INSIGHTS INTO THE SEISMICITY AND ERUPTIONS OF PANTELLERIA ISLAND AND ITS SURROUNDINGS (SICILY CHANNEL, ITALY)

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Introduction. The Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Etneo (INGV-OE) manages a permanent local seismic network in Eastern Sicily, with the aim of monitoring the main tectonic areas (Iblei, Peloritani) and active Sicilian volcanoes (Etna, Vulcano, Stromboli). This network enables locating low magnitude earthquakes and detecting low energy signals that are typical of active volcanic areas (e.g. volcanic tremor, explosion quakes, LP events).
Apart from Mt. Etna and the Aeolian islands, another area characterized by active volcanism is the Sicily Channel, with the volcanic edifices of Pantelleria and Linosa islands. The emergence (and subsequent disappearance after about two months) in 1831 of the Ferdinandea island, as well as the Foerstner island in 1891 (about 4 km north of Pantelleria), is the most reliable and recent evidence of volcanism in the Sicily Channel, which is undersea for the most part (Fig. 1).
Since there are only a few onshore areas in the Sicily Channel, it is therefore difficult to instrumentally detect its seismicity with traditional onshore networks, with the exception of locating the foci of high-energy earthquakes, which often have poor azimuthal constraints. Ocean Bottom Seismometers (OBS) are not widely used owing to the high costs of the instruments and their running. Consequently, seismological knowledge of the Sicily Channel, and Pantelleria Island in particular, is still lacking in detail. Moreover, there is no permanent local network on the island, which could provide useful data, particularly on the microseismicity.
Between 2006 and 2007, we installed a temporary seismic network on the island of Pantelleria, with the aim of improving the knowledge on the local seismicity, and checking for any similarities with other volcanic areas, such as microseismic events that are typical of a hydrothermal environment (e.g. Fossa of Vulcano; Alparone et al., 2010).
In this paper, we compare the instrumental and historical seismicity, and provide a review on the historical eruptions in the Sicily Channel. Finally, we show the results of the experiment with the mobile seismic network deployed at Pantelleria.

Geological framework. Pantelleria is located in the Sicily Channel, a relatively shallow seaway (average depth 350 m), connecting the African continent to Sicily (Fig. 1). The Sicily Channel is affected by extensional tectonic processes, and characterized by three main tectonic depressions (the Pantelleria, Linosa and Malta troughs), which are the expression of a continental rift, extending in a NW-SE direction. The tectonic depressions of the Sicily Channel have been interpreted as large and discrete pull-apart basins involving deep crustal levels that developed in front of the Africa-Europe collisional belt within a large dextral wrench zone (Cello et al., 1985; Reuther and Eisbacher, 1985; Finetti and Del Ben, 2005).
The Sicily Channel is also a region of important volcanic phenomena. Regional magnetic anomalies clearly indicate an alignment of volcanic bodies on the seafloor NW and SE of Pantelleria as far as 37 km from the island, following a linear trend compatible with the main direction of the rift (Lodolo et al., 2012 and references therein). According to Argnani (1990), the basins are due to normal faulting, and strike-slip motion is found in a N-S trending "separation zone", located between the troughs of Pantelleria, Linosa and Malta. This zone separates elements with different structural features and age (Argnani, 1990) and an effusive, tholeiitic and alkaline type of volcanism has developed inside the area. The two volcanic islands of Pantelleria and Linosa, and a large number of seamounts, many of which are poorly known (Fig. 1), testify to the volcanic activity. The

main volcanic centres are aligned along N-S direction, from the Linosa Island to the Sicilian coast near Sciacca (Fig. 1). Historical eruptions were mainly underwater, of which there is only slight evidence for some of them (Calanchi et al., 1989), and the volcanism is still active.
The Pantelleria Rift forms the deepest part of the Straits and its floor consists of continental crust. The island of Pantelleria, with a NW–SE striking long axis of about 14 km and an orthogonal short axis of about 9 km, is the emerged portion of a volcanic structure, situated along the tectonic trench, which extends in a NW-SE direction for nearly 135 km. The recent eruption of the Foerstner volcano in 1891, along with the presence of thermal springs and fumaroles on the island, are evidence of a still active magmatic system at Pantelleria.

Historical eruptions in the Sicily Channel. Except for the last 1891 Pantelleria and the 1831 Ferdinandea island eruptions, historical data report little evidence of previous eruptions in the Sicily Channel. We carried out an historical research on some volcanological and seismological compilations, as well as regional and Italian libraries, looking for first-hand sources (diaries, chronicles, official records, travellers' reports, newspapers) and retrieving original documents written between 1600 and 1900. These documents have been critically analysed and interpreted to reconstruct the seismic and eruptive activity of the Sicily Channel.
The first earliest information from historical accounts about eruptions in the Sicily Channel dates back to 1632 (Perrey, 1848). The volcanic activity was probably located in the Banco Graham, in the same area where the 1701 eruption (Fuchs, 1881) and the well-known 1831 eruption occurred. A probable submarine eruption took place in 1818 (Imbornone, 1817). Lastly, the 1845 and 1846 eruptions were also observed offshore (Perrey, 1846). On the other hand, the 1863 eruption reported by Fucks (1881) and then by Mercalli (1883) is a fake event. The eruptions of 1818 and 1831 where preceded, accompanied and followed by seismic swarms. Most of the shocks were strongly felt in Sciacca and in southwestern Sicilian coast.
Regarding Pantelleria island, no eruption has occurred during the last 3000 years (Civetta et al., 1984), while a shallow submarine eruption occurred in 1891, about 4 km NW from the Pantelleria coast. This event was preceded by vigorous seismicity (Baratta, 1892) and increasing fumarolic activity on the island. Significant uplift (up to 0.8 m) occurred at the NE coast of Pantelleria in May-June 1890 (0.55 m) and in 1891 (0.30 m) (Riccò, 1891) preceded by some shocks. The eruption began on 17th October, emitting steam and throwing up large scoria (up to 1 m in diameter) to heights of 20 m. The activity culminated on the second day and then rapidly declined, ending completely on 25th October.

Sicily Channel seismicity. Although there are several studies on the ground deformation, gravimetry, petrography and structural geology of the island of Pantelleria (e.g. Mattia et al., 2007, Catalano et al., 2009, Lodolo et. al; 2012, and references therein), very little information about the seismic features of the Sicily Channel, and particularly Pantelleria island, is available.
In western Sicily, the only destructive known earthquakes are related to the seismic sequence of 1968 (Belice valley). Historical data show that most of the earthquakes are located along the Sicilian southern coast. According to Rigano et al. (1998), the seismic activity close to Sciacca (south-western Sicily), manifested by low-energy sequences and lasting for several months (1652, 1724, 1727, 1817, 1831), is located offshore. Sciacca was often the only site where the earthquakes were felt and for this reason, the location of the events is problematic. Many of these swarms could be related with volcanic activity, even if there is only evidence for the 1831 and 1891 earthquakes (Marzolla, 1831; Gemellaro, 1831; Washington, 1909) and probably for the 1816-17 sequence. Moreover, the historical information, which was gathered along the coasts and islands of the Sicily Channel, may be biased if the actual seismogenic sources are offshore. In some cases, the seismic activity was concomitant with submarine volcanic activity in the Sicily Channel, as for example in 1831 when the Ferdinandea Island was formed in the sea between Pantelleria and Sciacca (Gemmellaro, 1831; Mercalli, 1883). Evidence of more ancient earthquakes, which damaged the

town of Selinunte, located on the coast about 25 km west of Sciacca, are provided by archaeological investigations, which suggest the occurrence of two shocks dated around 400-200 B.C. and 400-1200 A.D. (Guidoboni et al., 2002; Bottari et al., 2009), but the seismogenic sources are unknown.
The knowledge of the seismicity of Pantelleria, and also in nearby areas of the Sicily Channel, e.g. the Maltese Islands (Galea, 2007), has suffered both from poor accuracy of earthquake locations due to inadequate network coverage (especially before the 1980s) and the difficulty in detecting low magnitude shocks . Instrumental data recorded in the past are insufficient to provide a realistic framework of the seismicity of Pantelleria area and Sicily Channel. In these areas, the set-up of permanent stations dates back to 1980s, when a 1-component short period (1s) sensor was installed at Pantelleria. In August 2010, this analog station was replaced by a digital one (PTMD), equipped with a three-component broadband seismometer, installed in the central part of the island and managed by INGV-OE. However, analytical location of low magnitude earthquakes, and/or typical low energy seismic signals often recorded at active volcanic areas, has been overlooked to date. This is mainly because of the lack of a permanent local seismic network at Pantelleria. According to literature data, seismic activity in the Sicily Channel is characterized by shallow earthquakes (typically less than 25 km), and with magnitudes generally below 5.0 (typically between 2.0 and 4.0).
According to Agius and Galea (2011) most of seismicity, especially south of the Maltese islands, is either unreported or badly constrained. These authors refer to many earthquakes detected only by a digital broadband station running since 1995 on Malta island, belonging to the MedNet network.
Besides, few earthquake fault plane solutions are available in order to characterize kinematic features of the Sicily Channel (e.g. Chiarabba et al., 2005; Pondrelli et al., 2002).

The experiment with a mobile seismic network. Between 2006 and 2007, a seismic experiment was carried out at Pantelleria, using five digital seismic stations equipped with 3-component broadband (20 s) sensors, belonging to the mobile network of INGV-OE. Unfortunately, the day after the installation the station PAN5 (Fig. 1) broke down and no substitution was available. The remaining four stations mainly monitored the central-southern sector of the island. Overall, the array recorded data from June 28, 2006 to February 23, 2007.
The mobile network recorded various types of seismic signals (i.e. teleseismic events, regional earthquakes, shocks in the Sicily Channel, and local events). Most of earthquakes were teleseismic, whereas the shocks that can be referred (see - http://iside.rm.ingv.it) to the Sicily Channel seismicity amount to sixteen. During the network operating period, only one earthquake (30/12/2006 – 00:02 UTC), with characteristics suggesting a source located very close to or on the island of Pantelleria, was detected. We could not perform any analytical location of this event, since it was recorded by PAN2 station alone, the other ones being out of order due to power supply failure. The analysis of the frequency content of the three components of the PAN2 records (Fig. 2) show a typical waveform of a low magnitude, local shallow volcano-tectonic earthquake.
To obtain some constraints on the epicentral area of the shock, we performed a single-station location, using a ray tracing method. Assuming a Vp equal to 5.2 km/s proposed by Chiarabba and Frepoli (1997), we located the earthquake at a distance of about 4 km offshore from the southwestern coast of Pantelleria. Moreover, the short S-P delay time (about 0.5 s) suggests a focal depth of few kilometres (< 5 km), We evaluated the magnitude Ml of the shock to be no greater than 1.0.

Seismic data analysis. To acquire information on the seismic characteristics of the Sicily Channel, and the island of Pantelleria in particular, we carried out a study of the instrumental seismicity by using earthquake catalogues (Castello et al., 2006), reports, and instrumental data recorded during the period 1981-2014 by the INGV permanent seismic network (http://iside.rm.ingv.it; http://bollettinosismico.rm.ingv.it/). We considered a roughly NW-SE oriented sector with coordinates of vertices: lat. 37.05 – long. 10.09, lat. 38.34 – long. 11.24, lat. 35.81 – long. 16.60,

lat. 33.73 – long. 14.91. We compiled a catalogue of 575 earthquakes in the time span 1983-2014 (Fig. 3a), although it should be noted that often hypocentres, with large vertical and horizontal errors, are not well constrained because of the few recording stations and unsatisfactory azimuthal coverage of the network. Daily earthquake rate and the associated cumulative seismic strain release (Fig. 3b) was fairly low from 1983 to 2005, except for 1990 and 1992. From mid-2005 to 2013, an increase both in the daily rate of earthquakes and cumulative strain release occurred. This increase could, at least partially, be due to the increase in the number of seismic stations in southern Sicily, and therefore improvement in the detection capability of the Italian Seismic Network (Amato and Mele, 2008). It is worth highlighting that the seismicity shows a prevalent release characterized by isolated earthquakes rather than swarms. Most of earthquakes have magnitude ranging between 2.0 and 4.0 and located within 30 km of depth.

In general, the epicentres show a widespread distribution, even if an approximately N-S oriented clustering, between Linosa and Pantelleria islands, can be observed (Fig. 3a).

However, a comparison between historical and instrumental seismicity shows that the seismicity seems to move from the coast to offshore, confirming that the shocks located in Sciacca occurred offshore.

Zooming in on the Pantelleria area (Fig. 3a), the epicentral map of earthquakes indicates a very low level of seismicity, particularly if compared to other tectonic and volcanic areas of Eastern Sicily (i.e. Mt. Etna). Moreover, the distribution of epicentres is scattered widely around the island, with few foci close to or on the island itself. This pattern concurs with the results of the analysis performed on the continuous seismic data recorded by PTMD station. We have scrutinized the seismograms of this station for the period 2010-2014, in order to highlight signals attributable to local earthquakes. Only six seismic signals of this kind have been recognized. Since these signals were recorded by only one station, it was not possible to obtain any analytical location.

Discussion and conclusion. Only few detailed studies deal with seismicity and historical eruptions of the Sicily Channel. For this reason, the aim of this study is to highlight the main features of the instrumental and historical seismicity of the Sicily Channel and provide an overview of the historical eruptions affecting this geodynamic sector.

South-western Sicily is characterised by seismogenic zones having different seismotectonic behaviour. Onshore, the strongest earthquakes are located in the Belice Valley, where six events with magnitudes ranging from 5.2 to 6.1 occurred in 1968. This intense seismic sequence seemed almost unexpected from a historical seismicity viewpoint, since no other strong earthquakes are reported in the catalogue for the previous period (Rovida et al., 2011).

Most of the historical earthquakes seem to be located in the southern coast of Sicily. The seismicity is characterised by low magnitude seismic swarms affecting mostly the area of Sciacca. Earthquake magnitudes did not exceed 5.1, and they were probably located in the near offshore. The swarm-like features and vague references to submarine degassing phenomena suggest relationships with the volcanic activity in the Sicily Channel, even if there is evidence only for the 1831 and 1891 earthquakes and probably for the 1816-17 event. Moreover, the historical information, which was gathered along the coasts and islands of the Sicily Channel, may be biased if the actual seismogenic sources are offshore.

The instrumental seismicity recorded by the INGV seismic network during the period 1983-2014 in the Sicily Channel and during the experiment carried out in the Pantelleria island show that the earthquakes are shallow, few and isolated events rather than swarms. They are characterised by low magnitudes (M~4.0) and are more densely located along the “separation zone" trending N-S, located between the troughs of Pantelleria, Linosa and Malta. These results are in good agreement with those obtained by Calò and Parisi (2014) which performed a relocation of the earthquakes.

A comparison of data from the permanent network with the mobile one allows stating that the Pantelleria island and the Sicily Channel are characterized by a low rate of seismicity linked to tectonic release and that the current seismicity is not due to volcanic processes. Historical data

indicate that seismic swarms and increasing fumarolic temperature preceded the eruptions, both in Pantelleria and in the Adventure Bank.
We cannot rule out *a priori* the existence at Pantelleria of seismic signals related to hydrothermal activity. We believe that the installation of a local permanent seismic network enables a better understanding of the seismic characteristics of the island and provides an important tool for volcanic risk assessment.
The eruption of 1891 near the island of Pantelleria, and the presence of a magma chamber (Mattia et al., 2007), would seem to point to its potentially high volcanic risk.

Captions

Fig. 1 - General framework (A) and structural pattern (B) of the Sicily Channel (modified after Lanzafame et al., 1994; Reuther and Eisbacher, 1985). The inset in the lower right corner shows the map of Pantelleria island; the yellow triangles show the stations of the mobile seismic network running at Pantelleria island from June 2006 to February 2007.

Fig. 2 - Waveform (left) of the local earthquake recorded by PAN2 station (30/12/2006 – 00:02 UTC) and relative spectrogram (right) obtained by 256-points FFT.

Fig. 3 - Earthquake density map during the period 1983-2014 using the algorithm ZMAP (Wiemer, 2001). The inset shows daily number of earthquakes and associated cumulative strain release in Sicily Channel between 1983 and 2014

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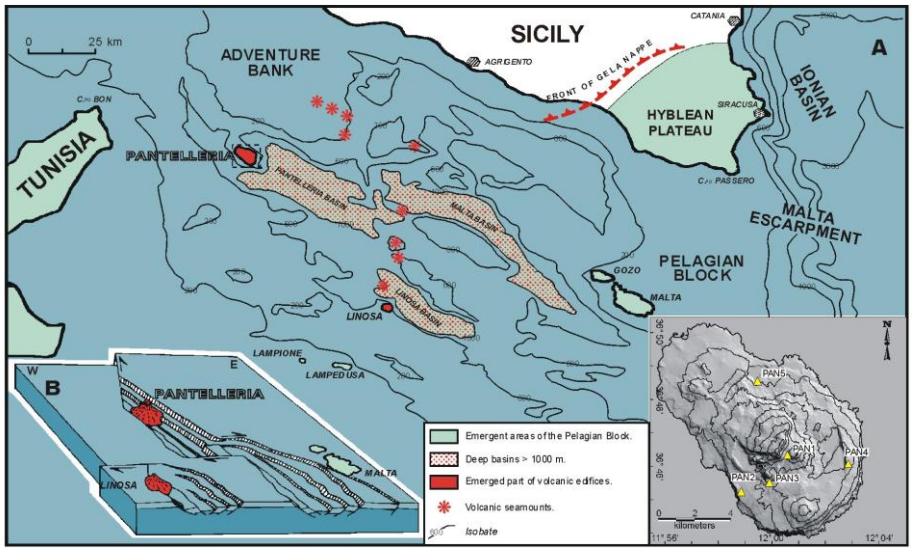

SICILY
ADVENTURE BANK
TUNISIA
PANTELLERIA
HYBLEAN PLATEAU
IONIAN BASIN
MALTA ESCARPMENT
PELAGIAN BLOCK
GOZO
MALTA
LINOSA
LAMPIONE
LAMPEDUSA
CATANIA
SIRACUSA
AGRIGENTO
FRONT OF GELA NAPPE
A
B
W
E
Emergent areas of the Pelagian Block.
Deep basins > 1000 m.
Emerged part of volcanic edifices.
Volcanic seamounts.
Isobate
PAN1
PAN2
PAN3
PAN4
PAN5
kilometers

Fig. 1

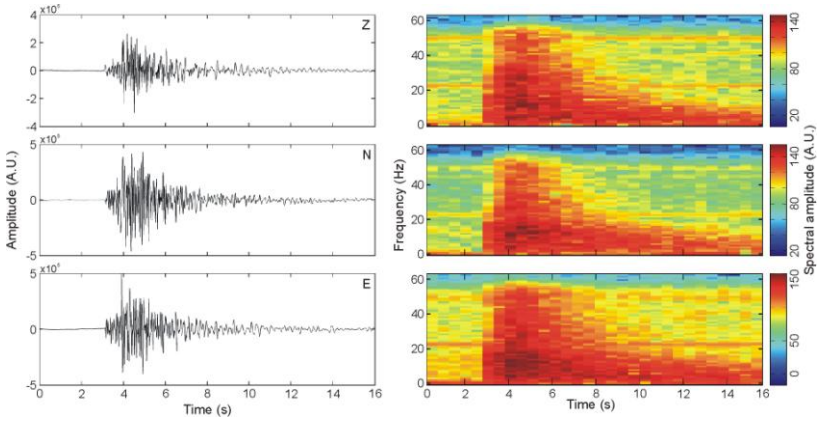
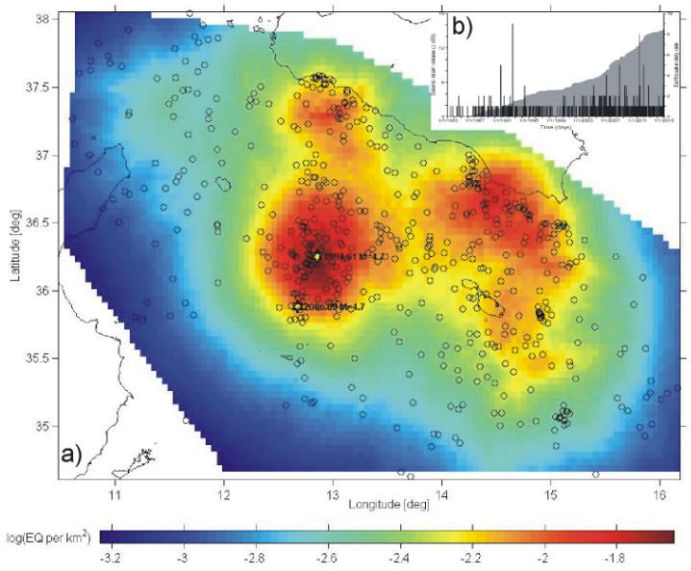


Fig. 2


a)
b)
Latitude [deg]
Longitude [deg]
38
37.5
37
36.5
36
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11
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log(EQ per km²)
-3.2
-3
-2.8
-2.6
-2.4
-2.2
-2
-1.8

Fig. 3