Seismic history of the Maltese islands and considerations on seismic risk

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Abstract
A historical catalogue of felt earthquakes in the Maltese islands has been compiled dating back to 1530. Although no fatalities were officially recorded during this time as a direct consequence of earthquake effects, serious damage to buildings occurred several times. In the catalogue time period, the islands experienced EMS-98 intensity VII-VIII once (11 January 1693) and intensity VII, or VI-VII five times. The northern segment of the Hyblean-Malta plateau is the source region which appears to pose the greatest threat, although large Greek events and lower magnitude Sicily Channel events also produced damage. Estimates of return periods for intensity ≥V are presented, and it is shown that expected peak ground accelerations justify the implementation of, at least, minimum anti-seismic provisions. The rapid and continual increase in the local building stock on the densely-populated islands warrants the implementation of an appropriate seismic building code to be enforced.

Key words *Maltese islands – historical earthquakes – earthquake catalogue – return periods – seismic risk*

1. Introduction

The Maltese archipelago consists of three main islands – Malta, Gozo and Comino, with a total land area of 316 km^2. The present population is around 400 000. The main Euro-African plate collision margin passes about 200 km to the north in Sicily and along the Hellenic Arc to the east, while the seismically active Hyblean-Malta Escarpment is situated about 100 km to the east. Despite this scenario, a culture of seismic risk awareness has never really been developed in the country, and the public perception is that the islands are relatively safe, and that any earthquake phenomena are mild and infrequent. This is probably due to the fact that no loss of life has ever been documented as a direct result of earthquake activity, and the last occurrence of serious damage to buildings was almost a century ago. As a result, a comprehensive study on the effects of past earthquakes was not developed and hence the compilation of a historical seismic catalogue, as a first step towards a seismic hazard assessment, has never been scientifically undertaken.

2. Seismotectonic framework

The Maltese islands lie in the Sicily Channel on a relatively stable plateau of the African foreland, the Pelagian Platform, about 200 km south of the convergent segment of the Europe-Africa plate boundary that runs through Sicily. The Pelagian Platform forms a shallow shelf separating the deep Ionian Basin from the Western Mediterranean. Its sea-bed topography is characterised mainly by the NW trending Pantelleria Rift, or Sicily Channel Rift Zone (SCRZ) – a

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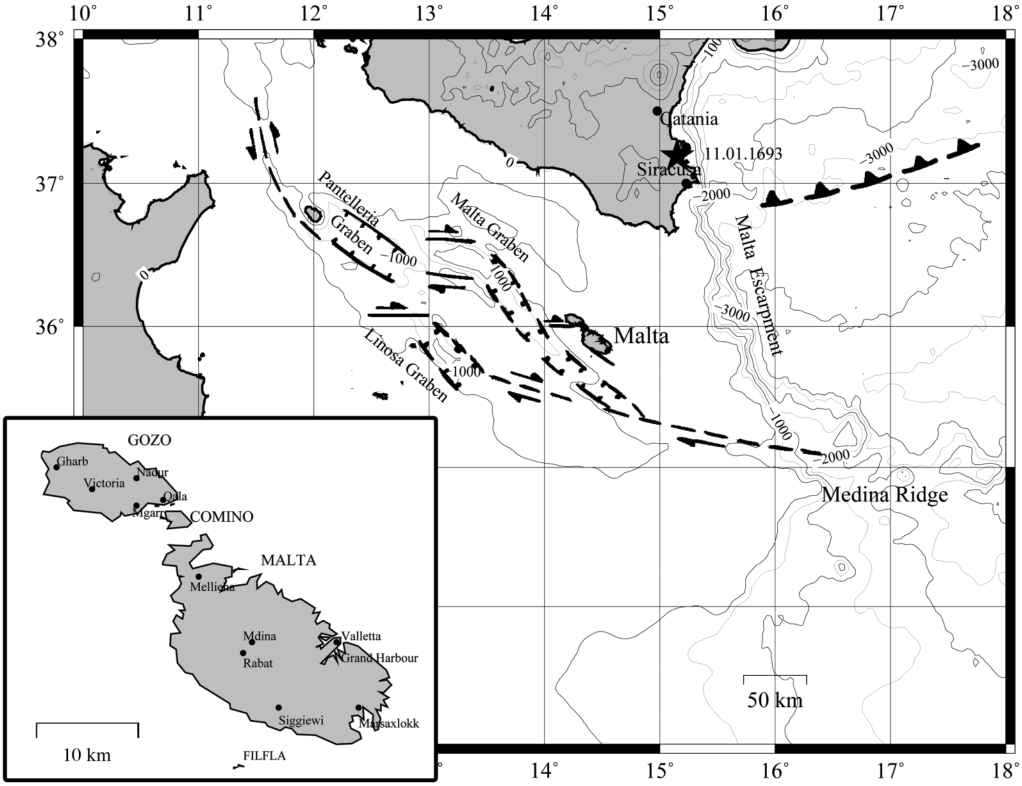

Fig. 1. Bathymetry of the Sicily Channel and main tectonic features of the Sicily Channel Rift Zone-bounding normal faults and strike-slip lineaments (modified after Reuther and Eisbacher, 1985 and Reuther, 1990). Also shown are the Calabrian Arc subduction zone and epicentre of the 11/01/1693 earthquake (Boschi *et al.,* 2000). Inset shows the Maltese islands.

system that features three grabens of Miocene-Pliocene age (Pantelleria Graben, Malta Graben and Linosa Graben) in which the water depth reaches a maximum of around 1700 m (Reuther and Eisbacher, 1985) (fig. 1). The grabens are governed by a fault system that extends throughout the Sicily Channel from Southern Sicily to Tunisia and which has also been responsible for the major tectonic and geomorphological development of the Maltese islands (Illies, 1981). The SCRZ has been interpreted in different ways, as a set of pull-apart grabens (Reuther and Eisbacher, 1985; Reuther, 1990) and as the result of a simple N-S extension regime related to Tyrrhenian back-arc spreading (Argnani, 1990). Jongsma *et al.* (1987) interpret the rift zone as part of the Medina Wrench, a more than 800 km long dextral transform fault which extends from the Sicily channel to the eastern end of the Medina Ridge, 200 km southeast of Malta. The wrench fault is interpreted as forming the southern boundary of the Iblean microplate. The grabens themselves are bounded by normal faults, trending mainly NW-SE, whereas a set of E-W trending features represent reactivated faults that now act as dextral transforms controlling the rift extension (Reuther and Eisbacher, 1985). The Malta Escarpment is a major geomorphological feature separating the Hyblean-Malta plateau from the deep Ionian Basin. It exhibits normal faulting, with a minor sinistral strike slip component (Grasso *et al.*, 1985; Reuther *et al.*, 1993).

The islands themselves are made up of an Oligocene-Miocene shallow water sedimentary sequence of carbonates and clays. The layer sequence is intensely faulted and disrupted, mainly through an older NE-SW trending fault set, while a more recent steeply-dipping normal fault trending NW-SE along the southern coast of Malta is the most prominent onshore expression

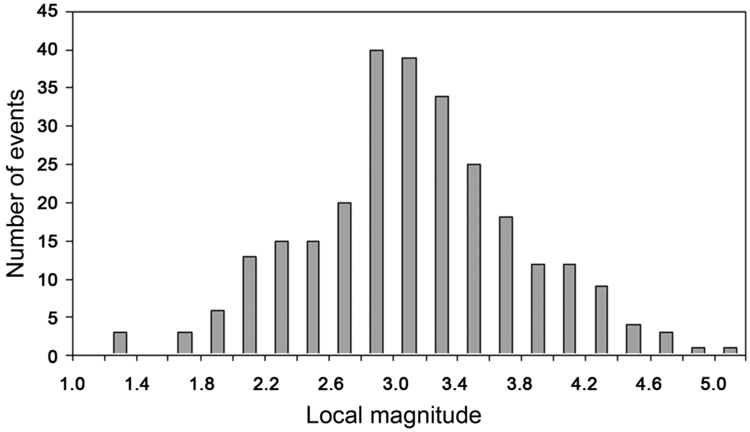

Fig. 2. Distribution of local magnitudes for earthquakes within 100 km of Maltese islands, 1995-present.

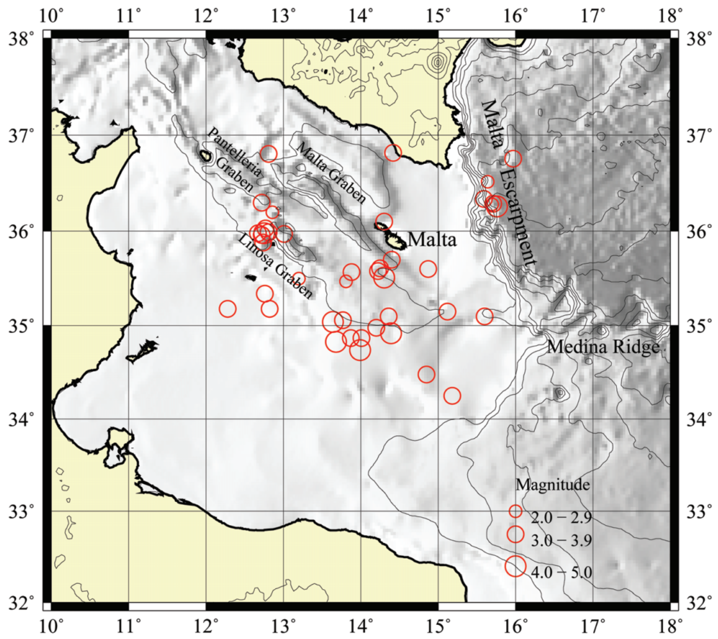

Fig. 3. More reliably located seismicity, 1990-2003 (from Said, 1997; Zammit, 2003).

of the similarly trending normal faults bounding the grabens of the SCRZ (Illies, 1981; Reuther and Eisbacher, 1985).

Knowledge of the seismicity on the Sicily Channel Rift zone has always suffered from poor epicentral location accuracy, especially in the case of earthquakes occurring to the south of the Maltese islands. This is due to inadequate network coverage, especially before the 1980s, as well as the generally small magnitude of the events. Figure 2 shows the distribution of local magnitudes as measured at station WDD (Malta) for events within a 100km radius, for the period 1995-present. The magnitudes peak at around 3.0. Figure 3 shows the seismicity which has been more reliably located in recent years, either by including individual event phase data from the Tunisian seismic network (Said, 1997; Zammit, 2003), or by considering events located by INGV that include WDD in their routine location procedure.

In a deterministic sense, the seismic source area that poses the greatest hazard to the Maltese islands is probably the northern end of the Malta escarpment, which appears to have the potential of generating the largest earthquakes in the region. This is the most probable source region of the 11 January 1693 event, that has caused the maximum intensity on the Maltese islands since 1500. Although there are several interpretations in the literature regarding the precise source of the earthquake (*e.g.*, Sirovich and Pettenati, 2001, who argue for an inland source on the Scicli Fault), it is most commonly associated with normal faulting on the escarpment just offshore Augusta-Siracusa, *e.g.*, Azzaro and Barbano (2000); Piatanesi and Tinti (1998). These conclusions are based on macroseismic effects as well as modelling of tsunami run-up data. Gutscher *et al.* (2006) give yet an alternative source on the subduction fault plane of the Calabrian Arc, which they interpret to be locked, and rupturing with a periodicity of 500 years, relating it to coseismic slip and the subduction velocity beneath the Calabrian Arc. Both Azzaro and Barbano (2000) and Gutscher *et al.* (2006) interpret the other equally large event of 1169 as having the same source as that of 1693. The 1169 event had produced a maximum intensity of XI in SE Sicily. To date, no historical information about the effects of the 1169 earthquake on Malta has been found.

The magnitude 5.4 event of 13 December 1990 (felt locally, I=IV) is also attributed to this source region (Amato *et al.*, 1995) but having a strike-slip mechanism, either along a N-S fault of the escarpment, or along an E-W transcurrent fault offsetting the same escarpment. Recently, on the 24th November 2006, a well-located magnitude 4.6 event occurred on a more southerly segment of the Malta escarpment (36.23N, 15.80E), (Bollettino Sismico Italiano, INGV) at a distance of 120 km from Valletta, and was widely felt on the Maltese islands. This event also had a left-lateral strike slip mechanism along a N-S trending fault (TDMT Catalogue, INGV).

3. Site catalogue

The first step in dealing with the problem of seismic hazard assessment is the compilation of a historical earthquake catalogue. There are a number of difficulties that are inherent to establishing an earthquake catalogue for a small island for the pre-instrumental period. Although a number of felt events can definitely be attributed to major earthquakes in Sicily or Southern Greece, many others are due to offshore earthquakes with epicentres in the Sicily Channel. In such cases there is usually very scant spatial information, making it impossible to estimate an epicentral location, especially if the event is reported to be felt only on the Maltese islands. In some cases, a consistent change in intensity throughout the islands can be readily inferred from the documentation, enabling a good guess to be made about the direction of the source. In other cases, this is also unreliable. Moreover, empirical relations for estimating magnitude from epicentral or maximum intensity clearly cannot be applied in such cases, making it impossible to estimate magnitudes. Nevertheless, for the purpose of seismic hazard estimation it is still useful to have a list of intensities of felt ground shaking going back to pre-instrumental times, together with a general estimate as to the seismic source area (see *e.g.,* Albarello and Mucciarelli, 2002).

The documented history of the Maltese islands in an organised form dates back roughly to the arrival of the Knights of the Order of St. John in 1530. Before this date some scant documentation survives from the Spanish rule of the Maltese islands since the 14th century. From personal discussions with local historians, it appears unlikely that any reference to major earthquake effects exists in these documents. The collections of documents are preserved in the National Library, Valletta (Archives of the Order of Malta, Melitensia), old Santo Spirito hospital, Rabat (documents dating from early British Rule, formerly part of the Palace Archives, Valletta), Mdina (Cathedral Archives, Inquisition Archives), and at the Gozo Public Library, together with other collections scattered at various centres, among them the Melitensia and Archives sections of the University Library and Religious Orders. Unfortunately, a large number of documents dated between 1800 and 1846, in the British Colonial period, were destroyed in the 1870s. It is also recorded (de Soldanis, 1746) that a quantity of archives and documents were destroyed or removed from Gozo by the invading Turks in the 16th century.

A number of early texts by Maltese authors describing in detail the history and natural history of the islands are also available, among them an early 20th century local publication by Faure (1913) which gives a rudimentary catalogue of natural phenomena experienced on the Maltese islands, including a list of felt earthquakes up to 1911. A number of the events in this list can be correlated with major earthquakes in the Mediterranean, with good accuracy in the reporting of the dates and times of day, thus making this publication a reasonably reliable source. From the second half of the 19th century, the best source of information regarding the macroseimic effects of earthquakes was found to be local newspapers, which began to be published around this time, in Italian and English. The newspapers are kept on microfiche at the National Library, Valletta and were read first hand. The main newspapers referred to are *The Malta Times, L'Ordine, Il Portafoglio Maltese, The Malta Mail, Il Mediterraneo, Malta, The Daily Malta Chronicle, The Times of Malta, The Bullettin, The Sunday Times*.

The problems of beginning to compile a first-time historical earthquake catalogue in an island state are well described, for example, by Musson (2001) in the case of the Faroe islands. The case of the Maltese islands turned out to be somewhat easier because of a considerable amount of archival research having already been carried out by local historians, and also because the proximity to Sicily means that significant earthquakes in the region would be well documented there. The amount of archived material is vast, and one must necessarily rely on secondary sources as well as personal discussions with historians and archivists to be able to state with enough confidence that, at least, no major damaging earthquake has been missed.

An excellent starting point for the compilation of the catalogue was provided in the form of an unpublished history dissertation entitled «Earthquakes in Malta» (Abela, 1969). The author carried out a detailed research of the archives of the Order of Malta, the Cathedral Archives, the archives of the Archbishop's Curia and Notarial Archives, Valletta, as well as researching most of the early texts describing the history of the islands. The thesis reproduces many local accounts, often very vivid descriptions, of tremors and other effects, associated religious practices, transactions, financial accounts, etc. As far as possible, the referred documents were re-read first hand, but in certain cases the quoted text in the thesis was taken as the primary source. The thesis does not attempt to attribute the effects to earthquakes of known origin, except perhaps for the major ones, such as that of 1693. It is the first aim of the present catalogue to identify as many as possible of the macroseismic events in terms of known earthquakes.

For the possible identification of pre-instrumental earthquakes, use was made of several existing catalogues, in particular the CPTI04 (Parametric Catalogue of Italian Earthquakes, Gruppo di Lavoro CPT, 2004), the CFTI4MED (Catalogue of Strong Italian Earthquakes, Boschi *et al.*, 2000), the DBMI04 (Macroseismic Database for Italy, Stucchi *et al.*, 2007), Guidoboni *et al.* (2005) (a catalogue of Mediterranean earthquakes 11C to 15C), Papazachos *et al.* (2000) (Greek catalogue) and several publications, such as Boughacha *et al*. (2004) (strong Algerian earthquakes since the 18C). For the instrumental period, the bulletins of the NEIC, ISC, EMSC and INGV were used to identify felt earthquakes and were also thoroughly searched for events in the Central Mediterranean, Southern Sicily and North Africa that could have been felt in Malta, then searching local newspapers for any felt reports. Publications about North African seismicity, such as Benouar (1994) for the Maghreb, Benouar and Laradi (1996) and Suleiman and Doser (1995) for Libya were also searched. None of the large earthquakes along the Maghreb coast and Libya appear to have been felt on Malta, except for the 19 April 1935, *M* 7.1 earthquake in Libya, which was «slightly felt» by some people in Malta, with no effects (*Malta*, 20/04/1935). The Jijeli earthquake of 21 August 1856, described by Ambraseys (1982) as in many respects similar to the M_s 7.3 El-Asnam earthquake of 1980, was felt as far as Genoa and Spain, but no mention of it being felt in Malta was found in the newspapers. It is unlikely that any significant effects on Malta can be attributed to earthquakes onshore the North African coasts. This is in contrast with large earthquakes along the Hellenic Arc, which have produced serious damage on Malta even from distances greater than 1000 km (see later discussion).

Felt events from 1929 onwards have almost all been assigned source parameters (epicentre and magnitude) or at least an approximate distance and azimuth from Malta. For earthquakes before this date, several events have been identified as occurring in Sicily, Southern Greece or the Ionian Sea. However, there are a number of other events that produced considerable macroseismic effects but could not be traced to any foreign catalogue. From the above discussion, it is reasonably safe to conclude that these «unidentified» events most likely originated along the numerous offshore fault systems in the Sicily Channel, and including the southern segment of the Malta escarpment to the east. It should be said that such events are now routinely recorded and located instrumentally, and occasionally also felt. Thus although no epicentral location can be assigned to these earthquakes, they have been labelled as «Sicily Channel» events.

Intensities have been assigned according to the European Macroseismic Scale, EMS-98 (Grunthal, 1998). The majority of buildings described in the historical accounts and considered for evaluating macroseismic effects, are masonry structures using manufactured local stone blocks, and fall into vulnerability class B or C. In some cases, the documents specifically referred to dilapidated buildings being damaged, or collapsed, and these are considered to be of vulnerability class A. In this work, only one intensity value is given for the whole islands. However there are a few cases in which there is a distinct attenuation of intensity from

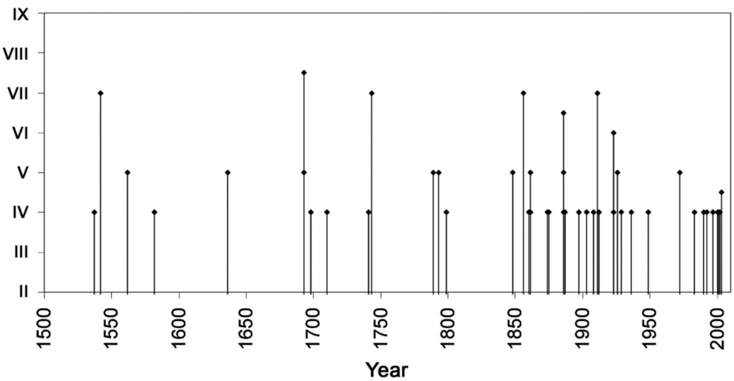

Fig. 4. Site seismic history for the Maltese islands since 1500, showing EMS-98 $I \geq$ IV.

Table I. Subset of felt earthquake catalogue, showing only events that produced EMS-98 I = V and over on the Maltese islands.

Year	Month	Day	Hour	Lat	Long	Region	I_{max} on Maltese islands	I_o	M	Parameter reference
1542	12	10	15:15	37.20	14.90	E. Sicily	VII	XI	M_w 6.6	Gruppo di Lavoro CPTI (2004)
1562	3	8	Morning			Sicily Channel?	V?			
1636	9	1				Sicily Channel(?)	V?			
1693	1	11	13:30	37.18	15.02	E. Sicily	VII-VIII	XI	M_w 7.4	Boschi *et al.* (2000)
1743	2	20	16:30	39.87	18.78	Ionian Sea	VII	IX	M_w 6.9	Gruppo di Lavoro CPTI (2004)
1789	1	19	Morning			Sicily Channel(?)	V?			
1793	2	26	Morning			Sicily Channel?	V?			
1848	1	11	12:00	37.20	15.20	E. Sicily	V	VIII-IX	M_w 5.5	Gruppo di Lavoro CPTI (2004)
1856	10	12	00:45	35.60	26.00	Crete	VII		M_w 7.7	Papazachos *et al.* (2000)
1861	2	8	23:45			Sicily Channel(?)	V?			
1886	8	15	02:45			Sicily Channel(?)	V			
1886	8	27	22:00	37.00	27.20	Aegean Sea	VI-VII	XI	M_w 7.3	Papazachos *et al.* (2000)
1911	9	30	09:25	36.4?	13.5?	Sicily Channel	VII			
1923	9	18	07:30	35.5?	14.5?	Sicily Channel	VI			ISC (2001)
1926	6	26	19:46	36.50	27.50	Aegean Sea	V		M_w 7.6	Papazachos *et al.* (2000)
1972	3	21	23:06	35.80	15.00	Sicily Channel	V		M_b 4.5	ISC (2001)

one side of the islands to the other, for example in the 1911 event which was probably located to the west of Gozo. In these cases, the intensity given here is the one estimated in the area of highest effect.

As usually occurs, many historical reports, especially in the Ecclesiastical archives, were found to emphasise mainly damage to churches and cathedrals. Although damage to residential buildings is often mentioned, it is sometimes difficult to guess the proportion of houses that suffered such damage. Other uncertainties involved in assigning the intensity values were the state of constructions in certain localities (for example, the city of Mdina dated back to mediaeval times at the time of the 1693 earthquake), and the fact that some reports (*e.g.*, in Faure, 1913) were very scant, and only mentioned «damage» with no further details, and for which no other reference was found.

The site catalogue contains close to 100 events which have produced effects of intensity ≥ II in the Maltese islands since 1530. However this includes events which form part of earthquake sequences or swarms, sometimes lasting several weeks, that appear to be characteristic of Sicily Channel seismicity. For example, a sequence of more than 6 shocks was felt in March 1710 (*Archivio Segreto Vaticano*, vol. 61), while 16 shocks were felt during August 1886 alone (*Malta,* 16, 17, 18, 21/08/1886). The catalogue, for intensities ≥IV, is illustrated in fig. 4. A subset of the catalogue containing events with site intensity V and over is presented in table I. The islands have experienced intensity VII-VIII damage once in this period, and intensity VII at least on four occasions.

4. Earthquake damage descriptions

In this section, earthquakes that produced significant damage are discussed individually. It should be said that the collection of archives in Malta and Gozo is extensive, and has by no means been exhaustively searched. There are several single references to «strong» earthquakes that «caused damage», especially in Faure (1913), for which no primary sources have yet been encountered, and no other information is known. For these events, it is not possible to estimate the intensity, so they have been listed with a tentative intensity of V?. It is recognized that further archival work needs to be done, even in foreign collections, however this publication is intended to provide a preliminary assessment and will possibly be updated in the future.

10 December 1542 – This earthquake is reported in Boschi *et al*. (2000) to have been felt in the Maltese islands with an EMS intensity of VII. This value is derived from a quotation in the contemporary Chronaca Siciliana del Secolo XVI that states that the earthquake was felt very strongly in Malta and a few one-floor dwellings (casupole) collapsed. So far, a search of the local documents related to that period has not revealed any mention of this event, although it must be said that this was soon after the arrival of the Order and documents are still sparse. Pending further evidence, the intensity value VII given by Boschi *et al*. (2000) will be adopted. Azzaro and Barbano (2000) attribute this event to the Scordia-Lentini graben fault (37.21N, 14.94E) with an equivalent surface wave magnitude of 6.4, a rupture length of 16km and a normal displacement. The maximum intensity is given as X.

11 January 1693 – This earthquake caused over 60000 deaths in Eastern Sicily, together with total destruction of several towns and villages in this region (Azzaro *et al*., 1999; Boschi *et al*., 2000). Locally, this was the most damaging earthquake that has affected the Maltese islands since 1500. It is extensively documented in the Archives, and is also described in a contemporary book by Shower (1693). The most important selections, relating to the earthquake damage, from the Archives of the Knights of Malta (AOM), the Cathedral Archives, records of the Universita' and other archives of religious orders, are reproduced in Abela (1969) and Ellul (1993) and referenced in detail. Ellul (1993) includes parts of the reports by a specially instituted commission, which was instructed by the Order to carry out a detailed inspection and assessment of the earthquake damage in Valletta and the nearby harbour cities of Cospicua, Vittoriosa and Senglea. The commission was accompanied by the chief engineer of the Order, Mederico Blondel and two Capo Mastri. Blondel also carried out an earthquake damage inspection of the island of Gozo and the city of Mdina. The earthquake was strongly felt throughout the whole of the islands. There was general panic among the whole population and most inhabitants spent a number of nights outside their homes, in tents or underground shelters. No direct fatalities are officially recorded. The earthquake was preceded by a magnitude 5.9 foreshock on the 9 January which was felt in Malta but produced no damage.

In Valletta it is reported that there was not one house that did not need some repair. The facades of some major buildings were detached from the main structure, and needed immediate repair, as they were in imminent danger of collapse. Some churches suffered collapse of, or major damage to their domes and severe cracks in walls. A number of Valletta houses also suffered seriously cracked walls and some had to be demolished because they were in danger of collapse. In Vittoriosa, Senglea and Cospicua, across the Grand Harbour, the damage was much less than in Valletta. The reports are mainly limited to severe damage in church domes and walls, some of which had to be demolished.

Serious damage was done to the old mediaeval city of Mdina, on the island of Malta. Here the Cathedral suffered partial collapse and many other buildings suffered serious damage. It should be noted that there are several remarks in the reports that show that many of the buildings in the city were very old and had been neglected for many years. In particular, the 13th century cathedral was already showing serious signs of disrepair before the earthquake, and plans had in fact already been drafted for its rebuilding before 1693. One part of the cathedral that had already been replaced, the choir, in fact escaped damage in the earthquake. Other buildings in Mdina that were damaged were the Banca Giuratale, many bastion walls and the bridge leading into the city, whose arches were cracked. The church of St. Paul in Rabat, also suffered severe damage when its bell tower and the apse of the choir collapsed and other parts were damaged. Damage also occurred to the Dominican Friary.

In Gozo, Blondel notes that the damage to the fortified Cittadella, was most probably due to «long years of neglect», as was the damage to coastal towers. The Cathedral in Rabat lost its bell-tower, and other churches sustained damage to their domes and spires, and parts of cliff faces are reported to have been detached and fell to the sea.

On the basis that some buildings suffered damage of Grade 4 in the areas of highest effects, but reflecting a degree of uncertainty in the vulnerability of the buildings, this earthquake has been assigned a local maximum intensity of VII-VIII. This agrees with the intensity assigned by Boschi *et al.* (2000).

This event, of maximum intensity X-XI in Eastern Sicily, is assigned a moment magnitude and surface wave magnitude of 7.4 in CPTI04. Azzaro and Barbano (2000) attribute this earthquake to normal faulting on the northern segment of the Malta Escarpment, with a rupture length of 41 km. Barbano and Rigano (2001) revise the CPTI04 estimate to 7.1 using EMS rather than MCS intensities. The event produced a tsunami along the eastern coast of Sicily, which was also reported in Gozo (de Soldanis, 1746). The tsunami has been modelled by Piatanesi and Tinti (1998), confirming the normal faulting nature of the source just offshore Augusta.

20 February 1743 – This earthquake coincides with a *M* 6.3 event in the Lower Ionian Sea, which also inflicted damage in the Italian peninsula, with a maximum intensity of IX on the Adriatic coast (Stucchi *et al.*, 2007), and was felt as far away as north western Italy.

The local historian de Soldanis (1746) reports that «... at 5:30 pm a strong earthquake shook the Maltese islands. It lasted 7½ min. It did great damage to both islands. In Gozo, St. George's Church, St. James Church and the chapel of Our Lady at Qala were badly damaged. In Malta, St. John's at Valletta, Mdina Cathedral and numerous other churches were heavily damaged. At Wardija in Qala, Gozo, the people reported that they saw the ground rise and fall with such force that the soil was left floating in the air, causing a mist like a fog for a long time. Many sections from hills in Gozo crumbled.»

In the dedication of his book, de Soldanis also mentions this event when he thanks the Bishop of the time for his generosity in «donating objects made of silver and gold to pay for the repair needed because of the damage caused by the 1743 earthquake».

A document in the Cathedral Archives, Mdina (ACM, *Misc.*, MS62) describes how the *coppolino* (small dome) of the cathedral collapsed into the church, the rear side of the choir was destroyed and the bell towers heavily damaged, and all the sides of the Cathedral suffered serious cracks, such that «no one dared enter the Cathedral, not even the bell ringer dared go near the bells» for fear of collapse. In the Minutes of the Cathedral Chapter (ACM, *Min.Cap.* vol. 7), a report by a team of 6 architects commissioned to inspect the damage caused to the Cathdral in Mdina details the damage done to the church, in particular the dome and choir, and recommend methods of repairing the damage. In particular, Giacomo Bianco described four approximately 3 cm-wide cracks running down the length of the dome, the dislodging of most stones of the dome, and serious damage to the walls of the choir.

This event has been assigned an EMS-98 intensity of VII.

12 October 1856 – This earthquake corresponds to the destructive earthquake that occurred in Southern Greece, near the island of Crete. It was one of the largest to occur in Greece, causing destruction and much loss of life in the epicentral area. Its magnitude is given as 8.2 in the NEIC catalogue, and 7.7 in Papazachos *et al*. (2000). Woo (1995) discusses the effects of this earthquake on the Maltese islands in some detail in the context of anomalously high intensity observed at large epicentral distances. He notes that the distance to Malta is around 1000 km, which would be expected to yield intensities of IV or V, however the damage done corresponds to a considerably higher intensity, which he attributes to the effect of long-period shaking.

This was one of the strongest shocks felt on the islands and its effects are well documented in most of the local newspapers of the days following the earthquake, mainly *Il Portafoglio Maltese*, *L'Ordine* and *The Malta Mail*. It is clearly reported that the earthquake woke up inhabitants all over the islands, and caused them to rush out of their houses during the night. Inhabitants inside houses lost their balance. The tremor was accompanied by a loud rumbling, and overturned objects and moved furniture. The duration of the shaking was variably reported to have lasted between 22 s and 60 s. Almost all houses in Valletta, and many houses in other villages and in Gozo suffered serious cracks to their walls, and the damage was more noticeable on the upper floors. Many churches on both islands suffered damage to their domes and walls, or detached crosses and other fixtures. The dome and sides of St. George's church in Victoria, Gozo were left «wide open» with detached blocks of stone. Parts of the dome of the Cathedral in Mdina collapsed into the interior. The damage to this Cathedral was estimated at over £ 1000. The steeple of the Carmelite Church in Mdina was so damaged that it had to be rebuilt. The side of a chapel on a hill near Siggiewi collapsed. In Gozo, a signal tower collapsed, and even newly built houses suffered damage. There are also references to the collapse of a chapel on Filfla Island (a minor island off the southern coast of Malta), and that of a coastal tower at Mellieha. The earthquake was also felt in Southeastern Sicily and caused damage to churches in Pozzallo, and some slight damage in Syracuse (*Malta Mail*, 18/10/1856).

The effects of this earthquake on people, objects and buildings are documented well enough for a good intensity estimate to be made. Considering that many buildings appeared to have suffered damage of Grade 3, the earthquake has been assigned an intensity of VII.

27 August 1886 – This event was felt throughout the Maltese islands, as well as throughout Sicily and Southern Italy, as reported in various telegrams sent to Malta from these localities and reproduced in local newspapers. In Malta, newspapers report a general panic, with most of the population having been awakened, and rushing out into the streets.

L'Ordine (01/09/1886) reports that in Valletta the Court of Justice, some churches and many houses suffered damage, as well some buildings and the Cathedral in Mdina, but «*come dicono, non sono danni molto gravi*» (damages are not very serious).

On the other hand, the *Malta Times* (28/08/1886) reports that «the damage done to many buildings in the city is in some cases very serious», The Superior Court has «been rendered unsafe by the splitting of the keystone and roof. The upper part of a coffee shop in Strada Reale also presents several apertures». A number of houses in Valletta, and the choir of St. John's Cathedral, are also reported to have been damaged, although the nature of the damage is not specified. In Mdina, the Cathedral and some churches suffered damage. In particular, «the Military Sanitarium at Citta Vecchia has suffered most severely, one crack extending from end to end of the building, through a wall of about 25 feet (?) in thickness» (*Malta Times*, 03/09/1886).

This event almost certainly corresponds to a magnitude 7.5 earthquake in the Aegean Sea on that day at 21:32 GMT (Papazachos *et al*., 2000), although there is slight conflict with the origin time. The *Malta Times* reports that «... just as St. John's Cathedral had boomed out the hour of 11, a rumour was heard, the source or cause of which one had hardly time to consider, when we were brought to a knowledge of our terrible position, by a fearful rumbling noise, accompanied by a slight vibration of the Earth which increased in intensity until the heavens seemed to rend the twain, and the ground to sway from beneath our feet. 70 s of fearful suspense, held almost every inhabitant of the Island, in a state of utter bewilderment, which was further intensified by a recurring shock, of force and duration if anything, exceeding that of its predecessor.» The onset times reported in the various telegrams from Greece and Southern Italy also vary quite widely. The event has been assigned an intensity VI-VII.

30 September 1911 – This event produced distinctly different intensities in the two islands of Malta and Gozo. The local newspapers report that most damage from this event occurred on the island of Gozo. The Italian language newspaper *Malta* (02/10/1911) gives a good account of damage to this island. Serious cracks appeared in the domes and steeples of several churches, especially in Victoria, Nadur and Gharb, as well as in the walls of several public buildings in Victoria. Many houses in other villages also suffered «*danni non indifferenti*» (significant damage) Several rural constructions (single-room stone buildings) were «completely destroyed» and some crosses and statues collapsed. The *Daily Malta Chronicle* (02/10/1911) reports that «at Fort Chambray (Gozo) there is a great long crack running across the square. All the walls of the barrack rooms are cracked, and numerous holes appear in the ground, one of them three feet wide and of inconceivable depth», and that «the hospital, which was happily empty, the mortuary and linen house are completely wrecked, and although the walls are standing their condition renders the occupation of the buildings unsafe» (Grade 3 damage). Some landsliding was also reported.

In Gozo, everybody abandoned their houses. Some furniture was overturned and some pendulum clocks stopped (*Malta*, 02/10/1911). The tremors are reported to have been accompanied by a «loud rumbling». In Malta, on the other hand, the damage was apparently limited to some cracks (Grade 1 damage), although the shaking was strongly felt and caused alarm.

The well-described damage corresponds to EMS-98 intensity VII on the island of Gozo, whereas on Malta, the intensity has been assigned as V.

Although no epicentral location exists for this event, some conclusions may be reached regarding its source parameters. The event was recorded on the seismograph in Catania and Riccò (1911) records an *S-P* time of 29 s. At Catania, the tremor was only slightly perceived. The *S-P* time places the epicentre at around 200 km from Catania, and since the tremor does not appear to have been felt in more northern parts of Sicily, and was felt much more strongly in Gozo than in Malta, it is likely that the epicentre was in the Sicily Channel to the north west of Gozo, possibly on one of the faults bounding the Malta Graben. The shock was also felt at sea in this area. The captain of the Danish ship *Calypso* reports that at latitude 36.2N and longitude 14.1E (about 20 km north west of Gozo) at 09:23 local time, «a slight agitation of the sea and a tremor» was felt, «enough to influence the movement of the ship» (*Malta,* 02/10/1911).

18 September 1923 – This event is well described in the local newspapers (*Malta, Daily Malta Chronicle*), and was also recorded on the Milne seismograph in Valletta. Unfortunately, the seismogram, which was inspected, did not yield useful information since the shock appears to have thrown the mechanism out of alignment. The majority of the population took to the street in panic in both islands, although the shock appears to have been felt most strongly around the harbour area in Malta (*Daily Malta Chronicle,* 19/09/1923). Damage reported was mainly non-structural, such as collapses of stone crosses on churches, cracks in church domes, the most serious being that of St. Paul's church in Rabat, and cracks in the walls of many residential and commercial buildings. This damage may be considered as of Grade 2, and the local site intensity has been assigned as VI. The earthquake was reported to be slightly felt in Syracuse, Sicily, but is not listed in any of the catalogues. It can therefore be assumed that this is a «Sicily Channel» event, possibly on the Malta Escarpment, given that it was more strongly felt to the east of Malta. The *Daily Malta Chronicle* reports that «We are authoritatively informed that the disturbance must have occurred some 50 or 60 miles away from the Island.» The ISC bulletin lists it as 35.5N, 14.5E, about 35 km south of Malta, with no other information, however, for this period, location of earthquakes deriving from instrumental data is unreliable.

5. Catalogue completeness

Considering the nature and reliability of local historical texts and other publications, it is extremely unlikely that any earthquake that produced a local intensity of VII or over since 1500 has been missed in this research.

Figure 5 shows graphs of the cumulative numbers of earthquakes of maximum local intensity ≥IV, V and VI respectively since 1500. These graphs show a break at around 1840, coinciding with the beginning of local newspaper publication. This reflects both the improved reporting of local events of public interest as well as the increased facility of documentary research.

The felt earthquake catalogue may thus be considered complete for the period after 1530 for intensities ≥VII and from 1848 for intensities ≥IV.

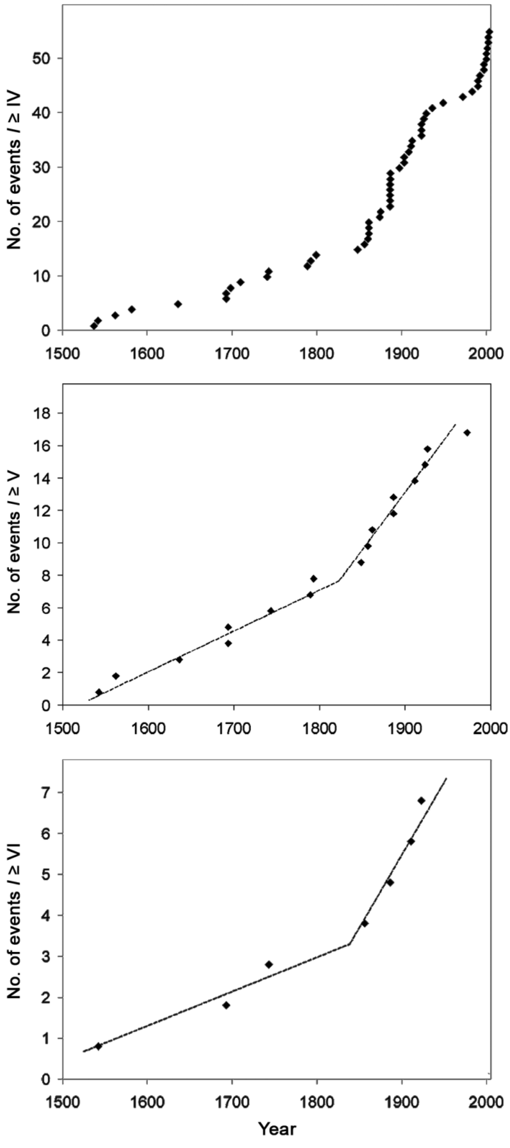

Fig. 5. Cumulative number of events having *I*≥IV, V and VI since 1530.

6. Seismic hazard and earthquake risk assessment

This paper is intended to make the case for a renewed effort at establishing the seismic risk level on a national scale, as this problem has never really been addressed in a holistic manner. Although the catalogue only goes back some 500 years, and damaging earthquakes are few, it is still possible to make some considerations about seismic hazard.

Some previous attempts have been made at defining the level of seismic hazard although a locally compiled seismic history was not available, and no strong ground motion data is available. A seismic hazard study commissioned before the construction of a new power station on Malta gives an expected PGA of 0.12 *g* for a 475-year return period (Mouchel and Partners, 1990). Camilleri (2003) estimates a return period of 1800 years for *I*=VII in the Maltese islands, and 333 years for *I*=VI. The ESC-SESAME Unified Hazard Model for the European-Mediterranean Region (Giardini *et al.*, 2003) classifies Malta in the top end of the 'Low Hazard' region, with a 475-year return period corresponding to PGA values of 0.04-0.08 *g*.

From the intensity catalogue it is possible to make simple estimates of return periods. For this purpose, the methodology of Magri *et al.* (1994) has been used. In this method, which is suitable for sites characterized by poorly-defined macroseismic data, and accommodates the use of ranged intensity values, each earthquake is associated with a discrete exceedance probability function $P(I)$, $I \in [1, 1]$, which is equal to the probability of intensity I having been reached. Thus if the ith event in the catalogue has been assigned intensity VII-VIII, the function could be

$$P_i(I) = \{1, 1, 1, 1, 1, 1, 1, 0.5, 0, 0, 0\}.$$

The estimated mean return period for intensity I is then given by

$$\tau(I) = \frac{T}{\sum_{i=1}^{n} P_i(I)}$$

where T is the duration of the seismic catalog and n is the number of events in the catalogue.

The estimated return periods for intensity ≥V using this method are shown in fig. 6. The return period for intensity V is 18 years, for intensity VI 40 years , for intensity VII 92 years, and for intensity VIII it turns out to be 1000 years. The latter is based on a single observation of intensity VII-VIII for the 1693 earthquake. It is worthwhile to discuss this further. It appears that this maximum intensity, at least for the time period under consideration, is uniquely attributable to the 1693 event. Indeed in Sicily, the only intensities ≥X are associated with this source region (*e.g.*, Barbano *et al.,* 2001). The same source most likely generated the equally large 1169 event that caused destruction in Eastern Sicily (Azzaro *et al.,* 1999; Barbano *et al.,* 2001). Using the methodology of Magri *et al*. (1994), Barbano *et al*. (2001) estimate return periods for several sites in SE Sicily. The site-specific return periods where the intensities in a given range can be attributed uniquely to the 1693 source region vary between 432 and 683 years, with a mean of 547 years. In other words, if the occurrence of the maximum experienced intensity (VII-VIII) is tied to the source region of the 1693 earthquake then we can expect this intensity to have a return period of around 500 years. This is consistent with fig. 6.

It is clear that a certain level of hazard is also presented by the lower magnitude Sicily Channel seismicity. At least two events in this region since 1900 have produced damage of intensity ≥VI. Perhaps more important is the hazard posed by long-period ground motion arising from large subduction zone earthquakes in the Hellenic Arc, capable of producing intensities up to VII even from distances greater than 1000 km. This effect is probably due also to a different kind of attenuation regime for propagation through the Ionian Basin. In any case, it is evident that this phenomenon must be seriously considered in any risk assessment, especially in the case of high-rise buildings.

In computations of seismic hazard the value of Peak Ground Acceleration (PGA) with a

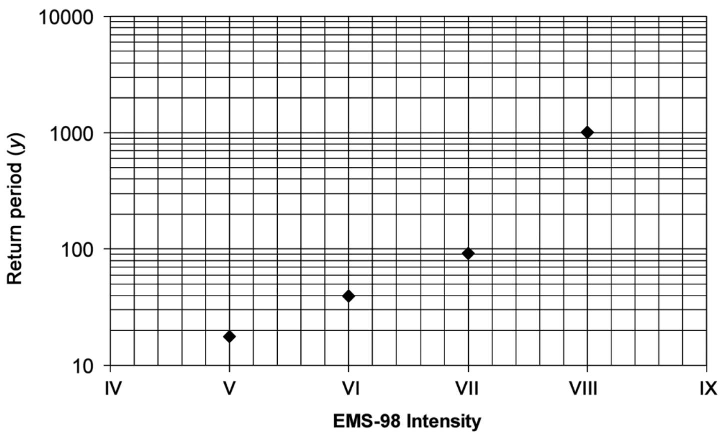

Fig. 6. Estimated return periods, following the methodology of Magri *et al*. (1994).

475-year return period is usually quoted, corresponding approximately to a 10% probability of exceedance in 50 years. In Malta this would correspond to intensity VII-VIII. There is no available strong-motion instrumental data or local attenuation relationships for the Maltese islands, and empirical relations between intensity values and ground motion parameters are usually of limited reliability. It is well known that a large amount of scatter exists when correlating ground motion parameters with site intensity values. For example, from global data, Ambraseys (1974) gives a mean PGA of (0.135±±0.027) g for I=VII and (0.207±0.052) g for I==VIII. Relationships developed specifically for the Italian territory (Margottini *et al.*, 1992) predict PGA's of 0.087 g and 0.13 g for intensities VII and VIII respectively. In Sicily during the 13 December 1990, M 5.4 earthquake, measured PGA values at different sites ranged from 0.04 to 0.247 g for I=VI, and from 0.06 to 0.1 g for I=VI-VII (Di Bona *et al.,* 1995; Stucchi *et al.,* 2007). Theoretical spectral attenuation relationships (*e.g.,* Berge-Thierry *et al.*, 2003) predict peak spectral ground accelerations of around 0.08 g at 5 Hz for the 1693 «design» earthquake (M_s 7.4, distance 150 km from Malta), but it is highly tentative, in the absence of local instrumental data, to predict such values.

7. Conclusions and final considerations

Since 1530, the maximum intensity experienced has been VII-VIII, and intensity VII has been experienced at least 4 times. The major seismic hazard to the islands arises from the northern segment of the Malta Escarpment, but active fault zones of the Sicily Channel Rift Zone as well as large Hellenic Arc earthquakes, also pose a potential hazard that cannot be neglected.

Using the available seismic history for the Maltese islands, together with deterministic effects of the most influential seismic sources, it is reasonable to arrive at intensity VII-VIII as the one with a 475-year return period. Although no accelerometric data are available, it is also possible, though tentative, to postulate that expected peak ground accelerations for this return period fall within the 0.04-0.1 g band, therefore belonging to the category of ground motions which necessitate seismic design procedures as detailed in EC8 seismic rules.

Although draft legislation is being formulated, there is at present no building code in use on the Maltese islands. Moreover the rate of construction is extremely rapid. During the past few decades, there has been a dramatic increase in building density, including many apartment blocks higher than 3 storeys, which have never experienced strong ground shaking, The fact that heavy earthquake damage has not been experienced for almost a century has led to complacency in the construction industry as well as a lack of knowledge about the behaviour of local buildings during ground shaking. Other factors to be taken into account are the fact that the building footprint is expanding rapidly onto areas of diverse geological typologies and topography, whose site response effect is still unknown, and the various states of deterioration of some of the old building stock still in use.

While recent constructions of a certain strategic and structural importance are generally cited as having been seismically engineered, the same probably cannot be said of many residential buildings that have mushroomed rapidly in recent years. Such buildings are for the most part 3-5 storey structures of unreinforced masonry, with heavy concrete flooring/roofing, and often incorporating large open basements acting as garages. These structures are known to be highly vulnerable to ground shaking, and liable to collapse under even moderate ground shaking.

The present study has shown that current building practices in the Maltese islands need to be modernised in order to include for a certain mandatory minimum level of protection against seismic action.

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REFERENCES

ABELA, M. (1969) Earthquakes in Malta, *History Thesis* (Malta), pp. 164.

ACM (Mdina Cathedral Archives), *Miscellanea MS62*, ff. 42-56.

ACM, *Minuti Capitulari*, **vol. 7**, 1739-1746, ff. 184-189.

ALBARELLO, D. and M. MUCCIARELLI (2002): Seismic hazard estimates using ill-defined macroseismic data at site, *Pure Appl. Geophys.*, **159**, 1289-1304.

AMATO, A., R. AZZARO, A. BASILI, C. CHIARABBA, M. COCCO, M. DI BONA and G. SELVAGGI (1995): Main shock and aftershocks of the December 13, 1990, Eastern Sicily earthquake, *Ann. Geofis.*, **XXXVIII** (2), 255-266.

AMBRASEYS, N. (1974): Notes on engineering seismology, in *Engineering Seismology and Earthquake Engineering*, edited by J. SOLNES, Nato Advanced Study, 33-54.

AMBRASEYS, N. (1982): The seismicity of North Africa: the earthquake of 1856 at Jijeli, Algeria, *Boll. Geofis. Teor. App.*, **93**, 31-37.

Archivio Segreto Vaticano, Segreteria di Stato, Malta, **61**, f. 497, f. 504.

ARGNANI, A.(1990): The Strait of Sicily rift zone: foreland deformation related to the evolution of a back-arc basin, *J. Geodyn.*, **12**, 311-331.

AZZARO, R. and M.S. BARBANO (2000): Analysis of the seismicity of Eastern Sicily: a proposed tectonic interpretation, *Ann. Geofis.*, **43** (1), 171-188.

AZZARO, R., M.S. BARBANO, A. MORONI, M. MUCCIARELLI and M. STUCCHI (1999): The seismic history of Catania, *J. Seismol.*, **3**, 235-252.

BARBANO, M.S. and R. RIGANO (2001): Earthquake sources and seismic hazard in southeastern Sicily, *Ann. Geofis.*, **44** (4), 723-738.

BARBANO, M.S., R. RIGANO, M. COSENTINO and G. LOMBARDO (2001): Seismic history and hazard in some localities of south-eastern Sicily, *Boll. Geofis. Teor. Appl.*, **42**, 107-121.

BENOUAR, D. (1994): Materials for the investigation of the seismicity of Algeria and adjacent regions during the twentieth century, *Ann. Geofis.*, **XXXVII** (4), 459-853.

BENOUAR, D. and N. LARADI (1996): A reappraisal of the seismicity of the Maghreb countries – Algeria, Morocco, Tunisia, *Nat. Hazards*, **13**, 275-296.

BERGE-THIERRY, C., F. COTTON and O. SCOTTI (2003): New empirical response spectral attenuation laws for moderate European earthquakes, *J. Earthquake Engin.*, **7**, 193-222.

BOSCHI, E., E. GUIDOBONI, G. FERRARI, D. MARIOTTI, G. VALENSISE and P. GASPERINI (2000): Catalogue of Strong Italian Earthquakes from 461 B.C. to 1997, Introductory texts and CD-ROM, Version 3 of the Catalogo dei Forti Terremoti in Italia, *Ann. Geofis.*, **43** (4), 609-868.

BOUGHACHA, M.S., M. OUYED, A. AYADI and H. BENHALLOU (2004): Seismicity and seismic hazard mapping of Northern Algeria: map of Maximum Calculated Intensities (MCI), *J. Seismol.*, **8**, 1-10.

CAMILLERI, D. (2003) Malta's risk minimization to earthquake, volcanic and tsunami damage, *Disaster Prevention and Management*, **12**, 37-47.

DE SOLDANIS, G.P. (1999): *Gozo – Ancient and Modern, Religious and Profane* (translation into English by Rev. Fr. Anthony Mercieca of original manuscript 1746), (Media Centre Publications).

DI BONA, M., M. COCCO, A. ROVELLI, R. BERARDI and E. BOSCHI (1995): Analysis of strong-motion data of the 1990 Eastern Sicily earthquake, *Ann. Geofis.*, **XXXVIII** (2), 283-300.

ELLUL, M. (1993): The Earthquake of 1693 – A historical survey, in *Mdina and the earthquake of 1693*, edited by C.J. AZZOPARDI (Heritage Books, Malta).

FAURE, G. (1913): *L'Istorja ta' Malta u Ghawdex* (E. Lombardi, Malta).

GIARDINI, D., M.-J. JIMENEZ and G. GRUNTHAL (2003): The ESC-SESAME unified seismic hazard model for the European-Mediterranean region, European Seismological Commission/UNESCO-IUGS International Geological Correlation Program, *Project No. 382 SESAME*.

GRASSO, M., H.M. PEDLEY and C.-D. REUTHER (1985): The geology of the Pelagian Islands and their structural setting in relation to the Pantelleria rift (Central Mediterranean Sea), *CENTRO*, **1** (2), 1-19.

GRUNTHAL, G. (Editor) (1993): European Macroseismic Scale 1992 (updated MSK-scale), *Cahiers du Centre Europeen de Geodynamique et de Seismologie*, Conseil de l'Europe, **vol. 7**.

GRUPPO DI LAVORO CPTI (2004): *Catalogo Parametrico dei Terremoti Italiani,* versione 2004 (CPTI04), (INGV, Bologna).

GUIDOBONI, G. and A. COMASTRI (Editors) (2005): *Catalogue of Earthquakes and Tsunamis in the Mediterranean Area from the 11th to the 15th Century* (INGV-SGA, Bologna), pp. 1037.

GUTSCHER, M.-A., J. ROGER, M.-A. BAPTISTA, J.M. MIRANDA and S. TINTI (2006): Source of the 1693 earthquake and tsunami (Southern Italy): new evidence from tsunami modeling of a locked subduction fault plane, *Geophys. Res. Lett.*, **33**, L08309.

ILLIES, J.H. (1981): Graben formation: the Maltese islands, a case history, *Tectonophysics*, **73**, 151-168.

ISC (2001): *On-line Bulletin* <http://www.isc.ac.uk> (International Seisomological Center, Thatcham, U.K.).

JONGSMA, D., J.M. WOODSIDE, G.C.P. KING and J.E. VAN HINTE (1987): The Medina Wrench: a key to the kinematics of the Central and Eastern Mediterranean over the past 5 Ma, *Earth Planet. Sci. Lett.*, **82**, 87-106.

MAGRI, M., M. MUCCIARELLI and D. ALBARELLO (1994): Estimates of site seismicity rates using ill-defined macroseismic data, *Pure Appl. Geophys.*, **143**, 617-632.

MARGOTTINI, C., D. MOLIN and L. SERVA (1992): Intensity *versus* ground motion: a new approach using Italian data, *Eng. Geol.*, **33**, 45-58.

MOUCHEL, L.G. and PARTNERS, BRITISH ELECTRICITY INTERNATIONAL LIMITED (1990): Delimara power station Malta: seismic risk analysis, *Rep. 26562*, Enemalta Corporation, Malta.

MUSSON, R.M.W., T. MIKKELSEN and H. ZISKA (2001): Historical seismicity of the Faroe Islands, *Ann. Geofis.*, **44** (5/6), 1031-1047.

PAPAZACHOS, B.C., P. E. COMNINAKIS, G.F. KARAKAISIS, B.G. KARAKOSTAS, CH.A. PAPAIOANNOU, C.B. PAPAZACHOS and E.M. SCORDILIS (2000): A catalogue of earthquakes in Greece and surrounding area for the period 550 BC-1999, *Pub. Geophys. Lab. University of Thessaloniki*, **1**, pp. 333.

PIATANESI, A. and S. TINTI (1998): A revision of the 1693 Sicily earthquake and tsunami, *J. Geophys. Res.*, **103** (B2), 2749-2758.

REUTHER, C.D. (1990): Strike-slip generated rifting and recent tectonic stresses on the African foreland (Central Mediterranean Region), *Ann. Tectonicae*, **4**, 120-130.

REUTHER, C.-D. and G.H. EISBACHER (1985): Pantelleria Rift-crustal extension in a convergent intraplate setting, *Int. J. Earth Sci.*, **74** (3), doi: 10.1007/BF01821214, 585-597.

RICCÒ, A. (1911): Fenomeni geodinamici consecutivi alla eru-zione Etnea del Settembre 1911, *Boll. Soc. Sism. Ital.*, **16**.

SAID, J. (1997): Relocation of earthquake epicentres in the Central Mediterranean, *B.Sc. Dissertation* (University of Malta).

SHOWER, J. (1693): *Practical reflections on the late earthquakes in Jamaica, England, Sicily, Malta, etc.*, London.

SIROVICH, L. and F. PETTENATI (2001): Test of source parameter inversion of the intensities of a 54000-death shock of the seventeenth century in southeast Sicily, *Bull. Seismol. Soc. Am.*, **91**, 792-811.

STUCCHI, M. *et al.* (2007): DBMI04, il database delle osservazioni macrosismiche dei terremoti italiani utilizzate per la compilazione del catalogo parametrico CPTI04 (available on line at: http://emidius.mi.ingv.it/DBMI04/), *Quad. Geofis.*, **49**, pp. 38.

SULEIMAN, A. and D.I. DOSER (1995): The seismicity, seismotectonics and earthquake hazards of Libya, with detailed analysis of the 1935 April 19, $M = 7.1$ earthquake sequence, *Geophys. J. Int.*, **120**, 312-322.

WOO, G. (1995): Long-period damage in historical European earthquakes, *Terra Nova*, **7**, 476-469.

ZAMMIT, S. (2003): A study of seismicity and earthquake swarms in the Central Mediterranean, *M.Sc. Thesis* (University of Malta).

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