable parts of the European and African converging plates. The Tyrrhenian Sea, a back-arc basin with a maximum depth of around 3600 m that progressively opened starting from about 10 Ma ago (KASTENS *et alii*, 1988) (CARTER *et alii*, 1972), is bordered by the orogenic belt of the Apennines on the north and east, and by the Corsica-Sardinia block and Sicily on the west and south respectively (fig. 1).

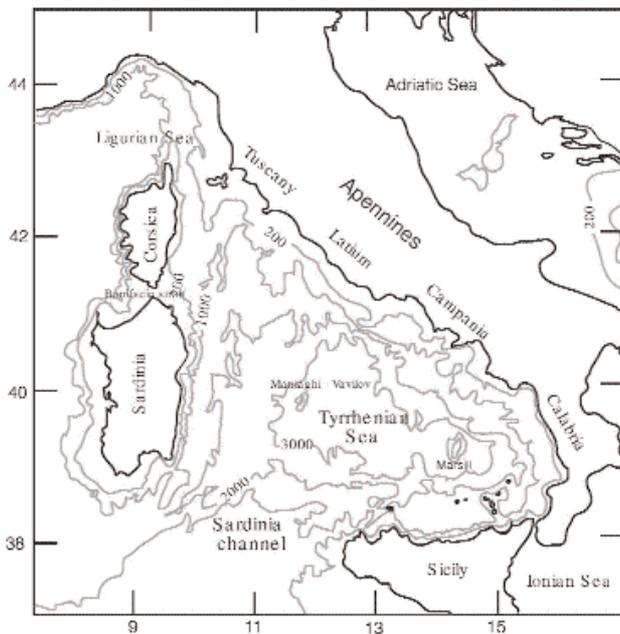


Fig. 1 - Map of the Tyrrhenian basin and surroundings. The isobaths of 200, 1000, 2000 and 3000 m are shown. Most of the geographic names used in the text are also reported, other names are included in the next figures.

The opening of the Tyrrhenian basin has been related to the sinking of the lithosphere with a roll-back mechanism (e.g., MALINVERNO & RYAN, 1986; ROYDEN *et alii*, 1987; PATACCA & SCANDONE, 1989). Its morphology is complex but similar to larger ocean basins in having an abyssal plain, seamounts, and well-developed continental shelves. Two main structural domains are recognised, respectively N and S of a prominent E-W lineament, named "41st N Parallel" (SERRI, 1990; FAVALI *et alii*, 1993a; b and references therein) running from northern Sardinia to Campania, evidenced also by E-W striking magnetic (CHIAPPINI *et alii*, 2000) and free-air gravity anomalies (MORELLI, 1970). North and south of this parallel, extension rates should have been markedly different if only in

the south they were so high as to generate oceanic lithosphere (PATACCA *et alii*, 1993). The northern sector has a continental crust (about 20 km thick) while some basins (Magnaghi-Vavilov and Marsili) in the southern sector are underlain by thin oceanic crust (6-10 km thick, STEINMETZ *et alii*, 1983; BRUNO *et alii*, 2000). More in general, strong lateral heterogeneities affect the Tyrrhenian lithosphere (MORELLI *et alii*, 1975; CALCAGNILE *et alii*, 1979; 1982; CALCAGNILE & PANZA, 1981; SCARPA, 1982; STEINMETZ *et alii*, 1983; PANZA *et alii*, 1990; AMATO *et alii*, 1993; CIMINI, this volume, PANZA *et alii*, this volume), whose main features are the thickening of both the crust and LID from the abyssal plain of the central part of the southern sector to the Calabrian Arc. This thickening accompanies a decrease of heat flow (EL ALI & GIESE, 1978; LODDO & MONGELLI, 1979; MONGELLI *et alii*, 1989) and gravity anomaly values (MORELLI, 1970; 1981; COLOMBI *et alii*, 1973; MONGELLI *et alii*, 1975; MORELLI *et alii*, 1975). Refraction and reflection experiments have shown that the bathial plain has an oceanic crust with a thickness of only about 8 km, underlying surficial, 1.5 km thick sediments (FINETTI & MORELLI, 1973; MALINVERNO 1981, STEINMETZ *et alii*, 1983; RECQ *et alii*, 1984; DUSCHENES *et alii*, 1986; FINETTI & DEL BEN, 1986; PASCUCCI *et alii*, 1999). A noticeably different crustal structure has been found under the Tyrrhenian shelf along the southern Apennines, Calabria and Sicily where "continental" velocity structures accompany a crust with a thickness of 18-20 km (MORELLI *et alii*, 1975). Onshore within only few kilometres from the coast, the crustal thickness increases abruptly to 45-50 km in places (MORELLI *et alii*, 1975; CASSINIS, 1981; NICOLICH, 1989).

One of the peculiarities of the Tyrrhenian area is the presence, in the basin and eastern adjacent areas, of volcanoes among the most important in Europe. Some of the Tyrrhenian seamounts are still very poorly explored in spite of their dimensions: as an example, the activity of the Marsili seamount, with an extension of around (70 x 30) km² and an elevation of around 3000 m from the sea bottom (MARANI, this volume), is still debated and remains largely unknown. In addition, Vesuvius and Etna, large volcanoes adjacent to the basin, are known to extend their roots in marine areas, contributing to the underwater volcanic, seismological and hydrothermal activity of the border of the basin with not well-investigated implications. Notably, rocks typical of continental crust have been dredged from seamounts in part of the Tyrrhenian Sea (HEEZEN *et alii*, 1971), thought as remnants of extremely stretched continental material that are floating on an oceanic crust.

Other seamounts, the largest ones of the central Tyrrhenian, namely Marsili and Vavilov, are basaltic (BARBERI *et alii*, 1973; TRUA *et alii*, 2003). Basalt has also been recovered from Deep Sea Drilling Project (DSDP) Core Site 373-A from the Tyrrhenian seafloor (DIETRICH *et alii*, 1978). According to some Authors (SARTORI, 1990; BECCALUVA *et alii*, 1994; KASTENS *et alii*, 1988; ZITO *et alii*, 2003) the age of these rocks is

estimated 4.1 and 1.8 Ma for the Magnaghi-Vavilov and the Marsili basins respectively, indicating a relatively young age for the formation of the central Tyrrhenian crust, progressively younger toward the S-SE.

A considerable spread of opinions still exists about the geodynamic evolution and present tectonic setting of this zone. The seismicity is undoubtedly one of the most basic elements to be explained in the geodynamic framework of the region. Many studies yielded important information bearing on our understanding of the specific features of the basin. However, in spite of a constant development of the telemetered Italian seismic network and the operation of local networks over the last 20 years, the knowledge of the Tyrrhenian basin seismicity is still incomplete and restricted to the southern Italian coasts and the Aeolian island arc. This limitation is mainly due to the inability, even at present, of the land-based monitoring networks to detect and localise earthquakes, especially of medium and weak energy, in many parts of the basin. The peculiar shape of the Italian peninsula has constrained the geometry of the land-based monitoring networks. In addition, from the beginning of their development, the seismological networks have been firstly considered as a tool for civil protection and consequently concentrated in deemed highly hazardous areas.

The recent technological advances in scientific marine instrumentation and communication systems, have produced modules and observatories for the seismological monitoring at seabed able to operate both autonomously and cabled. The adoption of this new investigation equipment, nowadays obtainable with relatively accessible resources, is essential to make a significant step forward in the seismological observation in marine zones that are still excluded from systematic monitoring.

As a result, most of the studies on seismicity are addressed to the southernmost sector, namely the Calabrian Arc, Sicily, the Tyrrhenian coasts and Aeolian Islands, which is considered to have a key role in the comprehension of the geodynamic evolution of the central Mediterranean.

The occurrence of destructive earthquakes and, differently from most of the other Italian regions, the presence of intermediate and deep seismicity related to the subduction were attractive elements for many geophysicists. The Ligurian Sea and restricted coastal areas of Tuscany and Latium, where weaker seismicity than the southernmost sector occurs, were also studied.

The Italian region, together with the Greek one, is considered the most exposed to tsunami risk in the Mediterranean, having experienced a relevant number of destructive and minor tsunamis. From 79 b.C. to 2002, 68 tsunamis have been identified (TINTI & MARAMAI, 1996; TINTI *et alii*, 2004). According to these Authors, the most frequent source of tsunamis is represented by earthquakes occurring along the coasts. Volcanic activity and gravitational sliding are

recognised, although to a lesser extent, as tsunamigenic events. In particular, the Tyrrhenian coasts have been the site of a large number of tsunamis, 70% of which occurred in the south-eastern sector and related to the volcanic activity of the Vesuvius, Campi Flegrei and Aeolian Islands. The two most destructive tsunamis so far known are related to seismic activity and they respectively took place along the Calabrian coast in 1783 (I_0 =IX-X MCS, m_b =6.3) and in the area of the Messina Strait during the 1908 Messina earthquake (I_0 =XI MCS, m_b =7.2)

This paper presents a review of the Tyrrhenian seismicity mostly addressed to offshore areas and the narrow coastal belt of few kilometres, with the aim to highlight how much knowledge is still lacking concerning the seismicity of large portions of this basin.

2. - SEISMICITY

2.1. - LIGURIAN AND NORTHERN TYRRHENIAN SEAS

The Ligurian Sea is an oceanic basin originated in the Oligocene-Miocene by the counter-clockwise rotation of the Sardo-Corsican block respect to the European plate (DE VOOGD *et alii*, 1991; MAKRIS *et alii*, 1999; SPERANZA *et alii*, 2002). A system of shallow normal faults extends alongside the Ligurian coast and the NW sector is steep and incised with canyons transversal to the strike of the fault system (CHAUMILLON *et alii*, 1994). The Moho depth under the basin is in the order of 20 km (GINZBURG *et alii*, 1986; PASQUALE *et alii*, 1997; EVA *et alii*, 2001). Gravitational sliding, over- and under-thrusting, which could have caused crustal thickening and embryonic subduction, are mechanisms proposed in the literature to explain the regional tectonics of the Ligurian margin (REHAULT & BETHOUX, 1984; CASSINIS *et alii*, 1990; DE FRANCO *et alii*, 1998; MAKRIS *et alii*, 1999; CONTRUCCI *et alii*, 2001).

The seismic activity is related to two distinct structural systems: one located in the western part of the Ligurian Sea and the other on land, between the Nice-Savona coast and the Maritime Alps (ISSEL, 1887; MERCALLI & TARAMELLI, 1888; CATTANEO *et alii*, 1987).

The seismicity distribution appears asymmetric as it is mainly concentrated in the western part, on the northern margin of the sphenochasm of the Sardo-Corsica block (fig. 3) (BETHOUX *et alii*, 1992). Seismicity is characterised by a low number of events with some large shocks with magnitude greater than 5.0 and one event (1887) reaching magnitude 6.2 (Gruppo di Lavoro CPTI, 1999). Figure 2 shows the epicentral locations of the most relevant events, while figure 3 shows the instrumental seismicity (1983-2003; INGV, 2004). All the on land earthquakes have very shallow focal depth (within 6 km) while the offshore hypocentres, related to the structures in front of Imperia, are usually located at larger depths. The focal mechanisms related to the two structural systems are

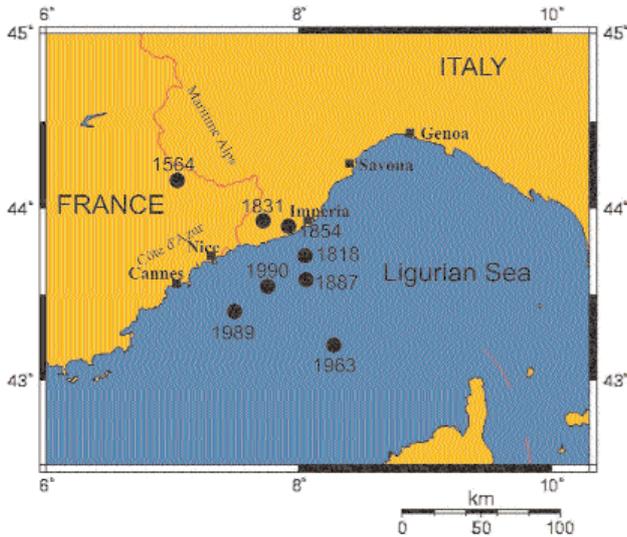


Fig. 2 - Seismicity of the Ligurian Sea, the most relevant events in term of magnitude ($4.2 = M_L = 6.2$) are shown in the period 1564 to 1990.

also different: the events of the western Liguria-Maritime Alps domain have mainly transpressive mechanisms, while a compressive regime dominates the offshore earthquakes (CATTANEO *et alii*, 1987). Offshore seismicity is rare and a gap of seismicity appears roughly coincident with a high heat-flow

region ($80-100 \text{ mW m}^{-2}$) in the central Ligurian Sea (PASQUALE *et alii*, 1995; 1997; EVA *et alii*, 2001).

BETHOUX *et alii* (1988; 1992) suggest that the northern margin of the Ligurian Sea is affected by to a general compressive regime which results from the tectonic setting of the area and hypothesise the closing of the Ligurian Sea as a consequence of the lateral expulsion of the south-western Alps along the south-western sidewall of the Apulian indenter (TAPPONNIER, 1977; VIALON *et alii*, 1989). The compressive focal mechanisms of some of the major recent seismic events seem to confirm this hypothesis; the 1963, 1989 and 1990 earthquakes occurred offshore in front of the Italian-French border, with the principal horizontal stress vector lying in the NW-SE direction (EVA & SOLARINO, 1998).

As far as concerns tsunamis, the two contiguous areas of Liguria and Côte d'Azur can be assumed as a unique single tsunamigenic-source zone, even if within this area the exact source location for some events is rather uncertain. Along these coasts, ten events affected Liguria from 1564 to 1979, involving in many cases also the French coasts. The most relevant tsunami is the February 1887 tsunami, associated to a destructive shock ($I_0=X$ MCS) with epicentre in the Ligurian Sea (MERCALLI & TARAMELLI, 1888). The tsunami, recorded by tide-gauge stations at Genoa and Nice, hit a large portion of the coast with an initial sea withdrawal followed by

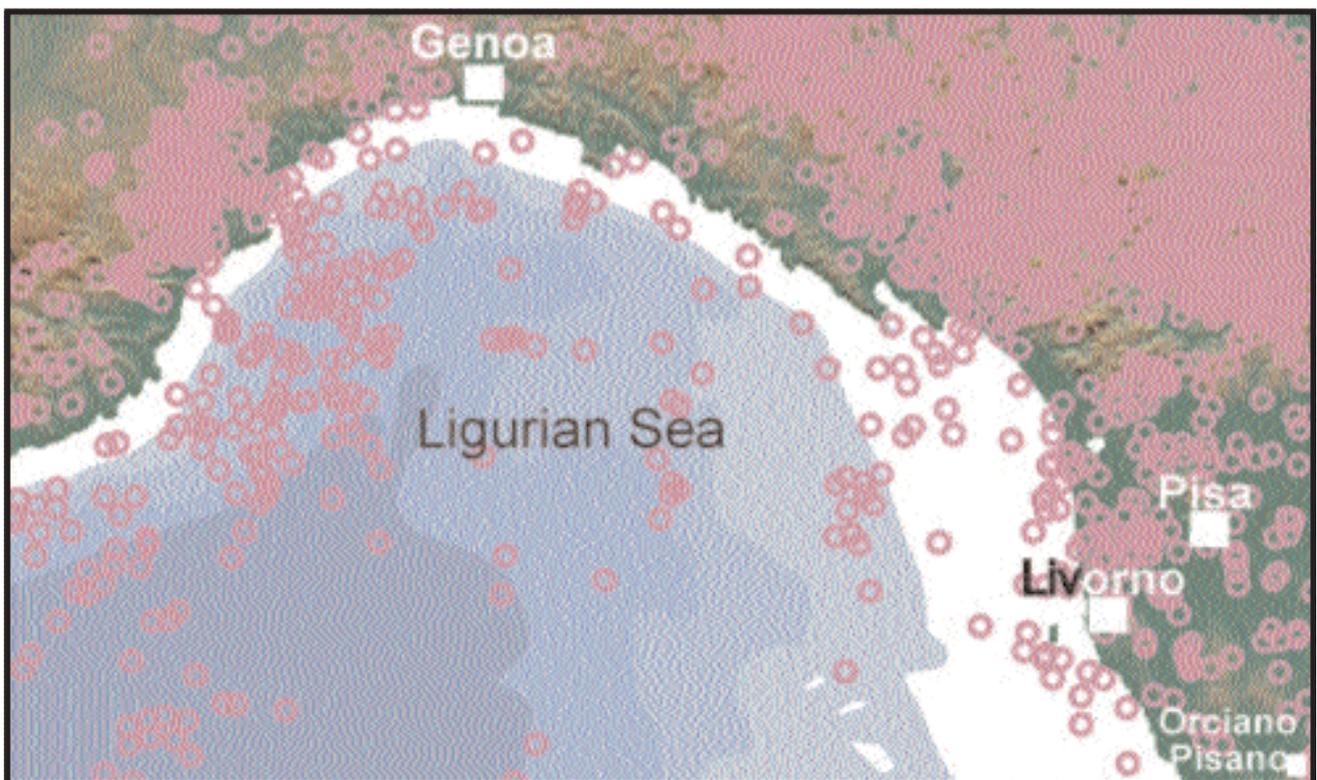


Fig. 3 - Map of the seismicity of the Ligurian Sea (1983-2003; INGV, 2004).

an inundation. The maximum run-up of 1,5 metres was measured at Imperia. Excluding the 1887 event, all the other tsunamigenic earthquakes of this area are located in land roughly close to the coasts, some of these having small magnitude (ranging from 3.2 to 4.0). The capability of those weak earthquakes to generate tsunamis can be explained by the triggering of submarine landslides in very unstable sediments of the Ligurian Sea canyons.

To the south, of note is the northern Tyrrhenian basin along the coastal area of Tuscany where seismicity is related to extensional tectonics. From the analysis of the historical and instrumental seismicity it is possible to identify two different areas of seismic activity, one located offshore in front of Pisa and Livorno and the other on land some kilometres south of Livorno (fig. 3). The offshore seismic activity is characterised by events with shallow depths and low energy with effects in coastal villages rarely reaching an intensity of VII MCS, like in the case of the 1646 Livorno earthquake. On land, scattered seismicity characterises the area south of Livorno, where some historical relevant events occurred (1742, 1771, 1846) reaching a maximum intensity of VIII-IX MCS (MARAMAI & TERTULLIANI, 1994; BOSCHI *et alii*, 1997). Only two weak tsunamis, affecting Livorno with small run-up, can be associated with shocks that occurred in

this area in 1646 and 1742 (I_0 =V-VI MCS). Associated with the inland-scattered seismicity located south of Livorno, only one tsunami event certainly occurred on the occasion of the most relevant shock of August 1846 in Orciano Pisano (I_0 =IX MCS).

2.2. - CENTRAL TYRRHENIAN SEA

Many studies have been carried out on the evolution of the Tyrrhenian basin (e.g., MALINVERNO & RYAN, 1986; MANTOVANI *et alii*, 1990; 1996) but without fully considering the evolution of the central part of the basin. Only few studies on tectonics and seismicity are available in the literature.

Historical catalogues and modern instrumental databases do not report relevant seismic events located in the central Tyrrhenian Sea. This characteristic, although excluding medium-high levels of seismic activity, does not give sufficient elements to consider this area lacking in seismicity.

The Campania-Latium Tyrrhenian margin is characterised by NW-SE elongated structural depressions, limited by WNW-ESE to NW-SE and by NE-SW striking faults (BRUNO *et alii*, 2000). From a geodynamic point of view the Latium Tyrrhenian margin presents a system of basins oriented both NW-SE and NE-SW and created by the activity of normal

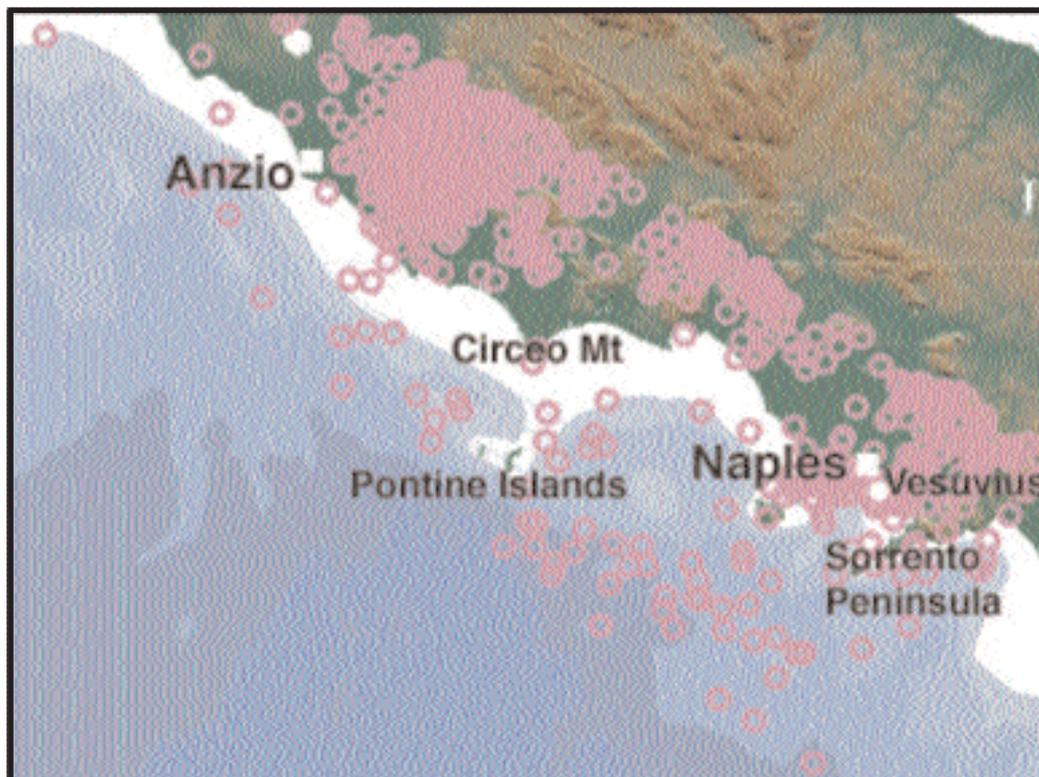


Fig. 4 - Map of the instrumental seismicity located along the Italian coasts of the northern and central Tyrrhenian Sea (1983-2003; INGV, 2004).

faults from Messinian to early Pleistocene (FACCENNA *et alii*, 1994). Offshore, the Latium area is separated from Campania by the eastern propagation of the E-W magnetic and free-air gravimetric anomaly of the 41st parallel (BRUNO *et alii*, 2000; CHIAPPINI *et alii*, 2000). Extensional tectonics, generally pertaining to the whole Tyrrhenian margin of the Italian Peninsula, is associated to the presence of the volcanic systems in the Latium area.

On the basis of historical and instrumental data, it emerges that the Latium area is characterised by low seismic activity both in occurrence and energy (for instrumental seismicity see fig. 4).

Nevertheless two distinct areas can be identified: the first one is located offshore and includes the Pontine Islands, a Pleistocene volcanic complex built on the continental slope in front of the Circeo promontory (fig. 4). This area is characterised by frequent weak earthquakes, which reached the maximum felt intensity with the 1781 April 13 earthquake (VII MCS). The second area includes the Latium coast south of Rome characterised by small to moderate, rare seismic events (fig. 4). The largest known earthquake, referred in literature as the "Anzio earthquake", in this area occurred in 1919 ($M=5.0$), with epicentre located offshore about 20 km from the coast. TERTULLIANI *et alii* (2003) make a careful revision of this shock, underlining that seismic events appear only at the end of 1800s, becoming more frequent after 1980. This is due both to the recent development of the Italian seismic network and to the lack of sources before the 1800s for the uninhabited territory. On the basis of historical data, the southernmost part of Latium coast was supposed to be almost a-seismic, with very few weak events with maximum intensity V MCS (MOLIN & PACIELLO, 1995). On the contrary, from the analysis of instrumental data the presence of rare seismic activity with low magnitude and focal depth roughly ranging between 5 and 10 km has been observed (CAPOCERA *et alii*, 1995). The coasts of Latium are believed to be almost exempt from tsunamis. TINTI (1991) shows that only one event, and moreover very doubtful, could have occurred in this area, with description of sea withdrawal at the Tevere mouth during the February 1703 shock ($I_0=X-XI$ MCS) that occurred in the central Apennines. No tsunami events are associated with the offshore seismicity of the Pontine Islands.

The western border of the Tyrrhenian basin, from the Ligurian Sea to the Sardinian-Tunisian strait along the eastern coasts of Corsica and Sardinia Islands, is reported in literature as an area affected by scarce and moderate seismicity. In fact, the analysis of the French database on historical seismicity for Corsica and Sardinia islands put in evidence that since the XVIII century only three seismic events have reached intensity greater than or equal to VI EMS98 (BGRM, 2004). In particular, the maximum earthquake occurred along the western coast of Corsica in 1775 ($I_0=VII$ EMS98). Another interesting event took place

on November 1948 ($I_0=VI$ EMS98), with epicenter located in the sea close to the northern Sardinian coast. This shock caused light damages in some villages in Sardinia, while it was felt in southern Corsica (PERONACI, 1953). As far as concerns the seismicity of the last 20 years for the Sardinia-Corsica zone, the available instrumental data report about 200 events with maximum magnitude reached in the Bonifacio strait area (June 2000, $M_L=4.6$; EOST, 2004); moreover, this area has to be considered the most seismically active of the whole Sardinia-Corsica block. Finally, only one relevant event has been localised in the Sardinia channel. The CMT focal mechanism of this shock, that occurred in August 1977 ($m_b=5.1$), shows a compressive trend (GIARDINI *et alii*, 1984).

2.3. - SOUTHERN TYRRHENIAN SEA

The southern part of the Tyrrhenian basin has attracted the interests of many Authors given its complex tectonics, large scale geodynamic deformations and high-frequency and deep seismicity. Frepoli *et alii* (1996) summarises the main geodynamic features as follows: i) subduction of the Ionian oceanic lithosphere beneath the Calabrian Arc (MALINVERNO & RYAN, 1986; ROYDEN *et alii*, 1987; PATACCA & SCANDONE, 1989; DOGLIONI, 1991; SELVAGGI & CHIARABBA, 1995); ii) recent opening (post-Tortonian) of the Tyrrhenian basin (BARBERI *et alii*, 1973; 1978; CARMINATI *et alii*, 1998); iii) present uplift of the Calabrian Arc (WESTAWAY, 1993; BORDONI & VALENSISE, 1998); iv) high heat-flow (HUTCHISON *et alii*, 1985; DELLA VEDOVA *et alii*, 1991; MONGELLI & ZITO, 1994; 2000); v) volcanic activity of the Aeolian islands linked to the subducting slab (BARBERI *et alii*, 1973; SERRI, 1990; BECCALUVA *et alii*, 1994). The whole Southern Tyrrhenian region is characterised by shallow to deep seismicity (e.g., CAPUTO *et alii*, 1970; 1973; ANDERSON & JACKSON, 1987; GIARDINI & VELONÀ, 1991; CACCAMO *et alii*, 1996).

The models at different scales proposed in the last thirty years witness the still continuing debate on the geodynamic evolution and present tectonics of the southern Tyrrhenian region. The existence of subduction processes and the consequent key role of the basin in Mediterranean geodynamics has been recognised starting from the early seventies (e.g., CAPUTO *et alii*, 1970; 1973) on the basis of seismological data from teleseismic and regional stations. BARBERI *et alii* (1973) also suggested a subduction process probably active beneath the Southern Tyrrhenian Sea, with a trench zone close to the Ionian coast of Calabria and a W-NW slab immersion. In this context, the southern Tyrrhenian Sea is assumed to be a back-arc basin. The model would explain the arc structure, the location of seismicity, and the volcanism of the Aeolian Islands. The Etna and the Ustica extensional volcanism marks the southern limit of the compressive tectonic sector,

while the Tyrrhenian abyssal plain is interpreted as a marginal basin (NERI *et alii*, 1991). The Wadati-Benioff zone, formerly identified by CAPUTO *et alii* (1970; 1973) dipping from the Calabrian arc to the NNW, has been interpreted by GASPARINI *et alii* (1982; 1985), PATACCA *et alii* (1990) as a relic of a subducted lithosphere. SCANDONE & PATACCA (1984) interpret the Tyrrhenian area as a fragment inside a large and partially ductile belt separating the stable margins of the African and European plates. These Authors hypothesise the presence of a passive subduction of the residual slab and spreading mechanisms probably still acting in the southern Tyrrhenian region. MANTOVANI *et alii* (1985; 1990; 1996) suggest that the kinematics of the Adriatic microplate, with anticlockwise rotation with respect to the European plate, play a relevant role in the evolution of the Tyrrhenian basin.

Recently, the improvement in seismological station coverage has allowed to refine the analysis of event records, leading to the identification of a WNW-oriented Benioff zone down to 500 km of depth (NERI *et alii*, 1991; FREPOLI *et alii*, 1996; LUONGO & MAZZARELLA, 1997). The upper part of the slab, dipping around 70° above 250 km and around 50° below, should intersect the Earth's surface near the Ionian coasts of Calabria (NERI *et alii*, 1991; SELVAGGI & CHIARABBA, 1995; FREPOLI *et alii*, 1996).

The southern Tyrrhenian subduction zone is the Italian region with highest seismic energy release given the yearly occurrence of many $m_b \sim 5$ earthquakes (AMATO *et alii*, 1997). Figure 5 shows all the instrumental seismicity localised by INGV in the period 1983-2003 (INGV, 2004).

Differently from most of the other Italian areas which experience crustal seismicity, the southern Tyrrhenian basin is characterised by the occurrence of shallow, intermediate and deep earthquakes, with maximum depth estimated at about 400 km. In the last decade the geometry of the seismogenic volume interested by the deep seismicity has been studied by many Authors, also through tomographic techniques. A discussion on the most recent results is given in this volume (see CIMINI; PANZA *et alii*).

Due to the presence of an intense seismic activity and of remarkable volcanic processes, the southern Tyrrhenian basin is of great interest also with respect to tsunami genesis. Here we can identify five coastal zones where most of the Italian tsunamis and all the strongest events are concentrated, respectively Campania, Tyrrhenian Calabria, Aeolian islands, northern Sicily and Messina Straits (TINTI & MARAMAI, 1996; TINTI *et alii*, 2004).

Two tsunami events that occurred in June 1760 and in July 1805 are associated with earthquakes not related with the Vesuvius activity. The first shock ($M=$

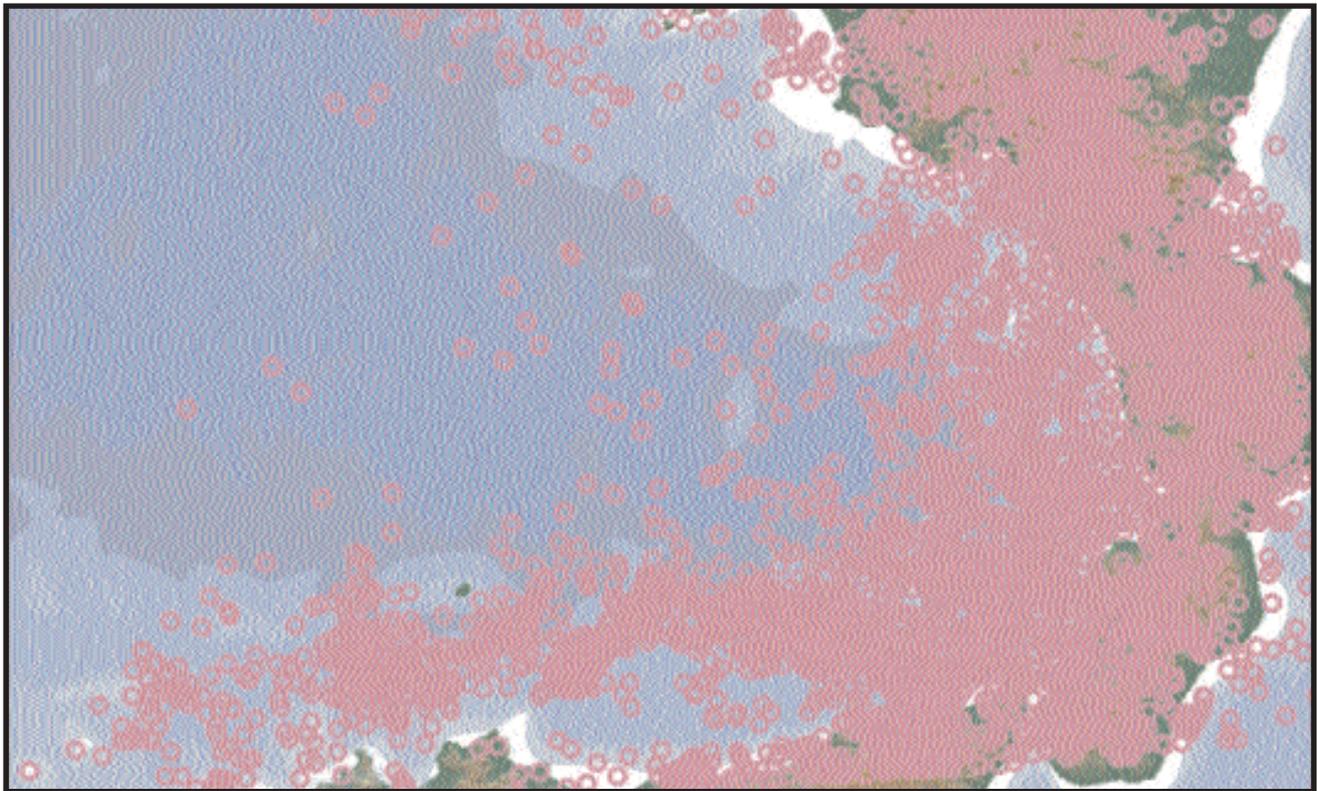


Fig. 5 - Map of seismicity of the southern Tyrrhenian Sea (1983-2003; INGV, 2004).

4.3) was located offshore and caused a very large withdrawal in the Portici harbour (nearby Naples) that remained dried for a few minutes. The second one was a destructive event ($M=6.6$) causing more than 5,000 victims and generating a tsunami involving the coast from the Sorrento peninsula to southern Latium with sea level rising up to 3 metres in some coastal villages.

The Tyrrhenian Calabria and the Messina Straits coastal zones are the regions with the highest tsunamigenic potential from the point of view of the largest tsunami waves observed. In Tyrrhenian Calabria, eight tsunamis occurred from 1638 to 1905, related with seismic shocks located on land close to the coast. Most of them are strong and one is the catastrophic tsunami that occurred in February 1783, caused by a huge earthquake-induced rock fall: a portion of the Monte Paci (south-western side of the Scilla beach) collapsed suddenly into the sea, triggering a violent tsunami with maximum run-up of about 9 metres, causing about 1500 victims at Scilla and also involving the coast of Sicily. Two rather strong tsunamis occurred on November 1894 and September 1905, related to violent seismic shocks in southern Italy, the first one along the Calabrian Tyrrhenian coast and the second in the north-eastern Sicilian coast. In both cases the sea receded, then flooded the shore causing severe damage to vessels and rising up to 6 metres.

The northern Sicily zone is the source area of two tsunamigenic events, both located offshore in front of Palermo. The earthquake that occurred on September 1726 caused a strong sea withdrawal in Palermo and in many other places. For the December 1823 shock, tsunami effects were observed along the whole coast between Cefalù (60 km east of Palermo) and Palermo. Investigations carried out after the earthquake that occurred on September 6, 2002, located offshore between Ustica and Alicudi (not far from the source of the 1823 event), pointed out that anomalous sea behaviour had been observed in the northern coast of Sicily, particularly in areas adjacent to Cefalù.

In the Messina Straits area two minor events (only causing some damage to ships) occurred in 1649 and in 1784 while the strongest tsunami recorded in Italy took place in this zone on December 28, 1908, associated to the catastrophic earthquake causing the destruction of Messina, Reggio Calabria and many other localities in Calabria and Sicily. The generated tsunami hit the Calabrian and the whole eastern Sicily coasts provoking severe damage and many victims. The maximum tsunami intensity was reached in the Calabrian coast (maximum run-up 13 m) and in north-eastern Sicily (maximum run-up 12 m).

The Aeolian islands zone is, together with Liguria-Côte d'Azur, the region with the highest tsunamigenic potential from the point of view of the number of the events: seven tsunamis occurred in the last century, from 1916 to 1988. All events are related to volcanic activity and they are mainly due to explosions and/or earthquakes associated with volcanic episodes as well as to gravitational landslides. The analysis of the

Italian tsunami catalogue (TINTI & MARAMAI, 1996) underlines that Stromboli, the most active volcano in the area, is responsible for most of the tsunamis, both in number and in intensity, also causing severe destruction in the villages of the island. Some events with minor effects are also generated at Salina and Vulcano islands. A new strong tsunami, caused by two episodes of submarine slide, occurred in Stromboli Island at the end of 2002 (TINTI *et alii*, 2004).

3. - DISCUSSION AND CONCLUSIONS

The results, over the years, of research concerning the Tyrrhenian basin seismicity, have led to a very inhomogeneous knowledge of the area. This is mostly due to the impossibility of investigating wide offshore areas without the aid of appropriate technology. Some offshore sectors, in proximity of observation sites, have captured the attention of many Authors involved in assessing the role of the basin in central-Mediterranean geodynamics. Other parts were studied because of the great relevance of earthquakes and tsunamis that had occurred, which in some cases determined heavy casualties and destruction over large areas. Nonetheless, a reliable reconstruction of the seismological past of the Tyrrhenian basin is limited by the deficiency of historical information in remote areas, for example the islands, with fragmentary descriptions of the observed events. An example can be represented by the case of the Aeolian Islands: the available seismological catalogues only account for events that have occurred in the last century.

The transition to modern seismological sensors has helped in the identification of seismogenic marine areas. For example in the Ligurian Sea, the hypocentres of the recent events that occurred at sea, likely generated by the same marine structures that originated the historical ones, are localised farther and farther from the coast. This advance in the event localisations can be explained by the enhanced characteristics of the present-day monitoring systems (e.g., broad-band sensors, 24-bits digitisers), the improvement of hypocentre computation algorithms, and, at times, the assumption of more appropriate structure models based on the progress in the knowledge of the lithosphere.

In recent times, numerous marine geophysical campaigns (e.g., GAMBERI *et alii*, 1997) have once again put in light the presence of important seismogenic structures together with the persistence of terrestrial structures, more deeply investigated, toward the sea.

In spite of these latter advances, the study of the seismicity and of its relationship with other phenomena associated with marine structures is still at a very early stage, notwithstanding the key role attributed to the Tyrrhenian basin in regional geodynamics. As an example, nothing is known of the importance, the distribution also with depth, the temporal evolution and associated phenomena (e.g., volcanic activity, hydrothermalism, degassing) of the

seismicity of south western sectors of the basin, supposed to be weaker than the remaining sectors. To neglect these additional features results in a limited view of the geodynamic framework of the Tyrrhenian area and of its relationships with neighbouring sectors.

The monitoring systems presently operating on land all around the basin, although very dense in some areas and based on modern technology, are still inadequate for an efficient monitoring of marine regions. The major critical aspects relate to the detection capacity and localisation accuracy. The extent of the basin and the scarcity of seismological stations in Sardinia and Corsica islands, represent obstacles for the complete and systematic detection of events of medium and low magnitude and of course of micro-seismicity. The localised seismicity available

from the INGV bulletin for the central sector of the Tyrrhenian basin is reported in table 1 (INGV, 2004).

The low number of localised events (20) over a period of around 20 years and the depths, in the majority fixed at 5 and 10 km, reveals the difficulty of application of the localisation procedures. In addition to the inhomogeneous distribution of the network stations, the unfavourable large lateral velocity variations of the lithosphere below the basin, determine large location errors. Estimates of probable errors in the location of offshore and coastal events can be over 50 km with respect to the mislocation of the terrestrial events that is typically 5-10 km (DI GIOVAMBATTISTA & BARBA, 1997).

Some experiments of seafloor monitoring have allowed a rough quantification of the undetected seismicity by the land-based monitoring at least for

Tab. 1 - Localisations of seismic events in the central sector of the Tyrrhenian Sea from instrumental catalogue (INGV, 2004). Only 20 events were recorded over 18 years. Most of the localisations are estimated keeping the depth fixed (5 or 10 km) due to the instability of the solutions.

N.	Date	Time	Lon	Lat	Depth	M_a	M_L
1.	1983-04-21	04:32:03	12.714	40.640	* 10.000	31	—
2.	1983-10-10	22:01:59	13.470	39.698	* 10.000	—	—
3.	1984-04-02	21:47:08	11.658	40.910	* 10.000	31	—
4.	1986-01-09	18:51:08	12.881	40.293	* 10.000	34	—
5.	1988-04-03	07:47:16	13.259	39.501	* 10.000	31	24
6.	1989-07-03	14:54:07	12.926	40.659	* 5.000	40	34
7.	1989-07-09	10:58:55	12.752	40.339	* 10.000	30	—
8.	1989-08-02	14:27:21	12.946	40.367	* 10.000	27	25
9.	1991-03-27	09:49:22	11.648	41.485	* 10.000	38	32
10.	1991-06-30	03:17:13	10.906	39.751	* 10.000	34	33
11.	1992-05-08	16:50:36	13.535	39.578	* 10.000	30	25
12.	1992-10-08	18:46:17	13.431	39.452	* 10.000	27	24
13.	1993-09-20	17:47:31	12.554	39.376	* 5.000	29	26
14.	1996-01-21	12:16:54	13.394	39.984	611.046	32	34
15.	1996-08-19	22:48:20	12.436	39.464	* 10.000	29	22
16.	1996-12-21	08:45:35	13.188	39.878	681.422	40	43
17.	1998-12-13	22:57:46	13.585	39.497	646.026	—	46
18.	1999-09-07	07:13:30	12.062	39.333	* 10.000	29	26
19.	2000-04-27	22:04:18	10.638	40.788	* 10.000	28	—
20.	2001-04-21	17:31:41	10.540	40.995	* 10.000	34	28

(*): depth kept fixed during the localisation procedure

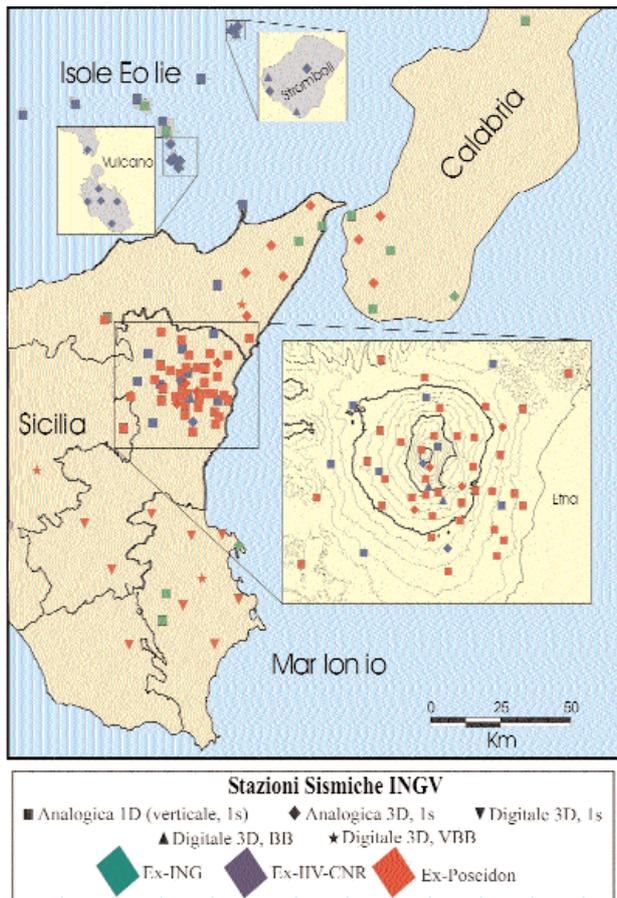


Fig. 6 - Map of the seismic stations in Eastern Sicily, Etna volcano, Aeolian Islands and part of Calabria managed by INGV.

some sectors of major interest. In 1987 an experiment was carried out in the Southern Tyrrhenian Sea at a depth range of 1000-2800 m. The experiment used five Ocean Bottom Seismometers (OBS) and land-based stations opportunely thickened with temporary stations (SOLOVIEV *et alii*, 1990). Over only 12 days of operation, about 200 local shocks with $M_L=3$, approximately concentrated beneath sub-sea volcanic seamounts and located offshore the central Calabria coast, were recorded exclusively by the OBS network. The experiment pointed out that land-stations, regardless of their number, are unable to record the numerous minor earthquakes occurring in the crust because of the low energy of these events, the attenuation of the seismic signals and the level of noise. The seismic activity within the crust in the Tyrrhenian basin is thus underestimated if determined from land station records only. A further experiment was conducted in 1996 in the framework of cooperation among INGV, Tokyo and Chiba Universities (BERANZOLI *et alii*, 1997). In the experiment ten OBS were deployed for around eighteen days in a depth range from 1500 to 3400 m in the southern Tyrrhenian Sea, northwest of the Aeolian islands. During the experiment, more than

150 crustal events with $M_d=3.5$ were recorded mostly at the OBS closest to the Aeolian volcanic arc. Most of these events were neither localised nor detected by the on land network, due mainly to their low energy.

In the period December 2000-May 2001 a new experiment, the Tyrrhenian Deep Experiment (TYDE) conducted by INGV, and the German institutes of GEOMAR and Forschungsgemeinschaft-Hamburg Universitaet, made use of 14 ocean bottom instrumented modules equipped with seismometers and hydrophones (OBS/H), deployed in water depth of 1500 to 3500 m in the southern Tyrrhenian Sea (DAHME *et alii*, 2002). More than 350 events, exclusively recorded by the OBS/H, could be localised (Sgroi, personal communication) revealing once again the inadequacy of the land-based monitoring to efficiently cover the area.

In the period October 2002-May 2003 the multidisciplinary seafloor observatory SN-1, built up and operated in the framework of a project coordinated by INGV and funded by the Italian National Group for the Defence against Earthquakes (GNDT), was deployed in the western Ionian Sea around 25 km off Catania town (eastern Sicily) at a depth of 2105 m (BERANZOLI *et alii*, 2003). The seismicity of the area is generally considered sufficiently guaranteed by a very dense coverage of land seismological stations (see fig. 6).

In table 2 the monitoring efficiency reached through the integration of the land-based networks and the SN-1 seafloor observatory data reveal an increment of up to 78% in a monthly period (10 November-10 December 2002) with a consistent amount of very local events. Figure 7 represents the position on the sea bottom of SN-1 observatory during the experiment, the two circles indicate the distance of 35 and 100 km respectively according to table 2.

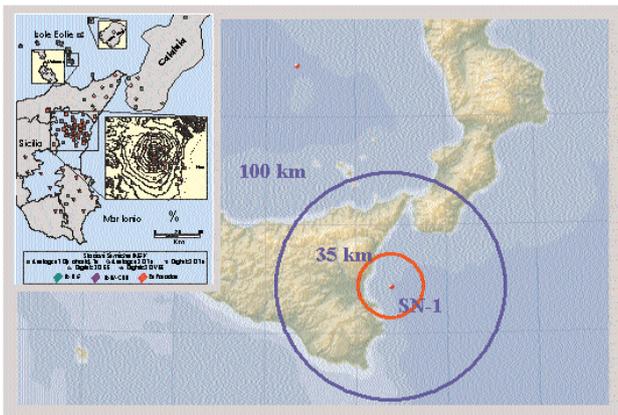
In addition, 25 events became localisable due to the availability of arrival times at SN-1. Basically, it can be concluded that all the sea experiments carried out till now have demonstrated that seafloor observations can improve the event detection from 50% to 75%



Fig. 7 - Map of Eastern Sicily, the red dot represents the position of SN-1 observatory on the sea bottom during the 2002-2003 experiment. The 2 circles indicate the distance of 35 km (internal circle) and of 100 km (external circle) from the observatory (see tab. 2).

Tab. 2 - Number of events registered by the on-land Italian networks operating in the western Ionian area and by SN-1 seafloor observatory in the period 10 November-10 December 2002. The category of the events (Very Local, Local, Regional and Teleseismic) is set on the basis of the distance from SN-1 site (see Fig. 7). The number of events detected simultaneously by the Italian national centralised seismological network (RSNC), by the local monitoring network of Eastern Sicily (CT) and by SN-1 is compared to the number of events detected exclusively by SN-1 and not observed at the other stations. The number in bold (25) is the increment in the number of events that became localisable thanks to the detections of SN-1. The increment of efficiency in Very Local, and Local event detection through the inclusion of SN-1 data is around 78%, while 25 among the Very Local and Local events (around 25 %) become localisable thanks to SN-1 data.

Event category	RSNC, CT, SN-1	Only SN-1
Very Local (Dist. \leq 35 km)	12 25	78
Local (35 < Dist. \leq 100 km)	90	34
Regional (100 < Dist. \leq 3000 km)	32	19
Teleseismic (Dist. >3000 km)	2	-
TOTAL	136	131



with an increase in the number of localisable events of more than 20%.

The progress of marine monitoring and communication systems and the increasing synergy between science and technology are favourable conditions to undertake scientific-technological programs addressed to the development of seafloor observation networks integrated to the land-based ones. The study of Earth structures in offshore zones of the Italian and the Mediterranean regions can largely benefit from these opportunities.

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