FIRST LEVEL SEISMIC MICROZONING OF SULMONA (CENTRAL ITALY): MAJOR RESULTS AND EVIDENCES OF 2D/3D AMPLIFICATION

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Introduction. The city of Sulmona (AQ, Italy) lies above a deep sediment-filled active tectonic basin, flanked by steep uplifted carbonate blocks. It is characterized by a series of complex geological, geomorphological and tectonic features which can determine important seismic amplifications due to the local stratigraphic effects, buried topography and to instability phenomena like those linked to active and capable normal faults and landslides. Here we show the results of the first level Seismic Microzoning (MS) and we discuss the possible implication for 2D or 3D amplification effects from earthquake records.

The first level of MS study in the Sulmona city represents the first step of a "pilot study" that the Abruzzo Region, referring to the OPCM 3907 and the LR n. 28 of the 11.08.2011, has committed to the Engineering and Geology Department (InGEO) of the University "G. d'Annunzio" of Chieti-Pescara in collaboration with the INGV (branch of Milan for the HVSR measurement and branch of Rome for the study of the historic seismicity), with the purpose of complete the MS third level of the Sulmona city.

The Sulmona basin is an intramontane depression developed with a NW-SE trend in the more external portion of the Abruzzi central Apennines. It extends with width between 4 and 7 km, for a length of 21 km, it is limited to the east by the Mt. Morrone active normal faults system (Vittori *et al.*, 1995; Miccadei *et al.*, 1999; Gori *et al.*, 2014 with references) and it is filled by a thick sequence of fluvio-lacustrine Quaternary continental deposits.

The available field geological-structural studies and few subsurface geophysical data (eg., Di Filippo e Miccadei, 1997) suggest a half-graben-like geometry of the basin with a wedge pattern of the some hundreds of meters thick infilling Quaternary deposits.

The late-Quaternary activity of the Mt. Morrone fault has been documented by several authors and, on the base of empiric criteria, its capability has been evaluated to produce a Mmax equal to 6.5-6.7 (eg., Barchi *et al.*, 2000; Pizzi *et al.*, 2002). Despite the seismic history of Sulmona is particularly rich of seismic events with effects above the damage threshold, there are no certain information about the activation of this fault in historic times. Also the earthquake of the third of November 1706, in fact, which produced an intensity (I) of 9-10 MCS in the area of Sulmona (Locati *et al.*, 2011), has been attributed, on the base of the damage distribution, to a different seismogenic source.

On the base of archeoseismological studies (Galadini and Galli, 2001; Ceccaroni *et al.*, 2009), instead, the major probability of the last activation of the Mt. Morrone fault could be attributed to a seismic event happened in the II century A.D., responsible of important collapses diffused in the Sulmona area, and that maybe could represents the most strong earthquake of the local seismic history. However, following this hypothesis we need to consider that about two thousand years of inactivity represent a long recurrence interval for typical Apennine normal fault, highlighting the high seismic hazard for the Mt. Morrone fault.

Moreover, the comparison between the seismic intensities of the Sulmona surrounding area with regard of several historical earthquakes (eg., 1349, 1456, 1706, 1915, 1933, 1984 and 2009) highlights that, in some cases, the city of Sulmona has suffered the most heavy damages

(DBMI11 database, http://emidius.mi.ingv.it/DBMI11/). This could suggest that, for this city, the consequences of an earthquake are also dependent from site effects.

The Geological-Technical Map and reconstruction of the subsurface model. The original geological survey provided a lithological and litho-technical characterization of the terrains exposed in the Sulmona area. Regarding the classification of the geological units, they have been divided into marine and continental units. The first commonly represent the geological bedrock units, the second include the Quaternary deposits with a minimum thickness of 3 m.

In particular, we have distinguished Meso-Cenozoic calcareous bedrock units, extensively outcropping along the basin sides. These rocks show middle to very thick strata and are generally strongly fractured giving rise to cataclastic zones along the Mt. Morrone fault zone.

The main Quaternary continental units can be grouped in lacustrine deposits, alluvial deposits (terraced and/or alluvial fan), slope deposits, eluvial-colluvial and landslide deposits. In particular, the stratigraphic succession of the Sulmona basin is made up of fine silty-clay and sandy-silt lacustrine sediments with local intercalations of gravel and conglomerate (*Lower to Middle Pleistocene*). Following the strong regional uplift and the consequent regressive erosion, which characterized the chain from the end of the early Pleistocene, the depositional conditions drastically changed leaving space to a gravelly sand, with silty clay intercalations, fluvial sedimentation. Important detrital supplies and alluvial fans have continuously influenced the sedimentation at the base of the slopes and also in the inner portion of the basin, with more or less intensive phases associated to climatic changes and to the tectonic activity during the Quaternary (e.g., Miccadei *et al.*, 1997 with references therein).

For the reconstruction of the geological and lithotechnical setting, field data have been compared and integrated with the available data from boreholes, well, Down-Holes (DH), Cross Holes (CH), SPT, SDMT and geophysical surveys and 42 new noise acquisitions specifically carried out for the MS project. A first analysis of the geological and lithothecnical setting was already carried out within the Region-sponsored Projects "*S.I.S.M.A.*" and "*Microzonazione sismica di secondo livello; indagini e risultati ai fini della progettazione esecutiva della Microzonazione sismica del centro abitato di Sulmona*". In these projects, developed between the 2006 and 2007, were involved the University "La Sapienza" of Rome (scient. resp. G. Scarascia Mugnozza), the Ingegneria Strutture, Acque e Terreno Department of L'Aquila University (scient. resp. G. Totani), the Regione Abruzzo (with E. D. Iannarelli) and G. Naso for the Italian Department of Civil Protection.

Through the boreholes it was possible to constrain, with an appropriate level of confidence, the base of the sandy-gravel deposits attributed to the "Terrazza Alta di Sulmona" (Fig. 1). It is worth noting that the different data coming from DH and CH seismic tests (in addition to the MASWs), generally show Vs values characterized by a clear velocity inversion at 20-30 m depth, and then in correspondence of the transition between the gravelly "Terrazza Alta di Sulmona" unit and the silty-clay lacustrine one.

The synthesis of the underground 2D model has been reconstructed through 11 geological-technical cross section, 9 of which performer in a NE-SW direction and two in a NNW-SSE direction. The NE-SW sections are about perpendicular to the main developing axis of the Sulmona basin, to the main river courses and corresponding terrace escarpments, and to the trace of the active and capable normal faults. The NNW-SSE sections show the relationships between the bedrock and the continental deposits and their probable geometry at depth, moving from the southern bound of the basin toward the depocentral area. Clearly, the correlation performed through the stratigraphic data of all the available boreholes has allowed to represent the lithological variations within every single recognized unit from the field survey and to extrapolate them, with good details, until 20-30 m at depth (mean boreholes depth). The exception is represented by some very deep wells, one of which reaching 435 m (Medibev well) (Fig. 1).

In general, we can recognize the presence of two macroareas, both in the surfaces and at

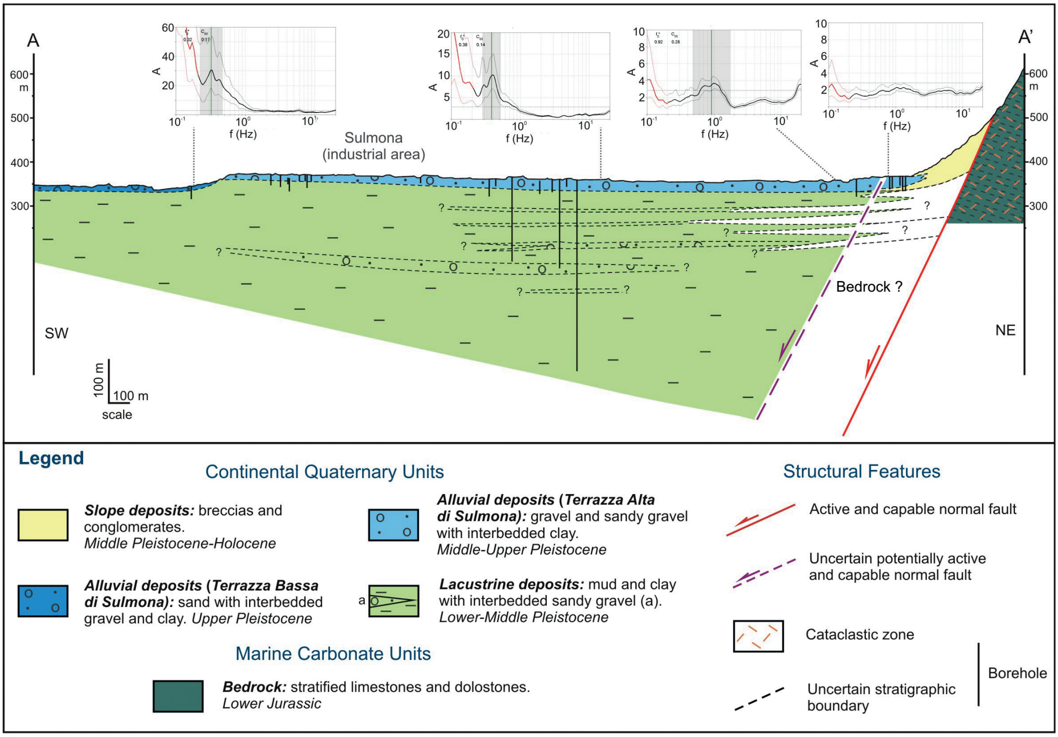


Fig. 1 – Geologic cross-section across the Sulmona tectonic basin. HVSR diagrams are also reported above the topography. See text for explanation. See Fig. 2 for cross-section location.

depth, that have different geological-technical characteristics and that correspond to the present-day areas of the fluvio-lacustrine plane and of the base of the slopes.

The first area corresponds mainly to the inner part of the basin and shows a depocenter deep more than 435 m and filled by a thick (≥ 400 m) fine lacustrine succession, on which lay sandy-gravel terraced alluvial deposits of the Middle-Upper Pleistocene (Terrazza Alta di Sulmona), about 30-40 m thick (Fig. 1), in turn cut and filled by younger alluvial deposits (Upper Pleistocene-Holocene) (Fig. 1).

The second macroarea, in proximity of the carbonate ridges at the border sides of the basin, shows a very different lithostratigraphic and morphological setting. Here the clastic supply from slope and alluvial fans has guided the sedimentation and controlled the complex lateral and vertical transitions with the fine lacustrine deposits within the basin. Fig. 1 schematizes the complex setting of the western slope of the Mt. Morrone. It is bounded by an important active and capable normal fault that determines the contact between the Mesozoic carbonate bedrock, strongly cataclastic, and the slope deposits passing laterally to the terraced alluvial deposits of the Middle-Upper Pleistocene. At the base of the slope, these deposits are probably displaced by an inner splay of the major boundary fault. The main uncertainties regard the area included between the two tectonic structures where the performed noise measurements do not show any frequency of amplification. This kind of response could be attributed either to the presence of the carbonate bedrock in the near surface (eg., downthrown fault block) or to a thick sequence of slope deposits, probably cemented, above the carbonate bedrock.

Considering that within the basin area the carbonate substratum has never been intercepted by any borehole, noise data provided useful constraints on the geometry between the continental succession and the bedrock within the basin. Noise measurements have been carried out in correspondence of 43 sites in the Sulmona basin, with the aim of evaluating their resonant

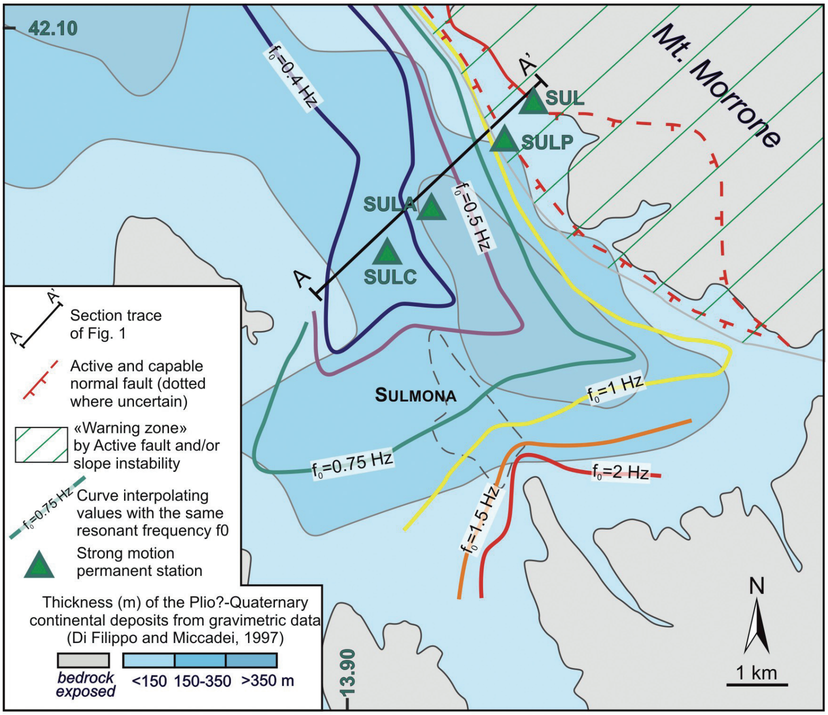


Fig. 2 – Thickness of the Plio-Quaternary continental deposits from gravimetric data (Di Filippo and Miccadei, 1997) and interpolated pattern of the resonant frequency f0, in Hz, obtained by noise measurements (this study). See text for explanation.

frequency (f0). The acquisition, with variable length between 30 and 45 minutes, was performed with a short period sensor (Lennartz LE-3D/5s (www.lennartz-electronic.de) coupled with a Reftek-130 datalogger (www.reftek.com). The continuous signal has been subdivided into 60 s windows and the Fourier spectrum of each window has been calculated considering 1640 frequencies equally spaced in logarithmic scale between 0.01 and 20 Hz. The spectrum has been smoothed using the algorithm proposed by Konno and Ohmachi (2006), fixing the b parameter to 40. The vector composition of the Fourier spectra of the two horizontal components has been subdivided by the Fourier spectrum of the vertical component as proposed by Nakamura (1989, 2000) and the mean and the standard deviation of the ratios have been calculated. In order to compare the noise data with the geological setting the obtained F0 values have been interpolated to reconstruct lines with same value of f0 (Fig. 2). A progressive decrease of the resonant frequency (from 2 Hz to 0.37 Hz) is observed from S to N, which indicates an increasing depth of the sediments from Sulmona to the north (Pratola Peligna). In parallel, the resonant frequencies are progressively increasing from the basin centre to the basin edges (see HVSR data in Fig 1). The peaks observed in correspondence of the resonant frequency are well identifiable in the central part of the basin, indicating a strong impedance contrast between sediment and bedrock. At the base of the Mt. Morrone slope, the H/V curve has very low amplitudes (about 2.7) and the peak corresponding to the resonant frequency is hardly identifiable.

Results of first level microzoning. The map of the homogeneous microzones in seismic perspective (MOPS) summarized the main results of the first level MS of Sulmona. This map, in fact, derives from the comparison of the geological, geothecnical and geophysical data and their integration with the values of the resonance frequencies obtained from the noise measurements. Considering that the urbanized areas and urban development lying almost completely above thick sequences of continental deposits (fluvial-lacustrine succession of the basin tectonic Sulmona) the MOPS are exclusively represented by “ Stable Zone Susceptible for Local Amplification”, as well as by the presence of “Unstable Zone”.

The comparative analysis between the lithostratigraphic data and those of the resonance frequencies (f0) allowed us to group the “stable zone susceptible for local amplification“in two Macrozones: 1) microzones susceptible for local amplification where f0 <1 Hz; 2) microzones susceptible for local amplification with f0 ≥ 1 Hz. Although this choice has led, almost, to a duplication of the number of micro-zones, it is justified by the fact that the areas with f0 ≥ 1 Hz have a greater engineering interest (phenomenon of double resonance). Despite this distinction has been made on point noise data and knowing that the behavior of seismic waves during an earthquake may be much more complex, we believe this solution provides a first broad grouping for the subsequent numerical modeling of micro-zones.

Further to the above lithostratigraphic and geometry complexity of the buried basin, the achievement of the level 3 of MS is necessary for the presence of different zones and types of instability observed in the Sulmona area.

They include the occurrence of active and capable faults along the slope of Mt. Morrone (Fig. 2), whose definition of the fault trace and expected earthquake parameters must be analyzed through detailed geological and geophysical studies and paleoseismological investigations. Problems of slope instability, due particularly to the phenomena of rock-fall from the very steep slope of the M. Morrone (Fig. 2), also emerged from studies of level 1, which require detailed surveys and geomechanical modeling. Moreover, areas susceptible to instability due to liquefaction and differential settlement have also been identified, respectively, in the recent fine alluvial sediment and in the center of Sulmona, rebuilt several times over a complex stratigraphy of superimposed Roman and medieval archaeological levels.

Hints for a 2D or 3D amplification effects from earthquake records. The Italian Department of civil protection has installed four stations of the permanent strong motion network to monitor the area of Sulmona (see Fig. 2).

Station SULA and SULC are installed in the centre of the plain, SULP in correspondence of a debris fan, while SUL is installed in correspondence of a rock outcrop. Three stations (SUL, SULC and SULA) have contemporarily recorded one seismic event occurred on 2013-02-16 at 21:16:09 GMT (Mw 4.9, Ml 4.8) at an epicentral distance of about 50 km.

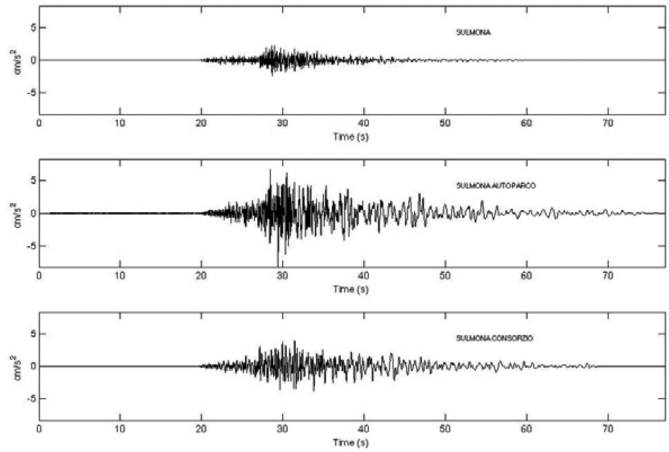
The acceleration, velocity and displacement records are obtained from the Italian accelerometric archive (itaca.mi.ingv.it) and are plotted in Figs. 3a to 3c.

As observed for other intramontane basins [Gubbio: Bindi *et al*. (2009); Norcia: Bindi *et al*. (2011)] there is a remarkable amplification of the ground motion in the centre of the basin, when compared to the rock outcrop, in terms of amplitude ground motion peaks (Tab. 1). In particular, Station SULA has recorded velocity and displacement peaks that are about 6 times the peaks recorded at the rock site SUL. Surface waves, that could be locally generated, are also observed in the records.

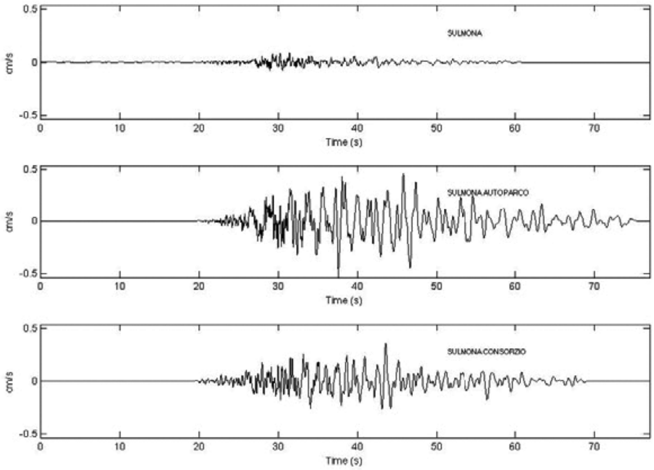
The characteristics of the ground motion recorded at the stations in the basin are hints for a 2D or 3D amplification effects, that should be evaluated after a monitoring of the plain with a seismometric array.

Tab. 1 - Peak ground acceleration, velocity and displacement (in bold the ratio between the peak values of soil sites, SULA and SULC, and the rock site (SUL)

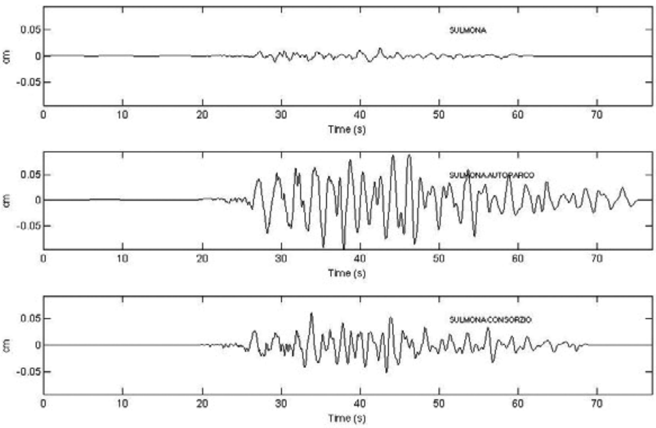
Station	PGA (cm/s2)	PGV (cm/s)	PGD (cm)
SUL	2.342	0.093	0.015
SULA	8.271 (3.53)	0.540 (5.80)	0.093 (6.20)
SULC	4.927 (2.10)	0.363 (3.90)	0.062 (4.13)



(a)



(b)



(c)

Fig. 3 – a) Acceleration; b) velocity; c) displacement recorded at the station Sulmona (SUL), Sulmona Autoparco (SULA) and Sulmona Consorzio (SULC).

References

Barchi M., Galadini F., Lavecchia G., Messina P., Michetti A.M., Peruzza L., Pizzi A., Tondi E. e Vittori E; 2000: *Sintesi delle Conoscenze sulle Faglie Attive in Italia Centrale: Parametrizzazione ai Fini della Caratterizzazione della Pericolosità Sismica*. CNR-Gruppo Nazionale per la Difesa dai Terremoti, Roma, p. 62.

Bindi D, D., S. Parolai, F. Cara, G. Di Giulio, G. Ferretti, L. Luzi, G. Monachesi, F. Pacor, and A. Rovelli; 2009: *Site Amplifications Observed in the Gubbio Basin, Central Italy: Hints for Lateral Propagation Effects,* Bulletin of the Seismological Society of America, 99(2A), 741–760, doi:10.1785/0120080238.

Bindi, D., L. Luzi, S. Parolai, D. Di Giacomo, and G. Monachesi; 2011: *Site effects observed in alluvial basins: the case of Norcia (Central Italy)*, Bull Earthquake Eng, 9(6), 1941–1959, doi:10.1007/s10518-011-9273-3.

Ceccaroni E., Ameri G., Gomez Capera A.A., Galadini F.; 2009: *The 2nd century AD earthquake in central Italy: archaeoseismological data and seismotectonic implications*. Natural Hazards, 50, 335-359.

Di Filippo M. e Miccadei E.;1997: *Studio gravimetrico della conca di Sulmona*. Il Quaternario, 10(2), 489-494.

Galadini F. e Galli P.; 2001: *Archaeoseismology in Italy: case studies and implications on long-term seismicity*. Journal of Earthquake Engineering, 5, 35-68.

Gori S., Falcucci E., Dramis F., Galadini F., Galli P., Giaccio B., Messina P., Pizzi A., Sposato A. e Cosentino D.; 2014: *Deep-seated gravitational slope deformation, large-scale rock failure, and active normal faulting along Mt. Morrone (Sulmona basin, Central Italy): Geomorphological and paleoseismological analyses*. Geomorphology, 208, 88-101.

Konno, K., and T. Ohmachi; 2006: *Ground-Motion Characteristics Estimated from Spectral Ratio between Horizontal and Vertical Components of Microtremor*, Bulletin of the Seismological Society of America, 88(1), 228–241.

Miccadei E., Barberi R. e Cavinato G. P.; 1999: *La geologia quaternaria della Conca di Sulmona (Abruzzo, Italia centrale)*. Geologica Romana, 34, 58-86

Nakamura, Y.; 2000; *Clear identification of fundamental idea of Nakamura's technique and its applications*, Proc. of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand.

Nakamura,Y. and Samizo M.; 1989: *Site Effect Evaluation of Surface Ground using Strong Motion Records* (in Japanese), Proc. 20th JSCE Earthquake Eng. Symposium, 133-136.

Pizzi A., Calamita F., Coltorti M. e Pieruccini P.; 2002: *Quaternary normal faults, intramontane basins and seismicity in the Umbria-Marche-Abruzzi Apennine Ridge (Italy): contribution of neotectonic analysis to seismic hazard assessment*. Boll. Soc. Geol. It., vol. spec. 1, 923-929.

SESAME; 2005: *Site Effects Assessment using Ambient Excitations*. European project (2005) Deliverable D23.12— Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measure- ments, processing and interpretation. http://www.sesame-fp5.obs.ujf-grenoble.fr.

Vittori E., Cavinato G.P. e Miccadei E.; 1995: *Active faulting along the northeastern edge of the Sulmona basin, Central Apennines, Italy,* In: L. Serva and D. B. Slemmons (eds), Perspectives in Paleoseismology, Ass. of Eng. Geologists 6, 83–100.