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GEOLOGICAL AND GEOTECHNICAL MODELS DEFINITION FOR 3rd LEVEL SEISMIC MICROZONATION STUDIES IN CENTRAL ITALY

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ABSTRACT

The 2016-2017 seismic events that struck central Italy led the Government to carry out a project to produce the third level Seismic Microzonation studies in 138 municipalities. These activities have involved many experts in different disciplines such as geology, geomorphology, geophysics, seismology and geotechnical engineering. This project represented the first opportunity to perform nationally coordinated third level Seismic Microzonation studies over a wide area in a quite short time (6 months). It provided the chance to improve methodological procedures, to test the reliability of methods and models for site response analyses and to produce a huge amount of validated data. This paper focuses on the contribution of geological disciplines and concerns: a) the definition of the main "morphostructural domains" of the Central-Northern Apennines; b) the creation of an archive of all the lithostratigraphic units occurring in the study area with their conversion into engineering-geological units and their distribution in the different morphostructural domains; c) the construction of the reference geological and geotechnical models, which are essential to classify the territory into seismically homogeneous microzones and to perform the successive 1D and 2D numerical analyses of the local site response. The geophysical dataset acquired for the study allowed a first statistical characterization of the Vs values typical of the engineering-geological units identified in this study. Some examples of the recurrent geological and geotechnical models are shown to explain the complexity and variety of the geological and geomorphological features of the investigated area and to highlight the different seismostratigraphic behaviour of rocks and cover terrains. The analysis of third level Seismic Microzonation data made it possible to identify recurrent subsoil models and to note the main stratigraphic and morphological control-factors of the ground motion modification in the different morphostructural domains.

Key words: seismic sequence, Seismic Microzonation studies, morphostructural domains, engineering-geological units, subsoil model.

1. INTRODUCTION

The seismic sequence that struck Central Italy from August 24th, 2016 to January 18th, 2017 was characterised by a long-term duration of the seismic events along with a remarkable displacement of the epicentres (Fig. 1). Many strong and consecutive events (see Chiaraluce et al. 2017 for details) affected very different geological contexts, straddling four Regions (Lazio, Umbria, Marche and Abruzzo) (Fig. 1), from the external sector of the Central-Northern Apennines, to the west, to the Periadriatic belt, to the east. The Central Italy earthquakes thus provided the opportunity to evaluate the distribution of ground motion not only according to the distance from the epicentres, but also in relation to the effect of local geological context, geomorphological features and subsoil setting of the different areas struck by the main shocks. The evaluation of local amplification or site effects for seismic risk mitigation is the focus of Seismic Microzonation (*MS* from the Italian acronym) studies that aim at identifying and mapping the local response of a given inhabited area in terms of ground shaking intensity and susceptibility to ground instabilities (Pagliaroli 2018, and bibliography therein). These studies represent an important tool in seismic risk reduction, management strategy and urban planning.

In Italy, according to the "Guidelines and criteria for Seismic Microzonation studies" (Working Group MS 2008), the *MS* comprises three distinct levels of detail from Level 1 to Level 3, with a change from qualitative to quantitative results (e.g. Albarello et al. 2015; Albarello 2017). For each level it is expected to produce a series of maps and reports. The first level (*MS1*) is propaedeutic and aims at defining the preliminary geological and geotechnical model of the study area based on existing geological data and surface geophysical surveys. This step is of basic importance for the subsequent analyses, since it also allows planning geophysical and geotechnical surveys aiming at quantitatively characterizing buried geometries and seismic properties of the geological bodies. In this level, the study area (typically a municipality) is subdivided in microareas (seismically homogeneous microzones – MOPS from the Italian acronym) each characterized by specific co-seismic effects (ground motion amplification, soil instabilities). The second level (*MS2*) provides a quantification of ground-motion amplification phenomena by the use of simplified approaches. The third level (*MS3*) provide an extensive numerical analysis of the seismic response (including 2D phenomena) and instability phenomena (seismically induced landslides and liquefaction effects), which requires, on its turn, laboratory tests on subsoil materials and borehole geophysical measurements. The *MS3* activities therefore consist of a complex multidisciplinary process, involving expertises in geology, geomorphology, applied seismology and geotechnical engineering, which aims at achieving the subdivision of the investigated areas in microzones with homogeneous site response, derived by numerical analyses based on a detailed subsoil mechanical characterization (Pagliaroli, 2018).

Despite the high seismic risk of this portion of the Central-Northern Apennines and the well documented seismicity, at the moment of the 2016-2017 seismic events, almost the whole territory affected by the earthquakes was not yet covered by a *MS3* study. For many municipalities only the first level seismic microzonation studies (*MS1*) were available, thus very poor of geotechnical and geophysical data. For this reason, the Italian scientific community, coordinated in the frame of the Center for Seismic Microzonation and its Application (*MSCenter,* see [*https*://www.centrodimicrozonazionesismica.it](https://www.centrodimicrozonazionesismica.it)), was entrusted by the Italian Government to manage the extensive seismic microzonation of the whole area struck by the 2016-2017 seismic sequence, in order to support reconstruction activities. It was one of the largest seismic microzonation project on the Italian territory. The studies were carried out in 138 municipalities (considered as "diffuse town", since they often include many hamlets) regrouped into six macroareas, namely Umbria, Marche1, Marche2, Marche3, Lazio and Abruzzo, following a territorial proximity criterion as shown in Fig. 2. For each macroarea a Territorial Operating Unit (UOT) was identified to coordinate the activities, constituted by Italian experts of the *MSCenter* coming from Governmental Offices, Universities and Research Institutes. Local professionals (geologists) were committed to carry out the *MS3* studies, following special indications for data acquisition and processing edited *ad hoc* by the *MSCenter* (Working Group CentroMS 2017), according to the national guidelines for *MS* studies (Working Group MS 2008; 2015). The supervision of the *MSCenter* UOT experts was aimed at obtaining homogeneous products, in full compliance with the guidelines, and to ensure that the work was completed on time.

The adopted *MS3* procedures included the following work steps: a) collection, validation and processing of existing geological-geomorphological, geotechnical and geophysical data; b) validation and processing of first level microzonation studies (*MS1*), if existing; c) planning of new surveys; d) acquisition of new data in the field (geological and geomorphological mapping, geophysical investigations, boreholes, down-hole tests, *in situ* and laboratory geotechnical tests); e) construction of subsoil model and reference cross-sections, including stratigraphy, thickness, geometries, geotechnical and geophysical properties; f) definition of the reference input motions; g) performing of numerical analyses (1D and 2D); h) drawing up of the maps at 1: 5.000 scale.

The products realized for each municipality are: 1) the Map of Investigations, in which the previous and the new field surveys are reported; 2) the Map of natural frequencies (F_0); 3) the Engineering-geological Map (from here in after *GT_Map*), with the related engineering-geological cross-sections; 4) the map of Seismically Homogeneous Microzones (from here in after *MOPS_Map*) divided in: a) *stable zones*, areas where no significant local effects are expected, b) *stable zone susceptible to local amplification*, areas where amplification of seismic motion is expected as a result of local lithostratigraphic and morphological setting, c) *attention zone for instabilities*, areas in which the seismic effects expected and predominant are ascribed to permanent land deformations; 5) three Seismic Microzonation Maps (*MS_Maps*), representing the amplification factors (FA) related to three different ranges of period intervals, calculated for each MOPS; 6) the explanatory *Report*.

The *MS3* studies started from the definition of the local "geological and geotechnical model" that summarizes the site-specific information on the lithostratigraphy, the subsoil geometry and the seismostratigraphy, aiming to differentiate the territory into seismically homogeneous microzones. Within each homogeneous microzone the ground motion modification was then evaluated by means of 1D and 2D numerical analyses as better described in the following.

The paper will focus on the process that led to the geological/geotechnical modelling in the 138 municipalities. The first step of this analysis is the preliminary conversion of the lithostratigraphic units into engineering-geological units (*gt_units* from the Italian acronym) and the successive definition of their 3D geometry, mostly depending on the tectonic and morphological evolution of each examined area. Starting from a brief description of the main morphostructural domains of the Central-Northern Apennines, this paper provides an archive of the main lithostratigraphic units, with their classification in terms of *gt_units* and their distribution and geometry in the different geological and morphostructural domains of the region. The archive is completed with the results of statistical analyses on some peculiar mechanical parameters related to the described *gt_units*. Finally, the paper illustrates the recurrent geological models, highlighting the main stratigraphic and morphological control-factors of the ground motion modifications in the different geological domains of the region.

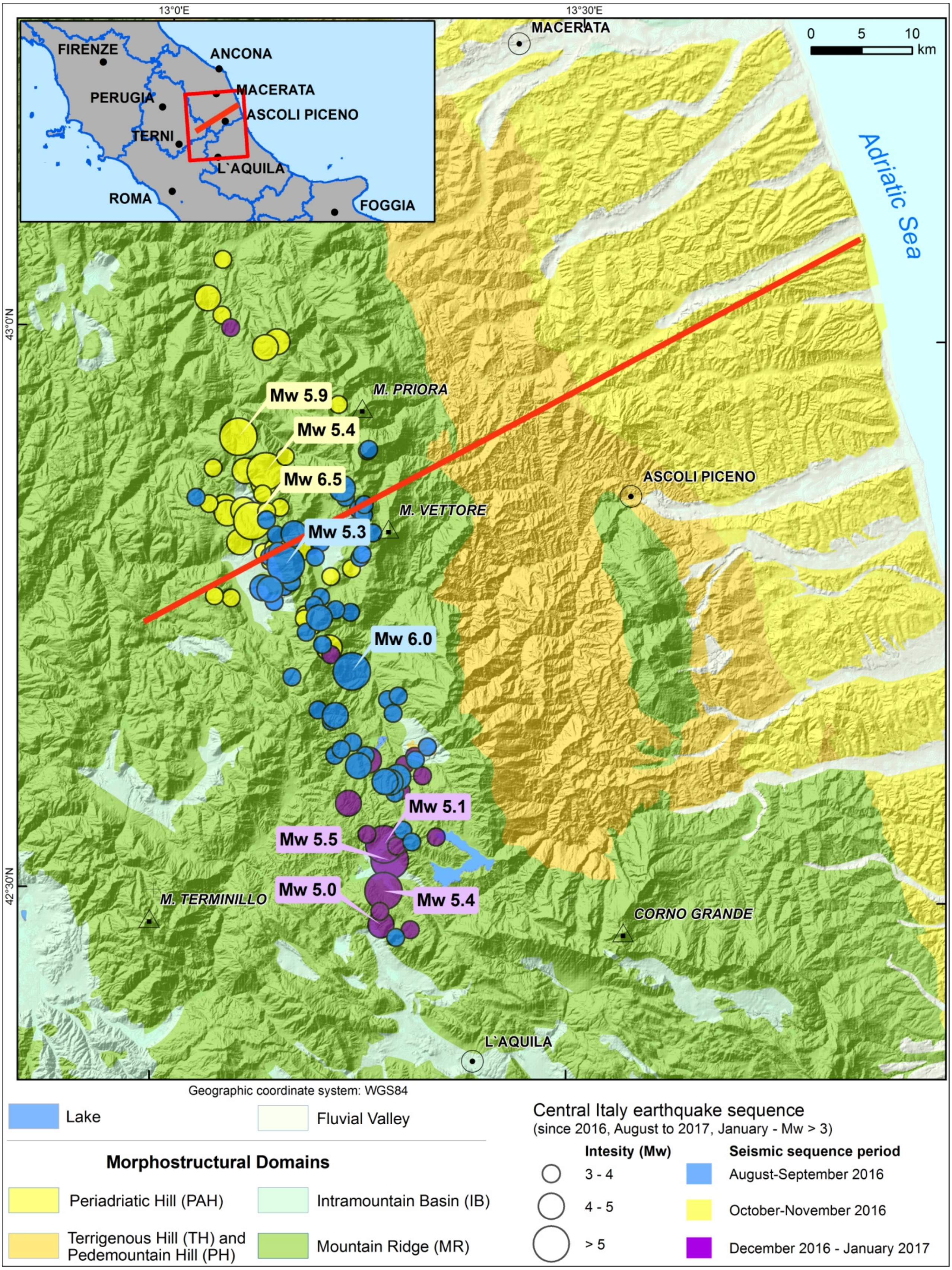

Fig. 1 - The main morphostructural domains of central Italy and the 2016-2017 earthquake sequence. The red line represents the trace of the cross section shown in Fig. 3.

2. REGIONAL GEOLOGICAL SETTING AND MORPHOSTRUCTURAL DOMAINS

The Central-Northern Apennines (Fig. 2) are a north-east verging fold-and-thrust belt, originated by the convergence and collision between the African (Adria-Apulia) and European plates (Boccaletti et al. 1990; Cavazza et al. 2004; Cosentino et al. 2010 and bibliography therein).

The region is dominated by arc-shaped thrust-ramps (Calamita and Deiana 1988; Pierantoni et al. 2013; Pizzi et al. 2017), affecting the Meso-Cenozoic carbonate units (the Umbria-Marche and the Lazio-Abruzzi successions; Fig. 2) that border the axial zone of the orogen, here designed as Mountain Range domain (Fig. 1). At the footwall of these overthrusts, the low lying sectors of the belt, here designed as Hill Range domain (Figs. 1, 2, 3), are mostly composed of the Messinian foredeep siliciclastic turbiditic deposits of the Laga Basin and minor basins (Centamore et al. 1991a). The Hill Range hosts N-S-trending anticlines, along which the Mesozoic carbonate bedrock underlying the Tertiary terrigenous units culminates (e.g. Gorzano, Acquasanta and Montagna dei Fiori anticlines; Ghisetti and Vezzani 1991; Centamore et al. 1991b) (Fig. 2). In the easternmost sectors of the Hill Range, the Upper Pliocene-Lower Pleistocene siliciclastic deposits of the Argille Azzure Fm (Bigi et al. 1997) unconformably overlie the Laga deposits. Since 2.1 My ago, the activation of normal faults affected the inner portions of the orogen leading to their fragmentation and to the formation of large intramountain basins, widespread in the central Apennines (Cosentino et al. 2017; Figs. 1, 2). Some of these faults are considered capable faults by several Authors (Nocentini et al. 2017, 2018; Civico et al. 2018; Villani et al. 2018).

This complex geological context has strongly influenced the geomorphological evolution of the studied area (Coltorti et al. 1996; Calamita et al. 1999) along with other factors such as the large pattern of outcropping lithotypes and the succession of Quaternary climatic events.

A morphostructural domain is therefore defined as the result of the combination between the geological context and the geomorphological evolution. Each morphostructural domain is characterised by distinctive structural setting, peculiar morphological features and by different types of rocks and cover terrains. The main morphostructural domains identified are two: the Mountain Range and the Hill Range. The Mountain Range is subdivided into Mountain Ridges (MR) and Intramountain Basins (IB); the Hill Range (HR) includes three distinct morphostructural domains: the Pedemountain Hill (PH), the Terrigenous Hill (TH) and the Periadriatic Hill (PAH), defined on the base of their lithological and geomorphological features (Fig. 3). The Pedemountain Hill and the adjacent Terrigenous Hill show the same bedrock units, consisting of deformed Tertiary substratum, but differ for the distinctive features of the covers terrain units. On the contrary, the Periadriatic Hill differs from the rest of the Hill Range for the nature of the bedrock units that are composed of the Plio-Quaternary marine deposits.

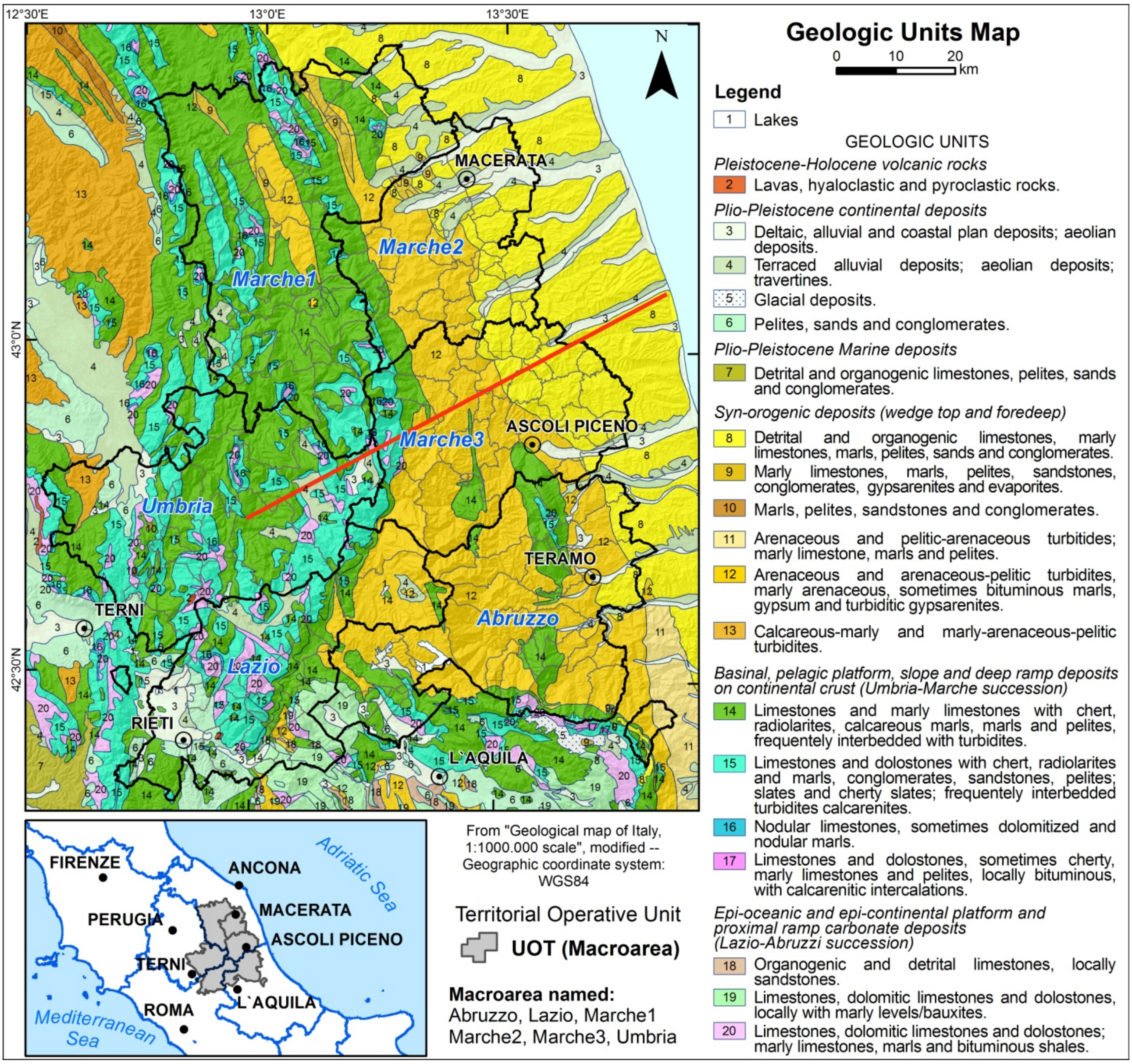

Fig. 2 - Simplified Geological Map of central Italy. After Compagnoni et al. (2011), modified.

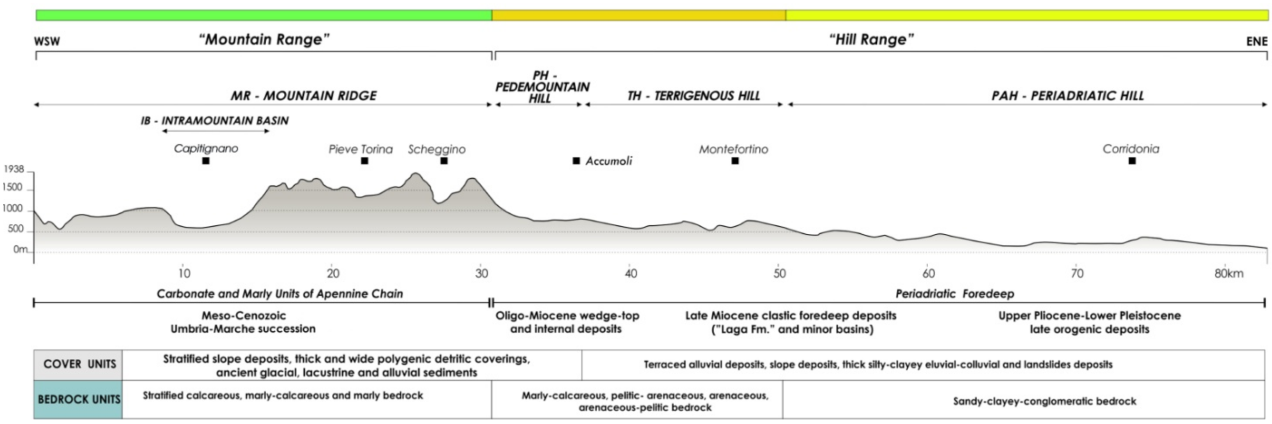

Fig. 3 – Cross-section (for the trace see Figs. 1 and 2) through the different morphostructural domains of central Italy. The selected *MS3* case studies are located along the cross-section line with the exception of Capitignano village, located in another Apennine sector, best representing the IB domain. Colour top bar legend: green, Mountain Range; orange, Pedemountain Hill and Terrigenous Hill; yellow, Periadriatic Hill.

The Mountain Range domain consists of calcareous-cherty-marly of the Umbria- Marche succession, calcareous-dolomitic rocks of the Lazio-Abruzzi succession, and turbiditic siliciclastic deposits of the western part of the Laga Basin. This domain is characterised by strong relief and steep (> 40°) to very steep slopes (70°-90°). The ridges are crossed by narrow transversal deep valleys and gorges. The gravitational landforms are represented by rock walls affected by fall and toppling landslide bodies located at the base of steep scarps, their geometry is controlled by the morphostructural setting of the rocky mass. In areas of high relief energy, rotational and translational landslides and debris flows are also frequent. Complex landslides also occur.

The Intramountain Basins are wide half-graben basins (few to several hundred of metres), caused by the extensional tectonic phase affecting the Meso-Cenozoic carbonate bedrock, filled with up to several hundreds of meters by fine-grained (clayey-silty) lacustrine deposits, interbedded with coarse-grained (sandy-gravely) alluvial and slope-debris deposits. Along the margins of the basins large alluvial fans, colluvial and slope deposits often crop out.

The tectonic boundary between the Mountain Range and the Hill Range is marked by an impressive morphological step on a regional scale, as the result of the different amount of relief energy combined with the selective erosion due to the different geo-mechanical behaviour of the rock units across the structure.

At the transition between the Mountain Range and the Hill Range, the Pedemountain Hill domain is characterised by valleys progressively widening towards the east and confined within steep slopes. In the Pedemountain Hill domain, the bedrock is made of alternation of contrasting lithotypes (limestones and marls; arenites and pelites) or cohesive lithologies. In the footwall of the main thrust front, constituted by the units of the Mountain Range, the bedrock of the Pedemountain Hill is usually strongly fractured and weathered. The cover terrains in the Pedemountain Hill show a very high variability due to their peculiar position at the transition between the two main topographic domains of the orogen. They usually consist of gravelly alluvial deposits, originated by the discharge from the adjacent calcareous valleys of the Mountain Range, progressively fining towards the east. Sandy-silty layers are interfingered within the coarse-grained levels at the confluence of the tributaries within the main rivers. Unsorted, loose to cemented, both massive and stratified, coarse-grained debris-slope deposits, showing variable amount of sandy-silty matrix, occur at the base of the steeper slopes. Colluvial sandy-silty deposits cumulated within small channels along the foot-slopes. The Pedemountain Hill is characterised by high energy relief (slopes >40°), due to the deep valley downcutting, that predisposes and triggers slope instability, with the formation of small to large landslides (flows and slides).

The central portion of the Hill Range corresponds to the Terrigenous Hill domain, which is characterized by larger valleys with gentler slopes (generally from 20° to 40°). The bedrock mostly consists of alternations of soft and hard terrigenous lithotypes, triggering the widespread formation of stepped slopes, due to the selective erosion. In some cases, tabular local relief is enhanced by the occurrence of hill-top cap of hard thick arenaceous rocks lying on softer pelitic-arenaceous succession. The lower gradient of slopes has favoured the development of surficial weathered rock horizons, locally exceeding the 10 m in thickness, that are particularly diffused where the bedrock is fractured. In the Terrigenous Hill domain, the cover terrains mainly consist of unsorted, coarse- to fine-grained alluvial and alluvial fan valley filling deposits, progressively thinning and fining to the east, passing from the Pedemountain Hill domain to the most external Periadriatic Hill domain. Eluvial and colluvial sandy-silty deposits cover large portions of the slopes, where widespread gravity instabilities such as mud- and earthflows and rotational slides are also frequent. Local rockfalls affect the steeper selective erosion escarpments.

The Periadriatic Hill shows a more gentle morphology, which gradually decreases toward the coast with elevations ranging from 600m to west to about 200 m to the east, with gentle slopes (10°-20°) and valleys becoming even larger. The occurrence of alternated softer pelitic-arenaceous or pelitic and harder arenaceous-conglomeratic rocks lead to the formation of stepped slopes and generates locally tabular reliefs, depending on the dip of the strata. The bedrock is mostly weathered to a depth exceeding 10 m, and it is also fractured in correspondence of hard lithotypes. The cover terrains consist of alluvial deposits similar to those of the adjacent domain, with prevalent fine-grained horizons and thinner gravelly blankets. Flights of wide hanging gravelly dominated alluvial terraces rest at the top of the hill and at several altitudes along the flanks of valleys. Sandy-silty-clay colluvial deposits are widely distributed along the slope. The gravitational landforms are mainly represented by earth and mud flows. Solifluction and rare rotational slides also occur. Rockfalls locally affect the steeper selective erosion escarpments.

3. THE ARCHIVE OF THE ENGINEERING-GEOLOGICAL UNITS OF CENTRAL-NORTHERN APENNINES

The *MS3* studies are based on the correct identification of the engineering-geological, geomorphological and geophysical setting, which is essential for the construction of the subsoil model to be adopted for the numerical simulations. The achievement of this goal requires the production of a very detailed Engineering-geological Map **(***GT_Map*), with the related cross-sections. These are the preparatory tools to obtain the boundaries of the sismically homogeneous microzones of the *MOPS_Map* from which the final parameterized Seismic Microzones (*MS3_Map*), each showing peculiar resonance frequency and amplification factor, derive.

A *GT_Map* represents a synthesis of available data (official Geological and Geomorphological Maps; borehole logs; geophysical investigations; remote sensing images; official Hydrogeological Hazard and Risk Maps or database for landslide and flooding, etc.) and data derived from new field activities. The *GT_Map* derives from the Geological-Geomorphological Map by commuting the lithostratigraphic units (*gg_units*) into engineering-geological units (*gt_units*). The construction of a *GT_Map*, thus, needs the availability of detailed geological and geomorphological maps (1: 5.000 scale), mainly aimed at: 1) the definition of the lithostratigraphy, attitude and structural setting of the bedrock units; 2) the accurate reconstruction of the buried geometry of the interface between bedrock and cover terrains units; 3) the accurate description of the cover terrains, in terms of number of strata, texture, depositional environment and geometry.

According to the Guidelines and criteria for *MS* studies (Working Group MS 2008; 2015), the lithostratigraphic units can be assigned to distinct *gt_units* that are grouped in two categories, the “Cover terrains” units and the “Bedrock” units (Tabs. 1, 2), also depending on their age, features and position. The mechanical properties of the lithotypes are defined on the basis of field investigation, laboratory data, data from nearby areas on the same cover deposit/rock and bibliographic data correlating the lithostratigraphic characteristics of the terrains with the geotechnical parameters (Rollins et al. 1998; Agencies of the Department of the Defense 2006). The “Bedrock” units group all the *gt_units* deriving from the lithostratigraphic units of the geological substratum. They correspond to the “Seismic bedrock” if transmit the shear waves at velocity Vs>800 m/s. Where shallower portions of the geological substratum with Vs<800m/s occur, they form the “geological bedrock”, potentially responsible, as well as the overlying covers, for modifications of the ground motion.

The lithotypes of the bedrock are classified (Tab. 1) on the base of lithostratigraphic criteria, structural features and setting, facies and sedimentological analyses. The rock mass structural analysis is also necessary to evaluate the jointing degree of bedrock units to assign the correct engineering-geological unit, especially where the jointing is widespread and pervasive, due to the intense tectonic deformation of the region. Such a jointing also predisposes the weathering of the outcropping rock masses, thus implying that the same formation constitutes a seismic bedrock (Vs ⩾

800 m/s) if intact and a geological bedrock (Vs < 800 m/s) if very weathered/fractured. In central Italy, the bedrock may show significant jointing and weathering at varying depths (from 5 to about 20m), depending on the different lithotypes. For instance, the marly formations (e.g. some parts of the Marne a Fucoidi Fm and Scaglia Cinerea Fm) usually display a thicker level of altered rock than the more calcareous formations (e.g. Maiolica Fm). For the purpose of the *MS3* studies, the presence of a weathered/fractured in the upper portion of the bedrock is relevant as it changes considerably the geotechnical parameter (e.g. Elastic Modules, shear strength as cohesion and angle of shear resistance) at specific sites.

BEDROCK									
gg_unit acronym	**gg_unit name**	**Geological domain**	**gt_unit**	**MD**	**gg_unit acronym**	**gg_unit**	**Geological domain**	**gt_unit**	**MD**
MAP	MARNE A PTEROPODI	Umbria-Marche succession	*ALS, SFALS*	MR	**UAP**	UPPER MIOCENE TURBIDITIC UNIT	Minor Miocene Foredeep Basin	*ALS, SFALS*	MR
UAM	MARLY CLAYEY UNIT	Umbria-Marche succession	*ALS, COS, SFALS*	MR	**CEN_1**	CELLINO FM - MASSERIA DI FERMO MBR	Pliocene Foredeep Basin	*COS, SFALS*	PAH
SPT	SPONGOLITIC UNIT	Umbria-Marche succession	*LPS, SFLPS*	MR	**MVO**	MARNE DEL VOMANO	Pliocene Wedge-Top	*ALS, SFALS*	PAH
CRR	MARNE CON CERROGNA	Umbria-Marche succession	*LPS, SFALS*	MR	**FAA**	ARGILLE AZZURRE	WedgeTop/Foredeep Basin	*CO, GRS, COS, ALS, SFGRS, SFCOS, SFALS*	PAH
CRR_a	marly-calcarenitic lithofacies of CRR	Umbria-Marche succession	*ALS, SFALS*	MR	**FAA_c**	arenaceous lithofacies of FAA	WedgeTop/Foredeep Basin	*GRS*	PAH
CRR_b	calcarenitic-calciruditic lithofacies of CRR	Umbria-Marche succession	*ALS*	MR	**FAA_d**	arenaceous-pelitic lithofacies of FAA	WedgeTop/Foredeep Basin	*ALS*	PAH
SCH	SCHLIER	Umbria-Marche succession	*ALS, SFALS*	MR	**FAA_e**	pelitic-arenaceous lithofacies of FAA	WedgeTop/Foredeep Basin	*COS*	PAH
BIS	BISCIARO	Umbria-Marche succession	*COS, ALS, SFALS*	MR	**FAA_f**	pelitic lithofacies of FAA	WedgeTop/Foredeep Basin	*COS*	PAH
SCZ	SCAGLIA DETRITICA	Umbria-Marche succession	*LPS*	MR	**FAA_2**	BORELLO SANDSTONES MBR	WedgeTop/Foredeep Basin	*ALS*	PAH
SCC	SCAGLIA CINEREA	Umbria-Marche succession	*LPS, ALS, SFLPS, SFALS*	MR	**FAA_{2b}**	arenaceous-congomeratic lithofacies of FAA_2	WedgeTop/Foredeep Basin	*GRS*	PAH
VAS	SCAGLIA VARIEGATA	Umbria-Marche succession	*LPS, ALS, SFLPS, SFALS*	MR	**FAA_{3c}**	SPUNGONE MBR - arenaceous lithofacies	WedgeTop/Foredeep Basin	*GRS, SFGRS*	PAH

SAA_3	UPPER MBR of SAA	Umbria-Marche succession	*LPS, ALS*	MR	**FAA_{3d}**	SPUNGONE MBR - arenaceous-pelitic lithofacies	WedgeTop/Foredeep Basin	*ALS*	PAH
SAA_2	MIDDLE MBR of SAA	Umbria-Marche succession	*ALS*	MR	**FAA_4**	MONTE DELL'ASCENSIONE MBR	WedgeTop/Foredeep Basin	*COS*	PAH
SAA_1	LOWER MBR of SAA	Umbria-Marche succession	*LPS*	MR	**FAA_{4b}**	arenaceous-conglomeratic lithofacies of FAA_4	WedgeTop/Foredeep Basin	*GRS*	PAH
SAA	SCAGLIA ROSSA	Umbria-Marche succession	*LPS, ALS, SFLPS, SFALS*	MR	**FAA_{4c}**	arenaceous lithofacies of FAA_4	WedgeTop/Foredeep Basin	*GRS*	PAH
SBI_2	UPPER MBR of SBI	Umbria-Marche succession	*LPS*	MR	**FAA_{4d}**	arenaceous-pelitic lithofacies of FAA_4	WedgeTop/Foredeep Basin	*ALS*	PAH
SBI_1	LOWER MBR of SBI	Umbria-Marche succession	*LPS, ALS*	MR	**FAA_{4e}**	pelitic-arenaceous lithofacies of FAA_4	WedgeTop/Foredeep Basin	*COS, ALS*	PAH
SBI	SCAGLIA BIANCA	Umbria-Marche succession	*LPS, ALS, SFLPS*	MR	**FAA_{4f}**	pelitic lithofacies of FAA_4	WedgeTop/Foredeep Basin	*COS, SFCOS*	PAH
FUC	MARNE A FUCOIDI	Umbria-Marche succession	*LPS, COS, ALS, SFLPS, SFALS, SFCOS*	MR	**FAA_5**	OFFIDA MBR	WedgeTop/Foredeep Basin	*LPS, COS, SFLPS*	PAH
MAI	MAIOLICA	Umbria-Marche succession	*LPS, SFLPS*	MR	**FAA_{5c}**	arenaceous lithofacies of FAA_5	WedgeTop/Foredeep Basin	*GRS, ALS, SFALS*	PAH
CDU	CALCARI DIASPRIGNI DETRITICI	Umbria-Marche succession	*LPS, SFLPS*	MR	**FAA_{5b}**	arenaceous-conglomeratic lithofacies of FAA_5	WedgeTop/Foredeep Basin	*GRS*	PAH
CDI_2	SACCOCOMA and APTICI MBR of CDI	Umbria-Marche succession	*SFALS*	MR	**FAA_{5d}**	arenaceous-pelitic lithofacies of FAA_5	WedgeTop/Foredeep Basin	*ALS, SFALS*	PAH
CDI	CALCARI DIASPRIGNI	Umbria-Marche succession	*LPS*	MR	**FAA_{5e}**	pelitic-arenaceous lithofacies of FAA_5	WedgeTop/Foredeep Basin	*COS, ALS, SFALS*	PAH
DPO	CALCARI DETRITICI A POSIDONIA	Umbria-Marche succession	*LPS, SFLPS*	MR	**FAA_{5f}**	pelitic lithofacies of FAA_5	WedgeTop/Foredeep Basin	*COS*	PAH
POD	CALCARI E MARNE A POSIDONIA	Umbria-Marche succession	*LPS, SFLPS*	MR	**LAG**	LAGA FM	Foredeep Basin	*GRS, ALS, SFALS*	TH
RSN	MARNE di MONTE SERRONE	Umbria-Marche succession	*LPS, COS, ALS, SFLPS*	MR	**LAG_{1c}**	PRE-EVAPORITIC MBR - arenaceous lithofacies	Foredeep Basin	*LP, LPS, SFLP, SFLPS*	TH
RSA	ROSSO AMMONITICO	Umbria-Marche succession	*LPS, SFALS*	MR	**LAG_{1d}**	PRE-EVAPORITIC MBR - arenaceous-pelitic lithofacies	Foredeep Basin	*ALS, SFALS*	TH
COK	CORNIOLA DETRITICA	Umbria-Marche succession	*LPS, SFLPS*	MR	**LAG_{1e}**	PRE-EVAPORITIC MBR - pelitic-arenaceous	Foredeep Basin	*ALS*	TH

						lithofacies			
COI	CORNIOLA	Umbria-Marche succession	*LPS, SFLPS*	MR	**LAG_2**	EVAPORITIC MBR	Foredeep Basin	*LPS, ALS*	TH
MAS	CALCAR MASSICCIO	Umbria-Marche succession	*LP, LPS, SFLP, SFLPS*	MR	**LAG_{2c}**	arenaceous lithofacies of LAG_{2c}	Foredeep Basin	*ALS, SFLPS*	TH
	L-A CARBONATE PLATFORM UNITS	Lazio-Abruzzi succession	*LPS*	MR	**LAG_{3b}**	POST-EVAPOTITIC MBR - arenaceous-pelitic lithofacies	Foredeep Basin	*ALS, SFALS*	TH
CBZ	CALCARI A BRIOZOI E LITOTAMNI	Lazio-Abruzzi succession	*LPS*	MR	**LAG_{3d}**	POST-EVAPOTITIC MBR - arenaceous-pelitic lithofacies	Foredeep Basin	*ALS, SFALS*	TH
RDT	CALCARI A RADIOLITIDI	Lazio-Abruzzi succession	*LPS*	MR	**LAG_{3e}**	POST-EVAPOTITIC MBR - pelitic-arenaceous lithofacies	Foredeep Basin	*ALS, SFALS*	TH
FCO	COLOMBACCI FM	Minor WedgeTop/ Foredeep Basin	*LPS, ALS, SFLPS, SFALS*	TH	**LAG_{4b}**	CAMPOTOSTO MBR – arenaceous-pelitic II lithofacies	Foredeep Basin	*ALS, SFALS*	TH
FCO_c	arenaceous lithofacies of FCO	Minor WedgeTop/ Foredeep Basin	*LPS, GRS,*	TH	**LAG_{4c}**	CAMPOTOSTO MBR – arenaceous lithofacies	Foredeep Basin	*ALS, SFALS*	TH
FCO_d	arenaceous-pelitic lithofacies of FCO	Minor WedgeTop/ Foredeep Basin	*GRS, ALS, SFALS*	TH	**LAG_{4d}**	CAMPOTOSTO MBR – arenaceous-pelitic I lithofacies	Foredeep Basin	*ALS, SFALS*	TH
FCO_e	pelitic - arenaceous lithofacies of FCO	Minor WedgeTop/ Foredeep Basin	*COS, ALS, SFALS*	TH	**LAG_{4e}**	CAMPOTOSTO MBR – pelitic - arenaceous lithofacies	Foredeep Basin	*ALS, SFALS*	TH
FCI_b	CAMERINO FM – arenaceous-conglomeratic lithofacies	Minor WedgeTop/ Foredeep Basin	*LPS*	TH	**LAG_{5b}**	GYPSUM-ARENITIC MBR – arenaceous-pelitic II lithofacies	Foredeep Basin	*ALS*	TH
FCI_c	CAMERINO FM– Arenaceous lithofacies	Minor WedgeTop/ Foredeep Basin	*LPS*	TH	**LAG_{5e}**	GYPSUM-ARENITIC MBR – pelitic - arenaceous litofacies	Foredeep Basin	*ALS*	TH
FCI_d	CAMERINO FM – arenaceous-pelitic lithofacies	Minor WedgeTop/ Foredeep Basin	*ALS*	TH	**LAG_{6a}**	TERAMO MBR – pelitic-arenaceous lithofacies	Foredeep Basin	*ALS, SFALS*	TH
FCI_e	CAMERINO FM – pelitic-arenaceous lithofacies	Minor WedgeTop/ Foredeep Basin	*COS*	TH	**LAG_{6c}**	TERAMO MBR – volcaniclastic pelitic-arenaceous lithofacies	Foredeep Basin	*ALS, SFALS*	TH
FCI_f	CAMERINO FM –	Minor WedgeTop/	*COS*	TH	**f_1**	calcareous tufa	Continental Deposits	*LP, LPS,*	TH

	pelitic lithofacies	Foredeep Basin						*SFGR, SFLPS*	
FSD	SAN DONATO FM.	Minor WedgeTop/ Foredeep Basin	*ALS*	TH		ancient alluvial deposits	Continental Deposits	*CO, AL, GRS, SFAL, SFGRS*	IB, TH
GES	GESSOSO SOLFIFERA FM	Minor WedgeTop/ Foredeep Basin	*ALS, SFALS*	TH		ancient lacustrine deposits	Continental Deposits	*CO, AL, GRS, SFAL, SFGRS*	IB, TH

Tab. 1 - Correlation among *gg_unit* acronym (refers to the legend of Italian Official Geological Cartography), lithostratigraphic unit (*gg_unit*), Geological domain, engineering-geological unit (*gt_unit)* and Morphostructural Domain (MD) of the bedrock formations occurring in the studied area. List of the *gt_unit* acronym with their descriptions: *LP*, lapideous; *GR*, grainy cemented; *CO*, cohesive overconsolidated; *AL*, alternations of contrasting lithotypes; *LPS*, lapideous stratified; *GRS*, grainy cemented stratified; *COS*, cohesive overconsolidated, stratified; *ALS*, alternations of contrasting lithotypes, stratified; *SFLP*, lapideous, fractured/weathered; *SFGR*, grainy cemented, fractured/weathered; *SFCO*, cohesive overconsolidated, fractured/weathered; *SFAL*, alternations of contrasting lithotypes, fractured/weathered; *SFLPS*, lapideous stratified, fractured/weathered; *SFGRS*, stratified grainy cemented, fractured/weathered; *SFCOS*, cohesive overconsolidated, stratified, fractured/weathered; *SFALS*, alternations of contrasting lithotypes, stratified, fractured/weathered.

The formations of Umbria-Marche and Lazio-Abruzzi successions (Tab. 1), cropping out in the Mountain Range and in the adjacent low-lying Pedemountain Hill domains, are part of the lapideous (*LP*), lapideous stratified (*LPS*) or alternations of contrasting stratified (i.e. limestones and marls) lithotypes (*ALS*) *gt_units*. The bedrock is frequently fractured, due to the diffuse tectonic deformation and, at places, it is physically weathered. In this case, the code *SF* evidences the fractured/weathered state of the lithotypes (e.g. *SFLP*, *SFLPS* and *SFALS*). The lithostratigraphy of the Mountain Range and of the Pedemountain Hill domains also includes bedrock units (e.g. UAM, BIS, FUC, RSN in Tab. 1) classified, in some cases, as stratified cohesive overconsolidated (*COS*) *gt_unit*. However, given the considerable extension and geological complexity of the area struck by the seismic sequence, the same bedrock formations change their features throughout the outcropping area, so they were sometimes assigned to different *gt_units* according to the site-specific lithological attributes.

Miocene and Pliocene-Lower Pleistocene units, forming the Hill Range domain (Tab. 1), show a large number of lithofacies that correspond to different *gt_units* listed in the Guidelines and criteria for *MS* studies (Working Group MS 2008; 2015). They range from cohesive overconsolidated (*CO* or *COS* if stratified; *SFCO* or *SFCOS* if fractured/weathered) to lapideous stratified (*LPS*; *SFLPS* if fractured/weathered), and alternation of stratified litofacies (*ALS*; *SFALS* if fractured/weathered). The arenaceous and conglomerate lithofacies of these formations correspond to the grainy cemented deposits (*GR* or *GRS* if stratified; *SFGR* or *SFGRS* if fractured/weathered) or, rarely, to lapideous stratified (*LPS* or *SFLPS*, if fractured/weathered).

On the other hand, the geotechnical characterization and classification of the cover terrains requires an accurate field analysis with the description of the lithostratigraphic features, depositional environment, grain-size, degree of cementation, plasticity, water content of these deposits directly in the field. The field data must be compared with the results of the geophysical investigations to better constrain the thickness of cover terrains, where no outcrop or borehole data are available.

The attribution of the cover terrains to the different *gt_units* is sometimes problematic, due to the heterogeneity of the deposits, which display frequent and irregular vertical and lateral facies changes. This variability, common in some Quaternary continental deposits, makes the attribution of these units to a single *gt_unit* someway approximate and inadequate to actually represent their very variable expected geophysical behaviour. It is thus recommendable to combine the classification of the cover terrains with an accurate description of the variability in their physical parameters, primarily the measured velocity of the shear-waves (Vs) (see next paragraph). These units include a large number of lithotypes: blocks, gravels, sands, silts, conglomerates, sandstones and calcareous tufa, corresponding to different *gt_units*, depending on the depositional environment. The use of the codes of the cover terrains units is intended exclusively for loose or weakly cemented sediments (for their description see Tab. 2). As consequence, several rock units, although continental in origin, are to be incorporated within the geological bedrock, as they consist of lapideous or well cemented layers, such as the case of the ancient lacustrine and alluvial deposits (classifiable as *ALS* or *GRS*) and continental calcareous tufa (classifiable as *LPS* or *GRS*).

COVER TERRAINS			
gt_unit	**Description**	**gg_unit**	**Depositional environment**
RI	Terrains containing remains of human activity	anthropic deposits	zz
GW	Well sorted gravels, mixed gravels and sands	slope deposits, landslide deposits, alluvial deposits, terraced alluvial deposits, calcareous tufa, lacustrine deposits	fd, fg, cd, tf, cc, es, lc, in, pi, ca
GP	Not sorted gravels, mixed gravels and sands	slope deposits, alluvial deposits, terraced alluvial deposits, lacustrine deposits	fd, ca, es, cd, lc, pi, tf, cz
GM	Silty gravels, mixed gravels, sands and silts	eluvial and colluvial deposits, slope deposits, alluvial deposits, terraced alluvial deposits	ca, cz, ec, cd, fg, fd, tf, es, in, pi, lc, pd, zz
GC	Clayey gravels, mixed gravels, sands and clays	eluvial and colluvial deposits, slope deposits, alluvial deposits, terraced alluvial deposits, lacustrine deposits	ec, fd, tf, ca, cd, lc, in, pi
SW	Well sorted sands, mixed sands and gravels	eluvial and colluvial deposits, terraced alluvial deposits, slope deposits, lacustrine deposits	ec, tf, td, lc
SP	Not well sorted sands	-	-
SM	Silty sands, mixed sands and silts	eluvial and colluvial deposits, slope deposits, alluvial deposits, terraced alluvial deposits, lacustrine deposits, marsh deposits, calcareous tufa, landslide deposits	ec, tf, lc, cc, cz, es, fd, pd, in, ca, pi, zz
SC	Clayey sands, mixed sands and clays	eluvial and colluvial deposits, slope deposits, alluvial deposits	es, ec, cd, in
OL	Organic silts, low plasticity organic silty-clays	eluvial and colluvial deposits, alluvial deposits, lacustrine deposits, marsh deposits	ec, lc
OH	Middle plasticity organic clays, organic silts	eluvial and colluvial deposits, alluvial deposits, lacustrine deposits, marsh deposits	ec, lc
MH	Inorganic silts, fine sands, diatomic silts	eluvial and colluvial deposits, alluvial deposits, lacustrine deposits, marsh deposits	lc, ec
ML	Inorganic silts, fine silty-clayey sands, low plasticity clayey silts	eluvial and colluvial deposits, slope deposits, alluvial deposits, terraced alluvial deposits, lacustrine deposits, marsh deposits	ca, ec, fd, tf, lc, pi
CL	Middle-low plasticity inorganic clays, gravel-sandy clays, silty clays	eluvial and colluvial deposits, alluvial deposits, lacustrine deposits, marsh deposits	ec, cd, lc, in

Tab. 2 - Correlation between *gt_units* and lithostratigraphic units (*gg_units*) of the cover terrains occurring in the studied area. Depositional environment typologies: fd - scree slope; fg - alluvial-glacial deposit; ec - eluvial-colluvial; cd - debris cone; ca - alluvial fan; cc - calcareous crust; pa - palustrine; cz - alluvial cone; tf - alluvial terrace; es - floodplain; lc - lacustrine; in - intramountain basin; pi - alluvial plain; pd - foothills flat; zz - other environment.

For the cover terrains classification, the same code as in the ASTM *Unified Soil Classification System* (2017) is adopted, consisting of the combination of two capital letters, referring to the dominant lithology and/or some specific characteristic of the sediment. The *MS* guidelines also require the classification of the cover terrains according to their depositional environment, by use a second code consisting of two lowercase letters. The Tab. 2 shows the description of the *gt_units* for the cover terrains occurring in the studied area and their relationship with the different typologies of sediment (*gg_unit* column) and depositional environment. It is clear that there is no direct correlation among the *gt_units,* the specific typologies of sediments (*gg_units*) and the depositional environments. The *gt_units*, with rare exceptions, may in fact include several types of sediments related to various depositional environments. This different information are however essential for the subsoil model reconstruction.

The anthropogenic deposits are classified as *RI*. In few cases a considerable amount of artificial, anthropic deposits were encountered; they derive from the rubble coming from buildings which were demolished after a previous earthquake. For example, the area SW of the Norcia town is built on top of a series of ruins deposits due to the 1979 earthquake which were accumulated in order to expand the city with the construction of a city park.

The areas affected by slope instabilities are also included into the *GT_Map*, according to their typology and activity status. The instabilities can be classified as follows: fall and toppling landslide, rotational and translational landslide; earth and mudflows; complex landslide and not defined landslide. The definition of the activity status accounts for four classes, namely: active; quiescent; non-active, not defined (Working Group ICMS 2008; 2015).

The contouring of the *gt_units* on a *GT_Map* should provide the surface information to be combined with subsurface data, for the reconstruction of the cover terrains/bedrock interface and the parameterization of the subsoil layers. The *GT_Map* should also lead to the planning of new geophysical survey (e.g. MASW, Seismic Refraction Tomographies SRT, HVSR) in order to collect additional information on the seismic behaviour of the different recognized lithostratigraphic units and to further constraint both the depth and the geometry of the bedrock/cover terrains units contact, especially where borehole logs are not available.

It should be remarked that the cover terrains/bedrock contact could not actually correspond to the top of the seismic bedrock, due to local discrepancy between “geological” and “seismic” bedrock and the difficulty in the identification of the transition between them. This is particularly evident where fault-related or gravity-driven jointing of rock masses causes the decrease of the S_waves below the 800 m/s. Large and elongated volumes of low-velocity cataclastic zones and gouges characterize the bedrock along the main regional tectonic alignments and the associated set of secondary faults and splays, sub-parallel to the master fault. Furthermore, most of the younger (Pliocene-Pleistocene) marine geological bedrock units within the Periadriatic area (e.g. Cellino Fm, Argille Azzurre Fm, Mutignano Fm) generally show characteristic Vs < 800 m/s.

4. STATISTICAL ANALYSIS OF Vs VALUES OF THE ENGINEERING-GEOLOGICAL UNITS

The *MS3* studies of central Italy produced a huge amount of Vs data measured on the different *gt_units*. The Vs values coming from the 138 *MS3* studies were collected in a database, which allowed us to perform for the first time the statistical analysis of their behaviour in the area. Among these measurements, 1164 refer to cover terrains units and 1029 to bedrock units. In this paper the statistical analysis exclusively refers to *gt_units* having at least 20 Vs samples. Tab. 3 summarizes the relevant statistics on the Vs values for the considered *gt_units*. The geotechnical categorization adopted in the *MS* studies seems to correctly differentiate seismic properties of soils. As concerns the cover terrains units, coarse-grained units generally show median Vs values significantly higher than fine-grained ones. In general, high velocity coarse-grained (median above 350 m/s) and low velocity (below 300 m/s) fine-grained soils could be identified, with the *CL gt_unit* falling between the two groups. Apparently no kind of cover terrains exhibits Vs values close to values characteristic of a seismic bedrock (>800 m/s).

Beyond these considerations, however, a scatter of Vs values appears relatively large for most of the *gt_units*, with a maximum of 70% in the case of GP and a minimum of 22% in the case of GC. This may be due to a number of factors, namely in order of importance: the accuracy of each experimental estimate, the intrinsic heterogeneity of the *gt_unit*, the effect of depth and the influence of the geomorphological setting. Firstly, we compare the well-constrained measurements provided by Down-Hole measurements and those deduced by inverting surface measurements (Fig. 4): it is worth to note that in this analysis, situations lacking information about the origin of the relevant datum (borehole or surface prospecting) were discarded. As a whole, 743 data out of 1457 were retrieved from DH measurements (about 22%), while the remaining ones were obtained in the largest part from the inversion of Rayleigh waves dispersion curves obtained by active (in the largest part) and passive surface waves measurements (MASW, ESAC, etc.). The frequency distributions relative to the Vs values obtained by DH and surface measurements for each *gt_unit* have been analysed by a Kolmorov-Smirnov test. The outcome of this analysis indicates that, except in the case of ML and ALS units, differences are not significant form the statistical point of view (at a significance level of 0,05). Thus, in the following the two units (respectively relative to DH and surface measurements) will be considered all together.

The Tab. 3 compares, for each *gt_unit*, the scatter of Vs values with the average accuracy of corresponding experimental estimates by means of the scattering on accuracy ratio, which is a tool to evaluate the influence of experimental uncertainty on the resulting apparent scattering. The experimental uncertainty or accuracy is defined in terms of the range of values compatible with experimental observations. The corresponding values have been supplied for values inferred from surface measurements and by accounting for the intrinsic multiplicity of inversion solutions able to explain observations within the relevant experimental errors. The best fitting solution has been considered as the preferred one. For most of the *gt_units*, low values of this ratio (close to or lower than 1) indicates that experimental uncertainty may explain apparent scattering of the relevant Vs values. In some cases, however, (e.g. *GP*, *CL*, *ALS*, *SFALS*, *SFCOS*) larger values of the ratio (>>1) suggest that some physical feature must be advocated to explain at least part of observed scattering.

COVER TERRAINS							
gt_unit	**N**	**25%**	**50%**	**75%**	**Scatter**	**Accuracy**	**Ratio**
GC	51	320	350	396	0.22	0.22	0.99
GM	483	340	400	500	0.40	0.37	1.08
GP	48	332	452	650	0.70	0.23	3.06
GW	61	340	441	540	0.45	0.34	1.33
SM	90	250	300	354	0.35	0.56	0.62
CL	132	300	450	570	0.60	0.32	1.88
ML	188	211	274	350	0.51	0.50	1.01
OH	81	155	250	295	0.56	0.49	1.14
RI	30	167	200	250	0.42	0.51	0.81
BEDROCK							
ALS	358	600	800	1000	0.50	0.32	1.56
COS	120	508	600	700	0.32	0.40	0.80
GRS	22	462	555	721	0.47	0.59	0.79
LPS	142	724	857	1100	0.44	0.36	1.22
SFALS	171	450	610	741	0.48	0.24	1.99
SFCOS	20	363	439	584	0.50	0.22	2.29
SFGR	25	500	509	600	0.20	0.67	0.29
SFLPS	151	500	600	700	0.33	0.44	0.76

Tab. 3 – Main statistical features of the population of Vs values (m/s) obtained for each *gt_unit*. Only groups characterized by at least 20 samples (N) have been considered for the statistical characterization. Scatter indicates the ratio between the interquartile range and median. Accuracy is the average ratio between the experimental uncertainty affecting the Vs estimate and the respective preferred value. In the last column, the ratio between Scatter and Accuracy is reported.

Scattering of Vs values (Tab. 3) appears relatively large for most *gt_units*, with a maximum of 70% in the case of GP and a minimum of 22% in the case of GC. This may be due to a number of factors, the main summarized as follows: a) the accuracy of each experimental estimate; b) the intrinsic heterogeneity of the *gt_unit* itself; c) the effect of depth; d) the geomorphological setting.

As concerns the first aspect, the scatter of Vs values for each *gt_unit* can be compared with the average accuracy of corresponding experimental estimates (Tab. 3). The ratio between these values can be associated to the role of measurement accuracy in the apparent scattering. When this ratio is much larger than 1, the observed scattering cannot be simply considered as the effect of measurement accuracy. This analysis revealed that the ratio is smaller or close to 1 for most *gt_unit*s, with the exception of GP, GW and CL. In these cases, observed scattering is much larger than expected as an effect of measurement accuracy.

In order to explain this discrepancy, we investigated the relationships with the depth of occurrence of the *gt_unit*s from the surface. In fact, the first hypothesis is that buried sediments might be more rigid than outcropping sediments. The possible effect of the depth of the *gt_unit* is modeled in the form of a power law. The outcome of this analysis (Tab. 4) indicate that, for finer-grained sediments, depth dependence is relatively stronger and may explain up to 45-70% of the global variance of the sample. More in details, Vs values of CL show the strongest dependence on depth and this could partially explain the relatively strong scattering affecting the respective values. Less important but statistically significant dependence on depth also exists for coarser-grained *gt_unit*s, with the exception of GC. The variance below 40% and the observed dispersion of gravelly dominated *gt_unit*s can be associated to their intrinsic geotechnical heterogeneity. However, in terms of depth, also in this case relatively stronger dependency is observed for GP and GW *gt_unit*s and this could explain the relatively larger scatter affecting Vs values of these units.

COVER TERRAINS				
gt_unit	**N**	**a**	**b**	**R2**
GC	25	365.1	-0.005	0.002
GM	155	356.7	0.152	0.208
GP	19	333.2	0.265	0.304
GW	22	302.6	0.211	0.373
SM	12	310.6	0.143	0.075
CL	90	244.9	0.248	0.684
ML	34	239.0	0.168	0.497
OH	24	206.7	0.142	0.458

Tab. 4 - Dependence of Vs values on the top h of the corresponding *gt_unit*. The dependence has been modeled assuming a power Law in the form $Vs=a\ h^b$.N is the number of considered samples. R2 indicates the fraction of variance explained by the power law. In the analysis, only buried formations have been considered (H>0). Statistically significant results (significance lower that 0.05) are indicated in boldface. Of course, since RI unit outcrops by definition, it has not been included in the analysis.

In order to explain the possible effect of the relevant geomorphological setting, Vs values relative to each *gt_unit* of the cover terrains units were also categorized, according to the domain of provenance (Fig. 5). The Vs values measured for many *gt_units* from the Intermountain Basin domain are significantly larger than those relative to the other morphostructural domains. This suggests that observed scatter might be at least partially the effect of the domain of provenance.

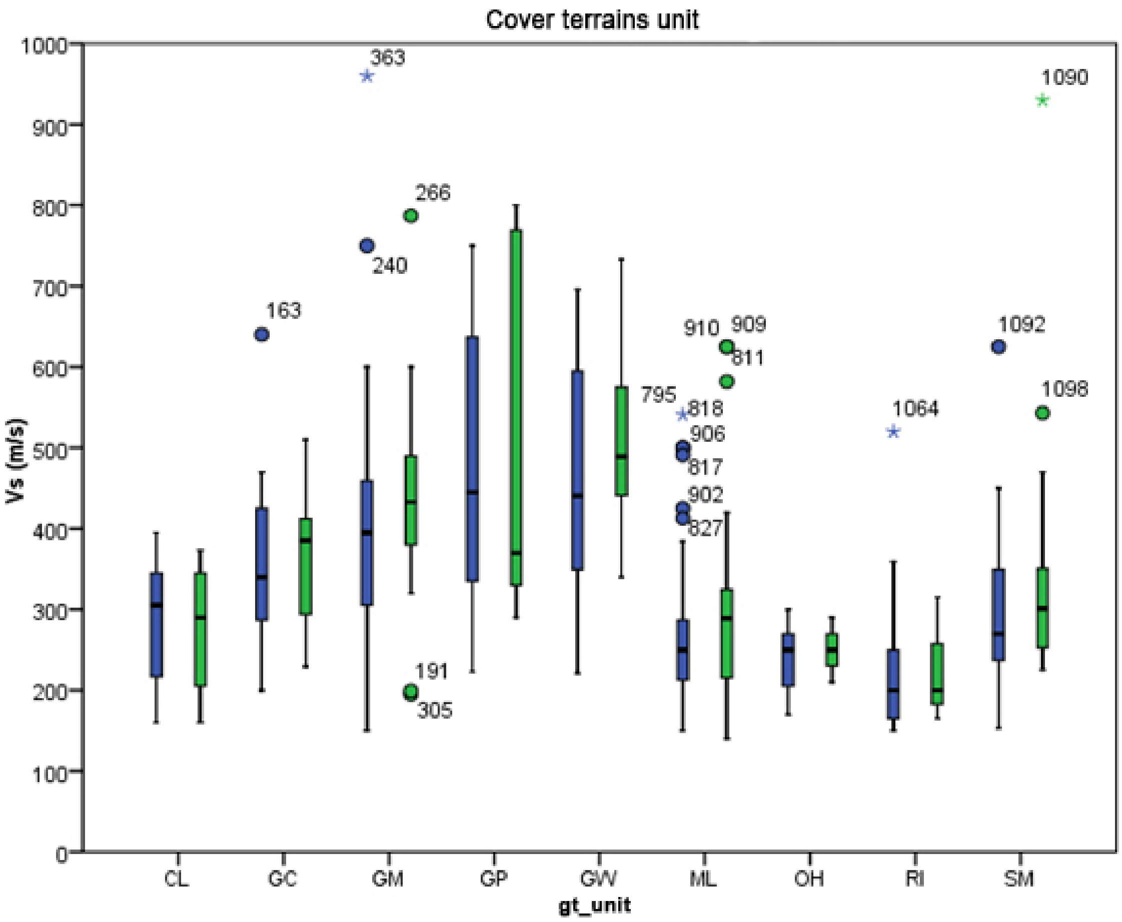

Fig. 4 – Box-Whiskers plot showing the distribution of the Vs values relative to each *gt_unit* of the cover terrains. Only groups characterized by at least 20 samples have been considered for the statistical characterization. For the same unit, distribution of Vs values deduced from surface (blue) and DH (green) measurements are reported separately. Each box represents the interquartile (IQ) range, which contains the middle 50% of the records. The whiskers are lines that extend from the upper and lower edge of the box to the highest and lowest values which are no greater than 1.5 times the IQ range. A line across the box indicates the median. Outliers (dots) are single occurrences (corresponding to the case number reported in the figure) with values between 1.5 and 3 times the IQ range, *i.e.*, beyond the whiskers. Extremes (star) are cases with values more than 3 times the IQ range.

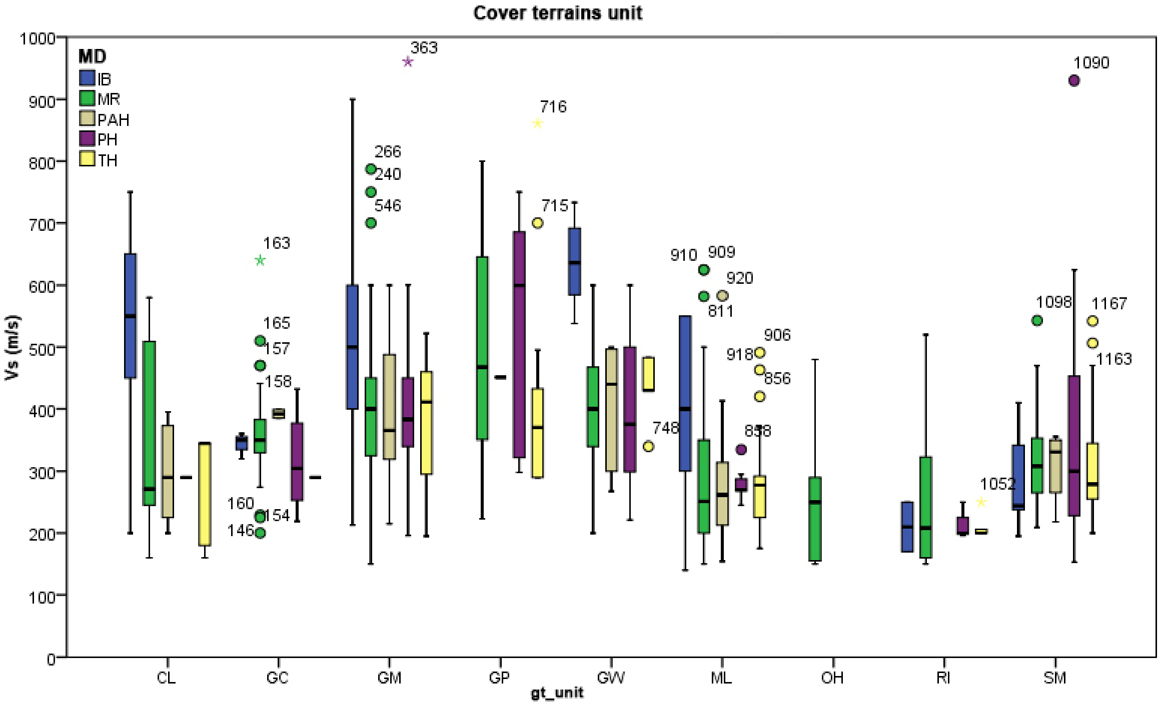

Fig. 5 - Box-Whiskers plot relative to the distribution of the Vs values relative to each *gt_unit* of the cover terrains (see Tabs. 2, 3 and 4 for details). Only groups characterized by at least 20 samples have been considered for the statistical characterization. *Gt_units* relative to different Morphostructural Domains (MD) have been separately considered: IB: Intramountain Basin; MR: Mountain Ridges; PAH: Periadriatic Hills; PH Pedemountain Hills; TH: Terrigenous Hills. (see caption of Fig. 1 for details).

The *gt_units* relative to the geological bedrock, as expected, show higher values of Vs with respect to the cover terrains units (Tab. 3). The highest Vs values refer to the *LPS* and *ALS*, which could be generally considered as a seismic bedrock. The other *gt_units* exhibit relatively lower Vs values (median around 600 m/s). Weathering severely affects Vs values by lowering respective values down to 450 m/s. As concerns scattering, most of *gt_units* are characterized by relatively large scattering in the range 22-50%. In most cases, the ratio between scattering and accuracy (Tab. 3) is close or lower than 1, except in the case of ALS, SFALS and SFCOS. This variability might be due to the different ages and degree of diagenesis of the litho-stratigraphic units, composing the single *gt_unit*. To evaluate this effect, Vs values relative to each *gt_unit* have been categorized by accounting for the domain of provenance (Fig. 6). The lithostratigraphic units are generally younger from the Mountain Range to the Periadriatic Hill, where the measurements evidenced the lower Vs values for most of the *gt_units*.

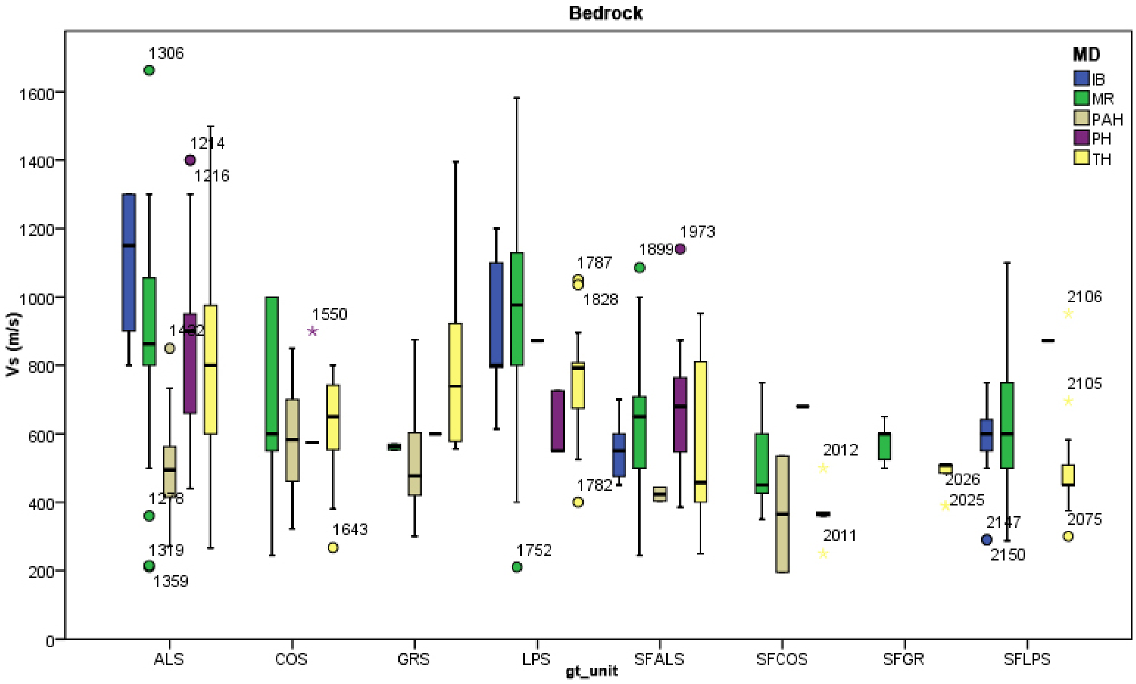

Fig. 6 - Box-Whiskers plot relative to the distribution of the Vs values relative to each *gt_unit* of the bedrock (see Tab. 1 and 3 for details). The different Morphostructural Domains (MD) have been separately considered (see Fig. 1 for details).

5. THE CROSS-SECTIONS IN THE PERSPECTIVE OF THE LEVEL 3 SEISMIC MICROZONATION MAP (MS_MAP)

The drawing up of the *MS_Map* included two fundamental steps concerning the geology and the engineering contribution to the studies: the construction of the subsoil model and the selection of the cross-sections to perform the numerical analyses of wave propagation phenomena by both considering only 1D vertical heterogeneities and also including 2D effects of morphological or subsoil lateral heterogeneities. The numerical analysis aims at quantifying motion amplification phenomena induced by the local seismostratigraphic and morphological settings. These effects are summarized by three integral parameters (amplification factors or FA from the Italian acronym) referred to each seismically homogeneous microzone that were previously defined in drawing the level 1 *MOPS_Maps* (considering *gt_units*, Vs values, geometry of the buried lithological contacts and cover thicknesses, see Working Group MS 2008). To compute these parameters, the integral of the acceleration response spectra (damping ratio 5%) is computed within a fixed frequency range, both for the input ground motion (at the reference soil conditions) and for the output ground motion computed at a the surface along the profile. The FA value is then computed as the ratio between these two integrals by considering three ranges of periods (0.1-0.5 s, 0.4-0.8 s and 0.7-1.1 s).

In this paragraph, we describe some representative cross-sections, reproducing relevant case histories that refer to different regional geological contexts. The aim is to show the most recurrent subsoil geological and geotechnical models in the distinct geological domains struck by the central Italy earthquakes and to decipher their relations with the amplification key factors, resulting from the numerical modelling.

The selected study sites are listed in Tab. 5 that reports, for each case history, the pertaining morphostructural domain (see Fig. 3) and the investigated amplification key factors.

UOT	Municipality	Morphostructural domain	Amplification key factor
ABRUZZO	CAPITIGNANO	IB - INTRAMOUNTAIN BASIN	2D EFFECTS + FILLED BASIN
MARCHE 1	PIEVE TORINA	MR - MOUNTAIN RIDGE	2D EFFECTS + FILLED BASIN
UMBRIA	SCHEGGINO	MR - MOUNTAIN RIDGE	2D EFFECTS + FILLED BASIN
LAZIO	ACCUMOLI	PH - PEDEMOUNTAIN HILL	2D EFFECTS + FILLED BASIN
MARCHE 3	MONTEFORTINO	TH - TERRIGENOUS HILL	TOPOGRAPHIC
MARCHE 2	CORRIDONIA	PAH - PERIADRIATIC HILL	STRATIGRAPHIC

Tab. 5 – List of the selected study sites in relation with the Morphostructural domain and the Amplification key factor.

The 2D subsoil models are based on geological cross-sections that reproduce the geometry of the distinct engineering-geological units, with the related *gt_unit* code and the measured Vs. Furthermore, above each cross-section, a table reports the fundamental resonance frequency (F_0) of the site, inferred from HVSR measurements (Nakamura 1989). The same table also shows the range of variation (min.-max.) of the 2D Amplification Factor (FA), calculated for the period-intervals 0.1-0.5 s, 0.4-0.8 s and 0.7-1.1 s, compared with the averaged 1D FA (between brackets). Indeed, the HVSR measurements provide the fundamental resonance frequency of a site, which is significant for a rough identification of the depth of the main impedance contrasts within the shallow stratigraphy of the site. Due to the complexity of subsoil model along most of the studied localities, the estimation of the local amplification and the recognition of 2D effects have been obtained using 2D numerical methods and comparing them with those from 1D analysis (like *e.g.* in Bindi et al. 2009, 2011; Chávez-Garcia and Faccioli 2000; Madiai et al. 2017; Sanchez-Sesma et al. 2002). The 2D numerical analyses have been performed using the 2D FEM codes LSR2D (www.stacec.it) and/or QUAD4M (Hudson et al. 1994), whereas STRATA software (Kottke and Rathje 2008) was used for 1D numerical analyses. The equivalent-linear visco-elastic approach was always used to model the soil behaviour under dynamic conditions. For further insights about the numerical analyses implemented during the *MS3* project in Central Italy the readers can refers to Pergalani et al. (2019). In the discretization of the models, Vs values within each geological unit has been considered as constant. This because in most cases the dimension of considered bodies was small enough to exclude significant Vs variations with depth.

The cross-sections are discussed from the Mountain Range, to the west, to the Periadriatic Hill domain, to the east (Figs. 7, 8, 9, 10, 11, 12). Please note that the total extent of the table above each cross-section reproduces the effective length of the microzonation study area along the trace of the profile.

The Capitignano village, in the Abruzzo region, is located at the margin of the Montereale Intramountain Basin, an half-graben that originated, within the Mountain Range, along the axial zone of the Apennines (Fig. 3; Tab. 5) (Chiarini et al. 2014). The analysed cross-section (Fig. 7) extends from the depocenter to the north-eastern margin of the structural depression, which is controlled by a NW-SE-trending, SW-dipping master fault zone (Capitignano Fault zone). The section can be divided into two portions, showing distinct seismic behaviours. To the southwest, at the hangingwall of the fault zone, the geological substratum is constituted by the arenaceous member of the Laga Fm (*LPS*; Vs=1300 m/s). The cover terrains units are represented by the continental deposits of the intramountain basin, consisting of basal lacustrine silts (*MLlc*; Vs=600-900 m/s), reaching a maximum thickness of about 140 m, and the overlaying alluvial fan deposits that form an almost continuous (10 to 50 m thick) layer, lithologically varying from coarse-grained gravels (*GMca*; Vs=300-450 m/s) to sands and silts (*SMca*; Vs=300-450 m/s), from the margin to the depocenter of the basin. In the depocentral area, the HVSR measurements provided low values of F_0 evidencing the signature of the deep-seated unconformity at the base of the lacustrine deposits, resting on the almost intact substratum, while towards the margin of the basin the presence of secondary peaks ($F_1>F_0$) relates to the boundary between the shallow alluvial fan deposits and the underlying lacustrine deposits. To the northeast, across the fault zone at the margin of the basin, the sandstones of the Laga Fm are highly fractured (SFLPS; Vs=900 m/s) and partially covered by a thin layer of alluvial deposits, made of silts (*MLca*; Vs=600 m/s) coarsening upward to gravels (*GMca*; Vs=450 m/s), and by slope deposits consisting in sandy-silty gravels (*GMfd*; Vs=300-450 m/s). In this sector, the progressive decrease of the F_0, is in contrast with the thinning of the cover terrains units, thus suggesting to refer the local resonance frequency to discontinuities within the geological substratum, such as the separation between the shallower weathered rocks and the deeper intact. Coherently with the geological and geotechnical model, the 1D numerical modelling across this section revealed that significant ground motion amplification of 1.98 is expected for periods in the range 0.7-1.1 s exclusively at the basin depocenter. In this portion of the section, the 2D modelling provided higher values of FA, for the same range period, with a maximum 2D/1D FA ratio of about 1.7, thus suggesting significant local contribution of the 2D effects. These are also recognizable at the faulted margin, characterized by the transition at depth from the intact geological substratum to the highly fractured rock volumes of the Capitignano Fault Zone. In this sector the 2D FA varies from 1.5 to 2.14 for periods in the range 0.4-0.8 s, with a maximum 2D/1D ratio of about 1.9.

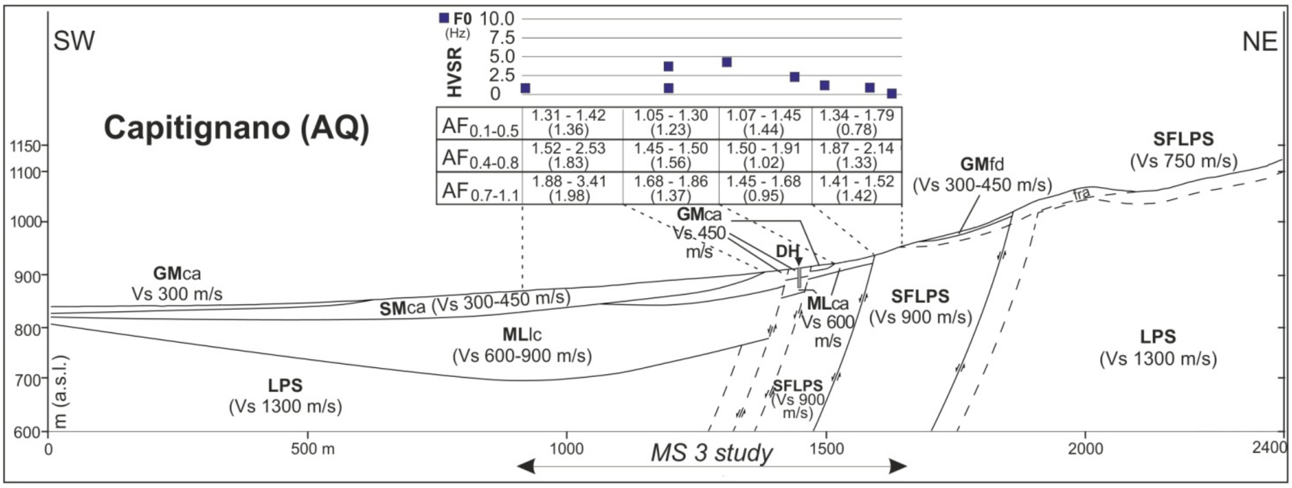

Fig. 7 –Capitignano cross-section within the Montereale basin. See text for explanation.

The Pieve Torina municipality section (Fig. 8), in the Marche region, is representative of the sedimentary filling of a 800 m wide and 35 m deep buried valley in the Mountain Range domain, which is entrenched on the calcareous marls and clayey marls of the Scaglia Cinerea Fm (*ALS*; Vs=1000 m/s). Alluvial sandy-gravel deposits (*GPtf*; Vs=800-850 m/s) fill most of the paleo-valley. At the top of the alluvial sequence there are 5-10 m of silty-gravel deposits (*GMtf*; Vs=300-500 m/s) as the shallower horizons. Along the northern flank of the valley, the alluvial deposits pass laterally to sandy-silty eluvial-colluvial deposits (*MLec*; Vs=200-300 m/s), about 10 m thick, that lie on few meters of fractured Scaglia Cinerea Fm (*SFALS*; Vs=370-500 m/s). The results of the HVSR measurements across the section indicate that there is a correlation between the F_0 and the buried geological setting. The lowering of the F_0 values toward the centre of the section relates to the thickening of the alluvial units. The very low values of the 1D FA is consistent with the shallow depth Vs profile characterised by the absence of impressive discontinuities. Only locally, the very thin low velocity cover terrains resting of the northern margin of the buried valley produces a weak 1D FA (1.8) for periods in the range 0.1-0.5 s. The very low 2D/1D FA ratio along the entire cross-section suggests the absence of local 2D effects, without any influence from the buried topography.

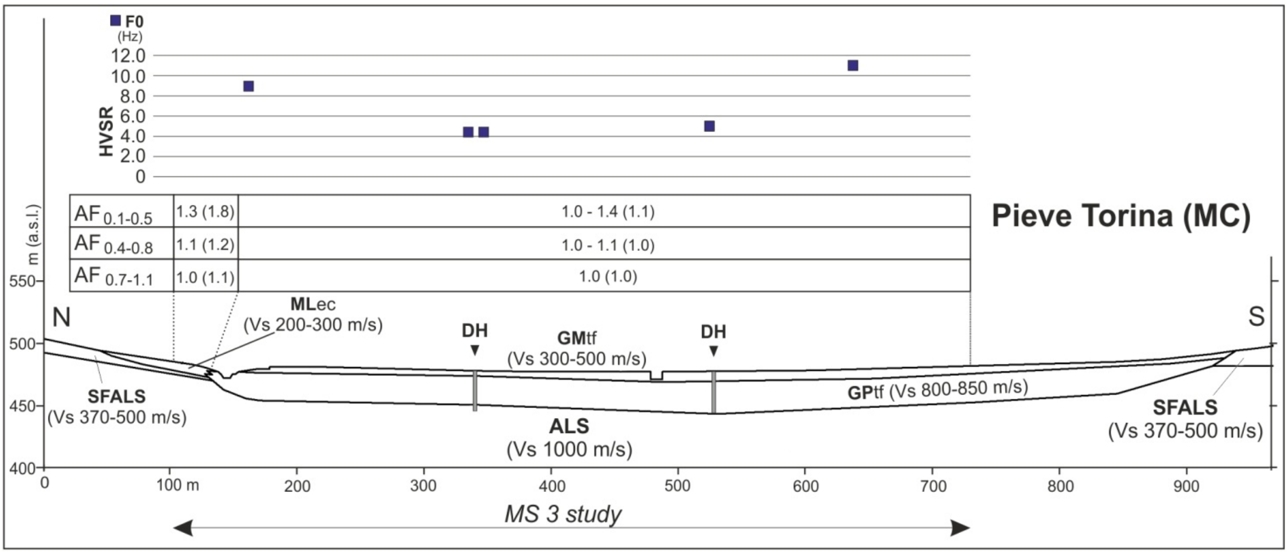

Fig. 8 – Cross-section of Pieve Torina. See text for explanation.

The Scheggino municipality section (Fig. 9), in the Umbria region, shows a 180 m wide and 40 m deep buried valley in the Mountain Range domain, carved on the limestones of the Scaglia Rossa Fm (*LPS*; Vs=800 m/s). Silts and sands of the alluvial plain (*MLin*; Vs=200-450, regularly increasing with depth) fill the valley. Two ancient slope deposits (*GMfd*; Vs=550 m/s), consisting of 10-15 m tick sandy gravels, cover the flanks of the valley. The HVSR measurements provide values of F_0, ranging from 2.0 to 3.0 Hz, suggesting a direct relation with the seismic impedance contrast along the cover terrains/bedrock contact. The 1D FA shows the highest values (1.84-2.00) in the range of periods 0.1-0.5s, confirming the background stratigraphic control on the site response, coherent with HVSR measurements. In addition, the 2D FA is maximum (2.47) in the depocenter of the buried valley, progressively decreasing towards the flanks. Accordingly, the 2D/1D FA ratio dramatically drops down from 1.3 to 0.65, going from the depocenter to the flanks of the paleo-valley, suggesting the contribution of a topographic 2D effects only beneath the axis of the valley.

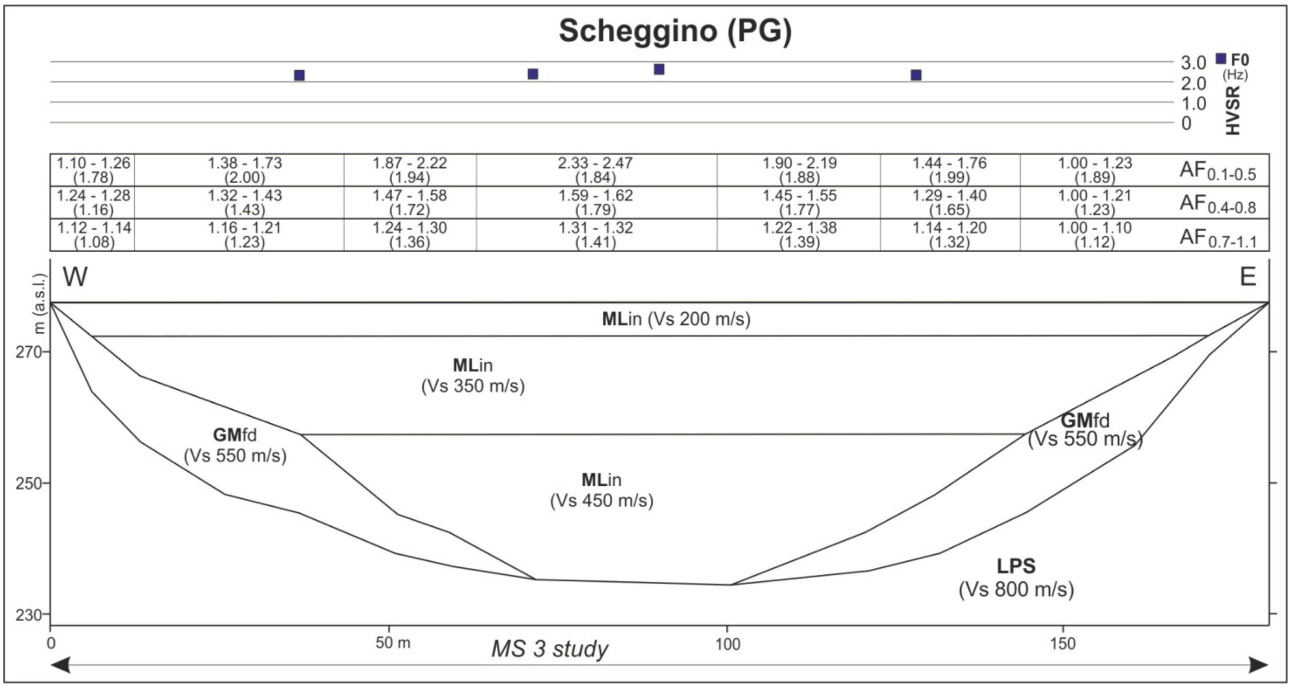

Fig. 9 – Cross-section of Scheggino. See text for explanation.

The site of Fonte del Campo, in the municipality of Accumoli, in the Lazio region, is located in the upper reach of the Tronto river valley just downstream the Amatrice intramountain basin. The analysed cross-section (Fig. 10) evidences the presence of an alluvial valley floor entrenched on the Upper Miocene arenaceous-pelitic sequence of the Laga Fm (*ALS*; Vs=1170 m/s) that acts as seismic bedrock, except some local weathered or fractured shallow layers (*SFALS*; Vs=480 and Vs=705 m/s). The bedrock is characterized by a wide range of jointing degree, due to the presence of two main NW-SE and SW-NE oriented fault systems. Distinct types of juxtaposed Quaternary cover terrains units conceal an articulated paleo-topography. They consist of prevalently coarse-grained deposits of different origin: recent alluvial plain deposits (*GMin*; Vs=285-441 m/s) infill the Tronto River alluvial plain, thin terraced deposits (*GMtf*; Vs=327 m/s) cover an erosional fluvial surface, and alluvial fan deposits (*GMca*; Vs=252 m/s) drape the pediment surface on the right flank of the valley. The results of the HVSR measurements collected along the section clearly indicate, in the area of the Tronto Rivers alluvial deposits, almost homogeneous fundamental frequencies, in the range of 5-6 Hz. Such values are consistent with the resonance frequency of the thick alluvial strata package infilling the paleo-valley pictured in the southern portion of the section. Across the paleo-valley, the higher values of both 1D and 2D FA for periods in the range 0.1-0.5s clearly indicate the contribution of the valley infilling to the local amplification. The HVSR peak disappears in the central part of the section where the bedrock crops out or where only a thin veneer of terraced alluvial deposits covers the geological bedrock with the partial interposition of the weathered/fractured layer. Local amplification effects have been also observed (2D FA=2.40) in the northern sector for periods in the range 0.1-0.5, likely due to the superposition of the thin low-velocity alluvial fan gravels directly on the bedrock.

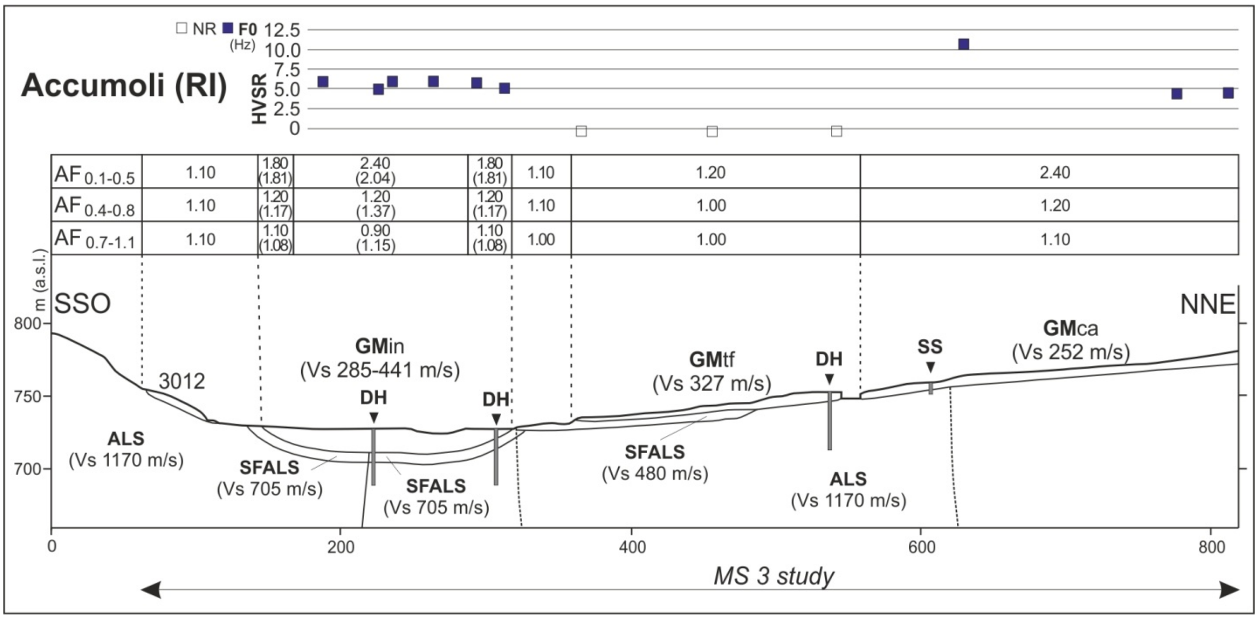

Fig. 10 – Cross-section of Fonte del Campo (Accumoli). See text for explanation.

The Montefortino municipality section (Fig. 11), in the Marche region, is representative of the Terrigenous Hill domain. The hill is made by a weathered or fractured alternation of marls, calcareous marls and marly clays pertaining to the “Marne con Cerrogna” and “Marne a Pteropodi” Fms (*SFALS*; Vs=600 m/s). Along the western slope of the hill, the weathered and/or fractured arenaceous turbiditic deposits of the Laga Fm (*SFLPS*; Vs=750 m/s) cover the marly deposits along a high-angle dipping stratigraphic contact. At the foot of the western slope a thick eluvial-colluvial deposit, made of clay-sandy silts (*MLec*; Vs=330 m/s) unconformably covers the geological substratum. The 2D numerical modelling of the section evidences three zones with distinct seismic behaviour. In the eastern part of the profile, where the weathered substratum (*SFALS*) outcrops, the maximum FA value of 1.6 occurs in the range of period 0.4-0.8 s. This site amplification is entirely due to topographic effects as suggested by the absence of stratigraphic contribution (1D FA≃1) with a 2D/1D FA ratio of about 1.6. The almost flat portion of the western side of the relief, where the stratified massive substratum outcrops, is characterized by both low values of the 1D and 2D FA. Finally, the maximum 2D FA of 1.62 and 1D FA of 1.35 calculated in the westernmost portion of the section in the range of periods 0.1-0.5 s is coherent with the resonance frequency of the cover terrains units (*MLec*) evidenced by the F_0 of 5.6 Hz observed in the HVSR measurement.

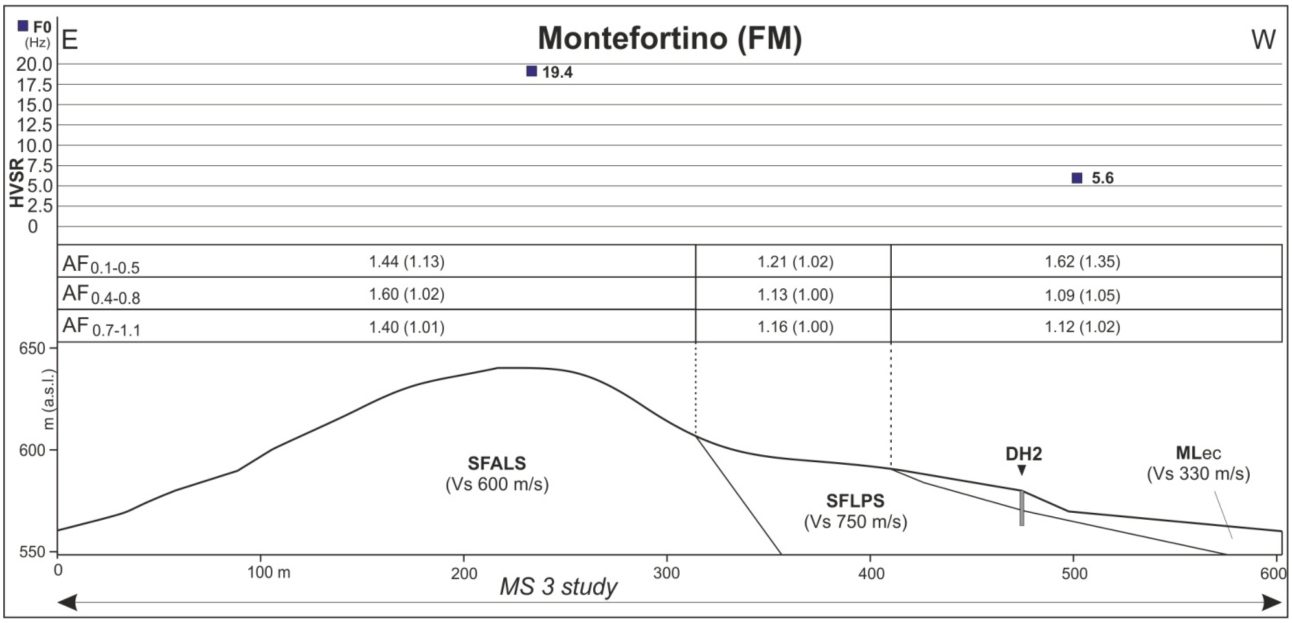

Fig. 11 – Cross-section of Montefortino. See text for explanation.

The Corridonia municipality, in the Marche region, rises up on top of a hilly morphology (Fig. 12) belonging to the Periadriatic Hill domain. The backbone of the relief is constituted by dark laminated clays of the Argille Azzurre Fm (*COS*; Vs=380-680 m/s). The geological substratum is covered by 20 m thick terraced alluvial deposits, characterized by grain size from silty-clayey (*Cltf*; Vs=400 m/s) to silty-sandy (*MLtf*; Vs=215-410 m/s), and by 5 to 15 m thick eluvial-colluvial deposits, consisting of clay-sandy silts (*MLec*; Vs=260 m/s), located at the top and along the slopes of the hill, respectively. The 1D numerical modelling provided uniform low values of AF along the entire section, likely due to the absence of significant discontinuities in the shallow Vs profile. On the contrary, the 2D numerical modelling of the section shows a very variable 2D FA, for the three considered period ranges, with the highest values that are concentrated around the peak of the hill. This seismic behaviour suggests to relate the modelled ground motion amplification essentially to topographic site effects. In this frame, the quite constant F_0 of about 2.5 Hz measured across the whole section could represent the signature of the top of the seismic bedrock, located at depth within the succession of the Argille Azzurre Fm.

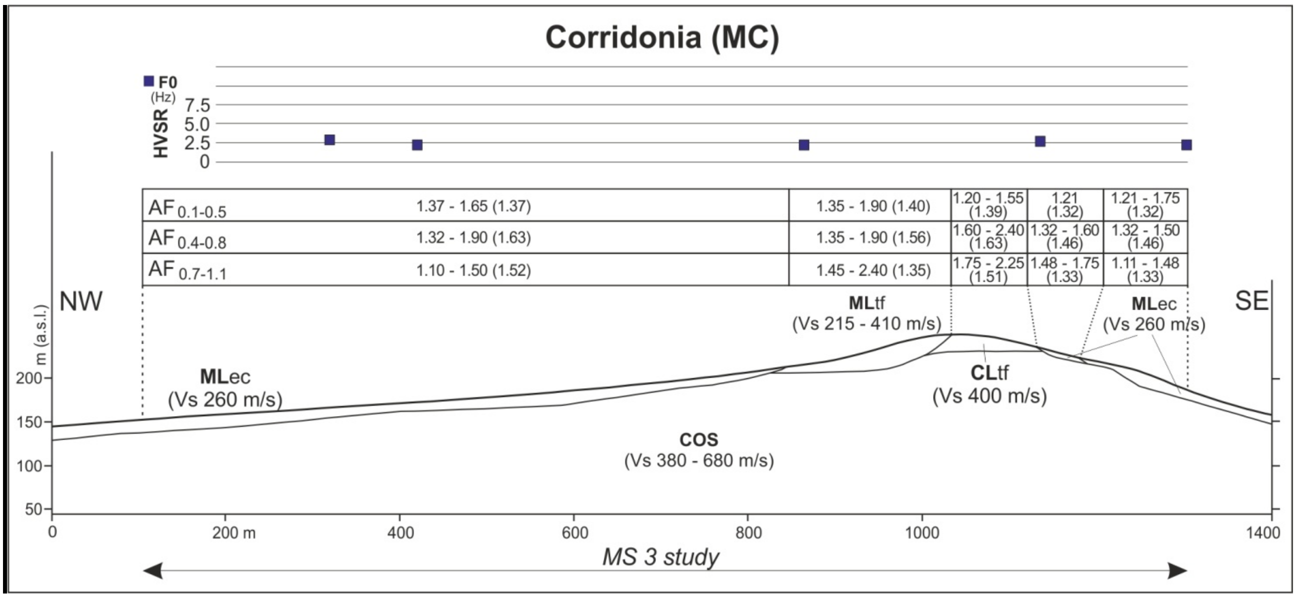

Fig. 12 – Cross-section of Corridonia. See text for explanation.

5. CONCLUSIONS

The *MS3* studies carried out after the august 24th 2016 to January 18th 2017 central Italy seismic sequence represent one of the largest coordinated project of third level seismic microzonation in the Italian territory. The methodological approach, with the participation of many local professionals and researchers from different institutions constituent the *MSCenter* Agreement, ensured the achievement of homogeneous results at a regional scale and can be considered as an example of good practice to be performed again in the future. The activities were carried out by many local professionals and by researchers from different institutions coordinated by the *MSCenter*. The regional extent of the investigated areas provided the opportunity to construct an archive of all the lithostratigraphic units occurring in the study area with their conversion into engineering-geological units, defined according to the Guidelines and criteria for *MS* studies (Working Group ICMS 2008; 2015), and their distribution in the different morphostructural domains.

The large amount of Vs estimations also allowed us to test whether the categorization of the lithological units in terms of *gt_units* corresponds or not to a peculiar seismic behaviour of the terrains. Apart the intrinsic variability of some *gt_units*, Vs estimations well differentiate the distinct *gt_units*, taking into account their burial depth and their location in the different geological and morphological domains of the region. The use of *gt_units* was the first Italian example of categorization on a regional scale and despite such a large number of different geological units and the intrinsic variability of the *gt_units*, the geophysical characterization in terms of Vs seems to support the validity of the adopted engineering-geological approach.

Even though the huge investigated area is characterised by different geological and geomorphological domains with a very complex tectonic setting, recurrent subsoil models were identified. The comparison between the resonance frequencies and the variability of the amplification factors in three distinct range of periods from 1D and 2D modelling with the subsoil geometry of the selected cross-sections evidences that in most of the recurrent subsoil models the amplification of the ground motion is mainly due to the stratigraphic conditions. In addition, the estimation of the 2D/1D FA ratio helped us to appreciate the local contribution of the 2D effects, superimposed on the background stratigraphic effects. The prevalent stratigraphic origin of the local site amplification and the frequent additional 2D contributions are the consequence of the extreme variability of the lithotypes (both considering the bedrock and the cover terrains) and their features (bedding, degree of fracturing/weathering, texture, grain-size, degree of cementation, plasticity, water content, etc.) as well as by the frequent and irregular vertical and lateral variation of their thickness and geometries. Moreover, pronounced 2D effects were observed along the highly fractured and weathered tectonic borders of the intramountain basins or along the axes of deep buried valleys.

This is the first time that a systematic approach has been adopted for *MS3* studies performed on a very large and geologically complex area. Further work is needed to: i) compare these *MS3* studies results with the macroseismic effects and the pre-existing *MS* (where available) in order to learn how to best calibrate the adopted approach for the future *MS3* studies; ii) to extend this approach to other seismic areas where the *MS3* studies are not yet available, in order to provide the local authorities a tool which can significantly decrease the susceptibility of the territory before the occurrence of an earthquake.

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