Development of a site conditions map for the Campania-Lucania region (southern Apennines, Italy)

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Abstract

Having a reliable site conditions estimate is an important step to analyze and predict earthquake ground motions. To provide this information for the Campania-Lucania region (southern Apennines, Italy), in the framework of a collaboration with regional civil protection agency, geologic units shown on 1:250,000 scale geologic map, have been sorted together into four categories based on age and geological similarities. According to the site classification defined in engineering building codes, we have assigned to each site classes, a value or range of values of the average shear-wave velocity to 30 m (Vs30) and of the site dominant period. Thus, we have digitized the category boundaries from the map tracing only the geologic contacts that separate units of different site classes. The accuracy of the site-conditions map is only limited by the number of Vs profiles, used to compute the Vs30, and geologic data available so far. Analyses with new data will allow updates and modifications of this map. Anyhow, the resulting site classification map may be an helpful tool to better characterizing the sites effects for those applications where amplification values at large scale are need, such as ground-shaking maps or seismic hazard maps.

Introduction

Local geologic conditions can amplify or deamplify seismic ground motion modifying shaking intensity both in the time and frequency domain (Bard and Bouchon, 1985; Bard et al., 1988). Studies of historic and recent earthquakes have indicated that damages at an unconsolidated site can be 10 times stronger than at rock site, even when their distance from the ruptured fault is the same. During both the 1906 San Francisco earthquake (M 7.8) and the 1989 Loma Prieta earthquake (Ms 7.1), for example, the local amplification over soft soils was responsible for intensity variations as large as two degrees. Nearly all recent destructive events, such as Michoacan, Messico 1985, Spitak, Armenia 1988, Iran 1990, Philippines 1990, Northridge 1994, Kobe 1995 and so on, have had dramatic evidence of site effects. As a consequence, seismologists and engineers have conducted many studies to quantify how the seismic energy is modified by physical properties of the near surface materials, and how engineering structures can behave during strong ground shaking. In this framework, a uniform estimate of site conditions is necessary component in the prediction of near-source ground motion. Recently, the measured shear-wave velocity (Vs) in shallow subsurface materials, has become the most common used parameter to define site classifications and to correct the predictions of spectral amplitude values. Vs parameter is an effective measure of the quality of foundation soils, because it depends on basic physical properties, such as density, porosity and degree of cementation of the materials through which the seismic waves propagate. To such purpose, many drilling programs have been conducted in several areas to establish important correlations between seismic response and average shear-wave velocity of various geologic units (Joyner and Fumal, 1985; Boore et al., 1993; Borcherdt, 1994). Joyner et al. (1981) proposed that velocity to a depth corresponding to one-quarter wavelength of period of interest, could represent the local site conditions. The need of having detailed subsurface information, and the complexity of using this approach, make the quarter-wavelength method difficult to apply.

Recent works have recommended alternative techniques that simplify the use of Vs in ground motion predictions. Borcherdt et al. (1991) suggested that site conditions can be classified on the basis of the average shear-wave velocity to a depth of 30 m (Vs30), in agreement with the typical depth that can be reached with drill rigs in a single day. This allows sites to be classified unambiguously by using only one parameter. Recent code provisions for buildings and other structures (1998 and 2003 NEHRP-UBC Site Classifications, Eurocode 8, or EC8, 2003, and so on), have defined site classifications based on Vs30.

Recognition of the importance of the ground motion amplification from regolith has led to the development of a standardized approach for mapping seismic site conditions measuring or mapping Vs30 (Park and Elrick, 1998; Wills et al., 2000; Holzer et al., 2005), as well as quantifying both amplitude- and frequency-dependent site amplification correction factors (Borcherdt, 1994) for future earthquake scenario studies. Boore et al. (1993, 1994, 1997) introduced site factors based on Vs30 in their empirical attenuation relationships to take into account for the potential modifications of ground shaking by local site conditions. These site factors can be used to correct large scale ground shaking maps, such as those provided in near-real time or seismic hazard map.

A key aspect of ground-shaking maps calculation is represented by the estimation of Ground- Motion Predictive Equations (GMPEs). The GMPEs are empirical equations that provide strong ground-motion parameters, given the earthquake magnitude and the source-to-site distance (Abrahamson and Silva, 1975; Akkar and Bommer, 2007; Boore and Atkinson, 2008). Nowadays, several authors have highlighted the importance of retrieving and/or refining the GMPEs also for low-magnitude seismic events (Frisenda et al., 2005; Massa et al., 2007) for which attenuation effects, related to the tectonic area of interest, can be predominant with respect to the source effects. In practice, these codes use corrective coefficients for peak parameters, based on geological maps obtained by grouping the main geological formation outcropping in the area of interest (Wald et al., 1999, Convertito et al., 2009, Emolo et al., 2010).

At the present time, maps of seismic site conditions on regional scales are not always available because they require substantial investment in geological and geotechnical data acquisition as well as interpretation. Such maps are available for only a few regions, generally in seismically active urban areas of the world.

Park and Elrick (1998) classified geologic materials in southern California using the age units reported on geologic maps. They characterized three main general categories which roughly correlate with the common site-conditions terms: Quaternary sediments (Q), Tertiary sediments and soft rocks (T), and Mesozoic hard rocks (M).

For the Italian territory, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) introduced the role local geology in the seismic hazard evaluation at national scale (Luzi and Meroni, 2007; Cultrera et al., 2004). This has been achieved by grouping the geological formation of the 1:500,000 Italian geological map into three classes A, B, C according to the EC8 provisions.

This article discusses our effort to build a site classification map for the Campania-Lucania region (southern Apennines, Italy). This work is part of a collaboration with regional civil protection agency which requires that maps of peak ground acceleration (PGA), peak ground velocity (PGV), and instrumental intensity should be provided in the immediate post-event occurring in the Campania-Lucania, southern Italy (Convertito et al., 2009). The Campania-Lucania region is one of the higher seismic hazard region in Italy (Cinti et al., 2004). It has experienced numerous strong earthquakes from medium to large magnitude, with the most recent event represented by the 1980 Irpinia earthquake (Ms 6.9) that resulted in about 3,000 deaths and enormous damages (Figure 2). The high density of inhabitants, the quality of buildings and the dissemination of industrial facilities, make the Campania-Lucania a region with seismic risk exposure rather high. To this aim, the geologic formations from 1:250,000 scale regional geologic map, have been sorted into four macro-classes described by units having similar age and physical properties (grain size, hardness and fracturing). These macro-classes have been considered representative of Quaternary alluvium (Q), Quaternary-Tertiary volcanic rocks (V), Tertiary sediments and soft rocks (T) and Mesozoic hard rocks (M), respectively. In order to design the Campania-Lucania site-conditions map, these categories have been digitized on a 1:250,000 scale regional geologic map, tracing only the geologic contacts that separate units belonging to different categories. According to the EC8 soil classes, we have assembled a database of Vs profiles by the National Strong Motion Network (RAN, Working Group ITACA, 2008), and used computed Vs30 to characterize QVTM units. Because of the wide extension of the map and to lack of Vs profiles in most geologic units, we have classified geologic units on the basis of the Vs measurements where available, and on lithological and age criteria for those units without Vs profiles.

The site conditions map, built with our current level of information, provides an outline of surface geology characteristics that can be used to account for site effect in the ground-shaking maps. We stress that, the accuracy of this map will evolve as more shear-wave velocity measurements and more geologic information become available, in order to highlight significant variations in site response for different geologic unit.

Geological and seismological settings of the Campania-Lucania, southern Apennine region. Southern Apennine mountain chain (Italy) is a Neogene post-collisional east-verging thrust belt formed as the result of the west-dipping subduction of the Apulian-Ionian lithosphere (Doglioni et al., 1996). The belt is associated with the Tyrrhenian back-arc basin to the west, and with the Bradano foredeep to the east. During the middle Miocene-upper Pliocene, several compressive tectonic phases associated with the collision between the African and European margin, have determined thrusting and piling of different units toward stable domains of the Apulo-Adriatic foreland (Figure 1). From late Tortonian to Quaternary, all the system rapidly migrates eastward as a consequence of the retreating of the sinking foreland lithosphere (Patacca and Scandone, 1989, Patacca et al., 1990; Pescatore et al., 1999).

The structural complexity of the Campania-Lucania region, is due to different paleogeographic domains involved in the southern Apennine thrust belt building. The basinal facies terrains have been involved in ductile deformations, while the carbonate platform sequences in brittle deformations. Additionally, the deformation did not proceed cylindrically but it was characterized by out-of-sequence thrust-propagation processes (Roure et al., 1991). During the upper Pliocene-lower Pleistocene, the tectonic evolution has determined the mountain chain subdivision into the NNW-SSE-trending Molise-Sannio, and the WNW-ESE-trending Campania-Lucania region. Afterwards, in the Middle-Pleistocene, the southern Apennine wedge has uplifted and has been involved in a NE-SW extensional tectonic event. This stress regime has determined the development of large extensional and transtensional structures and it is still active and responsible of the present-day seismicity of the region (Anderson and Jackson, 1987). Most of earthquakes are located into the narrow upper-crustal seismic belt (30-50 km). In particular, two different clusters of crustal earthquakes can be identified: the westernmost with shallow earthquakes (depths < 20 km) centred on the axis chain (Irpinia area), and the easternmost with deeper earthquakes (about 20-40 km) located on the outer margin of the chain (Potentino area) and the foredeep. These earthquakes have different focal solutions indicating a pure extensional regime to the west (Irpinia area), and strike-slip regime to the east (Potentino area). Moreover, it is possible to recognize a third zone, located within the Apennine chain from the Vallo di Diana to the Agri Valley, characterized by low seismicity (Figure 2a).

The larger seismic events occurred along the Apennine chain have shown normal faulting mechanisms in agreement with the regional NE trending extension. In this context, the Campania-Lucania region is one of the most active seismic zones of the southern Apennine, where important extensional faults are in connection with the major seismic events that struck the area historically (Westaway, 1992). The location and magnitude of the historic earthquakes retrieved from the CFTI (Catalogo dei Forti Terremoti in Italia, Boschi et al., 1997), are shown in Figure 2b. Among these, there is the most recent event represented by the 1980 Irpinia earthquake (Mw 6.9) (Westaway and Jackson, 1987; Bernard and Zollo, 1989). More recent studies indicate that the 1980' faulted area is currently interested by an intense seismic activity with the occurrence of small to moderate-size events. For this area Cinti et al. (2004) assign a relatively high probability (about 30%) for a moderate to large earthquake to occur in the next 10 years.

Developing of a site conditions map from geologic map

The first step for the generation of a site-conditions map to be used as a Vs category map, consists in selecting an appropriate geologic map. Geologic maps show units that are distinguished by their ages, lithologies, grain size, and other factors that may be correlated with Vs. Usually, the most detailed geologic maps are at 1:50,000 scale, where units that have major influences on the amplification ground motion, the Quaternary units, are split in different units. For the time being, only maps at 1:100,000 scale are completed and available for the study region. In order to cover the whole area, we would have had to assemble several 1:100,000 geologic scale maps into a uniform digital map. Another alternative is to use a 1:250,000 scale geologic map that includes completely the region. Although the most detailed geologic maps may provide a better site-conditions map, in the present paper, we have chosen to use a larger albeit less detailed map to completely cover the region of interest with a single map readily available, rather than to work with an unmanageable number of maps. Thus, we have used the 1:250,000 scale geologic map of southern Italy by Bonardi et al., 1988**.**

The southern Apennine area is characterized by a widespread of Quaternary cover, a few outcrops of Pliocene clastic deposits, and various Tertiary sedimentary successions. These main units can be grouped in three belts ranging from east to west, and identified as follows:

1. successions with basinal to marginal facies, in age from Cretaceous to Miocene, tectonically lying on Plio-Pleistocene foredeep deposits;
2. successions with shallow-water, basinal and shelf-margin facies, ranging in age from middle Triassic to Miocene (‘Lagonegro units’), overthrust on the previous ones;
3. Triassic to Miocene carbonate platform successions (‘Appeninic platform units’), overthrust on the Lagonegro units;

Moreover, volcanic rocks are extensively diffused in the Campania-Lucania region. The main volcanic vents are: the Campi Flegrei, an active volcanic complex located on the eastern border of the region, the Mt. Somma-Vesuvio, an active volcano situated in the central area near Naples, and the Mt. Vulture a not active volcano located on the western border of the region.

All the units have been sorted into four different categories on the basis of lithological and age criteria, as proposed by Park and Elrick (1998). The resulting four classes, that are expected to have similar V_S, are: Quaternary alluvial deposits (Q), Quaternary-Tertiary volcanic rocks (V), Tertiary sediments and soft rocks (T), and Mesozoic hard rocks (M). The four categories (QVTM) have been overlapped on the 1:250,000 scale regional map, tracing only the geologic contacts that separate units of different categories (Figure 3).

Shear-wave velocity of the proposed geologic categories

As discussed before, the Vs30 is an important parameter used for classifying sites in recent building codes and to predict their potential to amplify ground-shaking. As a consequence, to each of the identified QVTM categories a Vs30 value or a range of values, must be assigned. The main complication with this approach is that shear-wave velocities are only measured at few discrete points, and a method of extrapolation is thus necessary for any point other than the sampled ones. Sometimes, there are too few measurements in a given geologic unit in order to adequately characterize its response. Or two geologically distinct units may have similar velocity distributions and thus exhibit similar responses.

For the region considered in the present study, the only profiles currently available are those retrieved from the database of the National Strong Motion Network (RAN, Working Group ITACA (2008) - Data Base of the Italian strong motion data: http://itaca.mi.ingv.it). These velocity profiles present different depths. Among all the available profiles, we decided to use only profiles that can be correlated with the mapped category units.

Therefore, plotting the location of the site profiles on the QVTM map, we found twelve measured velocity profiles that fall within our site-conditions map. As shown in Figure 3, three fall within the Quaternary category, three within the Mesozoic category, four within the Tertiary category and only two profiles within the Volcanic category. For each profile of soil or rock, the representative average Vs30 has been computed from travel time of the vertically propagating shear waves according to the theoretical modelling of a uniform soil layer on top of the bedrock :

$$Vs30=\frac{30}{\sum_{i=1,N}\frac{h_i}{V_i}} \qquad (1)$$

where h_i and V_i denote the thickness in meters and shear-wave velocity in m/s of the *ith* formation or layer, in a total of N, existing in the top 30 meters.

The Vs30 is an important parameter used for classifying sites in recent building codes and to predict their potential to amplify ground-shaking. In these classification codes the depth of the first resonant layer is connected not only at the frequency but also the amplitude of local site response.

The shear-wave velocity profiles and the calculated Vs30 values for each category, are shown in Figure 4. Vs30 values calculated from profiles belonging to the Mesozoic class, are quite uniform ranging from 1122 to 1153 m/s (Figure 4a). These values are mostly representative of fractured hard rocks.

The widespread Tertiary sedimentary successions, instead, are highly variable both in lithology and amount of deformation. Commonly, these units are subdivided on geologic maps into many formations based on age, grain size and lithology. We have found that the various flysch units that outcrop prevalently in the central sector of the southern Apennines, show Vs30 ranging between 524 and 976 m/s depending on the weathering and amount of fracturing (Figure 4b). The only profile available for younger fine-grained deposits of the Tertiary age (Miocene and Pliocene), located in external area of the Apennine belt, shows a 365 m/s Vs30 value.

Quaternary units typically present extremely variable velocity characteristics because they vary in thickness, grain size, density, porosity, and cementation. In the present study, we have found that these young soil deposits have Vs30 values ranging from about 192 to 506 m/s (Figure 4c). The few Vs profiles currently available suggest that Vs30 calculated for these units, are only crude approximations of the Vs characteristics of the Quaternary units. Furthermore, Vs measurements would allow to identify variations in thickness and grain size, and an attempt to subdivide those units in several classes should be made.

Only two Vs profiles are available for Tertiary-Quaternary volcanic units. One of two has been measured in pyroclastic flows of the M.te Vesuvio, while the other one in sodic potassic lahars of the M.te Vulture. The average 618 m/s Vs30 value of these profiles, is typical of volcanic rocks which are harder than younger Tertiary deposits (Figure 4d). Generally, because of their lithologic variability, the volcanic rocks exhibit variable velocity characteristics. Units such as basalt, (hard rocks but extensively fractured), and pyroclastic rocks (loose agglomerations of volcanic ash) tend to have velocities ranging from about 360 to about 1000 m/s depending on the weathering and amount of shearing.

For each geologic category we have also computed a composite shear-wave profile following the method proposed by Wills et al. (2000). These profiles have been obtained by calculating the mean and standard deviation of shear-wave velocity using a 1 m depth sampling. Composite profiles help to highlight possible deficiencies in the available data set and units that must be further subdivided.

Figure 5 shows the composite profile for each geologic class along with the standard error. Although we have few profiles for each category, all composite profiles have clearly shown a variability of shear-wave velocity with depth and a large vertical variation of standard error. Moreover, as reported in Will at al. (2000), the shape and the variability of Vs profiles can also allow to identify where vertical variations along the Vs profile affect the Vs30 characteristic of a unit, where materials with differing Vs have been included in the same unit, or that a unit is extremely variable. The composite profile for Mesozoic class shows a relatively rapid increase in velocity from about 500 m/s at the surface to over 1600 m/s at 15 m (Figure 5a). Then, after three velocity inversions, it shows a highly variability until 72 m depth. The large standard deviation throughout the composite profile, reflects the variable shear-wave velocity related to different degree of deformations that rocks have undergone.

The composite profile for Tertiary class shows a slow increase in velocity from about 600 m/s at the surface to over 1000 m/s at 95 m depth (Figure 5b). The apparent regularity in the profile is probably due to few data measured on sites that are near, located in the central sector of Appeninic chain. This composite profile is, then, representative only of the Tertiary units that outcrop in the central sector of the southern Apennines.

The composite profile for Quaternary class shows an almost steady increase in velocity until to 70 m, and a more gradual increase both in velocity and in standard deviation from 70 to 95 m (Figure 5c). The velocity values are higher than would be measured at a site on alluvium deposits.

Generally, alluvium deposits have Vs30 ranging from 180-360/s as reported in EC8 Site Classes (2003). It's probable that measurements have been done in basins where young and thin deposits are at the surface, while the harder materials are at shallow depth in the subsurface. In these situations, Vs profiles may include significant thicknesses of harder rock that lies underneath thin layer of alluvium deposits. Given the small number of profiles measured in these units, we don't have subdivided the young deposits based on thickness and grain size.

For the Volcanic category we have calculated only the mean value, because up to this time only two shear-wave velocity profiles are available. The composite profile features rapid increase in velocity from about 400 m/s at the surface to over 1600 m/s at 80 m (Figure 5d).

Clearly for these units, as the Quaternary units, is desirable to have more shear-wave velocity measurements and more geologic data in order to highlight significant variations in site response for mapped young sediments.

Site-classification using the average shear-wave velocity

In order to test the accuracy of our geologically defined site categories, we have classified each site category in terms of EC8 site classes comparing the lithological features and the Vs30 values inferred from the our analysis, with the EC8 categories.

EC8 identifies 7 ground types A, B, C, D, E, S1 and S2, described by the stratigraphic profiles, that may be used to account for the influence of local ground conditions on seismic actions. Starting from class A, corresponding to hard rocks or hard rocks covered by very thin soil deposits, the code details grounds having gradually decreasing rigidity until ground types S1 and S2, much deformable. Following the provisions by EC8, sites can be classified according to the Vs30 parameter, if it is available, otherwise the value of NSPT (Standard Penetration Test). Recent developments of soil classifications include also the site predominant period as site class parameter (Japan Road Association, 1980, 1990). To a first order approximation, the dominant period is estimated as four times the S-wave travel time in the soil layer, assuming that medium can be represented by a single soil layer, 30 m in width, with a constant shear-wave velocity.

Table 1 lists outcropping formations of the Campania-Lucania region grouped into the four site classes QVTM built following the lithological and age criteria, the associated Vs30 values, the calculated dominant site period, and the categories from EC8. Our database is predominantly composed of ground types A, B and C, and we don’t have found any site belonging to class D. However, all measured Vs30 values fall within expected range for the unit within which are located. The QVTM map (Figure 3) has been compared with the Geological-Class map produced by Cultrera et al., Task 3.2 (2004), GNDT-INGV Project (framework program 2000-2002). This map has been built in order to introduce the role of local geology in the seismic hazard evaluation at nation scale. In this context, the geological units of the 1:500,000 Italian geological map (Servizio Geologico Nazionale,1978) have been grouped into the three classes A, B, C according to the EC8, using lithological and age criteria (Figure 6). Because of the large scale of the original geologic map, the small-size Quaternary basins characterizing the Apennines are often missed. The comparison between the two maps evidences the better detail of the QVTM map. In the National Geological-Class map shown in Fig.6, the volcanic units, extensively diffused in the Campania-Lucania region, haven’t been characterized. In practice, it is better to consider these volcanic units as an additional class, due to their attenuation characteristics, that may greatly affect the ground motion values. Additionally, the QVTM map shows a better characterization of units that outcrop along the central sector of the Southern Apennines.

Conclusions

In order to account for site conditions in calculating seismic hazards or ground-shaking maps soon after a moderate-to-large earthquake, a possible way investigated by several authors (e.g, Wald and Mori, 2000; Wills and Clahan, 2006; Wills et al., 2000), is to build a site classification using the average wave velocity to 30 m, as indicator of the quality of sites.

Using the available information of the local geology, we have developed some generalized site classes, according to the European norm, commonly referred to as EC8. The approach and geologic categories described in this work, results in a map, the QVTM site conditions map, that yields site conditions information for some units of the Campania-Lucania region. As underlined in Wills et al. (2000), the accuracy of a site-conditions map is limited by the number of Vs profiles available. It is clear that it is necessary to have a significant amount of data to represent each unit as a whole. Due to the lack of sufficient V_S profiles, we have not been able to highlight those areas with different thickness of younger deposits, nor to separate areas where coarser grain size might lead to higher velocities or others where finer alluvium might lead to lower velocities. Consequently, our approach has been to consider only the general geologic categories, alluvium, soft rock, and hard rock, which are correlated with the site conditions terms used in strong-ground motion attenuation equations.

To further refine the proposed map, detailed information on Quaternary and Volcanic units are needed in order to underline significant variations in site response for mapped young sediments. However, the resulting site classification map may provide a basis as is or in conjunction with other factors, for more precise characterisations of the site conditions in probabilistic seismic hazard calculations.

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Table

Ground Type	**Age**	**Site Natural Period (sec) (T=4h/β)**	**Vs30 (m/s)**	**Subsoil class and Vs30 (m/s) in EC8**
Carbonate platform successions	**Mesozoic (M)**	**T < 0.15**	**Ranging from 1122 to 1153**	**A (rock) Vs > 800**
Sediments, soft rocks and flysh deposit	**Tertiary (T)**	**0.15 = T < 0.3**	**Ranging from 365 to 976**	**B (stiff soil) 360 <Vs < 800**
Volcanic rocks	**Quaternary-Tertiary (V)**	**0.12 =T < 0.3**	**Ranging from 539 to 506**	**B (stiff soil) 360 <Vs < 800**
Alluvium and gravel deposits	**Quaternary (Q)**	**0.3 = T < 0.6**	**Ranging from 192 to 506**	**C (soft soil) 180 <Vs < 360**
Very soft soils	**Quaternary (Q)**	**T = 0.6**		**D < 180 (very soft soil)**

Table I. Comparison between the QVTM categories, the computed site natural period and Vs30 values, and the EC8 Site Classes (2003).

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Figures

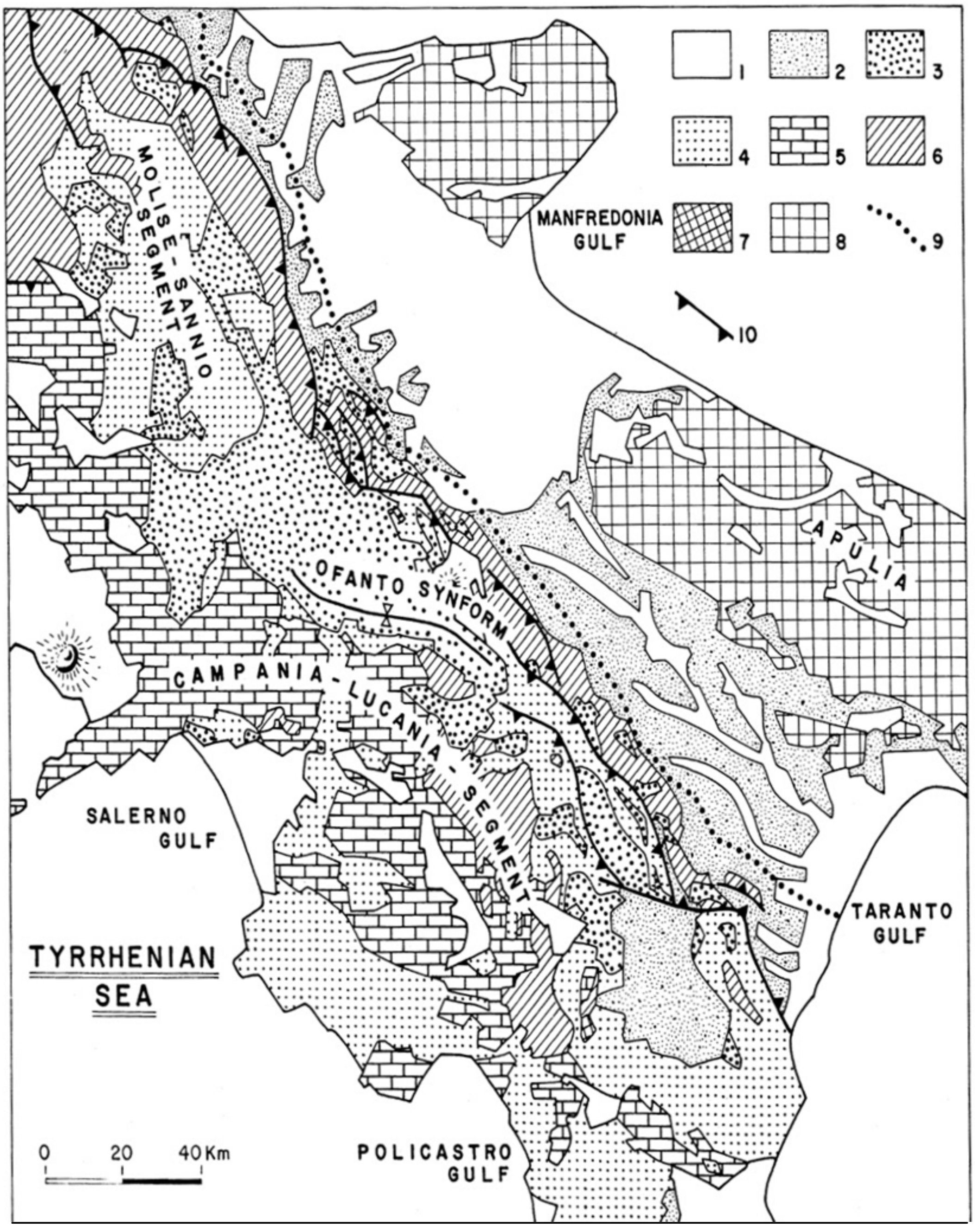
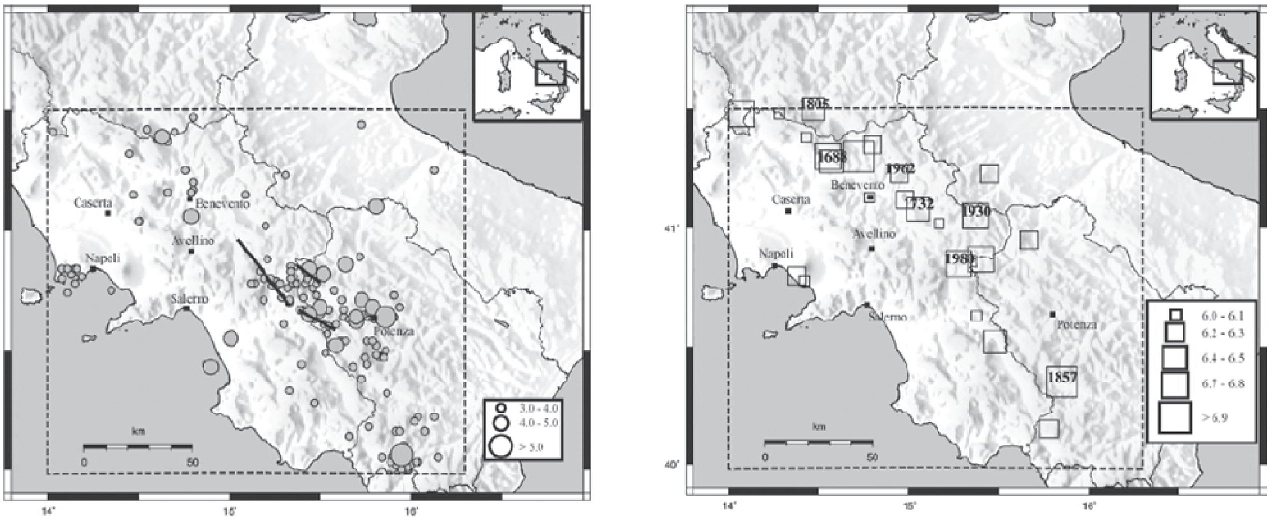


Figure 1. Simplified geological map of central and southern Apennines (from Cinque et al., 1993). 1) Continental and paralic Middle Pleistocene to Holocene deposits; Quaternary volcanoes. 2) Upper Pliocene-Lower Pleistocene marine to continental deposits, including the Bradano cycle. 3) Upper Tortonian to Upper Pliocene clastic deposits accumulated in piggy-back basins formed on top of the advancing nappes. 4) Appenninic nappes derived from internal paleogeographic domains, originally located between the European plate margins and the western carbonate-platform system.

5) Appenninic nappes derived from the western carbonate-platform system related marginal areas. 6) Appenninic nappes derived from a basinal realm originally located between the western platform and eastern platform domains.

7) Mt..Alpi unit. 8) Mesozoic-Tertiary carbonates of the Apulia foreland. 9) Frontal ramp of the Appennine thrust sheets. 10) Out-of-sequence thrust.



(a) (b)

Figure 2. a) Map of recent instrumental seismicity with M > 2.5 recorded by the INGV in the period 1981–2002 in the region defined by the dashed rectangle (Gruppo di lavoro CPTI (1999)). Dimensions of the circles are proportional to magnitude.

The black lines represent the surface projection of the three fault segments that broke in the 23 November 1980 earthquake (M 6.9). **b).** Locations of the main historical earthquakes retrieved from the CFTI database (Catalogo dei Forti Terremoti in Italia; Boschi et al., 1997) within the region defined by the dashed rectangle. The box dimensions are proportional to magnitude. The best-constrained historical earthquakes are reported along with their date of occurrence (from Weber et al., 2007).

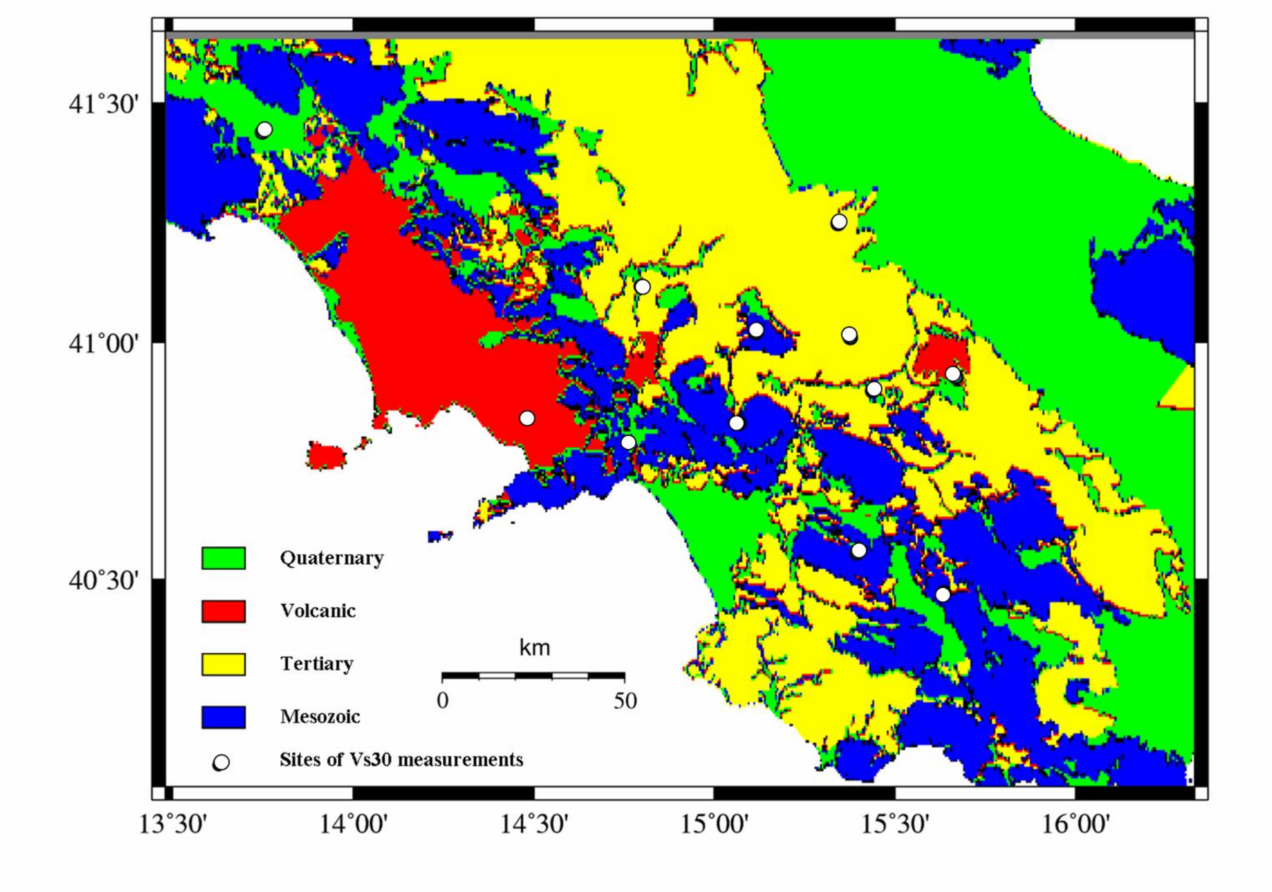


Figure 3. The QVTM site-conditions map, 1:250,000 scale, (Cantore, 2008). White circles indicate the sites of Vs30 measurements.

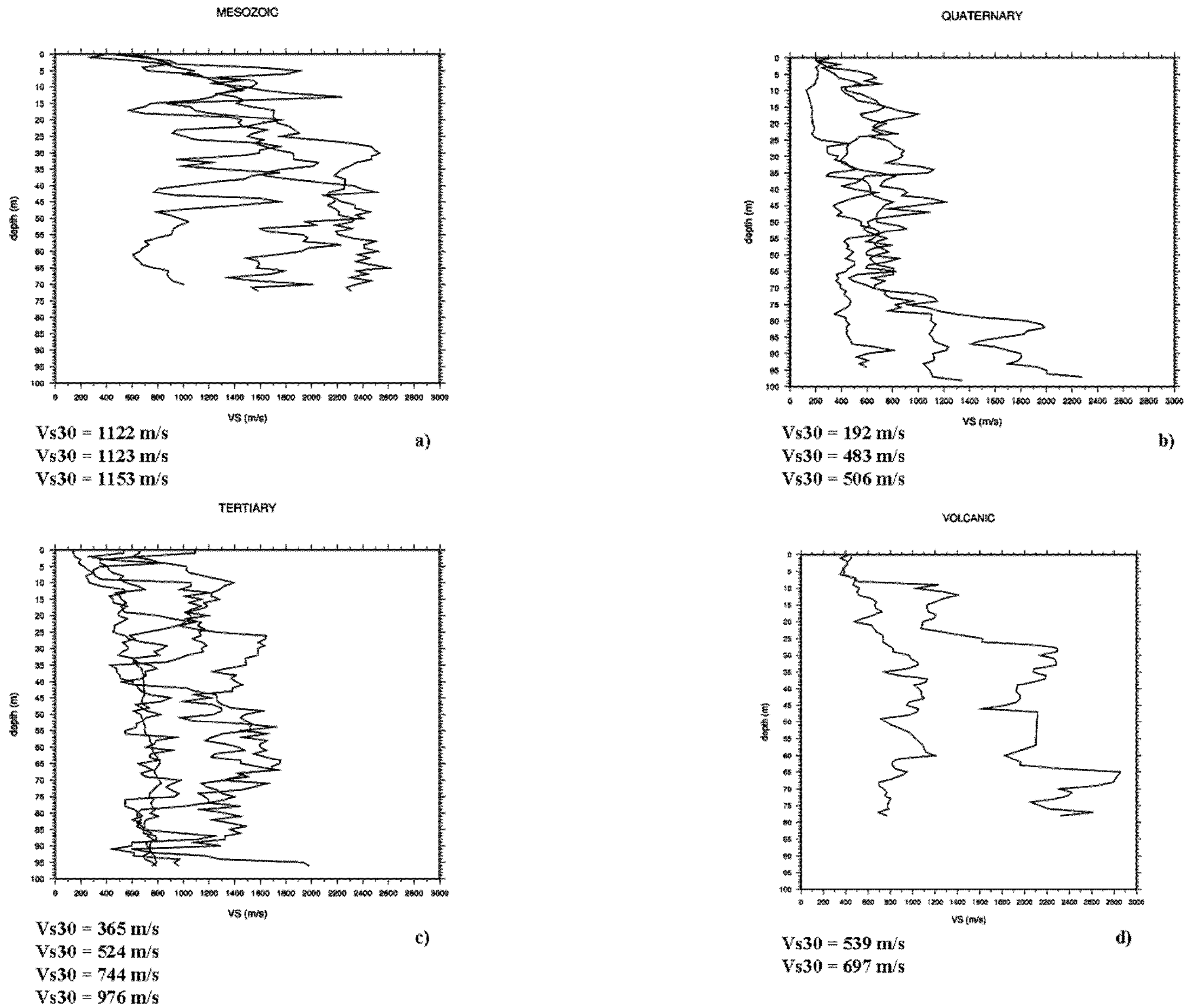


Figure 4. Shear wave velocity profiles and the calculated Vs30 for Mesozoic (a), Tertiary (b), Volcanic (d) and Quaternary (c) categories.

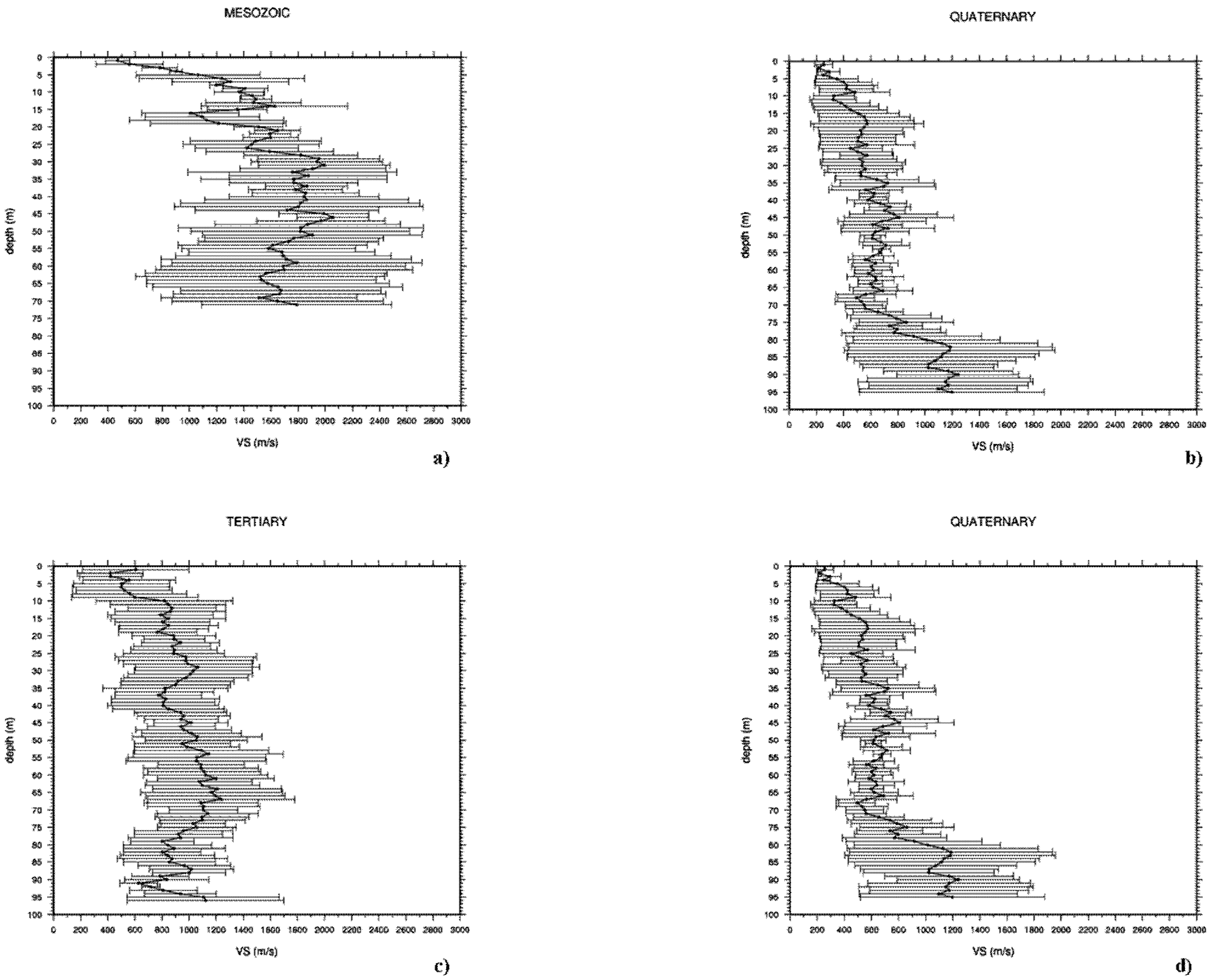


Figure 5. Composite profile for geologic Mesozoic (a), Tertiary (b) and Quaternary (d) categories. Shown are the mean and standard deviation shear-wave velocity at each meter depth. For sites classified as Volcanic class (d) the mean (dotted line), the minimum, and maximum profile are shown.

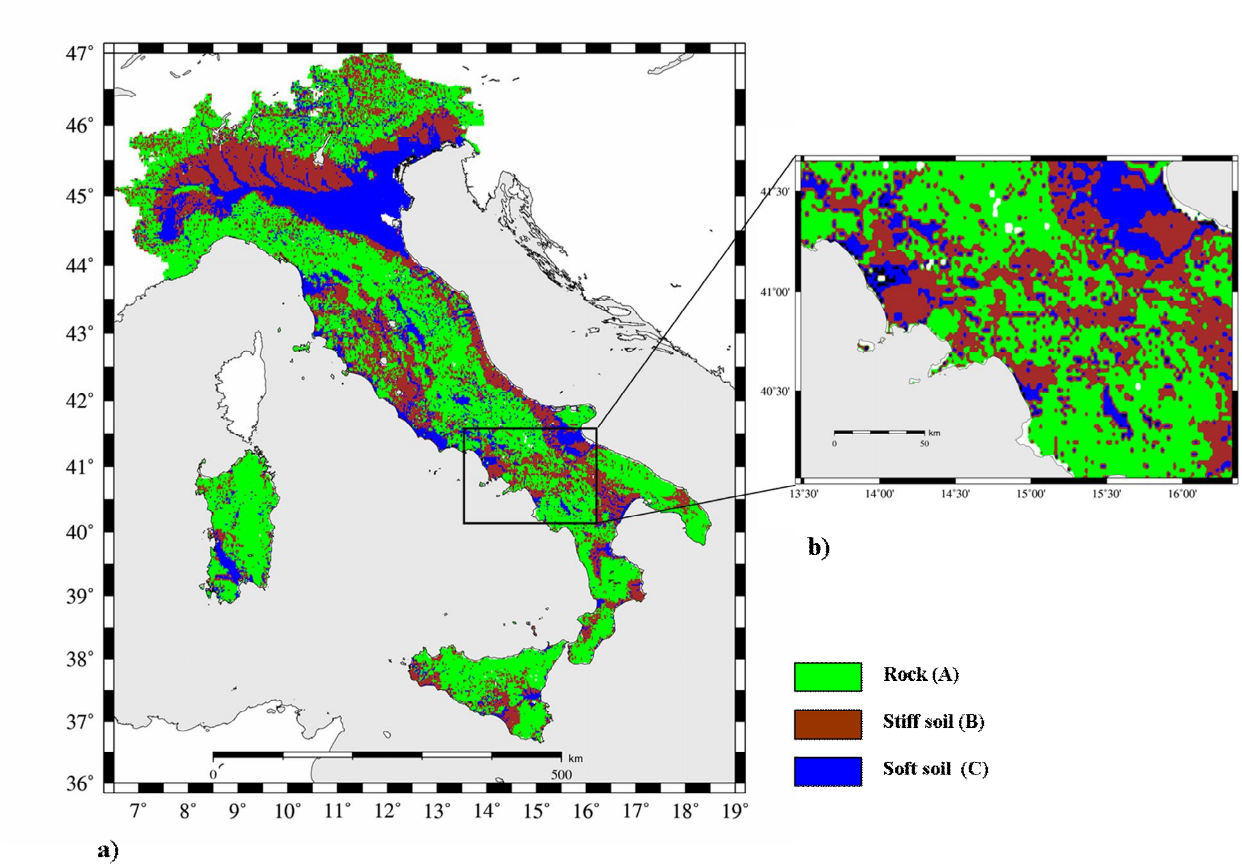


Figure 6. a). Geological-Class Map at 1:500,000 scale (SGN, 1978), reclassified according to the EC8 (INGV-DPC 2004-2006 S1 project).b). Zoom on the region of interest.