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The use of geological data to improve SHA estimates in Greece

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ABSTRACT The broader Aegean region is well known for the frequent and intense seismic activity which has caused great damages and human losses. In order to improve the seismic hazard assessment (SHA) in Greece and surroundings, several national and international projects were launched during the past years dealing with either the cause (seismogenic sources) and/or the result (ground effects). In this paper, we present the background and the state-of-the-art of two databases which contribute (each with its own way) to the SHA of Greece: GreDaSS (Greek Database of Seismogenic Sources) and DaLO (Database of Liquefaction Occurrences). Both databases are essentially built on geological information and investigation approaches and techniques. They confirm the important contribution of Earthquake Geology to an explicit improvement of our seismotectonic knowledge and to SHA analyses when this information is included in the estimates.

Key words: GreDaSS, DaLO, SHA, seismotectonics, Aegean region.

1. Introduction

Analyses on seismic hazard assessment (SHA) represent a societal crucial research field where different specialists contributing to mitigate the seismic risk (geologists, seismologists and engineers) commonly interface. Nowadays, two are the prevailing approaches for SHA: deterministic and probabilistic (DSHA and PSHA respectively). Both approaches assess the effects produced by an earthquake. Generally, these effects can be separated into the primary ones, including the fault surface rupture and the ground shaking, and the secondary ones like landslides, slope failures and tsunamis. PSHA and DSHA basically use the same seismological and geological information, but giving them different weights and following different approaches. The choice of the appropriate method is sometimes still controversial, causing the existence of a rich literature on the effectiveness of each approach or sometimes of their combination (e.g., Krinitzsky, 1995; Anderson *et al.*, 2000; Bommer, 2002; Klügel, 2008; Wang, 2011).

In this paper, we show the possible contribution of Earthquake Geology to SHA estimates as applied to the Aegean region, which is among the most tectonically active areas of the Mediterranean realm and has the highest seismicity both in terms of frequency of events and magnitudes (Fig. 1). In particular, we briefly present the background and the state-of-the-art

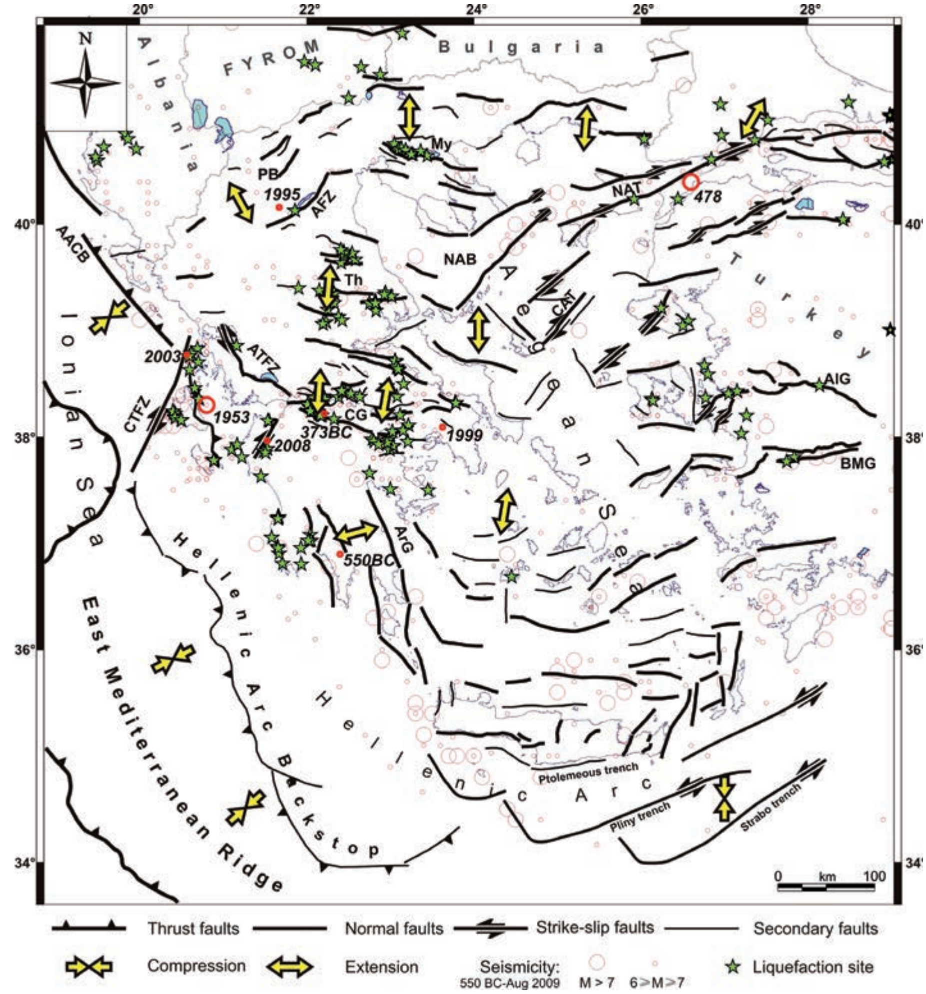

Fig. 1 - Symplified tectonic map of the broader Aegean region showing the Composite Seismogenic Sources taken from GreDaSS (for graphical reasons only the fault traces are shown) and the liquefaction sites from DALO (green stars), combined with the stress pattern (yellow double arrows) and the regional seismicity (red circles). Seismicity is from Papazachos *et al*. (2000, 2009) and the Hellenic Arc backstop is from Le Pichon *et al*. (2002) and Rabaute and Chamot-Rooke (2007). Bold circles and numbers in italics represent earthquakes referred to in the text. Acronyms refer to major tectonic structures: AACB: Adria-Aegean Convergence Boundary; AFZ: Aliakmonas Fault Zone; AlG: Alasehir Graben; ArG: Argolikos Gulf; ATFZ: Amvrakikos Gulf - Trichinida Fault Zone; BMG: Buyuk Menderes Graben; CAT: Central Aegean Trough; CG: Corinth Gulf; CTFZ: Cephalonia Transform Fault Zone; My: Mygdonia basin; NAB: North Aegean Basin; NAT: North Aegean Trough; PB: Ptolemaida Basin; Th: Thessaly fault system.

of two databases we are working at, essentially built on geological information (Figs. 2 and 3), investigation approaches and techniques, and their potential contribution to SHA analyses. Although this contribution is certainly not exhaustive for all SHA issues, it is undoubtedly crucial, like for recognising previously unknown seismogenic sources characterized by reactivation intervals longer than the historical record. As a matter of fact, when sources associated with morphogenic earthquakes (Caputo, 2005), like most crustal events with magnitude greater than *ca*. 5.5 (Pavlides and Caputo, 2004), are taken into account and included in the analyses, SHA estimates are generally improved. In particular, the parameterization of

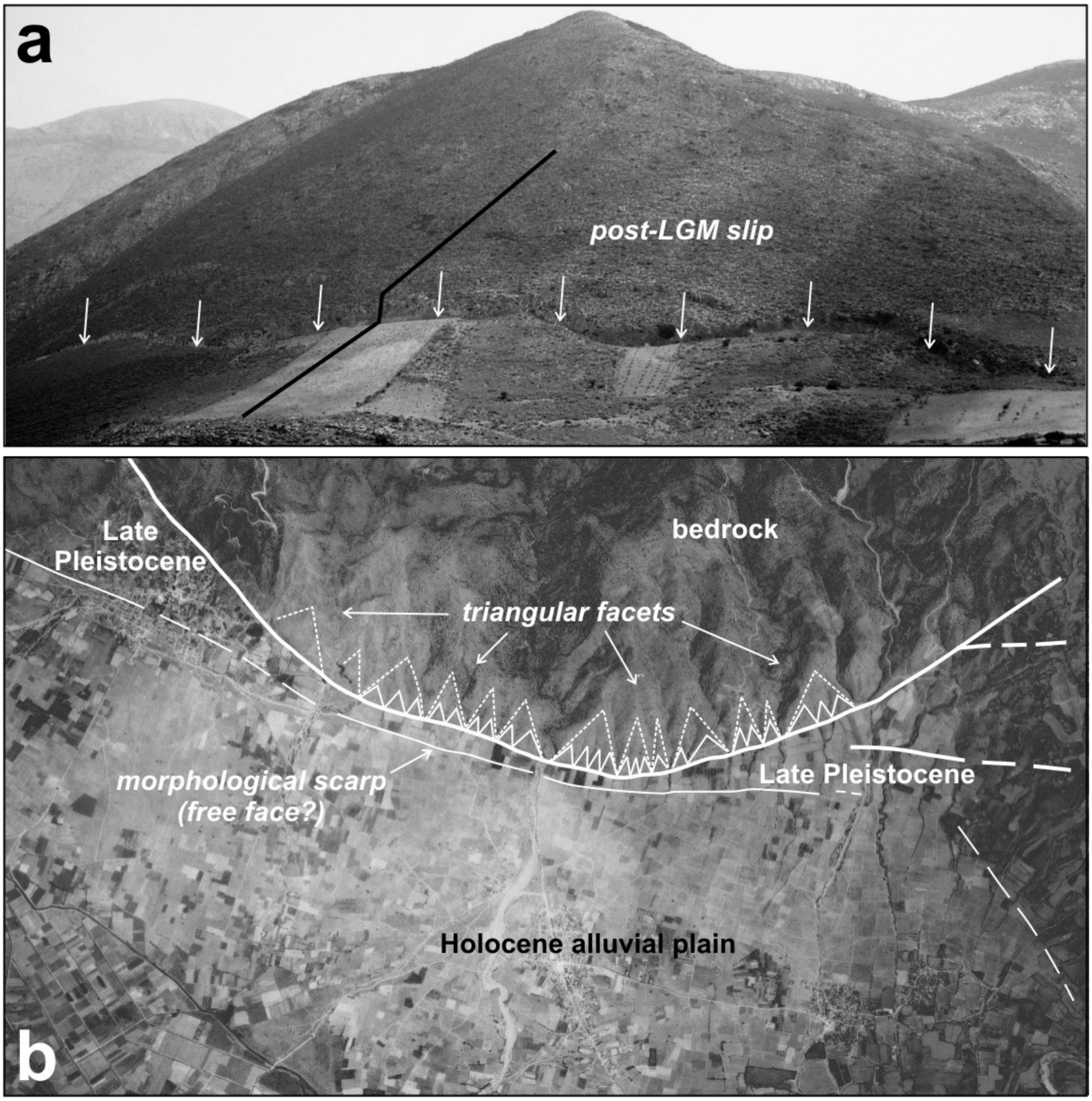

Fig. 2 - Examples of geological evidence used for the compilation of GreDaSS: a) post-LGM cumulative fault scarp (Kastelli fault, Crete); b) triangular facets and morphological scarps affecting Late Pleistocene and Holocene deposits (Rodia fault, Thessaly).

specific seismogenic sources in terms of their seismotectonic features, like real fault dimensions, segmentation and rupture scenarios, mean recurrence interval, long-term and/or short-term slip-rate, maximum and mean co-seismic displacement, etc. is strongly enhanced when geological information is considered.

The first database that we discuss in this paper is GreDaSS (Greek Database of Seismogenic Sources available at http://gredass.unife.it), a project started several years ago and aimed at reaching three major goals: (i) the systematic collection of all available information concerning neotectonic, active and capable faults (Fig. 2) as well as broader seismogenic volumes; (ii)

Fig. 3 - Examples of geological evidence used for the compilation of DaLO: a) ejected sand cones aligned along a ground fracture (June 8, 2008 Movri earthquake); b) earthquake induced rockfalls (August 14, 2003 Lefkada earthquake).

the critical analysis of the collected data and the quantification of the principal seismotectonic parameters of the various sources including the associated degree of uncertainty; (iii) provide an integrated view of potentially damaging seismogenic sources (Fig. 1) for a better SHA in Greece and surroundings. For this purpose, GreDaSS recently joined the European project SHARE (Seismic Hazard Harmonization in Europe; http://www.share-eu.org/) which aims at delivering measurable progress in all steps leading to a harmonized assessment of seismic hazard in Europe, in the definition of engineering requirements, in the collection and analysis of input data, in procedures for hazard assessment, and in engineering applications. In this frame, the development of GreDaSS, at present focusing on the shallow (crustal) seismogenic sources for the broader Aegean region, contributes to the homogenized seismogenic source model of Europe. Indeed, such an integrated data collection, informatization and parameterization of the principal seismotectonic parameters was lacking for this area.

Parallel to the GreDaSS, another major project was set-up by our research group concerning the earthquake induced ground deformations, especially focusing on liquefaction phenomena (green stars in Fig. 1) and/or also including landslides/rock falls (Fig. 3). The /Database of historical Liquefaction Occurrences (DaLO) is available at http://users.auth.gr/gpapatha/dalo.htm. The evaluation of the potential of the seismogenic sources represents a fundamental step for the quantitative assessment of earthquake-induced ground deformation hazard. Indeed, the generation of soil liquefaction and earthquake-induced slope failures are the most damaging secondary effects that should be investigated in order to decrease the risk for critical facilities. Observing, quantifying and cataloguing all these features associated with past events and correlating them to the occurred damage will be crucial for reducing their potential effects in the future. A better definition of the principal seismogenic sources and their seismotectonic characteristics provided by GreDaSS, will also eventually improve our evaluation of the susceptibility and hazard of secondary effects.

2. Seismogenic sources and GreDaSS

A first attempt to create a similar database for the Greek territory was carried out during the EU project FAUST (2001), where *ca.* 50 earthquake-related sources have been included. In contrast, the most recent and the most complete map of capable faults in Greece and the broader Aegean region, has been compiled by Pavlides *et al.* (2007).

Other attempts have been performed in the past, but all of them were lacking both fault and data completeness. For example, simple map compilations cannot provide much information except the geographical location and few geometrical-kinematic characteristics of the faults. In contrast, the informatic structure and methodological approach of GreDaSS is based on the well tested, time-proven, worldwide acknowledged database proposed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) for the Italian Database of Individual Seismogenic Sources (DISS; http://diss.rm.ingv.it/diss/), which represents the result of almost twenty years research experience of its Working Group (Valensise and Pantosti, 2001; Basili *et al.*, 2008). Accordingly, GreDaSS is built in a GIS environment containing different levels of information and different types of seismogenic sources. Probably, the two most important ones are represented by the Individual and the Composite Seismogenic Sources (ISSs and CSSs, respectively). A third type of seismogenic sources includes the Debated ones (DSSs); although the associated information is generally poor, this source type results very practical especially in the preliminary steps of the compilation. All data related to the sources have a multi-layered structure, such as comments, open questions, short summaries of the available literature and selected figures. Full information relative to the database architecture and its usage is available in the DISS3 Tutorial webpage (http://diss.rm.ingv.it/diss/usermanual.html) and will be not further described in this paper.

2.1. GreDaSS rationale

Even though the causative seismogenic sources, especially along well defined zones (e.g., gulf of Corinth, south Thessaly, Ionian Sea), are known and related with most of the historical and instrumental earthquakes, there are still seismic events that ‘surprise’ the scientific community. This can be explained by the fact that investigations are certainly not complete or even entirely lack in some regions, or existing information in the literature is not properly considered. Two examples from the 1990s clearly describe this problem. The first one is represented by the May 13, 1995 ($M_w = 6.5$) Kozani earthquake which occurred in an area that was assumed to be of low seismicity (or ‘aseismic’) specifically on the basis of the (lack of) historical and instrumental records (Voidomatis, 1989; Papazachos, 1990). The second example comes from the September 7, 1999 ($M_s = 5.9$) Athens earthquake, which even though it was a moderate-sized event, it strongly affected the metropolitan area of Athens, which accommodates nearly half the Greek population, causing many deaths and severe damage. Like in the former example, the area was previously considered of low seismic activity, since no important earthquakes were reported either historically or instrumentally (Papadimitriou *et al.*, 2002; Pavlides *et al.*, 2002). In this case, the causative Fili fault, which has a clear morphotectonic expression (Ganas *et al.*, 2004), was not recognized until the earthquake occurred. Sources that bear neither instrumental nor historical earthquake records, but show geological evidences of recent activity, are more hazardous, given that they are more probable to rupture in the near future. On the contrary, sources associated with recent earthquakes will be probably reactivated much later than the buildings' and infrastructures' lifetime. Following this (not uniquely Greek) experience, we re-addressed the rationale of GreDaSS by emphasising the geological information. As a matter of fact, the recognition of a larger number of active faults and their better seismotectonic characterization, that are based on other than just seismological tools allowed the enrichment and the higher level of completeness of the database. In this way, SHA estimates of highly seismogenic regions like Greece and its surroundings are crucially enhanced.

2.2. Sources categorization

In general, only a small percentage of faults affecting a large crustal volume is active or potentially active; therefore a first step in building GreDaSS was to decide which of the candidate faults are qualified for being considered in the database and in which layer (ISS, CSS, DSS) should they belong to. In order to achieve this target, the fault activity classification proposed by Pavlides *et al.* (2007) was followed. The principal criteria for evaluating the seismogenic potential of each fault, reflects the reliability of the diverse investigating methods, which are briefly recalled here below.

Geological and morphotectonic features: topography can be strongly affected by active tectonics and hence many morphological features can be recognized and characterized based on appropirate field investigations and laboratory analyses. Thus, morphotectonic mapping and analysis (e.g., of fault scarps, triangular facets and tilted Quaternary sediments) with the aid of remote sensing (for calculating quantitative morphometric parameters like basin asymmetry, etc.) and palaeoseismological investigations (for estimating the recurrence interval or slip rate) are the most common tools to define the geological and morphotectonic features of faulting.

Seismic activity: it can occur either as localised major earthquakes (moderate to strong) or diffuse microevents. It is useful to distinguish historical major events and instrumental ones for confidence reasons. In Greece the historical record starts with the 550 BC event in Sparta (e.g., Guidoboni *et al.*, 1994; Papazachos *et al.*, 2000, 2009; Papazachos and Papazachou, 2003; Ambraseys, 2009) and can be used even for events from the early 20th century. The catalogue completeness before the 19th century is generally from poor to fair (Pavlides *et al.*, 2007) and the information associated with a specific event is often poor making the correlation with the causative fault occasionally difficult. On the other hand, the instrumental period for the Aegean region is less than 100 years, but it probably starts to be sufficiently accurate only after the 1970s when the Greek seismographic network was definitely improved.

Geophysical surveying: this methodological approach consists of different techniques (electrical resistivity tomographies, ground penetrating radar, high-resolution seismic profiles, etc.) and can provide useful information and constraints for characterizing an active fault (e.g., Caputo *et al.*, 2003; Oliveto *et al.*, 2004; Karastathis *et al.*, 2007).

Regional geodynamic setting: the orientation of a fault plane with respect to the active stress field may represent a quite strong evidence of potential activity (Pavlides *et al.*, 2007). However, this approach could be somehow misleading in specific areas, where the tectonic regime is complex and characterised by lateral variations or debated reconstructions by different authors. Areas like the northeastern Aegean or the Ionian Sea belong to this complex regime.

3. GreDaSS contribution to SHA

The generation of seismic zonation maps is a crucial step when performing SHA analyses. At this regard, the first map published for the Aegean region has been proposed by Papazachos (1990). It was exclusively based on seismological data, practically ignoring most available geological information. As a consequence, that map shows some blank sectors considered by the author as of 'very low activity' or 'aseismic' crustal volumes. However, two recent events occurred within such volumes (e.g., 1995 Kozani and 1999 Athens earthquakes), therefore attesting the limitations of this approach. Following these two 'unexpected' events and the new available instrumental data, Papaioannou and Papazachos (2000) presented a second improved version of the seismic zonation map. Nevertheless, as lively discussed in the scientific community (e.g., Mucciarelli *et al.*, 2008; Mucciarelli and Albarello, 2012; Stucchi *et al.*, 2012) nobody can guarantee that another 'surprising' strong earthquake will not occur in the near future and for how long do we have to wait until the earthquake catalogues will reach the highest level of completeness, if there is any.

In order to emphasize the potential contribution of earthquake geology to SHA analyses, we compare the above mentioned seismic zonation map (Papaioannou and Papazachos, 2000) with the most updated version of the CSSs provided by the GreDaSS. This simple test obtained by overlapping the two graphical information layers shows several mismatches (Fig. 4). In particualr some major active faults, like the North Aegean Trough (NAT), North Aegean Basin (NAB) and Cephalonia Tranform Fault Zone (CTFZ) CSSs (respectively marked by numbers 1, 2 and 3 in Fig. 4) are 'artificially partitioned' into more than one polygon (i.e., seismic zone) in striking contrast with the seismotectonic behaviour of these structures. Another important difference in the proposed seismic zonation (Papaioannou and Papazachos, 2000), is that seismogenic sources are assumed as point sources, generally corresponding to the epicentral location, whereas the source dimensions and the different possible rupture processes are totally disregarded.

As a second test, we also compare the maximum expected magnitude of each seismic zone as obtained from: i) seismological data [M_{seis}; Papaioannou and Papazachos (2000)], and ii) from the geological information used in GreDaSS (M_{geol}). The comparison is reported in Fig. 5, where several important discrepancies are evident.

It is worth to note that the 'seismological' approach is based on standard statistical procedures, taking into account the maximum magnitude that derives from the observed historical and instrumental seismicity (Papazachos, 1990). However, seismic catalogues, no matter how complete they are, usually cannot cover the whole seismic cycle of a fault; as a matter of fact, the reactivation of a seismogenic source with a low slip-rate and a long recurence interval is likely missing from the catalogues and the maximum magnitude could be thus underestimated. Additionally, old historical events bear significant uncertainties in magnitude estimations that could further affect the value of M_{seis}.

In contrast with M_{seis}, M_{geol} is mainly obtained from geologically-based investigations by applying various empirical relationships [e.g., magnitude vs. fault rupture area or vs. fault length; Wells and Coppersmith (1994)]. In this regard, the geological record seems to be richer in terms of seismotectonic information at least in the Aegean region where most crustal active faults are emergent [Aegean-type active faults; Pavlides and Caputo (2004)] and their surficial

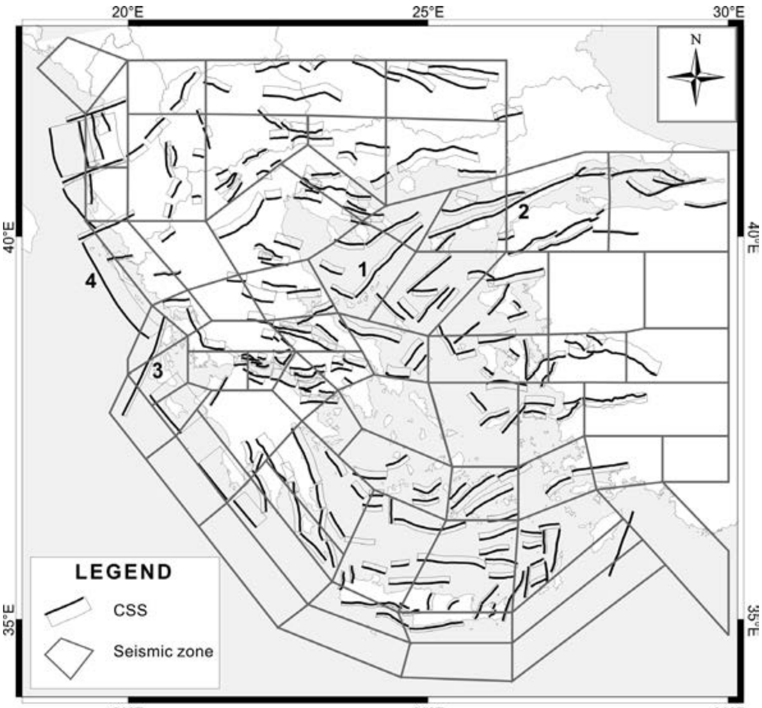

Fig. 4 - The incompatibility between the CSSs of GreDaSS and the seismic zonation suggested by Papaioannou and Papazachos (2000). Note how the CSSs are interrupted by the seismic zones, especially along large structures like the NAB (1), NAT (2), the Cephalonia-Lefkada Transform Fault (3) and the Corfu Offshore Thrust (4). See text for discussion.

exposure is the result of repeated morphogenic earthquakes (Caputo, 2005). Accordingly, the ‘geological’ approach could provide better information on the overall seismotectonic behaviour of the fault.

By comparing the two magnitudes, we may observe that most of the M_{geol} are systematically greater than the M_{seis} (Fig. 5), from > 0.1 and in some case up to 0.6 degrees of magnitude. Few exceptions are represented by the seismic zones along the Hellenic Arc, where we declared that the GreDaSS is still in progress and just few seismogenic sources have been included at the moment in the database, while further ones are under investigation.

As concerns the seismic zone including Corfu Island (marked by the number 4 in Fig. 4), the inverted difference ($M_{geol} < M_{seis}$) may be apparent and due to the fact that the major seismogenic source within the area has been placed in GreDaSS just outside the Papaioannou and Papazachos (2000) zone. If we consider it ($M_{geol} = 7.6$), this zone would thus not represent an exception.

Another small group of seismic zones where M_{geol} is slightly lower than M_{seis} is represented by the broader Corinth Gulf area where $M_{seis} = 7.0$. In this case, a careful re-analysis of the historical and instrumental database used by the authors shows that all strongest events are very old (the youngest is 1889, while the others are medieval or even B.C.) and therefore likely affected by large uncertainties. The important fault segmentation characterizing the area and the possibly consequent triggering could be another explanation of this local inversion ($M_{geol} < M_{seis}$). Indeed, the macroseismic field (and hence the M_{seis}) could be the result of two distinct earthquakes, where the second event was triggered by the first one very close in time and historically it could be not distinguished.

In conclusion, the systematic difference (with $M_{geol} > M_{seis}$) between the two approaches may have a great impact on future SHA analyses and will likely increase the values for critical facilities.

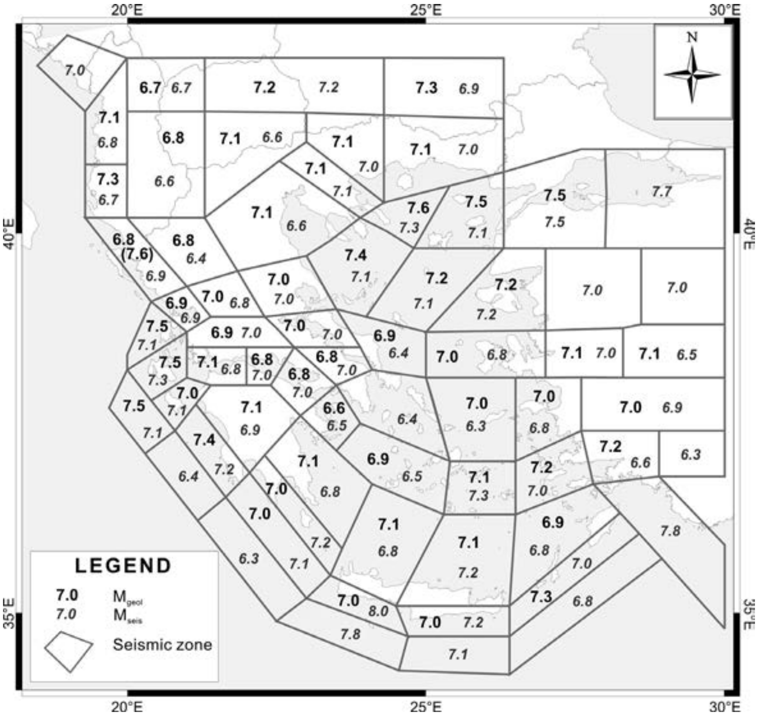

Fig. 5 - The comparison between the maximum expected magnitudes in each seismic zone as obtained from: i) geological information (M_{geol}, bold numbers) used in GreDaSS (see text for more details); ii) seismological data (M_{seis}, numbers in italics), proposed by Papaioannou and Papazachos (2000). Missing values of M_{geol} in some zones are due to the smaller coverage of GreDaSS in the area (see Fig. 4). Differences among the two datasets are discussed in the text.

4. DaLO contribution to SHA

Earthquake-induced landslides and soil liquefaction phenomena are the most common, and likely the most destructive, among the so-called secondary seismic effects. Characteristic and widespread soil liquefaction-induced damages were reported after the 1989, M_s= 7.1 Loma Prieta and the 1995, M_w= 6.9 Kobe earthquakes. For example, the latter event caused pervasive liquefaction throughout the reclaimed lands and the manmade islands in the Kobe region, inducing extensive structural damages to quay walls around the port facilities and associated damage to the cranes and other supporting facilities (Idriss and Boulanger, 2008). Soil liquefaction was also triggered by the two devastating earthquakes occurred during 1999 in Taiwan (M_w = 7.6, Chi-Chi) and Turkey (M_w = 7.4, Koçaeli). The former event induced damages and collapses of bridges, port facilities and buildings, while the latter caused important damages to ports and industrial facilities.

As concerns Greece, the most severe liquefaction-induced damage to infrastructures within an urban area was reported at the waterfront of the town of Lefkada as a consequence of the 2003, M_w = 6.2 earthquake. According to Papathanassiou *et al.* (2005) liquefaction occurrences (sand boils and vent fractures) were observed mainly in the waterfront area, and caused damages to pavements and sidewalks behind seawalls. Severe damages to port facilities, due to liquefaction of the subsoil layers, were observed in the Ionian islands at the towns of Argostoli, Lixouri and Zakynthos following the devastating 1953, M_w = 7.2 Cephalonia earthquake.

In order to compute the liquefaction potential, it is crucial, firstly, to evaluate the susceptibility to liquefaction. This can be achieved by collecting information regarding the occurrence of past liquefaction phenomena and the characteristics of the surface geology and hydrogeological conditions. The former approach can be realized using historical reports provided by newspapers and seismic catalogues, while the latter are obtained analysing existing geological maps and/or data provided by in-situ tests.

A database concerning past liquefaction occurrences has been developed and published by Papathanassiou and Pavlides (2011) for the broader Aegean region. The DAtabase of historical Liquefaction Occurrences (DaLO v1.0) is an open-access database where information regarding liquefaction-induced ground and/or structural deformations is provided. The oldest entry in the data set dates from the 16th century A.D. while the most recent one is represented by the earthquake-induced liquefaction phenomena associated with the June 8, 2008, $M_w = 6.4$ NW Peloponnesus earthquake.

The oldest events that are included in the seismic catalogues and at the same time are correlated to liquefaction phenomena are the Eliki (Helike) 373 B.C. and Sistos 478 A.D. earthquakes. A major outcome of this data set is represented by the compilation of maps showing the spatial distribution of liquefaction sites in Greece and in the broader Aegean region (Fig. 1), and the distribution of the earthquakes that induced liquefaction.

The major contribution of DaLO to SHA analyses is twofold. The first one provides direct information for the estimation of seismic hazard, which is achieved by recording the historical and recent liquefaction phenomena and suggesting a susceptibility degree for specific regions. In fact, the historical occurrences can be potentially enriched not only with reports but with geologically tracked evidences as well, like for example with data deriving from palaeoseismological trenches. At this regard, a recent case study is represented by the palaeoseismological evidences documenting the occurrence of older liquefaction phenomena within the epicentral area of the 2012 Emilia earthquake (Caputo *et al.*, 2013). Thus, in this way the database will provide important information about the local ground conditions that will by directly applicable for the seismic hazard calculations.

A second type of contribution has an indirect impact on SHA analyses and relies on the potential cooperation between DaLO and GreDaSS, by interconnecting the liquefaction occurrences with the specific seismogenic sources providing all necessary data at a glance to the end-user.

In addition, the quantitative assessment of earthquake-induced landslide hazard can be computed as the convolution of the spatial probability of occurrences of landslides and of the temporal probability of occurrence of triggering event (Guzzetti *et al.*, 2005; Jaiswal *et al.*, 2010). The former can be evaluated using statistical analyses, like logistic regression analyses, and the latter should be evaluated using the exceedance probability of an earthquake magnitude required to trigger landslides, following the method presented by Jaiswal and van Westen (2009). In particular, having estimated the probability of occurrence of the triggering threshold, the probability of landslide occurrence can be assumed since in this simplified model landslides always occur when magnitude M exceeds magnitude threshold M_t and never occur when the value of M is lower or equal to M_t (Jaiswal and van Westen, 2009). This approach has been applied in the Lefkada Island, Greece in order to compute the temporal probability of earthquake-induced landslide hazard (Papathanassiou *et al.*, 2013).

Furthermore, the identification of areas prone to earthquake-induced slope failures can be achieved by applying the Newmark approach introduced by Newmark (1965) and modified by Jibson (2007). The development of a Newmark analysis requires the evaluation of the parameters of the expected earthquake shaking and the capability of the geological unit to resist this dynamic effect. The latter parameter is quantified as a_c, a threshold ground acceleration necessary to overcome basal sliding resistance and initiate permanent downslope movement (Jibson, 2007).

In both cases, earthquake-induced landslide and soil liquefaction, the quantification of the parameters of the seismogenic sources is a fundamental step. In particular, the evaluation of the expected magnitude is essential for estimating the value of the generated ground motion, and particularly acceleration, a parameter commonly employed both in the procedures regarding the computation of liquefaction potential and the Newmark approach for the likelihood of induced slope failures. In addition, based on the recurrence rate of the fault, the temporal probability of the triggering mechanism (earthquake) could be also evaluated and constrained.

5. Concluding remarks

The comparison between the data provided by GreDaSS, and the so far published seismic zonations which are exclusively based on seismological data sets and investigations, clearly shows the importance not only of the geological information, but also of the need to combine as many investigation approaches as possible in order to provide more realistic solutions for SHA analyses. This issue has been faced while developping GreDaSS by taking into account several investigation approaches including many geological ones.

At the same time, the development of DaLO is essential for SHA because it provides important information not only for the local ground conditions, but relative to the seismogenic sources and past earthquakes as well, filling in possible gaps in SHA knowledge. For instance, DaLO could contribute to a better estimation of the maximum expected magnitude by using liquefaction-induced features (e.g., McCalpin, 1996).

Validation processes for both databases is based on different aspects. Regarding DaLO, validation can only be applied for the completeness of the database. Regarding GreDaSS, validation is not constrained only on the completeness, but it concerns the content in terms of seismotectonic parameters. Since many of the included seismogenic sources are purely based on geologic data, these cannot be validated *a priori* unless assuming the consensus of the scientific community and the independence and reliability of the various investigations and their results on which GreDaSS relies on.

In conclusion, the recently released databases of GreDaSS and DaLO, which represent the essence of Earthquake Geology in Greece, will certainly contribute to SHA analyses as stand-alone tools with an improved degree of confidence. The next challenge will be the future interconnection of both databases as well as any existing seismological ones. Therefore, the end-users will have the possibility to receive at once a complete perspective concerning most SHA-related issues, including not only the parameters of the seismogenic sources, but also the attributes of secondary effects as well as seismolgical information of the Aegean region.

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REFERENCES

Ambraseys N.; 2009: *Earthquakes in the Mediterranean and Middle East: a multidisciplinary study of seismicity up to 1900*. Cambridge University Press, Cambridge, UK, 968 pp.

Anderson J.G., Brune J.N., Anooshehpoor R. and Ni S.-D.; 2000: *New ground motion data and concepts in seismic hazard analysis*. Curr. Sci., **79**, 1278-1290.

Basili R., Valensise G., Vannoli P., Burrato P., Fracassi U., Mariano S., Tiberti M.M. and Boschi E.; 2008: *the database of individual seismogenic sources (DISS), version 3: summarizing 20 years of research on Italy's earthquake geology*. Tectonophys., **453**, 20-43.

Bommer J.J.; 2002: *Deterministic vs. probabilistic seismic hazard assessment: an exaggerated and obstructive dichotomy*. J. Earthquake Eng., **6**, 43-73.

Caputo R.; 2005: *Ground effects of large morphogenic earthquakes*. J. Geodyn., **40**, 113-118.

Caputo R., Piscitelli S., Oliveto A., Rizzo E. and Lapenna V.; 2003: *The use of electrical resistivity tomography in active tectonic. Examples from the Tyrnavos basin, Greece*. J. Geodyn., **36**, 19-35.

Caputo R., Chatzipetros A., Pavlides S. and Sboras S.; 2013: *The Greek Database of Seismogenic Sources (GreDaSS): state-of-the-art for northern Greece*. Ann. Geophys., **55**, 859-894, doi:10.4401/ag-5168.

FAUST; 2001: *FAUlts as a Seismological Tool, European Union Environment project*. Final Report, http://www.ingv.it/~roma/banche/catalogo_europeo/index.html (ENV4-CT97-0528).

Ganas A., Pavlides S.B., Sboras S., Valkaniotis S., Papaioannou S., Alexandris G.A., Plessa A. and Papadopoulos G.A.; 2004: *Active fault geometry and kinematics in Parnitha mountain, Attica, Greece*. J. Struct. Geol., **26**, 2103-2118.

Guidoboni E., Comastri A. and Traina G.; 1994: *Catalogue of ancient earthquakes in the Mediterranean area up to 10th century*. ING - SGA, Bologna, Italy, 504 pp.

Guzzetti F., Reichenbach P., Cardinali M., Galli M. and Ardizzone F.; 2005: *Probabilistic landslide hazard assessment at the basin scale*. Geomorphol., **72**, 272-299.

Idriss I.M. and Boulanger R.W.; 2008: *Soil liquefaction during earthquakes*. Earthquake Eng. Res. Inst., monograph series, MNO-12, 262 pp.

Jaiswal P. and van Westen C.; 2009: *Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds*. Geomorphol., **112**, 96-105.

Jaiswal P., van Westen C. and Jetten V.; 2010: *Quantitative landslide hazard assessment along a transportation corridor in southern India*. Eng. Geol., **116**, 236-250.

Jibson R.E.; 2007: *Regression models for estimating coseismic landslide displacement*. Eng. Geol., **91**, 209-218.

Karastathis V.K., Ganas A., Makris J., Papoulia J., Dafnis P., Gerolymatou E. and Drakatos G.; 2007: *The application of shallow seismic techniques in the study of active faults: the Atalanti normal fault, central Greece*. J. Appl. Geophys., **62**, 215-233.

Klügel J.-U.; 2008: *Seismic hazard analysis - Quo vadis ?* Earth Sci. Rev., **88**, 1-32.

Krinitzsky E.L.; 1995: *Deterministic versus probabilistic seismic hazard analysis for critical structures*. Eng. Geol., **40**, 1-7.

Le Pichon X., Lallemant S., Chamot-Rooke N., Lemeur D. and Pascal G.; 2002: *The Mediterranean ridge backstop and the Hellenic nappes*. Mar. Geol., **186**, 111-125.

McCalpin J.P. (ed); 1996: *Paleoseismology*. Academic Press, San Diego, CA, USA, 588 pp.

Mucciarelli M. and Albarello D.; 2012: *Comment on "Seismic Hazard Assessment (2003 - 2009) for the Italian Building Code" by M. Stucchi, C. Meletti, V. Montaldo, H. Crowley, G.M. Calvi and E. Boschi*. Bull. Seismol. Soc. Am., **102**, 2789-2792, doi:10.1785/0120120040.

Mucciarelli M., Albarello D. and D'Amico V.; 2008: *Comparison of probabilistic seismic hazard estimates in Italy*. Nat. Hazard Earth Syst. Sci., **7**, 273-278.

Newmark N.M.; 1965: *Effects of earthquake on dams and embankments*. Geotech., **15**, 139-160.

Oliveto A.N., Mucciarelli M. and Caputo R.; 2004: *HVSR prospections in multi-layered environments: an example from the Tyrnavos basin (Greece)*. J. Seismol., **8**, 395-406.

Papadimitriou P., Voulgaris N., Kassaras I., Kaviris G., Delibasis N. and Makropoulos K.; 2002: *The Mw = 6.0, 7 September 1999 Athens earthquake*. Nat. Hazards, **27**, 15-33.

Papaioannou C.A. and Papazachos B.C.; 2000: *Time-independent and time-dependent seismic hazard in Greece based on seismogenic sources*. Bull. Seismol. Soc. Am., **90**, 22-33.

Papathanassiou G. and Pavlides S.; 2011: *GIS-based database of historical liquefaction occurrences in the broader Aegean region, DALO v1.0*. Quat. Int., **242**, 115-125, doi:10.1016/j.quaint.2011.03.049.

Papathanassiou G., Pavlides S. and Ganas A.; 2005: *The 2003 Lefkada earthquake: field observations and preliminary microzonation map based on liquefaction potential index for the town of Lefkada*. Eng. Geol., **82**, 12-31.

Papathanassiou G., Valkaniotis S. and Pavlides S.; 2013: *Evaluation of the temporal probability of earthquake-induced landslides in the island of Lefkada, Greece*. In: Proc. 2nd World Landslide Forum, Roma, Italy, in press.

Papazachos B.C.; 1990: *Seismicity of the Aegean and surrounding area*. Tectonophys., **178**, 287-308.

Papazachos B.C. and Papazachou C.; 2003: *The earthquakes of Greece*. ZITI publications, Thessaloniki, Greece, 304 pp.

Papazachos B.C., Comninakis P.E., Karakaisis G.F., Karakostas B.G., Papaioannou C.A., Papazachos C.B. and Scordilis E.M.; 2000: *A catalogue of earthquakes in Greece and surrounding area for the period 550 B.C. - 1999*. Publ. Geophys. Laboratory, University of Thessaloniki, **1**, 1-333.

Papazachos B.C., Comninakis P.E., Scordilis E.M., Karakaisis G.F. and Papazachos C.B.; 2009: *A catalogue of earthquakes in the Mediterranean and surrounding area for the period 1901 - Sep 2009*. Publ. Geophys. Laboratory, University of Thessaloniki, http://geophysics.geo.auth.gr.

Pavlides S. and Caputo R.; 2004: *Magnitude versus faults' surface parameters: quantitative relationships from the Aegean*. Tectonophys., **380**, 159-188.

Pavlides S.B., Papadopoulos G. and Ganas A.; 2002: *The fault that caused the Athens September 1999 Ms = 5.9 earthquake: field observations*. Nat. Hazards, **27**, 61-84.

Pavlides S.B., Valkaniotis S. and Chatzipetros A.; 2007: *Seismically capable faults in Greece and their use in seismic hazard assessment*. In: Proc. 4th Int. Conf. Earthquake Geotech. Eng., Thessaloniki, Greece, paper n. 1609.

Rabaute A. and Chamot-Rooke N.; 2007: *Quantitative mapping of active mud volcanism at the western Mediterranean ridge-backstop contact*. Mar. Geophys. Res., **28**, 271-295.

Stucchi M., Meletti C., Montaldo V., Crowley H., Calvi G.M. and Boschi E.; 2012: *Reply to "Comment on ' Seismic Hazard Assessment (2003-2009) for the Italian Building Code" by M. Stucchi, C. Meletti, V. Montaldo, H. Crowley, G.M. Calvi and E. Boschi' by M. Mucciarelli and D. Albarello"*. Bull. Seismol. Soc. Am., **102**, 2793-2794, doi:10.1785/0120120190.

Valensise G. and Pantosti D. (eds); 2001: *Database of potential sources for earthquakes larger than M 5.5 in Italy*. Ann. Geofis., **44**, 797-807.

Voidomatis P.; 1989: *Some aspects of a seismotectonic synthesis in the north Aegean sea and surrounding area*. Boll. Geof. Teor. Appl., **31**, 49-61.

Wang Z.; 2011: *Seismic hazard assessment: issues and alternatives*. Pure Appl. Geophys., **168**, 11-25.

Wells D.L. and Coppersmith J.K.; 1994: *New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement*. Bull. Seismol. Soc. Am., **84**, 974-1002.

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