Scientific technical collaboration

*ISTITUTO SUPERIORE PER LA PROTEZIONE E LA RICERCA AMBIENTALE – **ISPRA***

*ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA – **INGV***

FINAL REPORT

Development of a conceptual geological model for five seismic station with accelerometer of the INGV Seismic Network

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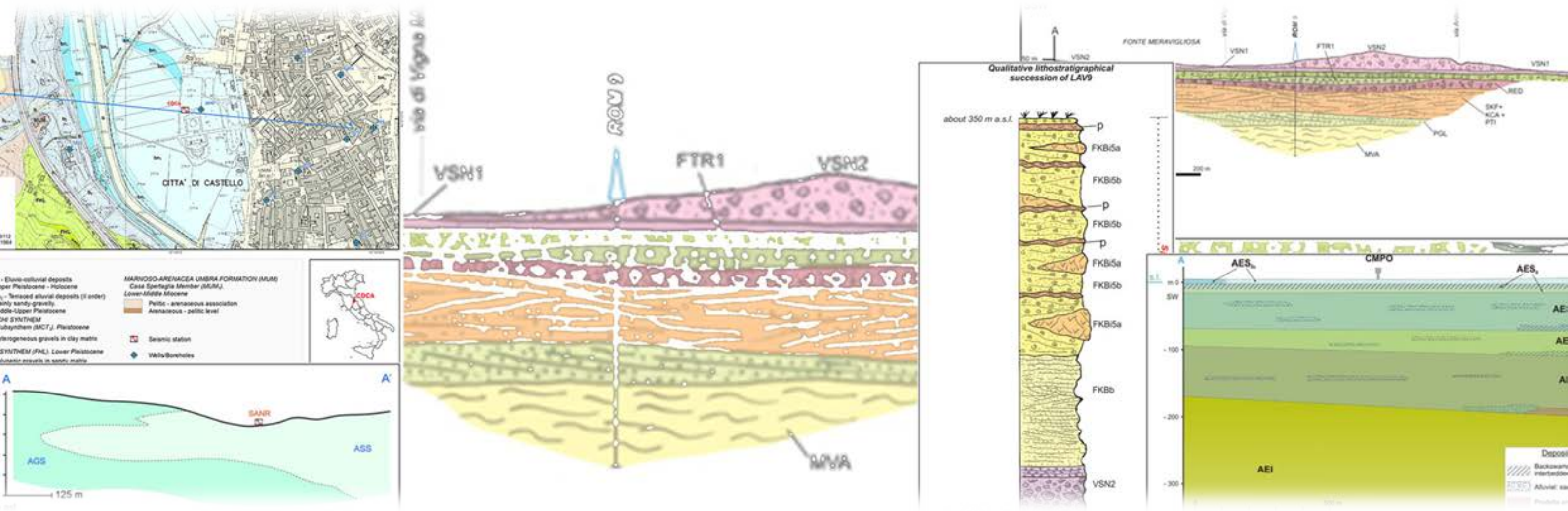

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SUMMARY

CMPO SEISMIC STATION

GEOLOGICAL SETTING

The seismic station CMPO is located on the southern side of the Reno river alluvial plain, along its tributary Idice creek. The region is almost completely flat, with areas below the sea level, with the exception of the artificial embankments of main streams and channels (Figg. 1 and 2).

Figure 1 – Photo of the area surrounding the CMPO station (view from south).
The seismic station is located near the small building in the background.

According to regional studies on the subsurface structural framework (CNR, 1990; REGIONE EMILIA-ROMAGNA & ENI-AGIP, 1998), based on seismic reflection profiles, this part of Pianura Padana is characterized by a NW-SE oriented wide syncline, gently dipping toward SE, bounded by thrusts aligned from Bagnacavallo to Buda, in the inner sector, and from Longastrino to Consandolo, in the outer sector.
The base of Pliocene deposits is at depth of 5,000 meters in the deeper part of the syncline and rises up at depth of 500 meters in the northeastern part of the area of Longastrino. The Pleistocene units follow this general trend.
The geological history of this sector is controlled, from Middle Pleistocene, by the evolution of fluvio-deltaic, coastal and alluvial depositional systems fed by the Apennine and Po river drainage network. This complex depositional system produced the Supersintema Emiliano-Romagnolo (AE) recognized at regional scale from the westernmost part of Pianura Padana to the present coastline; it is arranged in a stack of unconformity-bounded stratigraphic units (UBSU).
The lower boundary of Supersintema Emiliano-Romagnolo with the Sabbie di Imola (Middle Pleistocene) is observed along the Apennine margin and recognized in some borehole stratigraphies at a depth increasing from few, up to several hundred, meters below the Po plain, moving from SW toward NE.
The Supersintema Emiliano-Romagnolo is subdivided in two synthems: the Sintema Emiliano-Romagnolo Inferiore (AEI), not outcropping in this area, and the Sintema Emiliano-Romagnolo

Superiore (AES) that outcrops only with its youngest unit: AES_{8a} - Unità di Modena of Subsintema di Ravenna.
The AEI, furtherly subdivided into sub-synthems, is constituted by cyclical alternating clay and silt of alluvial environment, with sand and subordinated gravel related to fluvio-deltaic and coastal environments. Its maximum thickness is up to 150 meters.
On the other hand, AES is subdivided into sub-synthems mainly related to a fluvio-deltaic depositional systems; its total thickness is up to 300 meters.
The outcropping deposits of AES_{8a} Unità di Modena - Subsintema di Ravenna in the area of CMPO station are alluvial deposits that pass northward to deltaic sediments, and southward to alluvial fan or terraced deposits. The AES_8 registers the Upper Pleistocene-Holocene evolution of the Pianura Padana drainage network.

GEOLOGICAL FIELD DATA AND SUBSURFACE DATA

The area (≈ 1 km^2) surrounding the seismic station CMPO is completely flat except for the presence of the artificial banks of Idice river, its tributaries and drainage channels of Cassa Campotto, moreover the area is highly reworked by agricultural activities. For these reasons the area lacks of outcrops and the geological observations are limited to the weathering deposits and soils (Figg. 1 and 2).

Figure 2 – Photo of the area surrounding the CMPO station (view from north).

According to Foglio 222 "Lugo" - Carta Geologica d'Italia scala 1:50,000 (ISPRA – Geological Service of Italy, 2014b) the deposits that can be directly observed are constituted mainly by silty clay, clay and silt. These deposits are related to a flooding environment and attributed to Unità di Modena (AES_{8a}); locally, in the south-western corner of the mapped area, subordinated fine sand and sandy silt are attributed to channel and levee environments. The age of this unit, based on archeological data, is IV-V century b.C. (CALABRESE & CIBIN, 2014). In the area surrounding the CMPO station, the thickness of AES_{8a} unit, defined taking into account borehole stratigraphies and geotechnical investigations (penetrometer test), is from few meters up to 10 meters.

Due to the morphological characteristics of the area, the information needed to define the lithostratigraphic architecture are mainly derived from subsurface data obtained from borehole stratigraphies, geophysical and geotechnical investigations collected in a wider area.
The information related to lithology (texture and grain size), thickness, depth and lateral variation of the geological units are derived from several boreholes (Fig. 3) specifically drilled for the realization of the Subsurface Sheet of the Carta Geologica d'Italia scala 1:50,000. The maximum depth of these subsurface data in the area around the CMPO station is 157 meters (S2_222, ≈ 10 km south-east of the station), with a mean value of 40 meters.
Deeper data have been derived from isobath maps realized for the study of REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998) and available as supporting materials in the Foglio 222 "Lugo" – Carta Geologica d'Italia scala 1:50,000 (ISPRA – Geological Service of Italy, 2014b), together with regional geological cross-sections constrained to surface geological data and interpreted seismic lines.
The integration of data from field survey, with subsurface constraints, allows to produce the geological map and related cross-section (Figg. 4 and 5).
Further description of the units represented in the geological cross-section are reported in the following chapter Lithostratigraphic model.

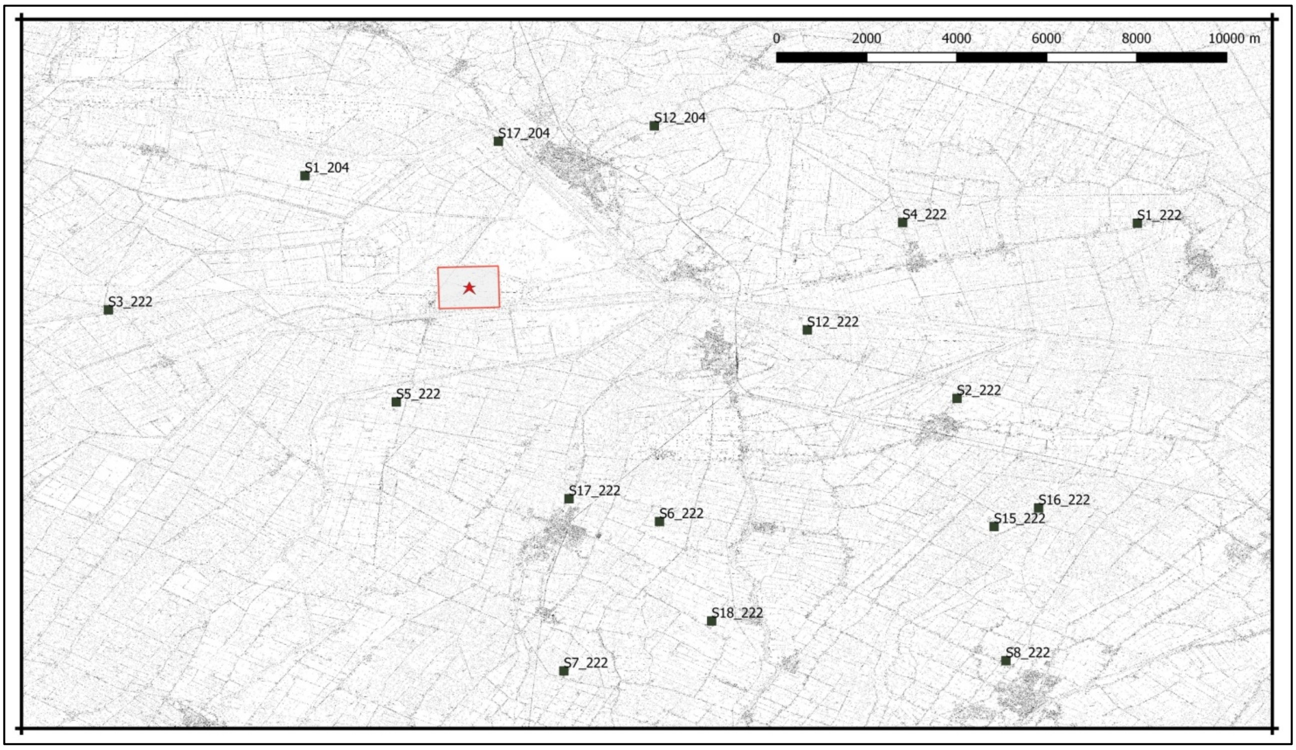


Figure 3 – Position map of the boreholes (black squares) drilled during the realization of Carta Geologica d'Italia Foglio 204 "Portomaggiore" and Foglio 222 "Lugo" (ISPRA – Geological Service of Italy, 2014a, b). The rectangle is the area surrounding the CMPO station (red star).

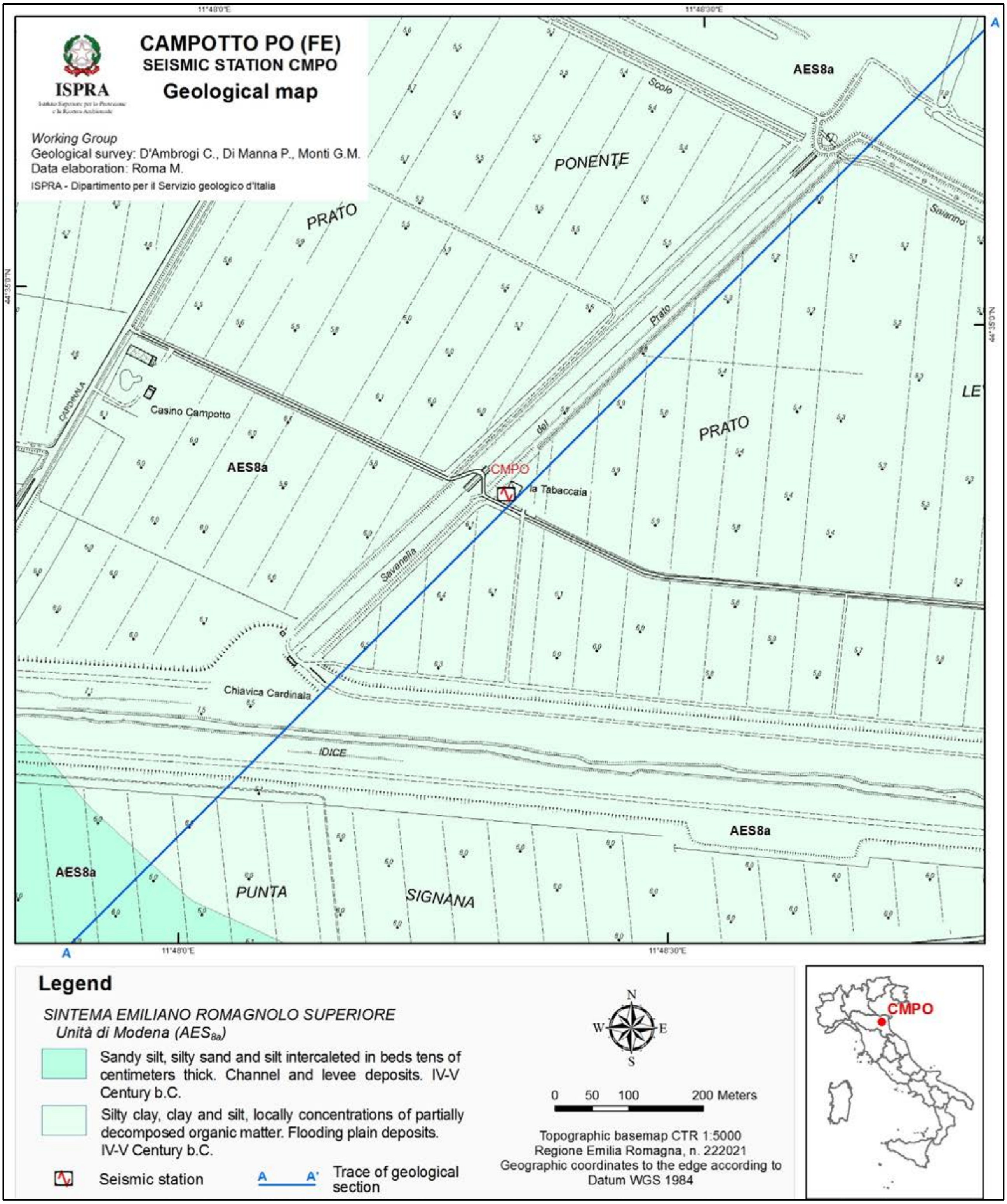


Figure 4 – Geological map after field work

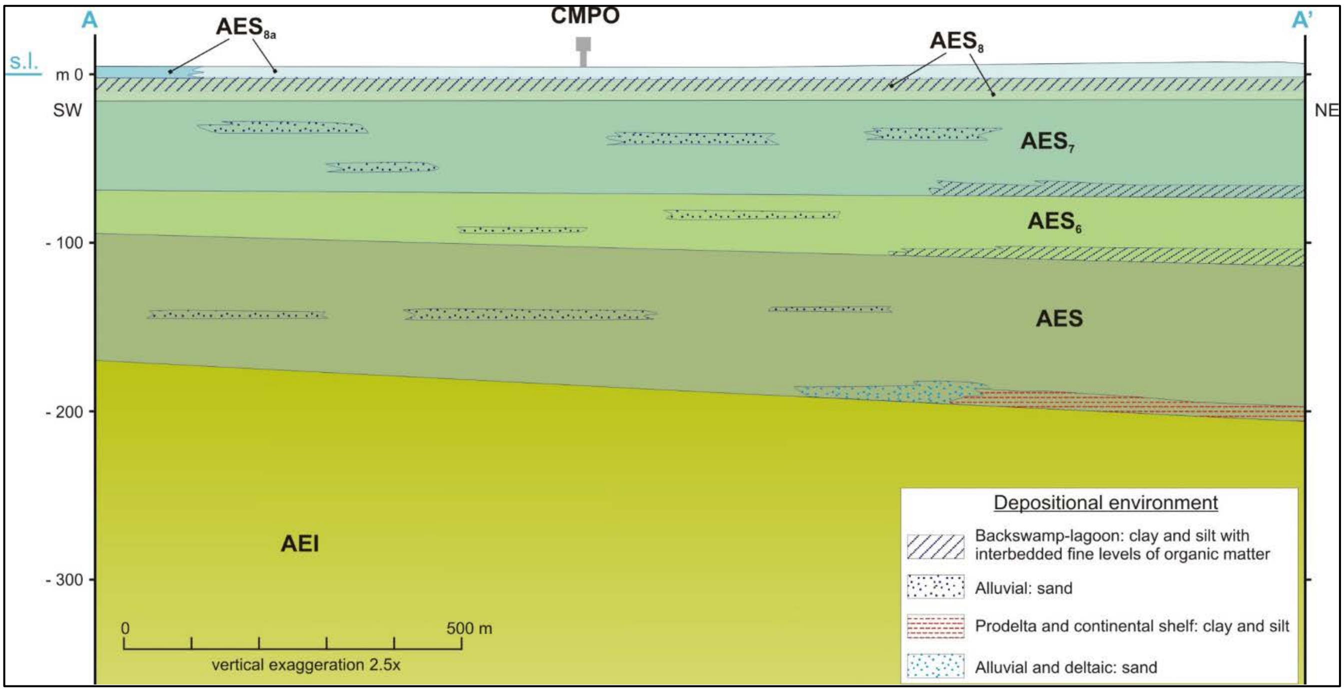


Figure 5 – Geological cross-section (see fig. 4 for the location)

LITHOSTRATIGRAPHIC MODEL OF CMPO STATION

A lithostratigraphic model for the area surrounding the CMPO station has been built according to data collected during geological field survey and deriving from literature or public database. The integration and correlation of data into a 3D modeling software allowed the reconstruction of main boundary surfaces for a wider area and to predict their shape and depth under the CMPO station area (1 km^2).

The lithostratigraphic model reaches a depth of 350 meters below sea level (Figg. 5 and 6), taking into account the distribution of borehole data (Fig. 3), the availability of isobath maps for specific stratigraphic surfaces, and correlation schemes. However, considering that the deepest borehole (S2_222) is 157 meters, starting from this depth the lithostratigraphic model and related unit descriptions must be considered less constrained and poorly characterized (see speculative stratigraphy in Fig. 6). Moreover it is not possible to define the exact position and extension of the sand bodies, that are sketched in Figure 5 and in Figure 6 just to indicate their existence.

The deeper reconstructed unit is represented by AEI – Sintema Emiliano Romagnolo Inferiore, regionally composed of alternating cyclic clay and silt with sand and gravel of fluvio-deltaic and coastal plain; clay and silt are the principal lithology, on the other hand the sand are not represented in the study area. The constrained thickness of the unit is up to 150 meters. At a regional scale it is known that the underlying unit is the formation of the Sabbie di Imola - IMO, here not constrained. Considering the regional trend it is possible to predict a depth of 450 meters below sea level for the Sabbie di Imola upper boundary.

The upward unit is the undifferentiated portion of AES – Sintema Emiliano Romagnolo Superiore. The unit is constituted, in this area, by cycles with a lower part characterized by clay and silt of

flooding environment, with organic-rich levels, passing to channel sand, with a typical coarsening-upward trend. The channel are wide up to 350 meters, with a thickness up to 15 meters. In the study area, due to the lack of boreholes reaching the needed depth, it is not possible to constrain or predict the position of these channel deposits. Moving toward NE the base of the unit is characterized by up to 20 meters of deltaic sand with lateral prodelta clay and silt (Fig. 5).
The boundary with the underlying AEI unit is gradual and not easy to recognize due to high similarity between the deposits. The total thickness of the undifferentiated AES is up to 100 meters.
Moving upward the next unit is represented by AES_6 - Subsintema di Bazzano, almost completely drilled by S2_222 borehole. Also this unit is characterized by a general coarsening-upward trend, with alluvial flooding clay and silt, with subordinated organic matter, passing toward north-east to clay and silt with inter-bedded levels of organic matter of backswamp and lagoon up to 10 meters thick. Upward the unit is characterized by fine sandy silt and silty clay with distal channel sand welded in tabular bodies (maximum lateral extension up to 500 meters, thickness up to 15 meters). These sandy bodies are not constrained in the CMPO area; their position and depth in the geological cross-section of Figure 5 are sketched. The maximum thickness of the unit is 40 meters.
The upper unit, AES_7 - Subsintema di Villa Verrucchio, is completely characterized in the S2_222 borehole ,and partially drilled by several other boreholes. The stacking pattern of this unit is the same of the underlying AES_6, with similar dimension of the tabular sandy bodies, and backswamp-lagoon clay and silt with organic matter extended at the base of the unit in the north-eastern sector. The maximum thickness of the unit is 60 meters.
The youngest unit is AES_8 - Subsintema di Ravenna, outcropping in the study area with the still evolving AES_{8a} - Unità di Modena AES_8. The AES_8 is constituted mainly by clay and silt with alternating silt and sand of flooding-not-drained plain, without evidence of the tabular sandy bodies characterizing the underlying units.
The most important element in this unit is represented by a well marked level referred to a backswamp-lagoon environment, up to 10 meters thick, of alternating grey to black organic-rich clay and silty clay, silt and sandy silt without organic matter; this level crosses both undifferentiated AES_8 and AES_{8a}. The total thickness of AES_8 is 20 meters.

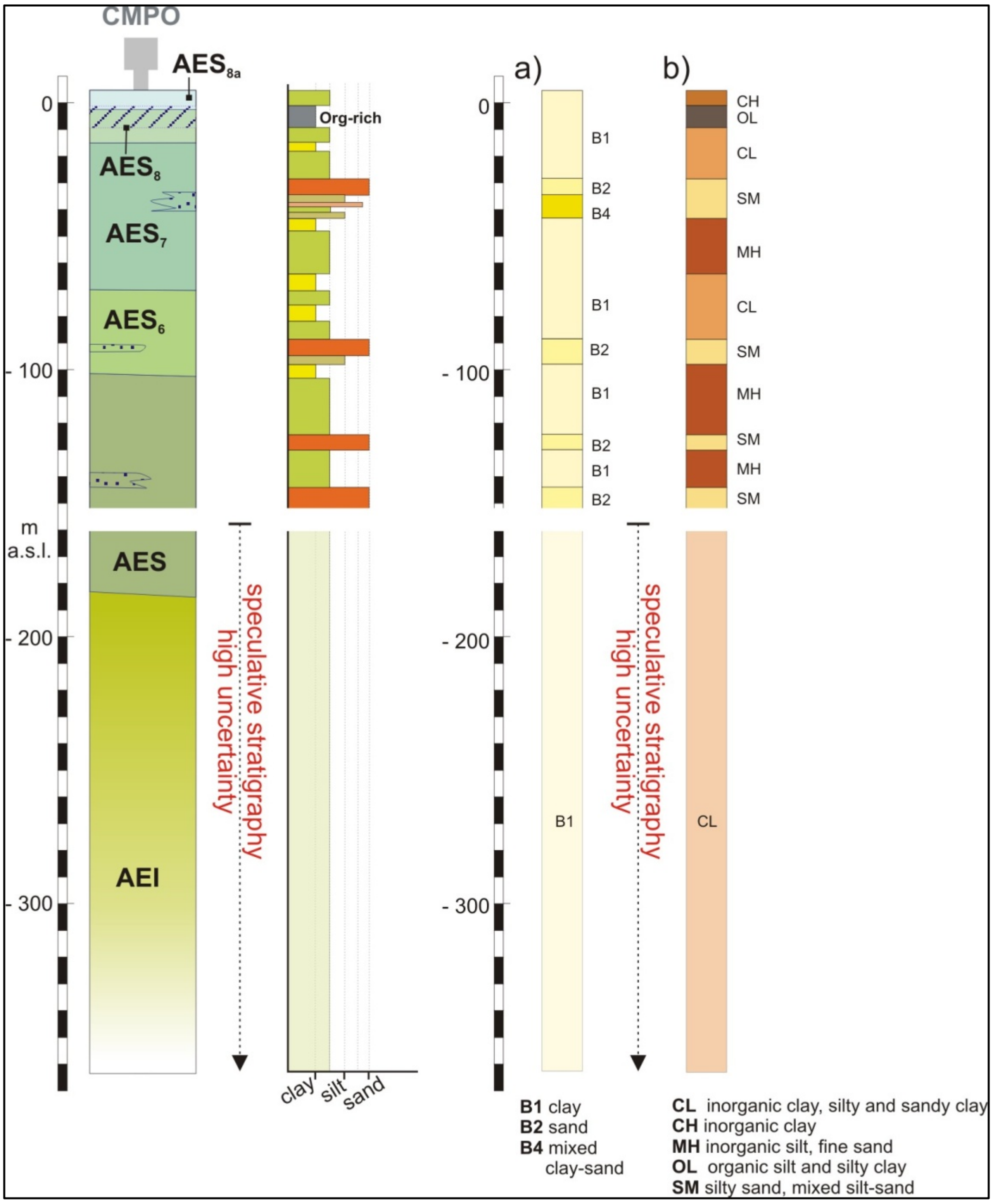


Figure 6 – (on the left) Lithostratigraphic model under the CMPO station and grain size classification. The position of the sand bodies and their depth are sketched due to the lack of constraints. The columns a) and b) represent the classification according to ISPRA lithological map and microzonation lithotechnical codes, respectively
Note that, starting from ≈ 150 meters (as marked in the figure), the proposed stratigraphy and related classification must be considered largely speculative and characterized by high uncertainty

Lithostratigraphic and lithotechnical classification

According to the geological field survey observations, and taking into account literature data, the following classification of the outcropping lithostratigraphic unit is proposed (Tab. 1 and Fig. 6). The resulting maps are in Figure 7 and Figure 8.

Lithostratigraphic unit (ISPRA, Geological map)		Lithological unit (ISPRA, Lithological map)		Lithotechnical unit (Guidelines 4.0b_MS, 2015)	
AES8a	Silty clay, clay and silt	B1	Clay	CHpi	Inorganic clay (flood plain)
AES8a	Sandy silt, silty sand	B2	Sand	SMes	Silty sand, mixed silt and sand (channel and levee)

Table 1 – Classification of geological units

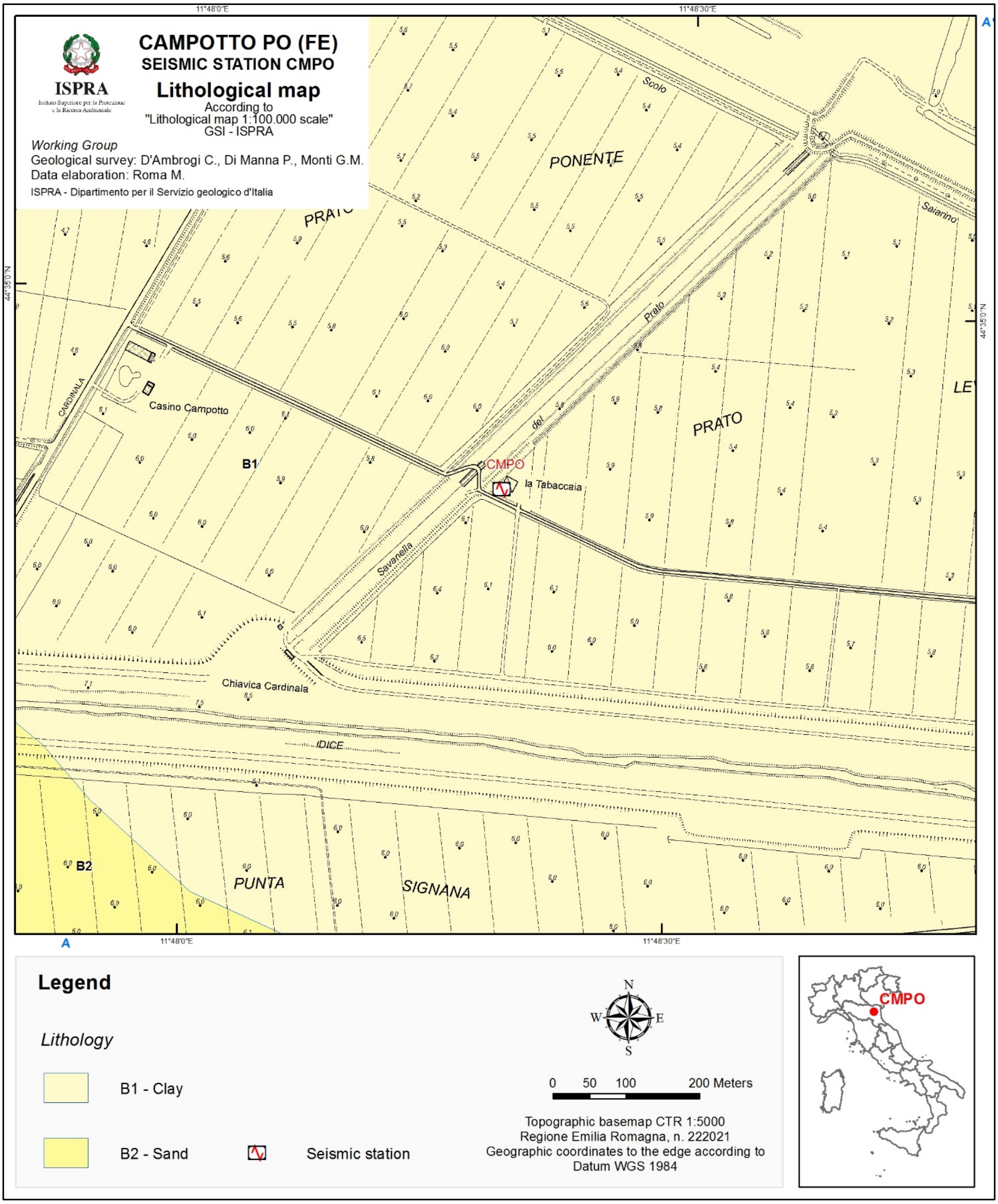


Figure 7 – Lithological map.

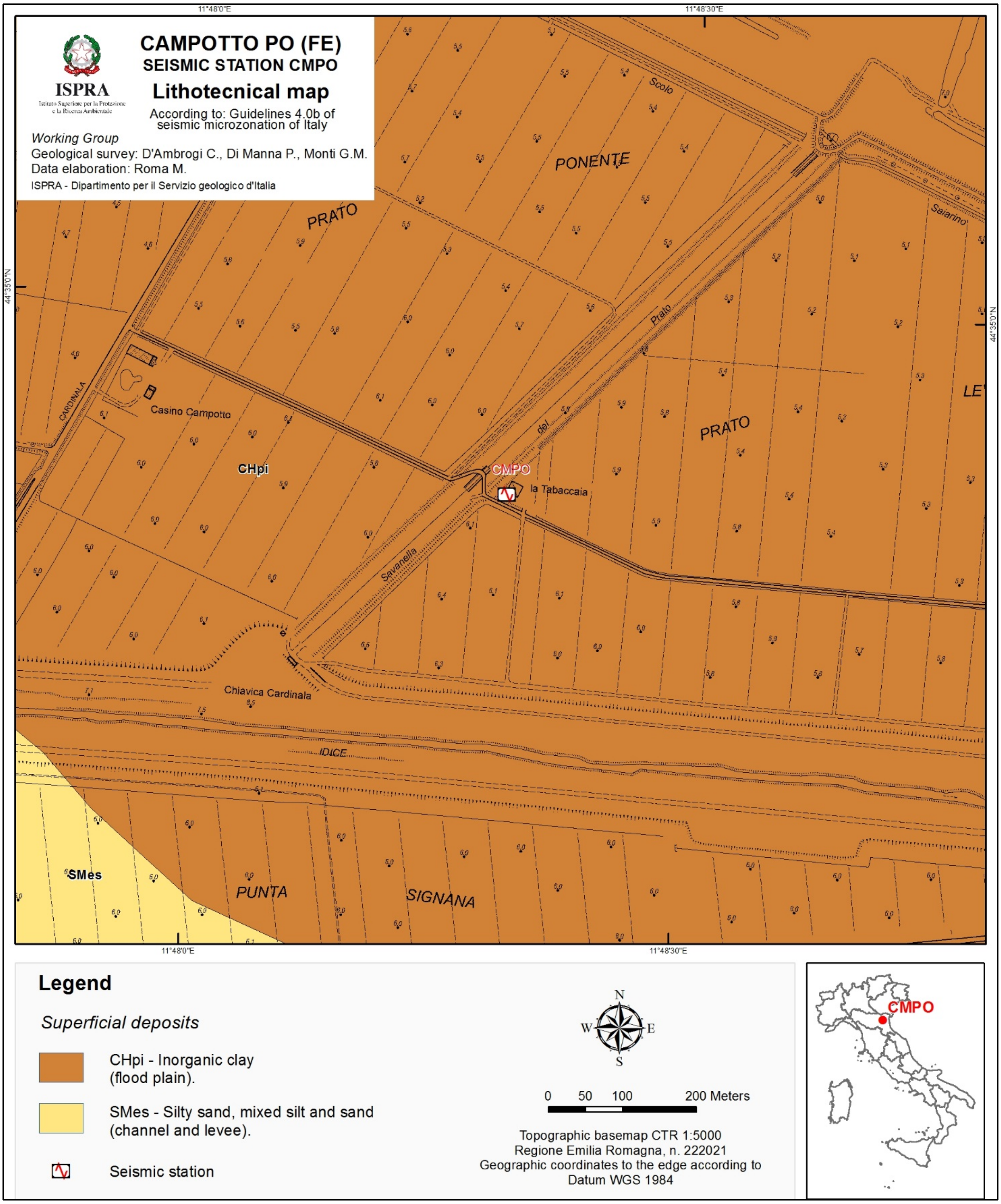


Figure 8 – Lithotechnical map.

ROM9 SEISMIC STATION

GEOLOGICAL SETTING

The ROM9 seismic station is located above an area straight interested by the Volcanic District of the Colli Albani, a composite volcano whose activity ranges from 600 ky to 5.8 ky BP, and marginally by the Sabatino Volcanic District, which was active from 550 to 80 ka BP, and whose fallout pyroclastic products could occur as records into the substratum (in such case, the Tufi Stratificati varicolori di Sacrofano).

In detail, the area of ROM9 lies above a succession of ignimbrite pyroclastic flow units (from below: Palatino unit, Casale del Cavaliere unit, Pozzolane Rosse, Pozzolane Nere, Tufo Lionato and Pozzolanelle), emplaced as planar bedded plateau, variably grainsized and with quite changing textural features; this succession is ascribed to the first eruptive stage of the Colli Albani, which was characterized by the mainly explosive caldera forming activity of the Vulcano Laziale lithosome. To the pyroclastic succession can interlayer at variable heights several pedogenic levels, reworked or lahar deposits (as the Conglomerato Giallo) deriving from the ignimbrite deposits and, more rarely, lava deposits, in particular flowing into the paleo-depressions of the ignimbrite plateau.

The pre-volcanic substratum is made of sedimentary units referable to the transitional and continental environments of the PaleoTevere river (Ponte Galeria formation; FUNICIELLO et alii, 2008), such as conglomerates and sandy-silty deposits that testified during the Lower Pleistocene the progressive rising of the area, the developing of a wide fluvial delta and the closing of the previous marine cycle. Below this sedimentary succession the boreholes drilled the marly-clayey lithotypes of the Monte Vaticano formation, a Pliocene bathyal unit (Argille Azzurre *Auctt*, FUNICIELLO & GIORDANO, 2008). The variable depth of the top of the clayey substratum has to be referred to the tectonics that from the Upper Pliocene faulted it into several blocks showing a mainly NW-SE display (MARRA *et alii,* 1995).

The whole succession is covered by the silts, sands and clays deposited in the alluvial plains by the Tevere River and his tributaries during the Holocene.

GEOLOGICAL FIELD DATA AND SUBSURFACE DATA

The field surveying has been made at 1:5.000 scale (Fig. 6)on the topographic map of the Latium Region. The study area is highly urbanized, so it was possible to acquire the textural and lithostratigraphical evidences, besides the minimum thicknesses, of only some of the main pyroclastic units such as Pozzolanelle (VSN_2) and Tufo Lionato (VSN_1), the two units of the Villa Senni formation, occurring in the few surrounding outcrops.

In the cut of a new road in the corner between Vigna Murata and Ardeatina roads the Pozzolanelle unit crops out for a thickness of 3 meters, as a red volcanoclastic deposit, scarcely coherent to semilithoid, made of dark scoria with abundant crystals, cm-sized Lc-bearing lava lithics, abundant loose analcimized Lc-, Bt and Px- crystals in a ashy cm-sized lapilli matrix. At places is possible to observe weakly organised bedding or variably sorted and cross bedded horizons, moderately reworked to pedogenic (Fig. 1). Laterally this cropping out deposit becomes more coherent and purplish in colour (Fig. 2).

Close to this outrop the escarpment of an abandoned quarry (Fig. 3) shows for all the visible height (about 6-8 m) the Pozzolanelle unit; the floor is instead an anthropic deposit made of multi cm-sized lava boulders. The escarpments of the quarry and of some cave in it are naturally sustained.

In general, the deposit is a semi-lithoid pinky-grey tuff, scarcely sorted coarse lapilli-sized ashy matrix-supported (fig. 4), with cm- to multi-cm-sized red scoria, very rich of cm- to multi-cm-sized lava lc-bearing xenoliths, loose crystals of Anl, Px and Bt. Gas pipes are frequently observed. It is a massive, incoherent and chaotic pyroclastic flow ignimbrite-type deposit (VSN_2).

Figure 1 - Red volcanoclastic deposit reworked from the Pozzolanelle unit.

Figure 2 - Coherent purplish outcrop of the Pozzolanelle unit (corner between via di Vigna Murata and via Ardeatina).


Figure 3 – Abandoned quarry escarpment exhibiting for all its height the Pozzolanelle unit. Right: a cave excavated into the unit.

Figure 4 - Pozzolanelle unit cropping out in the via Ardeatina quarry. Below: a particular of a scoria.

Other outcrops ascribed to the Pozzolanelle unit were recognized in the Fonte Meravigliosa and between Grotta Perfetta and Ardeatina roads.
The Tufo Lionato (VSN_1) was surveyed at the ground level close to Fosso di Tor Carbone and Ardeatina road(fig. 5). It crops out showing the typical facies, a yellow massive and Zeoloite pyroclastic deposit, ashy lapilli-sized matrix supported, with yellow pumice, grey scorias and lava clasts.

Figure 5 –Tufo Lionato (VSN1) unit cropping out in the via Ardeatina.

Field surveying added to data from 378 geological Map "Roma" (APAT, 2008; GIORDANO & RODANI, 2008), allowed us to elaborate a geological map at 1:5,000 scale of the examined area (Fig. 6).
The geological profile (Fig. 7) is based on the field survey, besides the data coming from the stratigraphical log of a well placed in the INGV seismic station ROM9 (see next paragraph) and from the stratigraphies furnished by some wells in the surroundings (VENTRIGLIA, 2002; ISPRA - Geological Survey of Italy - THE NATIONAL SUBSOIL SURVEYS DATABASE (ACCORDING TO LAW N.464/84): http://sgi.isprambiente.it/indagini/).

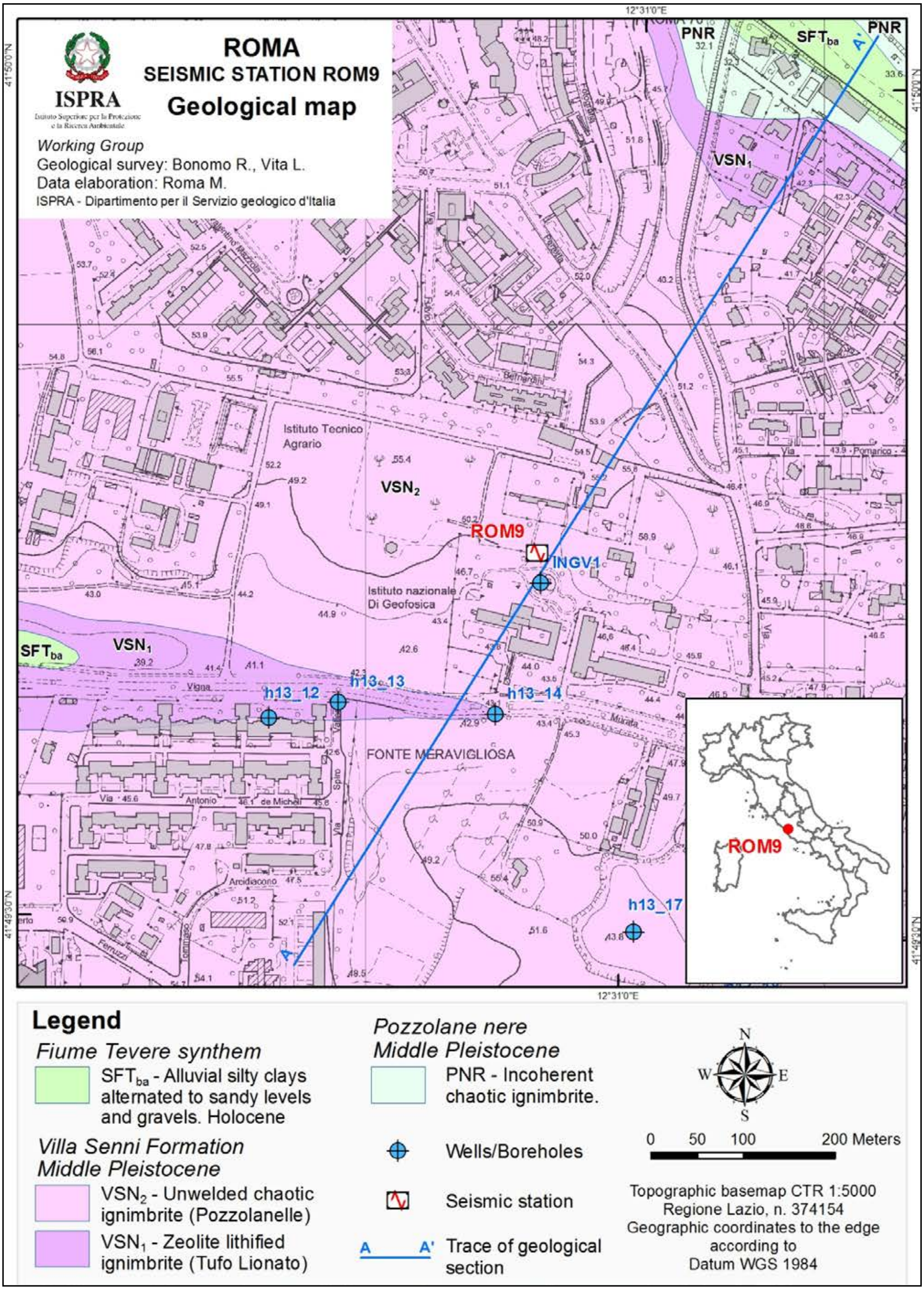


Figure 6 - Geological map after field work.

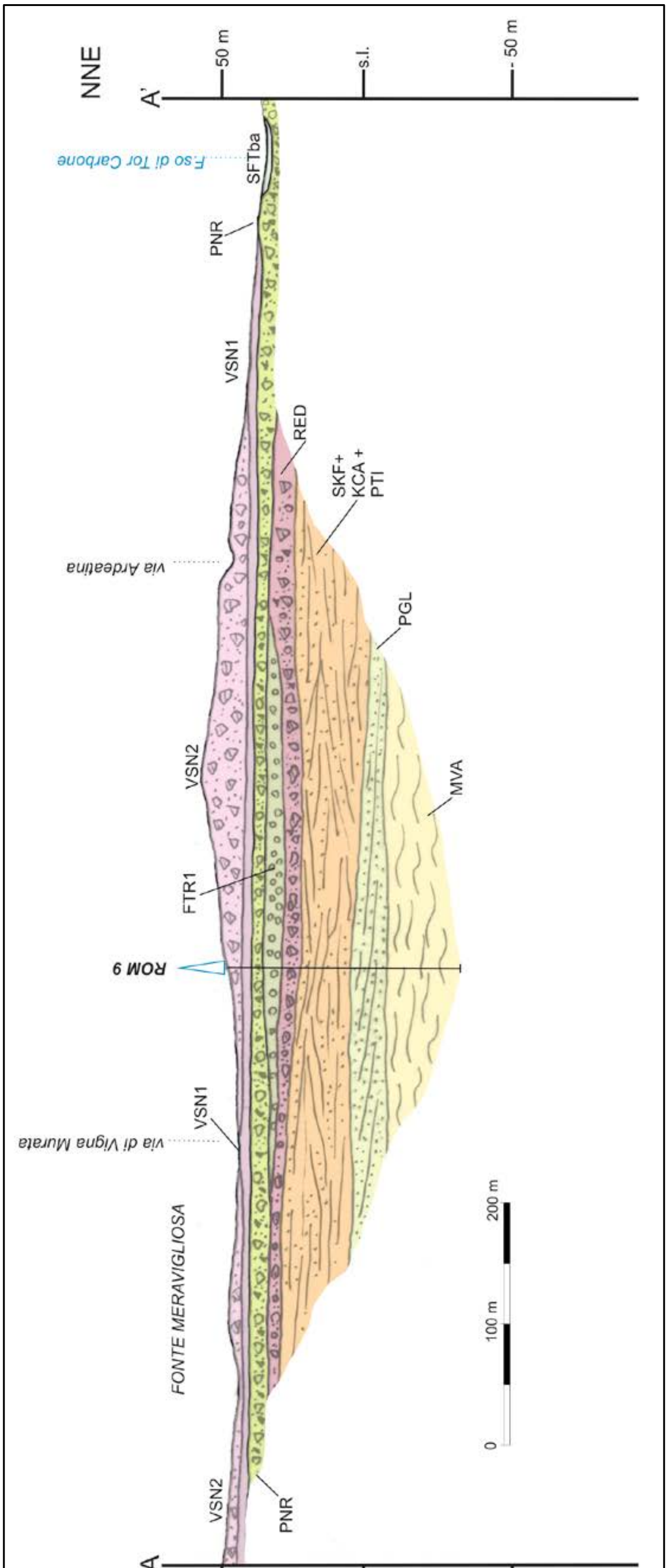


Figure 7- Geological profile SSW-NNE oriented, crossing the ROM9 Seismic Station; vertical exaggeration 2x.

LITHOSTRATIGRAPHIC MODEL

The stratigraphical succession below the site of the seismic station ROM9 is well known until the depth of 81 m as a well was drilled by INGV staff (1996), aimed to geophysical studies.
Well data are interpreted as the following:

- From the field level, the first level, 1 meter thick, is made of scarcely to moderately coherent sandy-silty volcanoclastics, that passes to an altered clayey-sandy silt, moderately coherent, with rare Lc-crysts, about 3 m thick.
- Below it is present for a thickness of about 2 m the Pozzolanelle unit (**VSN$_2$**) and downward it is followed by a 1,5 m thick layer referable to the Tufo lionato unit (**VSN1**). These two units are ascribed to the well known Villa Senni Formation (**VSN**). **VSN1** represents a massive and chaotic dark scoria, coarse-ash to fine-lapilli matrix-supported, purple to black, unconsolidated ignimbrite, with up to 30% of coarse lapilli- to block-sized lava and intrusive xenoliths; **VSN2** is a massive and chaotic, ash-matrix supported, zeolite-lithified, red to yellow ignimbrite, with yellow pumice and grey scoria lapilli and lava and intrusive xenoliths (FUNICIELLO & GIORDANO, 2008).
- Downward, the pyroclastic succession continues as an incoherent, massive and chaotic planar grey to black deposit, recognized as the Pozzolane Nere formation (**PNR**). It is an ignimbrite lying above a scoriaceous lapilli-sized fallout horizon of about 20 cm of thickness. The main deposit is an ashy matrix-supported deposit, glass-, Lc- Bt- and Px-crystals bearing, where loose lapilli- to bomb-sized (up to 15 cm) blackish and well vesiculated scoria occur, at places porphyritic for Lc, Px and Bt.
- Downward follows a 6 m thick volcanoclastic sorted to poorly sorted deposit, with a sandy-gravel grainsize, poorly layered in banks having a planar to lenticular geometry, made prevailingly of well rounded yellow and red altered scoria, and subordinately of lava lithic mm- to cm- sized clasts and Px, Bt and analcimized Lc crystals. It represents the unit of the Conglomerato Giallo (**FTR1**).
- Under this unit a massive and chaotic deposit is present, red/red-purple to dark grey in colour, generally incoherent, at places compact and semi-lithoid. It is a coarse ashmatrix-supported, poor of the finest deposit, made of vesiculated juvenile glass and subordinate analcimized Lc-, Cpx- and Bt- crystals. It is 15 m thick and represents the Pozzolane Rosse formation (**RED**), described by authors as a moderately vesicular scoria, up to 24 cm-sized, unconsolidated ignimbrite, with up to 15% of coarse lapilli- to block-sized volcanic and intrusive xenoliths (FUNICIELLO & GIORDANO, 2008).
- Downward are present cemented pozzolanaceous sandy-gravel-sized deposits, with plant macroremnants, probably referable to the Tufi Stratificati Varicolori di Sacrofano formation (**SKF**), and an ashy tuff deposit silty-sandy-sized, with abundant Bt and traces of plants macroremnants not easily recognizable; the whole thickess is about 7.5 meters.
- The succession continues downward with a 9 meters thick alternating of tuffs, referable to the Palatino unit (**PTI**), representing an incoherent well sorted deposit made of 90% lapilli-sized scoria and 10% of 1-2 mm-sized fragments of Lc-crystals; and below referable to the Casale del Cavaliere unit (**KKA**) which represents a phreatomagmatic pyroclastic flow low-angle cross-stratified deposit, made of alternating fine to coarse-, rarely lapilli-sized ashy levels, with vesiculated scoria and lavic lithics and up to 1,5 cm-sized accretionary lapilli horizons.
- Below, is present a 12 m thick succession of fluvial to lacustrine deposits referable to the Ponte Galeria formation (**PGL**). It is possible to observe inside it the passage from the clayey-silty facies to the sandy and to the gravelly ones, characterizing the several

members of this formation. The succession-type is made up of the following lithofacies: 1) "Conglomerati basali" (fluvial conglomerate lithofacies), 2) grey-bluish clays with *Helicella ericetorum*, 3) conglomerates and yellow beach sands with *Arctica islandica*, 4) cross-laminated sands and gravels, 5) clays with *Venerupis senescens*, 6) "Sabbie salmonate" (eolian lithofacies).

- Finally, in the last 17 meters the hole drills grey to grey-bluyish stratified and consolidated to very well consolidated marly clays, alternated to fine beds up to banks of fine qz-micaceous massive to graded sands, grey to ochre in colour. They are ascribed to the Pliocene "Argille Azzurre" *Auctt*. Formation, named in the area as Monte Vaticano formation (**MVA**).

From this depth to about -100 m a.s.l., it is possible to reconstruct the stratigraphy only on the base of some data coming from previous studies (MARRA *et alii,* 1995; APAT, 2008). In the study case, we assume that the stratigraphical succession probably continues until the depth of 150 m from the field level, with the same formation occurring at the bottom-well, that is the **MVA** formation.

Fig. 8 shows the reconstructed lithostratigraphical succession below the ROM9 seismic station of Vigna Murata. The stratigraphy under the depth of 31 m b.s.l. (under the white gap, and flanked by a dotted arrow with the phrase "**speculative stratigraphy high uncertainty**") must be considered largely speculative and characterized by high uncertainty.

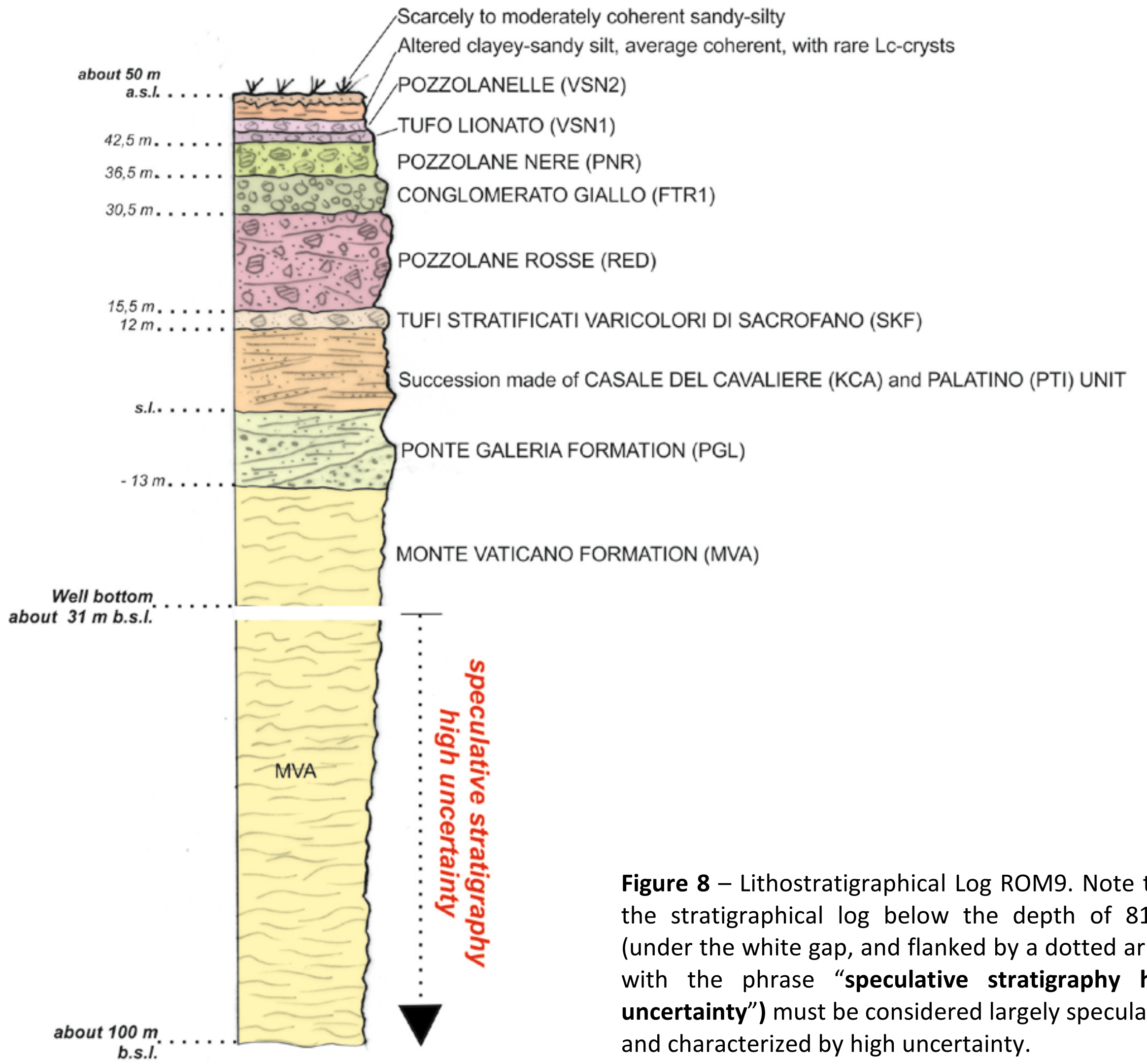


Figure 8 – Lithostratigraphical Log ROM9. Note that the stratigraphical log below the depth of 81 m (under the white gap, and flanked by a dotted arrow with the phrase "**speculative stratigraphy high uncertainty**") must be considered largely speculative and characterized by high uncertainty.

LITHOSTRATIGRAPHIC AND LITHOTECHNICAL CHARACTERIZATION

Basing on the geological and textural features, the recognized units (see Geological Map) have been classified as lithological units (Tab. 1), referable to the ISPRA Lithological map of Italy 1:100.000, and as lithotechnical units referable to the Standards for the Seismic Microzoning drafted by the Technical Committee (art. 5, c. 7 OPCM 2010, 4.0 b version).
For the great variability of the grainsize distribution and of the textural features of the different volcanoclastic lithotypes that a geological formation could show, we summarized some geological unit as the best, even though not entirely fitting class of the MS Standards.
Indeed, volcanic units under the seismic station ROM9 and its surroundings are characterized by lithotypes having considerably changing geo-mechanical behaviours, due to their different emplacing way. In detail, the lithological features of the pyroclastic flow deposits can be distinguished for the different cooling to which they were subjected. A fast cooling generally origins pozzolanaceous deposits, characterized by an apparent cohesion deriving from the weak textural strengths of the grains. At slower cooling times, high temperatures volatiles, trapped inside and interacting with the ashy- and lapilli-sized grains, develop new crystals (zeolites), building a secondary welding matrix; this process is known as ‘zeolitization’ and makes the deposits more coherent and with a characteristic semi-lapideous behavior, *e.g.* the Tufo Lionato.
Basing on this reflection, we made the legend of the volcanics of the CGT-MS (Geological-technical Map for the Seismic Microzoning) using both the tables proposed by the Technical Committee for the Seismic Microzoning: that referable to the cover terrains for the non-zeolitized pozzolanaceous volcanic units (**VSN_2** and **PNR**) and that referable to the geological substratum for the zeolitized one (Tufo lionato **VSN_1**)

Lithostratigraphic unit (ISPRA, Geological map)	**Lithological unit (ISPRA, Lithological map)**	**Lithotechnical unit (Guidelines 4.0b_MS, 2015)**
SFTba	B4	CLpi
VSN2	D8	GMig
VSN1	D5	SFGR
PNR	D8	GMig

Table 1 – Classification of geological units

The table 1 was utilized to elaborate the Lithological Map (Fig. 9) and the Lithotechnical Map (Fig. 10) of the sketched geological map of Vigna Murata seismic station site (ROM9).

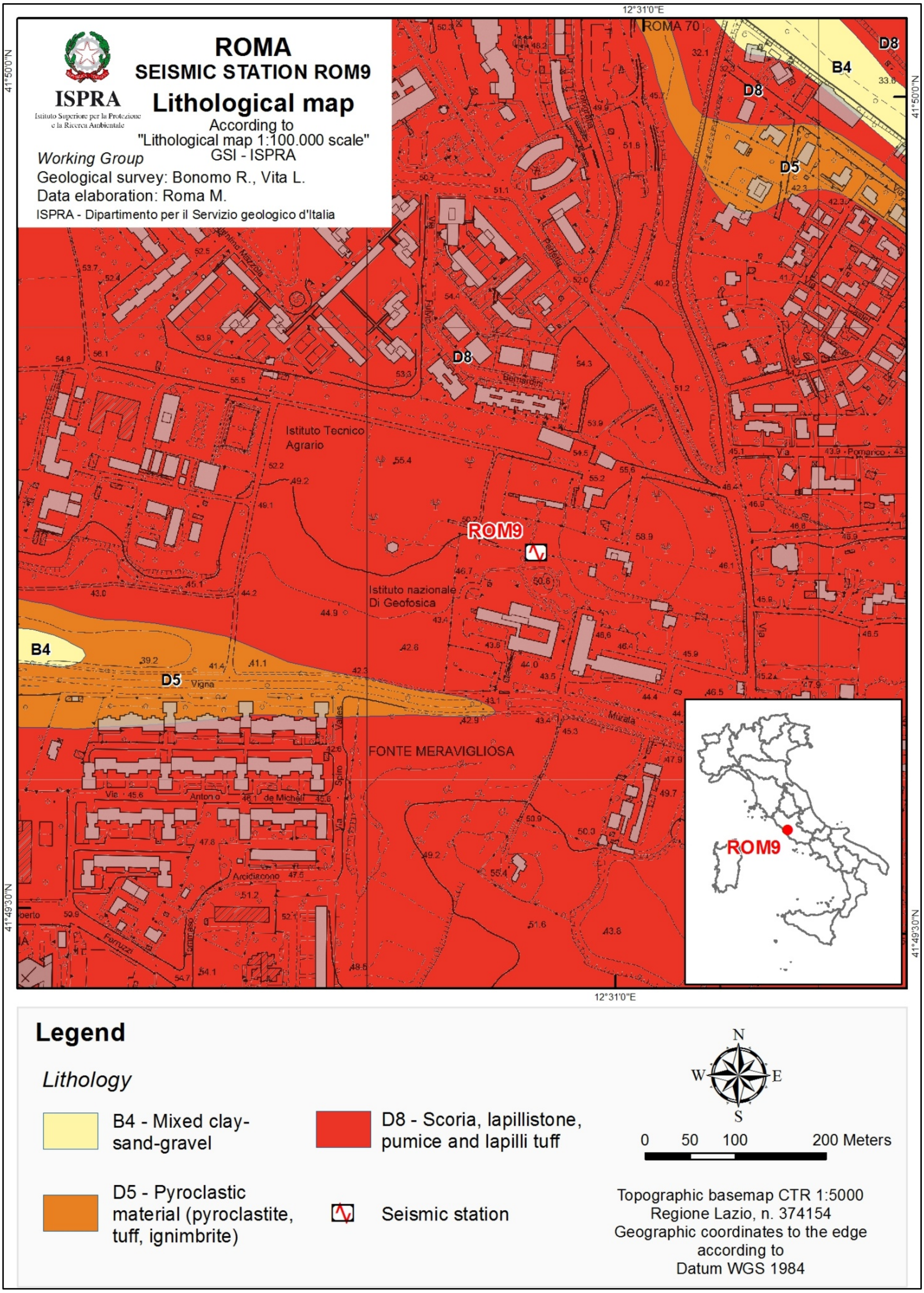


Figure 9 – Lithological map.

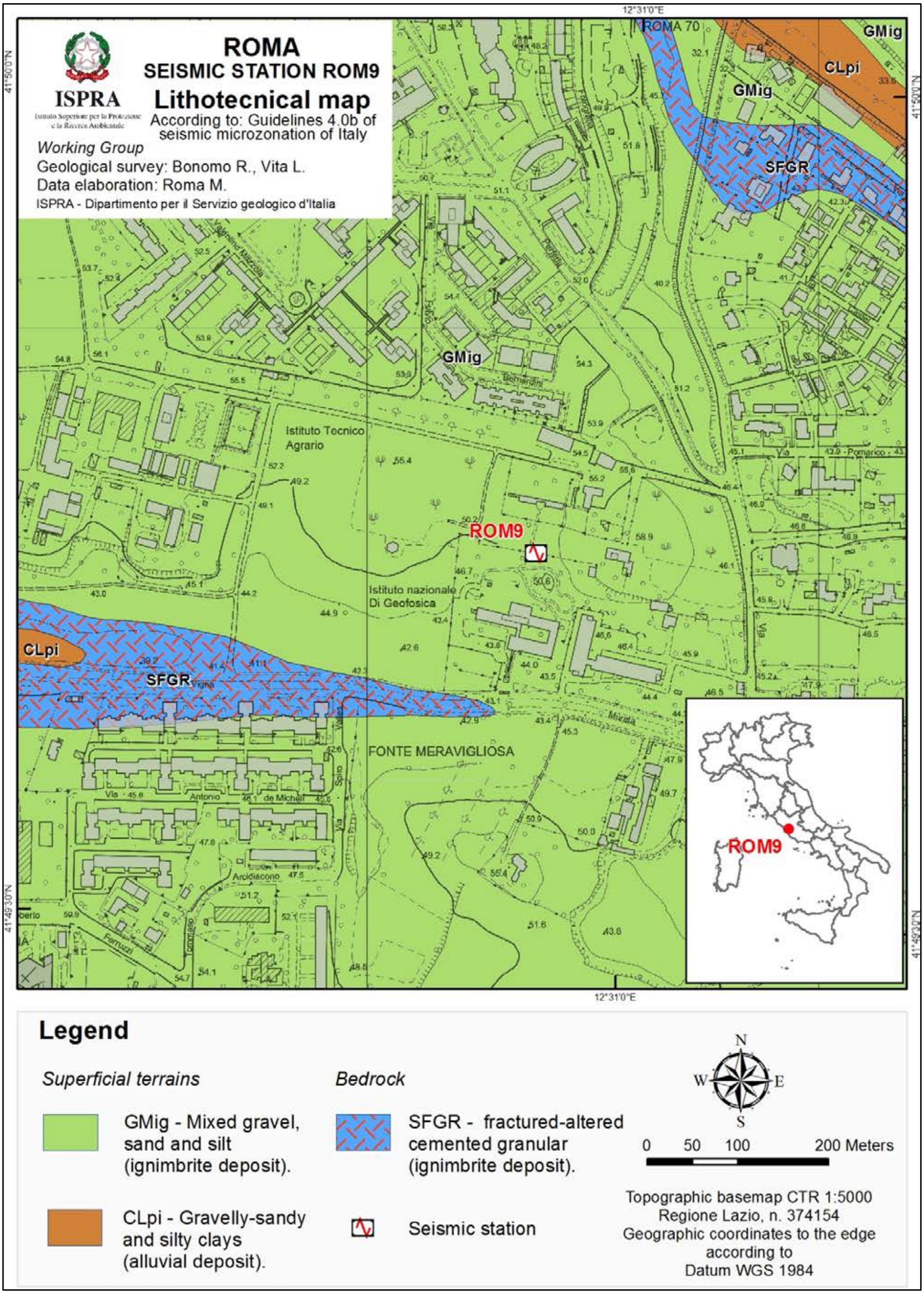


Figure 10 – Lithotechnical map.

SANR SEISMIC STATION

GEOLOGICAL SETTING

The Sandrigo seismic station (SANR) is located in the northwestern sector of the Veneto-Friuli alluvial plain, few km east to the Schio-Vicenza Line. The Veneto-Friuli alluvial plain extends over a portion of the Adriatic foredeep which is an articulated foredeep of three different chains (the External Dinarides to the east, the Eastern Southern Alps to the north and the Northern Apennines to the southwest, according to Pola et al., (2014b). This foredeep shows a complex structural setting deriving from its complex Meso-Cenozoic evolution as documented by several works (Ghielmi et al., 2013 and references therein). The western border of the foredeep is marked by the Schio-Vicenza fault system (SVFS), a NW-SE trending fault dipping at a high angle towards the NE developed during the Mesozoic regional extension and reactivated during the Pliocene – Quaternary (Pola et al., 2014a and references therein). Pola et al (2014a, b) identified three main faults in the SVFS (Schio-Vicenza fault - SV; Travettore-Codevigo fault - TC; Conselve-Pomposa fault - CP) and basing on the U/Th dating conducted on a travertine deposit of (Montirone Hill, Abano Terme) considered the Schio-Vicenza fault active at least until 20 ka (Fig. 1).

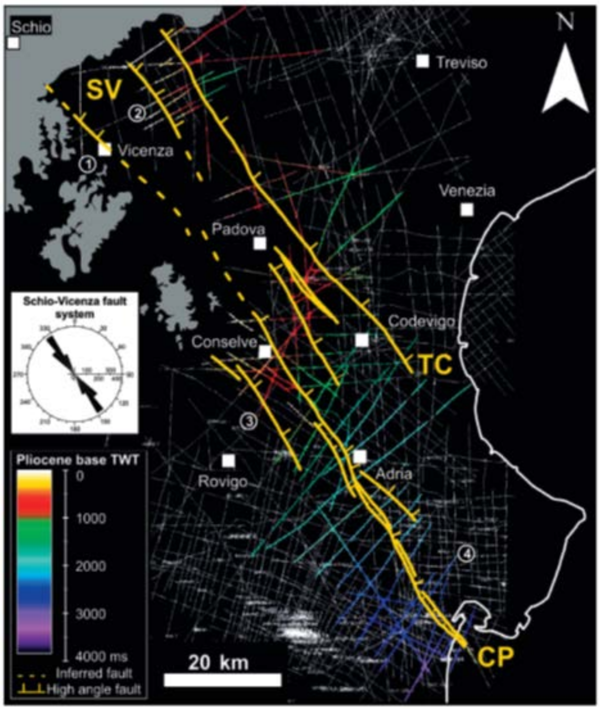
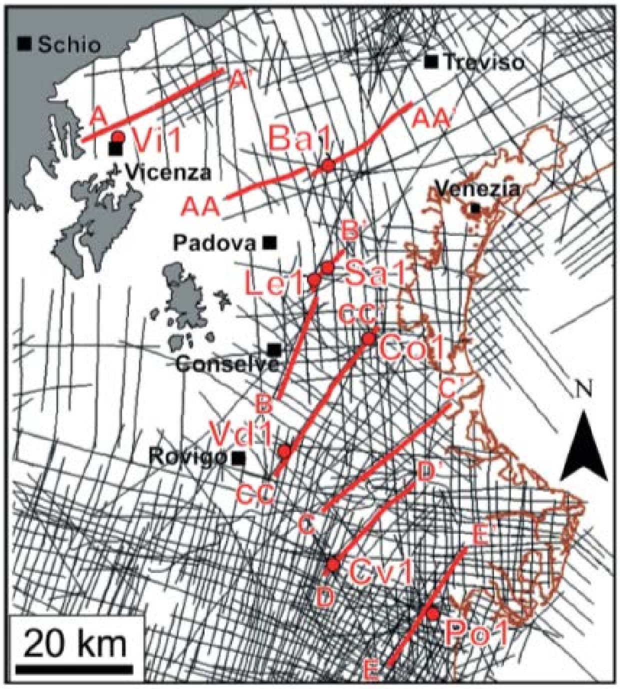


Figure 1 – Geometry of the SVFS with three main fault, the Schio-Vicenza fault (SV), the Travettore-Codevigo fault (TC) and the Conselve-Pomposa fault (CP). The red point identified the SANG station. Data and figure from Pola et al., 2014b.

During the Pliocene-Quaternary, the foredeep increase the flexuring towards south with the development of accommodation space filled by Pliocene shallow water sandstones (Eraclea sandstone) grading southward into fine-grained hemipelagic sediments (Santerno group). Locally, towards south, these pass into shallow water turbidites (Porto Corsini and Porto Garibaldi Formations) evolving upward to rapidly prograding deltaic deposits with Pleistocene-Holocene shallow marine sand and sandstone (Asti group; Ghielmi et al., 2010).
During the Late Pleistocene-Holocene, the inner northern sector of the basin was filled by continental (fluvioglacial and alluvial deposits) connected with an overall regressive trend (Mancin et al., 2009). In the Vicenza area the Pleistocene succession overlaps directly the Upper-Middle Miocene bedrock with a thickness of about 200-300 meters (Pola et al., 2014b; Fig. 2, Fig. 3). The bedrock under the Pleistocene deposits is constituted by the top of the Cavanella Group

represented by sandstones and conglomerates, up to 1000 meters thick, associated to a continental to coastal depositional environments.



Southern Part (Po Delta area)	Northern Part (Padova-Vicenza area)	Average Velocity (m/s)
Pleistocene Unconsolidated terrigenous units *Pleistocene Base*	Pleistocene Unconsolidated terrigenous units *Pleistocene Base*	2300
Upper Pliocene *Upper Pliocene Base*	Pliocene Unconsolidated terrigenous units *Upper Messinian Unconformity*	2750
Middle Pliocene *Middle Pliocene Base*		
Lower Pliocene *Upper Messinian Unconformity*		
Miocene Consolidated terrigenous units *Miocene Base*	Middle - Upper Miocene *Top of the Cavanella Group* Upper Oligocene - Lower Miocene *Base of the Cavanella Group*	
Oligocene Consolidated terrigenous units *Upper Oligocene Base*	Middle p.p. Eocene - Lower Oligocene Consolidated terrigenous units *Top of the Scaglia Rossa fm.*	3000
Middle p.p. - Upper Eocene Consolidated terrigenous units *Top of the Scaglia Rossa fm.*		
Upper Cretaceous - Middle p.p. Eocene Mainly carbonate units *Top of the Maiolica fm.*	Upper Cretaceous - Middle p.p. Eocene Mainly carbonate units *Top of the Maiolica fm.*	5200
Middle Jurassic - Lower Cretaceous Carbonate units *Top of the Calcari Grigi fm.*	Upper Triassic - Lower Cretaceous Carbonate units *Base of Dolomia Principale fm.*	6000
Upper Triassic - Lower Jurassic Carbonate units *Base of Dolomia Principale fm.*		
Carnian *Carnian Base*		5000

Figure 2 - On the left side, the database of the seismic sections performed by ENI and used by Pola et al (2014b) for mapping the seismic horizon of the intra-Messinian Unconformity (Pliocene base), the red bold lines indicate the traces of the geological cross sections. On the right side, the stratigraphic horizons recognized during the interpretation of the seismic sections. Both figures are from Pola et al. (2014b)

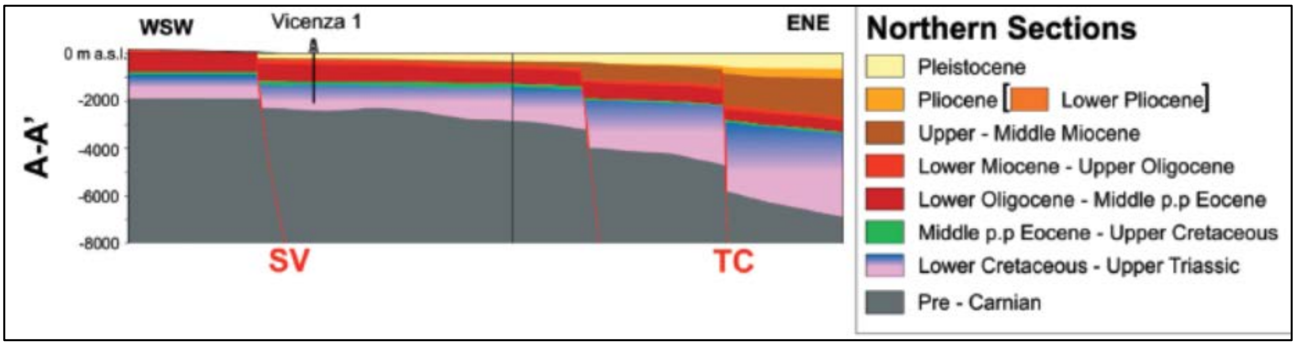


Figure 3 - A-A' geological cross-sections sub-orthogonal to the SVFS (Schio–Vicenza Fault System) obtained through the interpretation of the seismic sections and the subsequent depth conversion process (location in Figure 2). Different stratigraphic horizons are described in the Figure 2.

GEOLOGICAL FIELD DATA AND SUBSURFACE DATA

The Sandrigo seismic station (SANR) is located in the Lupia locality, on the left side of the Astico River. The area shows a flat morphology as typical for alluvial plain (Fig 4).

The outcropping deposits are represented by gravel and sandy gravel, locally silty sand with interbedded silt and clay. These deposits are the results of alluvial fan and alluvial plain deposition controlled by climate changes, fluvioglacial processes, fluvial diversion and tectonic to compaction subsidence. On the base of the field observations, two sectors have been differentiated, the first, north to the SANR station, where gravel texture are predominant, and the second, south to Lupia, with predominant sandy and silty texture (Fig. 5; Fig. 6).

The flat morphology and the lack of natural or artificial trenches not allows to observe more than 1-2 meters of the surface deposits.

Figure 4 - The Sandrigo seismic station is located in a sector of the Veneto alluvial plain. The area is characterized by flat morphology. The SANR is enclosed by a fence.

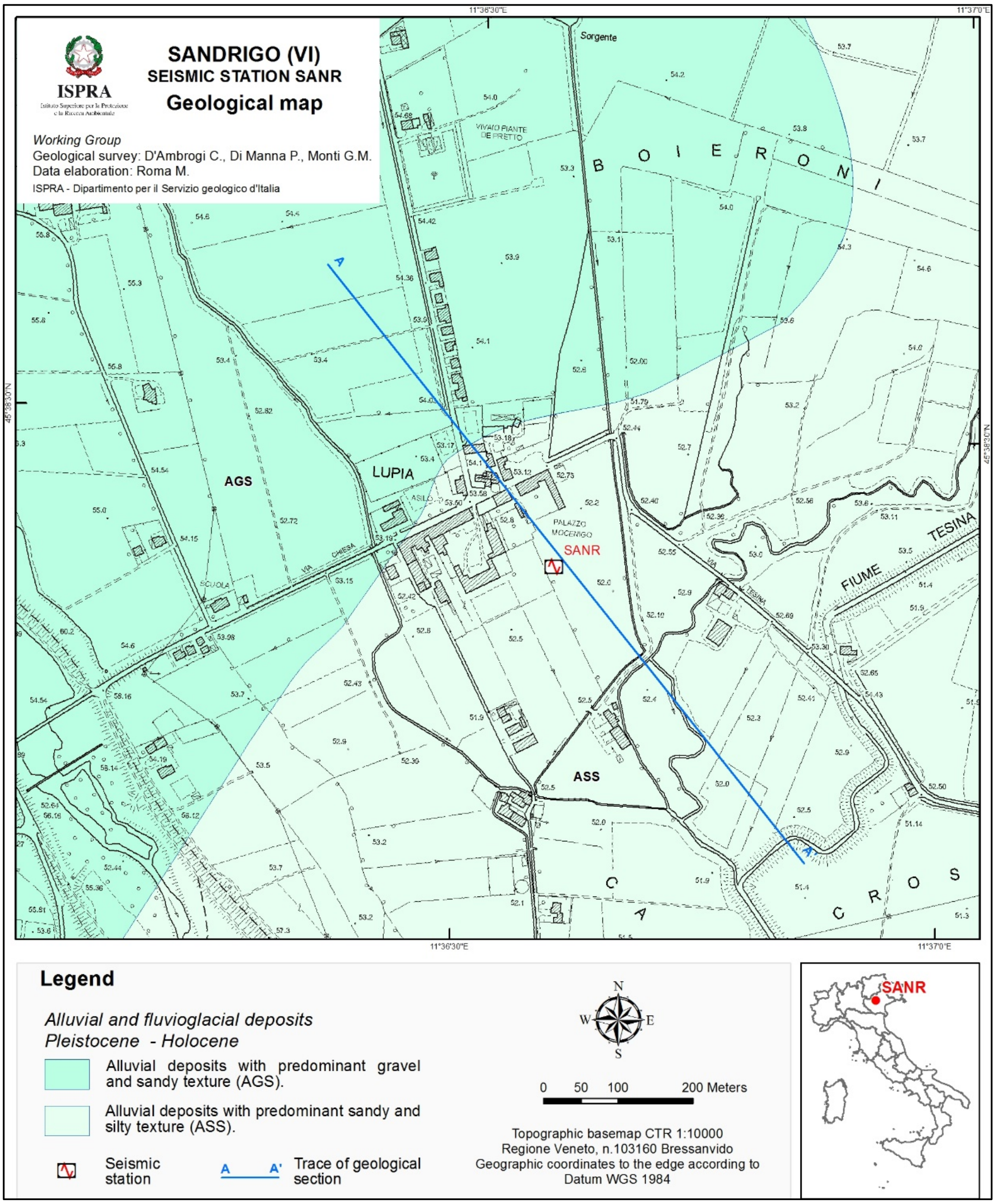


Figure 5 – Geological map after field work.

Figure 6 – The picture shows the right bank of a little canal running at about 10 meters from the SANR. The deposits are constituted by sand and silty sand with interbedded gravel.

Moreover, no specific geological data or geophysical and borehole investigations are available for the SANR site. Consequently, in order to better understand the subsurface geological setting, we collected the available subsurface geological data at regional and local scale.

Free available data are represented by: three boreholes for oil and gas exploration and their relative stratigraphic profiles (Travettore 1; Villaverla 1; Scaldaferro 1; Figure 7); two geological sections crossing NW-SE the alluvial plain at a distance of 6-9 km from the Sandrigo station (Figure 7, Figure 8); five well stratigraphies, drilled for water exploration in a radius of about 2 km respect to the SANR station, the data are collected in the database of the 464/84 Law (particularly we refer to the closest 158324 well; Figure 9); maps of the thickness of the alluvial deposits (Figure 10). We also considered and analyzed all the data available in the Veneto Region web portal (http://idt.regione.veneto.it), and the data deriving from specific project for the groundwater management and recharge as the AQUOR Life Project (http://www.lifeaquor.org).

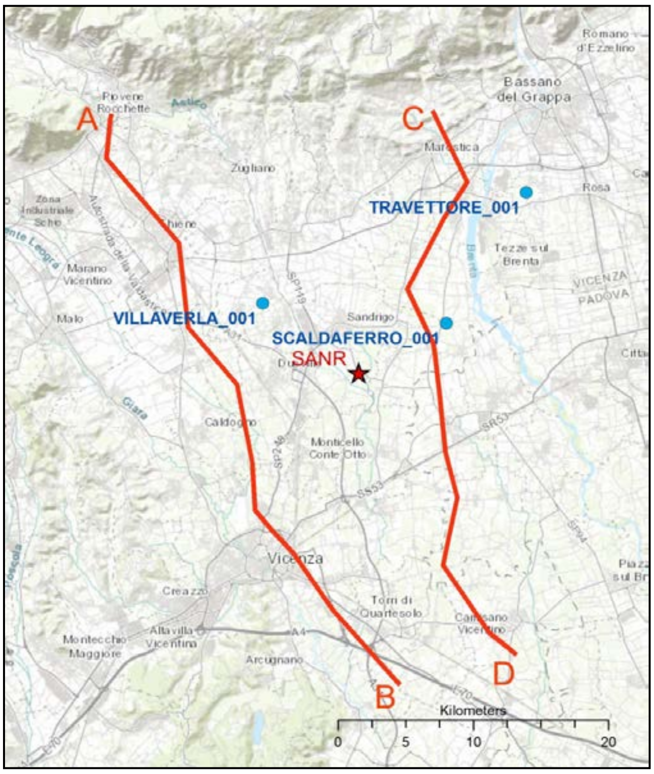


Figure 7 – Subsurface data and investigation available in the surrounding area of the SANR station. The blue points identified the borehole with public profiles from VIDEPI Project; the A-B and C-D red lines are the traces of the two geological cross sections deriving from well logs analysis (Sottani et al., 1982); the red star shows the location of the SANR seismic station.

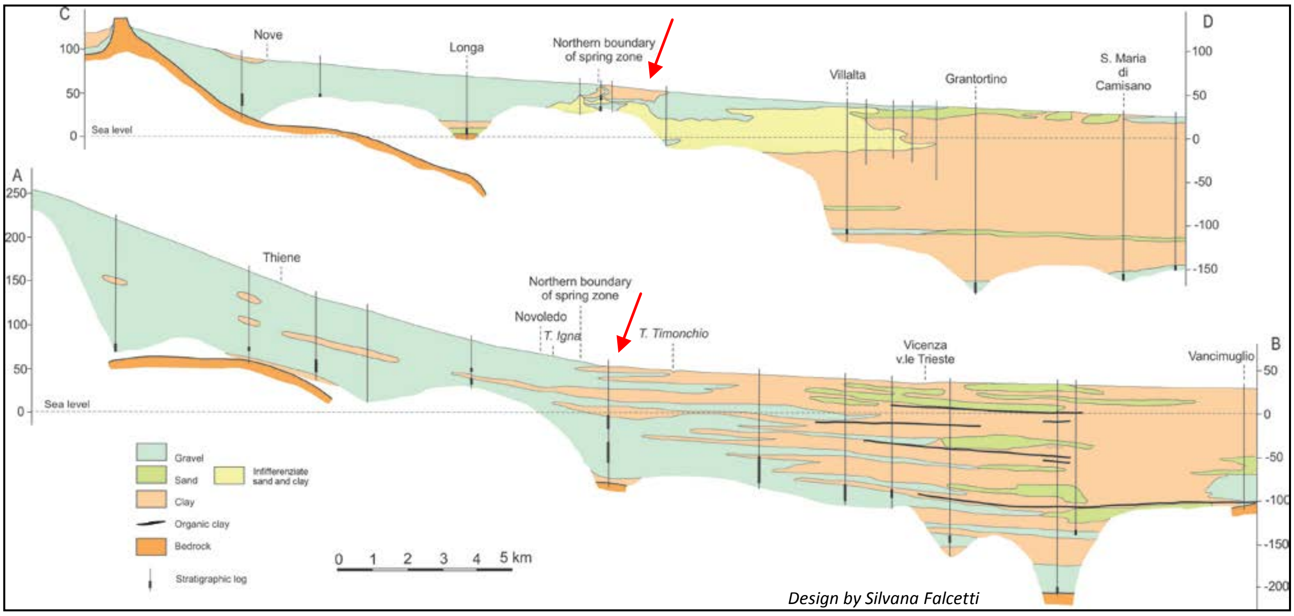


Figure 8 - Geological cross sections showing the relationship between the different sedimentary bodies. The traces are reported in Figure 6. The red arrows indicate the projected position of the SANR site. Modified after Sottani et al., 1982.

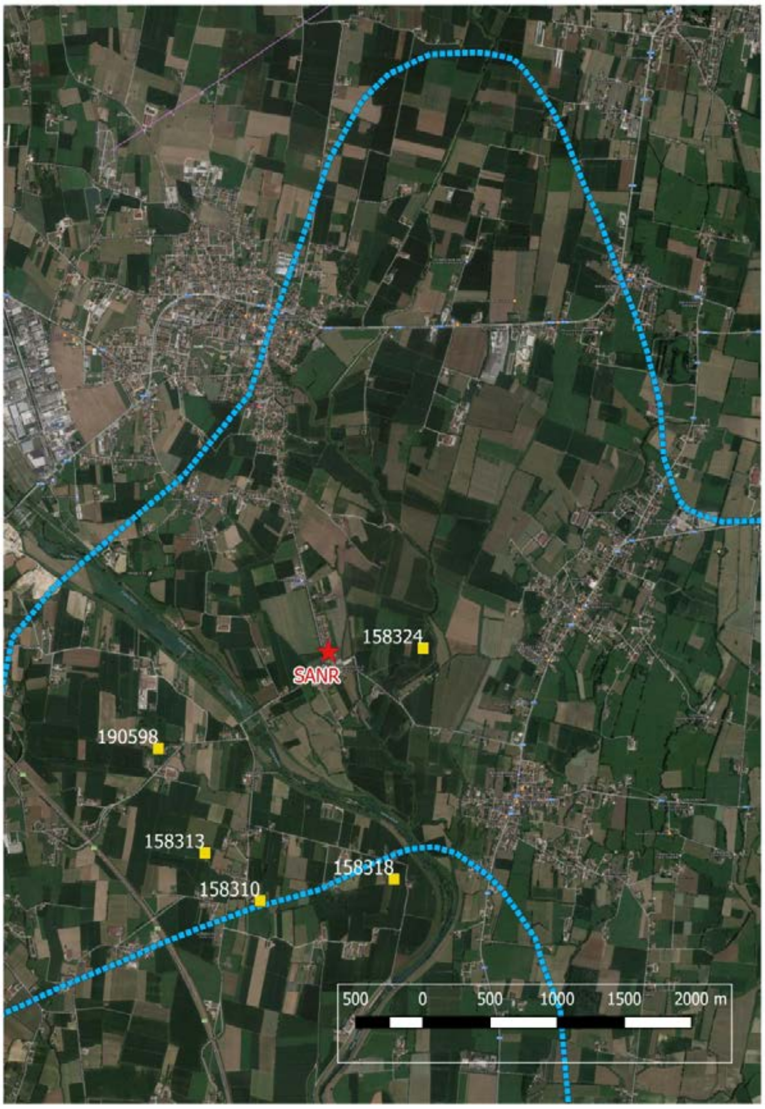


Figure 9 - Subsurface data and investigation available in the proximity of the SANR station. The yellow squares indicate the wells for water extraction deriving from the database of the Law 464/84; the red star is the SANR station, in the Sandrigo area; the blue dotted lines are the boundaries of the springs zone ("risorgive"), data are from the AQUOR Project - http://www.lifeaquor.org.

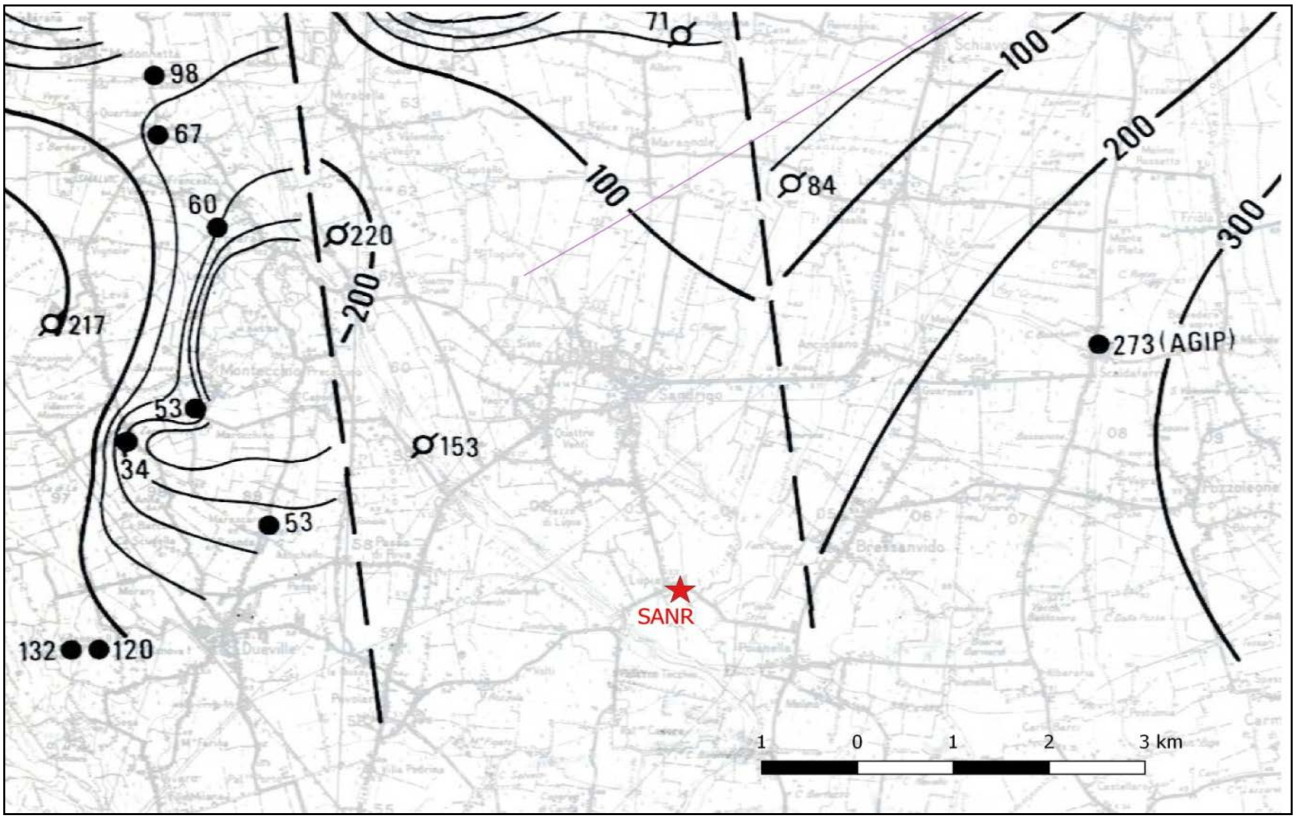


Figure 10 - Map of the thickness of the alluvial deposits; the black lines indicate the thickness of the undifferentiated alluvial deposits in meters; large dashed black lines represent the main faults, after Sottani et al. (1982). The red star identifies the site of the seismic station SANR.

LITHOSTRATIGRAPHIC MODEL

Basing on all the above mentioned regional and local data, we can represent the vertical succession of the deposits in the alluvial cover up to about 75 meters from the ground surface. We are also able to represent the eventual lateral relationship between the different sedimentary bodies up to a depth of 10 meters (Figure 11, Figure 12). For greater depth, we propose just a speculative stratigraphy using the information available from literature at regional scale. Best data are represented by the two geological cross sections by Sottani et al (1982). Basing on the A-B geological section the total thickness of the fluvio-glacial and alluvial deposits, south of the boundary of the springs zone, ranges between 130 and 240 meters; these deposits lie on the terrigenous bedrock consisting of Cavanella Formation.

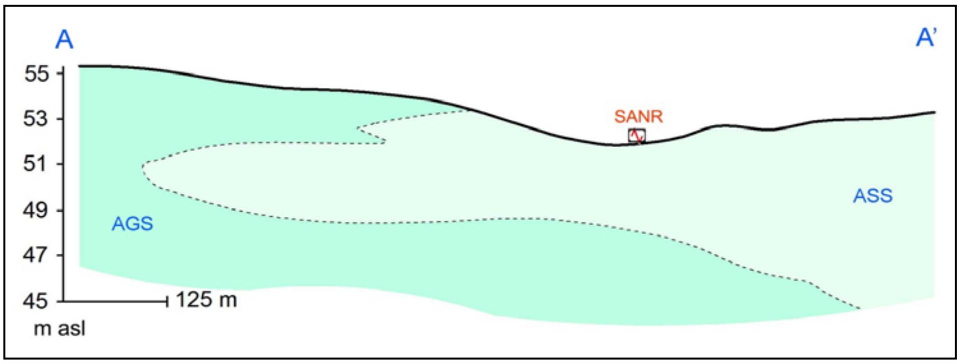


Figure 11 - Geological section across the SANR showing the lateral and vertical relationship between the sedimentary bodies. Vertical exaggeration 20x. The trace is reported in Figure 5.

The SANR station in located inside the springs zone, identified by the dotted blue lines in Figure 9. Therefore the water table is very close to the ground surface and the deposits are satured in water.

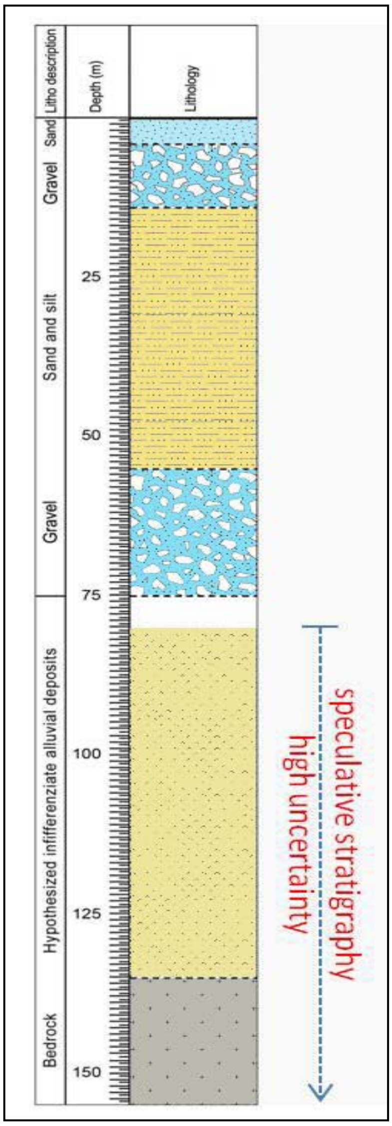


Figure 12 - Stratigraphic log showing the vertical succession of alluvial deposits under the SANR station; the proposed stratigraphy at a depth greater than 75 meters is largely speculative and characterized by high uncertainty.

LITHOSTRATIGRAPHIC AND LITHOTECHNICAL CHARACTERIZATION

On the base of the geological data acquired during field survey, considering the available literature correlations, we propose a lithological and a lithotecnical classification of the outcropping lithostratigraphic unit as reported in the following (Table 1). The resulting maps are in Figure 13 and Figure 14.

Lithostratigraphic unit (ISPRA, Geological map)		**Lithological unit (ISPRA, Lithological map)**		**Lithotechnical unit (Guidelines 4.0b_MS, 2015)**	
ASS	Alluvial deposits with predominant sandy and silty texture	B2	Sand	SMca	Silty sand, mixed sand and silt
AGS	Alluvial deposits with predominant gravel and sandy texture	B3	Sand - gravel	GPca	Gravel and mixed gravel and sand

Table 1 – Classification of geological units.

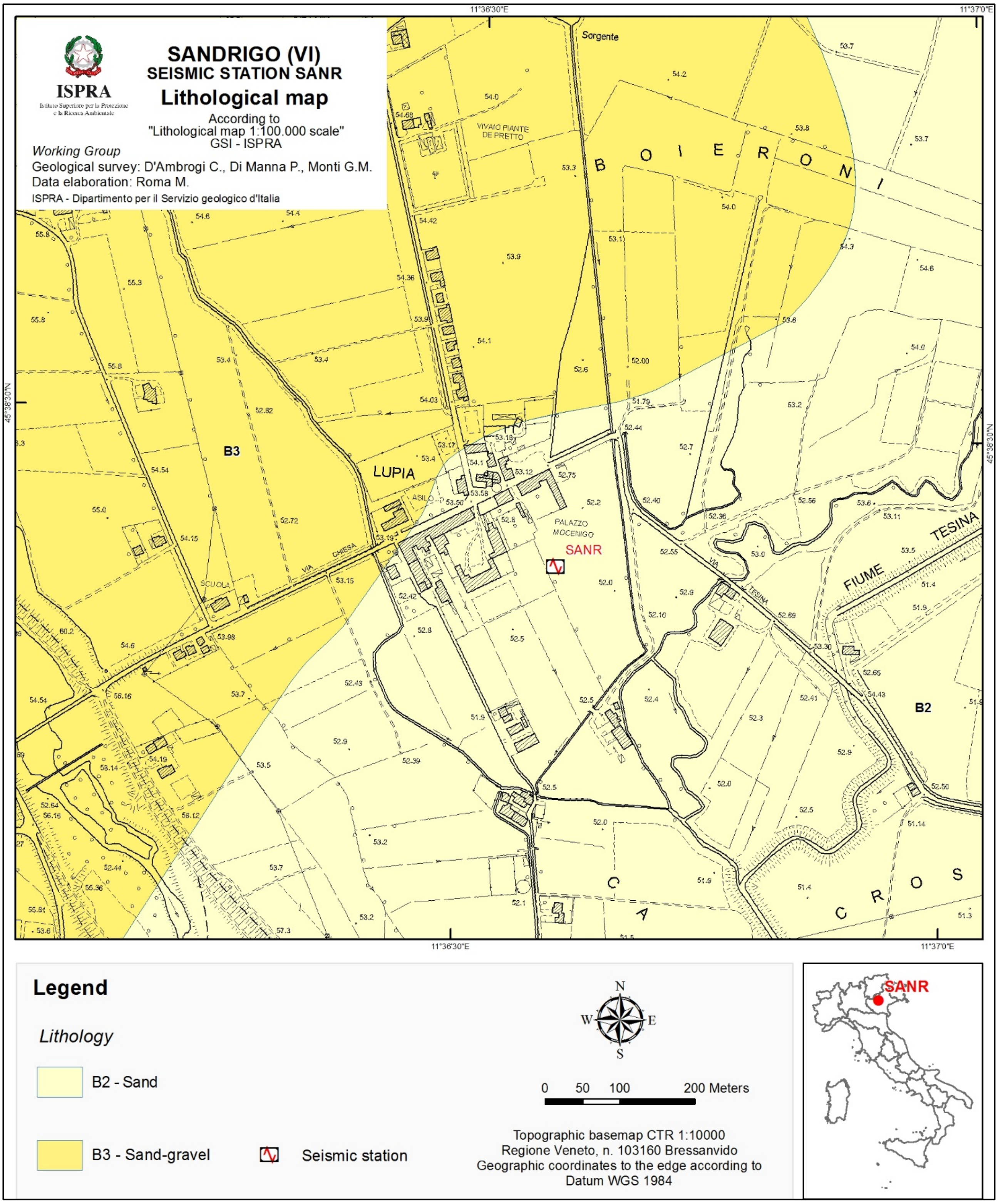


Figure 13 – Lithological map.

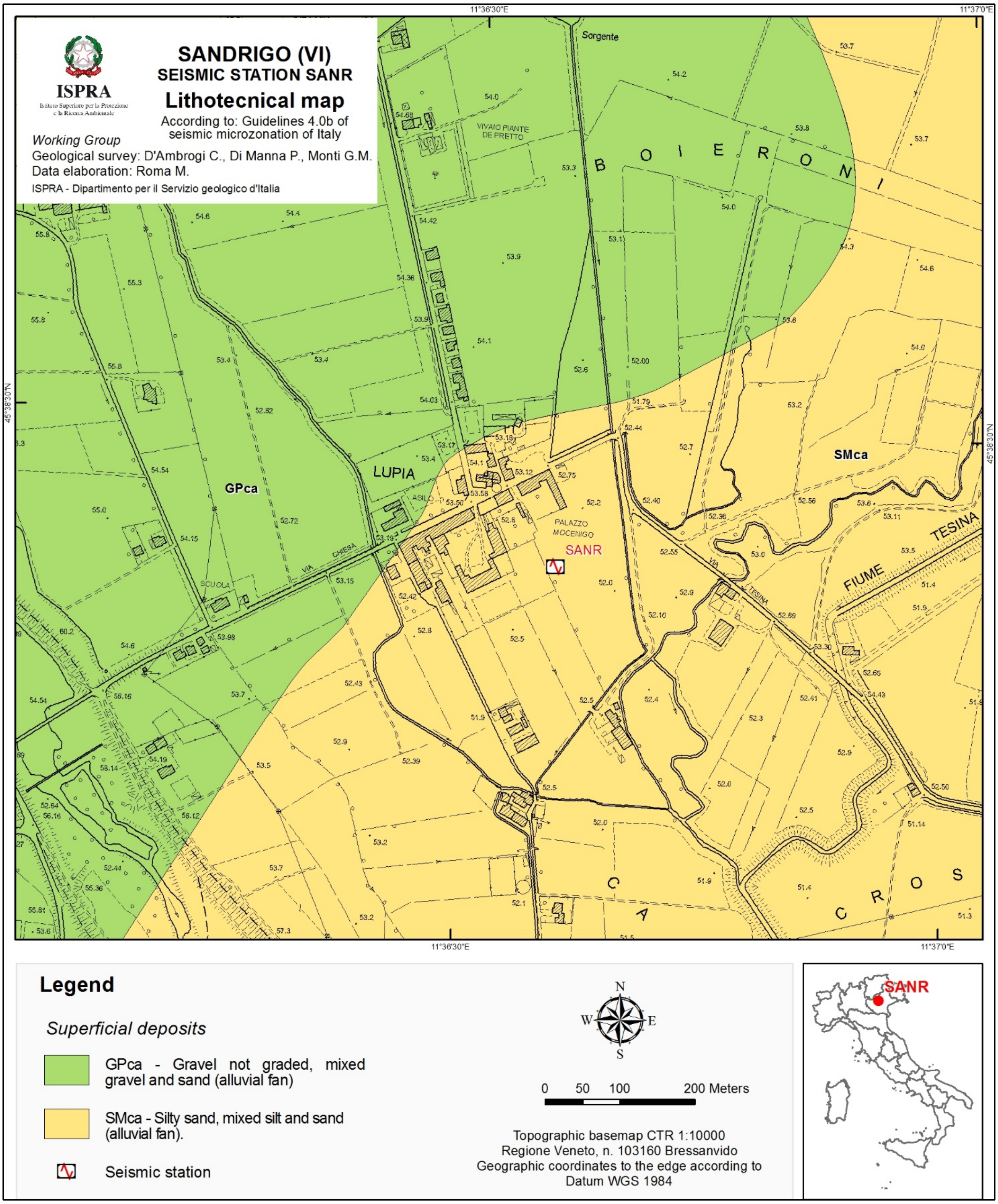


Figure 14 – Lithotechnical map.

CDCA SEISMIC STATION

GEOLOGICAL SETTING

The station is located on the left bank in the Upper Tiber Valley, slightly west of the historic centre of Città di Castello (PG), at a height of approximately 278 m a.s.l. (Fig. 1; Fig. 2)

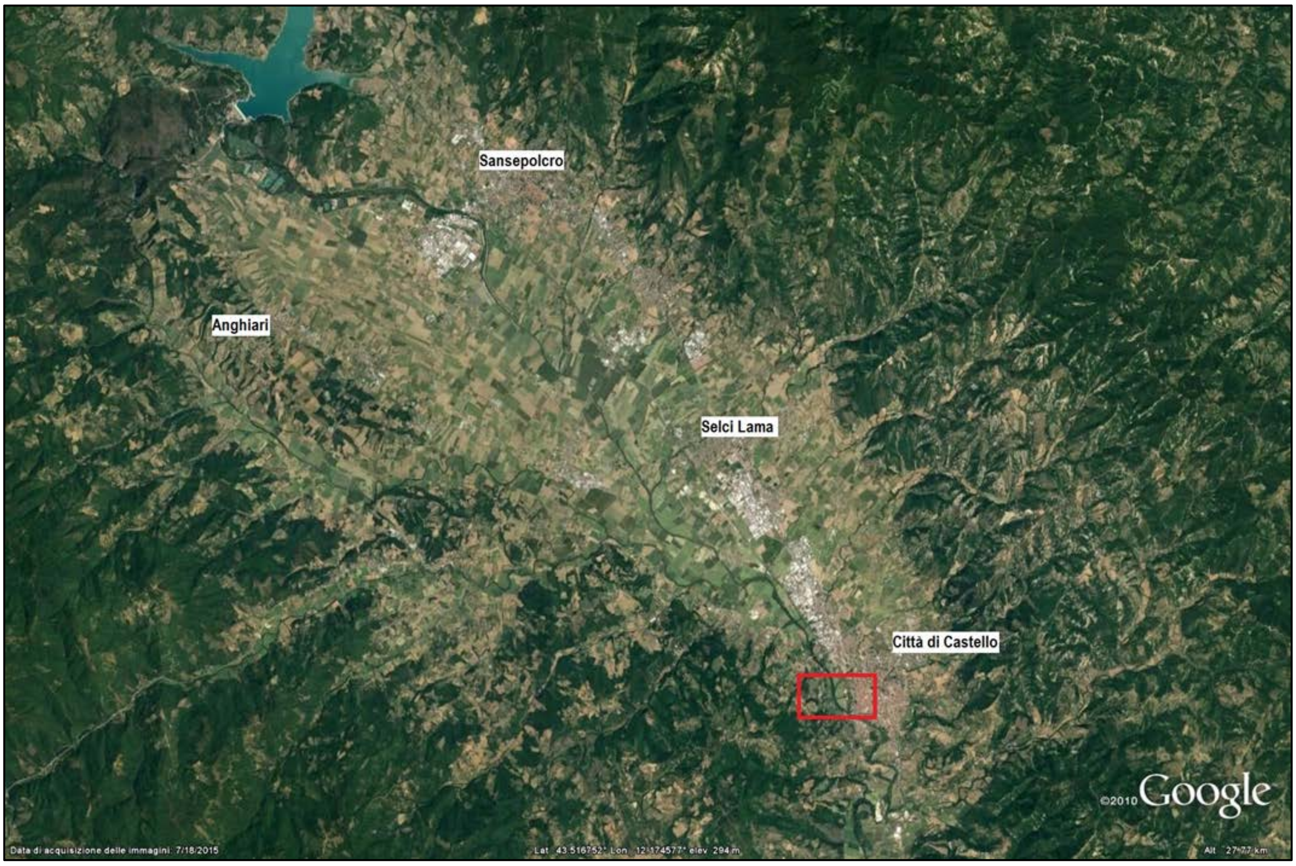


Figure 1 – Orthophoto of the Upper Tiber Valley, with the location of the seismic station "Città di Castello - PG". Study area in red rectangle.

Figure 2 - CDCA seismic station within the public park of Città di Castello (PG)

The Upper Tiber Valley, also known as High Valtiberina, develops in NW-SE direction, with an almost elliptical shape.
The area is characterized by a broad valley crossed by the Tiber River and the hydrographic network of its tributaries that, starting from the Sansepolcro's wide plain tends to shrink towards Città di Castello.
Elevations along the valley goes between 350 m to the north and 270 m a.s.l. to the south. The valley is enclosed between a western ridge that exceeds 1000 m of altitude a.s.l. and an eastern ridge, the Apennine watershed, up to a maximum of 978 m. a.s.l. (Cattuto, 2011).
The general orography is strongly controlled by the local tectonic structure, which has resulted in the formation of the large basins of Sansepolcro and Città di Castello, closely linked to each other. In addition to the Tiber River route, this structure has also affected the pattern of the secondary hydrographic grid, essentially characterized by a sub-angular pattern.
Human activities have been significant during the past centuries, with profound changes made to the morphology of the watercourse, to the hydraulic regime and to the track of the river Tiber.
In particular, the river lapped the north-western ramparts of Città di Castello, forming a meander. In the middle of 1700, in order to ward off the continual floods in the northern part of the city, the Tiber River route was rectified, as shown in Figure 3.

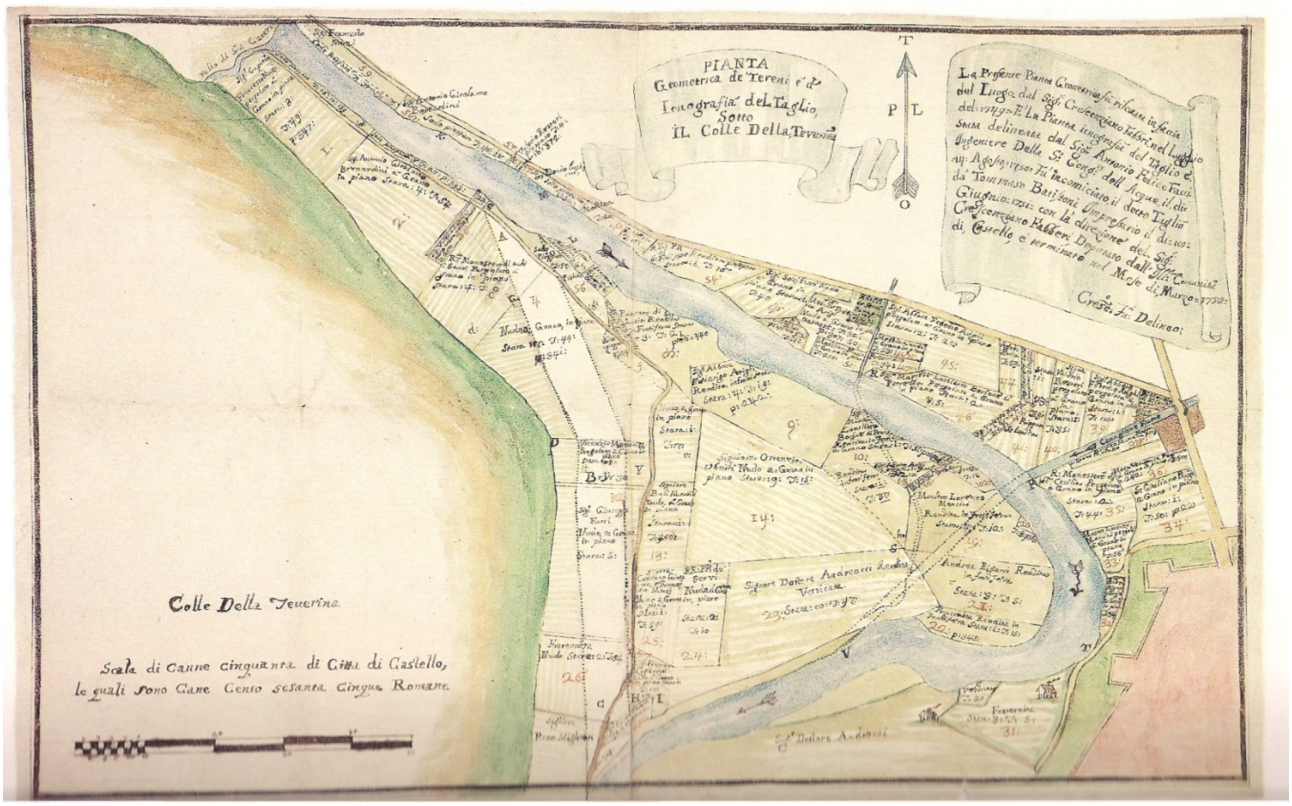


Figure 3 - "Pianta geometrica de' Terreni ed Iconografia del Taglio sotto il Colle della Teverina (1749)", tratta da "Città di Castello e il suo territorio in piante e carte d'Archivio" di Alvaro Tacchini – "Geometrical Map of Terrains and schematic of the river cut under the Tiber hill (1749)" abstract from "Città di Castello and its surroundings in drawings and maps from the Archive" published by Alvaro Tacchini.

From a geological point of view a closer look in the immediate surroundings of the seismic station (approximately 3 km radius) allows to provide a more detailed description (Figure 4). Based on what reported in the Geological Sheet 289 "Città di Castello" 1:50.000 (ISPRA – Geological Service of Italy, 2009a), the area is characterized by the presence of quaternary continental deposits and from Miocenic turbiditic litotypes from the Umbrian e Romagna Succession.

The first are composed by fluvial deposits from Holocene age (b) and terraced fluvial deposits of the Middle-Upper Pleistocene (b_n), and eluvio-colluvial deposits of the Upper Pleistocene-Holocene (b_2). These sediments are deposited inside the fluvial-lacustrine and colluvial Pleistocene sediments of Tiberino Supersynthem, which includes the synthem, from the earliest, of Fighille (FHL), Citerna (CTA), Monterchi (MTC) and the youngest of Selci-Lama (SLA).
In the area under study in Figure 4 only the first three stratigraphic units are exposed.

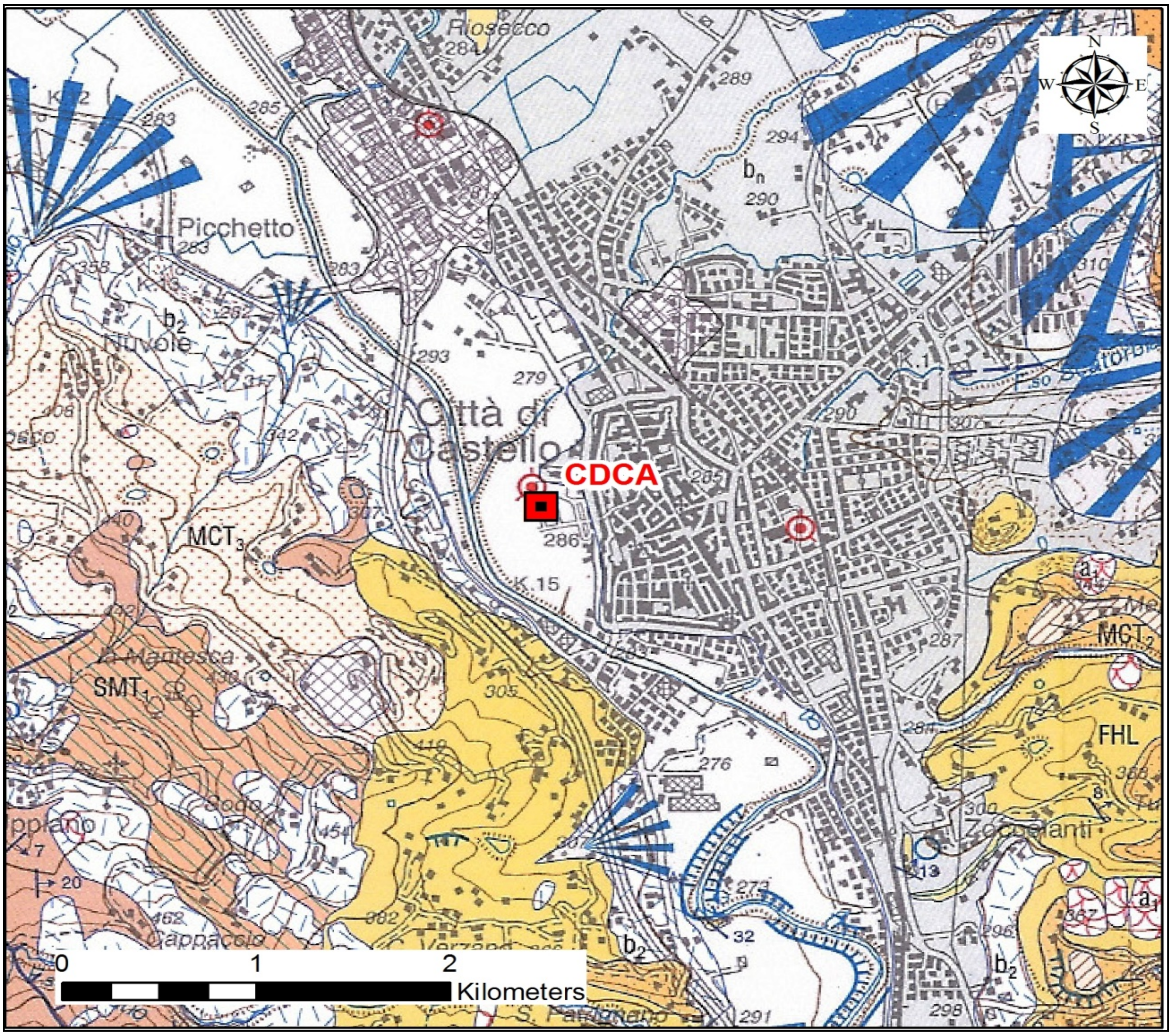


Figure 4 – Excerpt from the Geological Sheet 289 "Città di Castello" (ISPRA - Geological Service of Italy, 2009a). Legend: b = present alluvial deposits (*Holocene*); b_n = terraced alluvial deposits (*Middle-Upper Pleistocene*); b_2 = eluvium-colluvium deposits (*Upper Pleistocene? - Holocene*); MCT_2 = Anghiari Subsynthem (*Pleistocene*); MCT_3 = Nuvole Subsynthem (*Pleistocene*); CTA_2 = Monte Rotondo Subsynthem (*Pleistocene*); FHL = Fighille Synthem (*Lower Pleistocene*); SMT_1 = Monte S. Maria Tiberina Formation - S. Lorenzo Member (*Upper Burdigalian – Lower Langhian*); MUM_1 = Umbrian Marnoso-Arenacea Formation - Casa Spertaglia Member (*Middle Burdigalian - Lower Langhiano*); CDCA = Città di Castello seismic station.

The Fighille Synthem (FHL), largely exposed on the SW and SE of Città di Castello, is mainly composed of grey silty clays, in layers of few meters, interbedded with numerous sandy and silty sandy layers. In the upper part layers and lenses of gravel and polygenic conglomerates are more frequent. Said synthem is superimposed on the Miocenic substrata though an erosional

discontinuity that reveals an aerial erosional phase, followed by a depositional phase, firstly lacustrine and later fluvial-lacustrine.
The Citerna Synthem (CTA), consisting of two subsynthems, is represented only by Monte Rotondo Subsynthem (CTA_2), composed of polygenic pebbles with dimension up to decimetric, cemented, sometimes immersed in a sandy matrix.
The Monterchi Synthem (MTC), consisting of three subsynthems, outcrops only through Anghiari Subsynthem (MTC_2) and Nuvole Subsynthem (MCT_3). The Anghiari Subsynthem (MTC_2), surfacing in small outcrops in the E and SE of Città di Castello, consists mainly of silts and fine sands, in layers that are less than one meter thick, with subordinate clay fraction. There are also interbedded decimetric layers of little gravels.
The Nuvole Subsynthem (MTC_3), widely exposed on the Tiber left side west of Città di Castello, consists of blocks and gravel embedded in a matrix from sandy-gravel to silty-clay.
With regards to the terrains of the Umbrian-Romagnola Succession, parts of the Monte S. Maria Tiberina Formation (SMT) and, to a lesser extent, of Marnoso-Arenacea Umbra Formation (MUM), are exposed in the area considered in Figure 4.
Specifically, the Monte S. Maria Tiberina Formation, coeval and heterotopic of the Langhiano-Serravallian part of the Marnoso-Arenacea Umbra-Romagnola Formations, is represented only by the S. Lorenzo Member (SMT_1). This is composed of rich bioclastic calcarenites and calcirudites in thick or very thick layers.
The Marnoso-Arenacea Umbra Formation (MUM) is composed by a thick turbiditic sequence (approximately 1.300 m) arenaceous or pelitic-arenaceous, with variable composition from silicoclastic to carbonatic. In the study area this formation is represented by the Casa Spertaglia Member (MUM_1), characterized mainly by peliti, alternating with siltstones, sandstones and calcarenites.

GEOLOGICAL FIELD DATA AND SUBSURFACE DATA

In order to better define the geo-lithological characteristics around the seismic station (Fig. 5) a detailed geological survey was performed at scale 1: 5.000 in about 1 km^2 area.
Deposits characterization was performed by morphostratigraphic and facies analyses.
In addition to soil data and remote sensing, morphostratigraphic analysis has also used digital terrain model, compiled by the digital data of Umbria Region CTR 1: 5.000 (289112 element) (Fig. 7). These analyses allowed the identification and recognition of the following stratigraphic units, starting with the oldest:
Casa Spertaglia Member (MUM1) - Pelitic-arenaceous association – Silty clay in medium and thin layers, from moderately to heavily fractured (Figure 8a). In the finer fraction fractures have a typical concoid shape. The coarser fraction has a colour from gray, blue-gray to brown, brown-ochre.
Interbedded with the above are sandstone layers with medium thickness, from medium to coarse granulometry and somewhere laminated. In the outcrop observed along the unpaved road leading to "Casabianca", sandstones are affected by a fracture system generally oriented NNW-SSE. As a whole, the unit has an A/P ratio $<<$ 1.
In the deep incision of the Fosso del Cappuccio (western sector of the area), there is a five meter thick outcrop of sandstone, in medium-thick layers, with coarse sand and fine gravel granulometry, somewhere laminated (Fig. 8b). Sandstones are affected by the same fracture system as mentioned above. In this case, the A/P ratio is $>>$ 1.
The pelitic-arenaceous association is exposed along the base of the slope on the right-hand side of the Tiber River, from Casabianca until just over the E 45 highway.
Age: Lower - Middle Miocene.

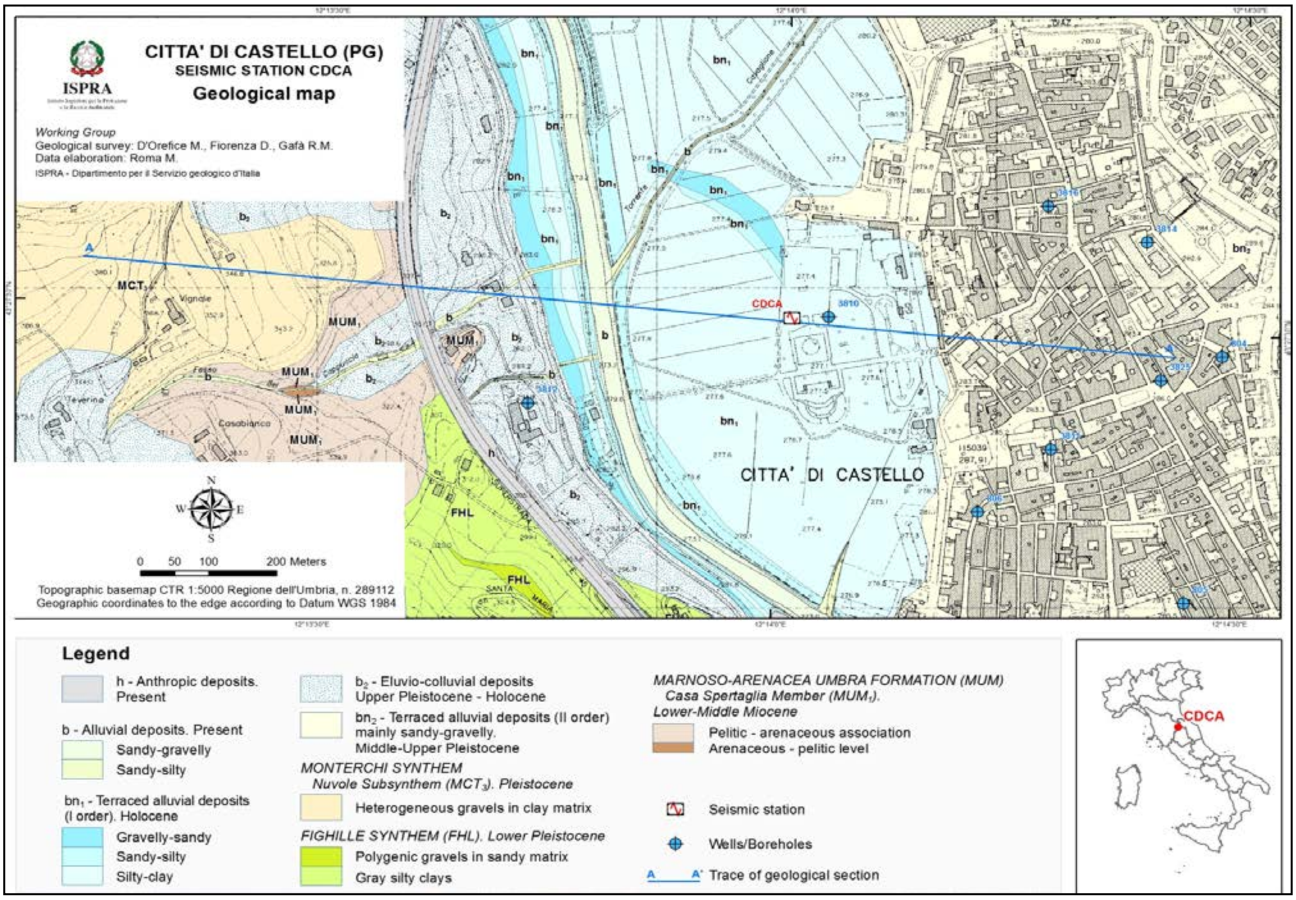


Figure 5 – Geological map after field work.

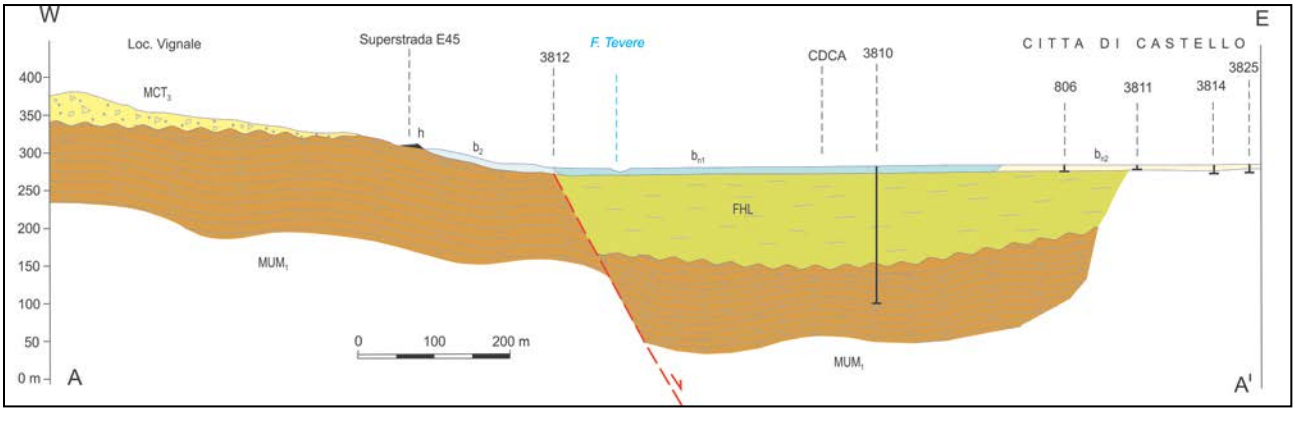


Figure 6 – Geological section with W-E direction, passing through the seismic station. The track is shown in the figure 5. The numerical codes (i.e. 3810) corresponds to the borehole locations listed in the data base of the Geological Survey of the Umbria Region.

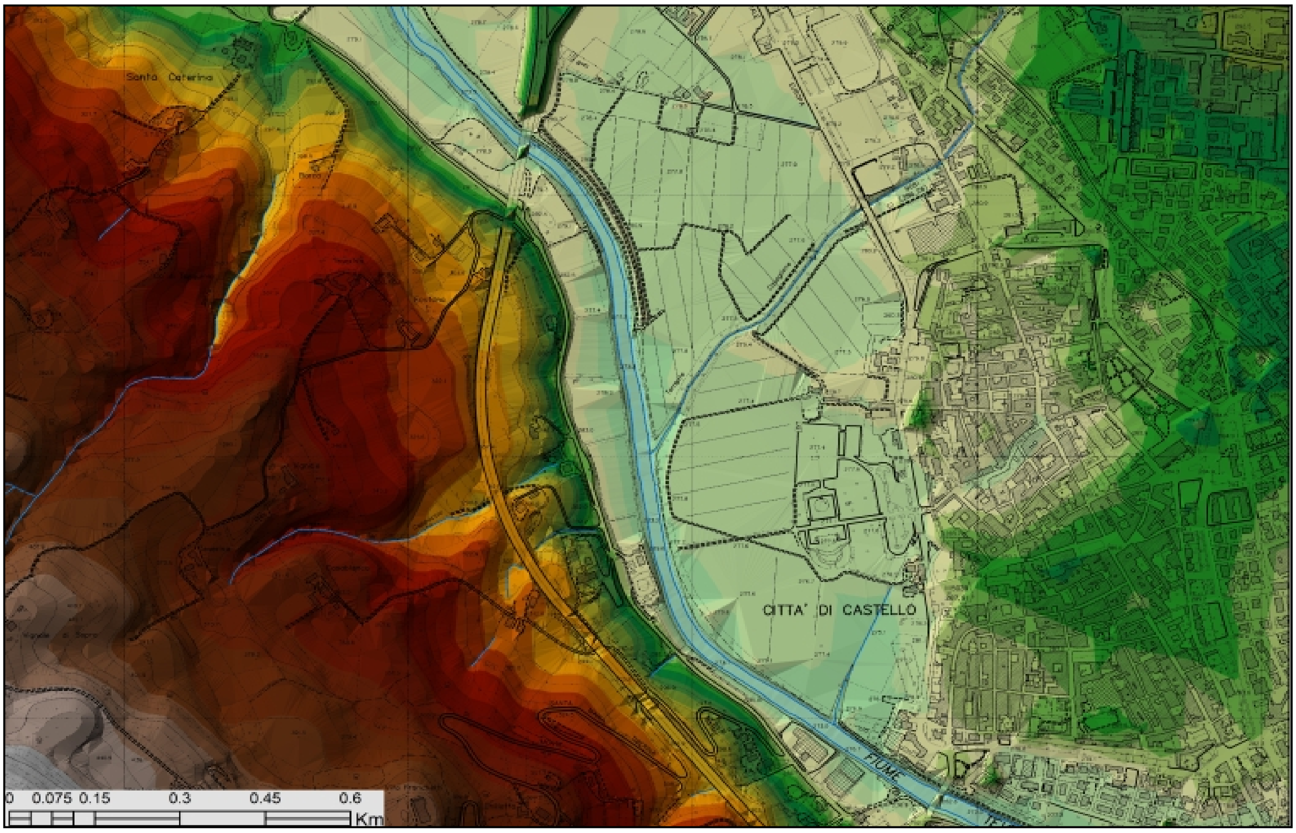


Figure 7 - Digital Terrain Model of study area. The DTM was processed by the digital data of the Umbria Region CTR 1: 5.000 (289112 element).

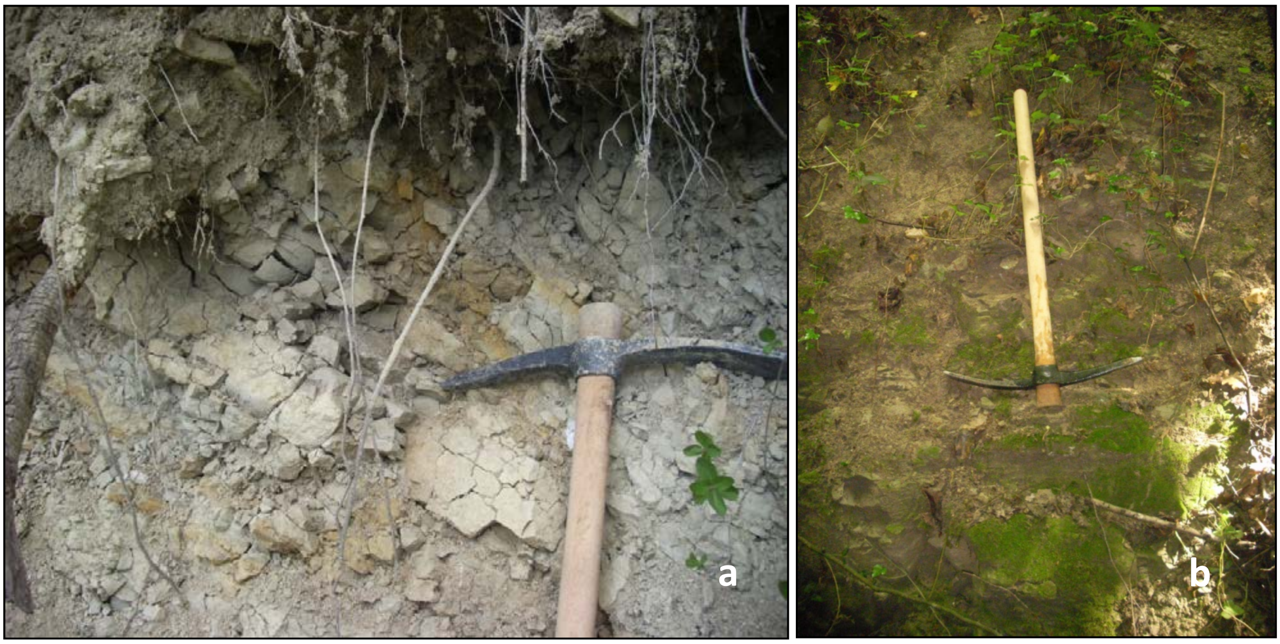


Figure 8 – Pelitic-arenaceous association of the Casa Spertaglia Member (**MUM$_1$**): a) Pelite in medium and thin layers very fractured; b) sandstones in medium and thick layers.

Fighille Synthem (FHL) – Grey silty clays, in medium and thin layers, with medium or high consistency, from moderately to heavily fractured (Figure 9a). In the coarsest fractions the colour is generally greenish-gray with brown shades. These contain charcoal remains and fragments of

gastropod shells. At different heights, polygenic gravels and sandy layers are interbedded, with lenticular geometries (Figure 9b).
The gravels are made mainly by sedimentary elements (limestone, marly limestone, sandstone) and subordinately by metamorphic elements (ophiolitic lithologies belonging to the unit of the Rognosi M.). Clasts are heterometric (diameter from a few centimetres to 6-7 cm), generally rounded and of discoidal shape, moderately classed to well-classed. The texture is generally clast supported and the matrix is sandy. Often, clasts imbrication is visible. The sandy silicoclastic layers are well densified. In the area under investigation the gravelly and sandy layers are characterized by variable inclinations between 16 ° and 40-45 °. This stratigraphic unit is exposed in the lower part of the hillside on the right of Tiber River. Age: Lower Pleistocene.

Figure 9 – Fighille Synthem a) Silty clays in medium and thin layers; b) Lenticular polygenic gravels, passing through underlying densified sands. Both levels dipping about 40-45° SE.

Nuvole Subsynthem (**MCT_3**) – Massive deposits made up of blocks and gravels with heterogeneous, etherometric, subangolose, rarely subarounded elements, immersed in abundant gravelly-sandy and silty-clayey matrix, stiff, somewhere soft, gray (Figure 10). This unit is exposed along the slope on the right side of the Tiber River close to "Vignale", where the most consistent component creates a ridge oriented NNE-SSW, while the less consistent and more pelitic is exposed further downstream, where a little artificial lake is located. Age: Pleistocene

Figure 10 – Nuvole Subsynthem (**MCT_3**): massive deposits consist of blocks and gravels in gravelly-sandy matrix.

Terraced alluvial deposits (b_{n2}) (II order) – Brown deposits predominantly silty, in layers that reach metric thickness, interbedded with polygenic gravel levels in sandy matrix and/or whitish carbonate nodules. These are exposed on the left of the Tiber, below the city centre of Città di Castello.
Age: Middle-Upper Pleistocene

Eluvio-colluvial deposits (b_2) – Predominantly silty-sandy deposits and subordinately silty-clayey, poorly cohesive, containing polygenic and heterometric clasts. They are characterized by a maximum thickness of about 5 m and generally appears massive or coarsely laminated. These are exposed at the base of the slope on the right of the Tiber, in particular along the connecting band with the riverbed. Age: Upper Pleistocene – Holocene.

Terraced alluvial deposits (b_{n1}) (I order) – Gravelly-sandy, silty-clayey and sandy-silty deposits (Figure 11). The coarser sediments are exposed continuously at the base of the slope on the right side of the Tiber and in a more limited area just NW of seismic station. They are made from polygenic rounded gravels in sandy matrix, essentially limestone, arenaceous and metamorphic (the latter probably originated from the Ophiolitic Unit of Rognosi M.). The clayey silts occupy a larger area, extending from the town of Città di Castello until the artificial embankment in the left of the Tiber. They are also exposed long a narrow strip in the N-S direction to the right Tiber. Near the banks of the watercourse these sediments tends to gradually change to silicoclastic fine sands without clayey fraction. Age: Holocene

Figure 11 – 1st order terraced alluvial gravelly-sandy deposits, gradually change to underlying silty-clayey sediments.

Present alluvial deposits (b) – Sandy-gravelly and sandy-silty deposits. The first occupy the existing riverbed of the Tiber River, while the latter are found on the bottom of the tributaries (Fosso del Cappuccio, Torrente Cavaglione, ecc.) Age: Present

Anthropic deposits (h) - They are mostly present in correspondence with the E 45, largely built on enbankment from 4 to 8 m thick. Age: Present.
The stratigraphic model of the study area was drawn based from known literature and maps, survey data and borehole data; it is represented by the geological section of Figure 6.

This geological section highlights a Miocenic turbiditic bedrock, mostly pelitic-arenaceous, (**MUM$_1$**), characterized by mildly undulating layers, with inclinations varying from horizontal to about 10°.
The bedrock is exposed on the right side of the Tiber River and disappears on the left side under the alluvial plain. The bedrock has been found here in the borehole n°3810 at a depth of 140 m from the ground level. The sudden deepening of the bedrock can be justified either by an abrupt flexure or by a tectonic displacement, or a combination of the two. The area is known to be affected by an extensional tectonic and this has suggested the presence of a direct fault, buried under the base of the hill on the right side of the Tiber. This tectonic element has displaced the turbiditic bedrock, deepening the eastern block. Also deducted from the above mentioned borehole data, in agreement with what summarized in the general geological setting, on top of the bedrock a very thick continental sequence of fluvial-lacustrine sediments is superimposed. This sequence is composed by an alternation of clayey silts, silty sands and gravels of the Fighille Synthem (**FHL**), approximately 135 m thick.
The lacustrine sedimentation is followed by a clastic accumulation on hillslope on Tiber right side: Nuvole Subsynthem (**MCT$_3$**).
On the riverbed, after an erosional phase on the Fighille synthem (**FHL**), the sedimentation is characterized by alluvial sediments, lately terraced, of the Middle-Upper Pleistocene and Holocene (**b$_{n2}$** e **b$_{n1}$**) and Recent (**b**). These have an overall thickness of 5.5 m.

LITHOSTRATIGRAFIC MODEL

From the stratigraphy of the borehole situated close to the seismic station CDCA, it is possible to schematize the stratigraphy of the ground vertically below the seismic station as in Table 1 and in Figure 12.

BOREHOLE STRATIGRAPHY				
Depth from ground level		**Thickness (m)**	**Lithological description**	**Acronym**
from m	**to m**			
0.0	0.8	0.8	Backfill	**h**
0.8	2.5	1.7	Clayey-sandy silt, brown and *avana*	**b, b$_{n1}$**
2.5	3.5	1.0	Coarse sand with middle-fine gravel	
3.5	5.5	2.0	Gravel with pebbles in sandy matrix	
5.5	10.5	5.0	Silty sand cemented, *avana*	**FHL**
10.5	24.0	13.5	Clayey silt, gray	
24.0	45.0	21.0	Sandy-clayey silt, gray	
45.0	51.0	6.0	Silty-clayey sand, gray	
51.0	75.0	24.0	Clayey silt, gray	
75.0	90.0	15.0	Sands and sandy silts interbedded with gray clayey silts,	
90.0	91.0	1.0	Gravel in sandy matrix	
91.0	115.0	24.0	Gray silty clay	
115.0	140.0	25.0	Gray silty-clayey sand	
140.0	180.0	40.0	Bedrock made of alternation of sandstones, marls, mudstones limesandstones with fragments of Ophiolitic material.	**MUM$_1$**

Table 1 – Stratigraphy of the borehole n°3810 from Geological surveys and geophysical database of the Umbria Region.

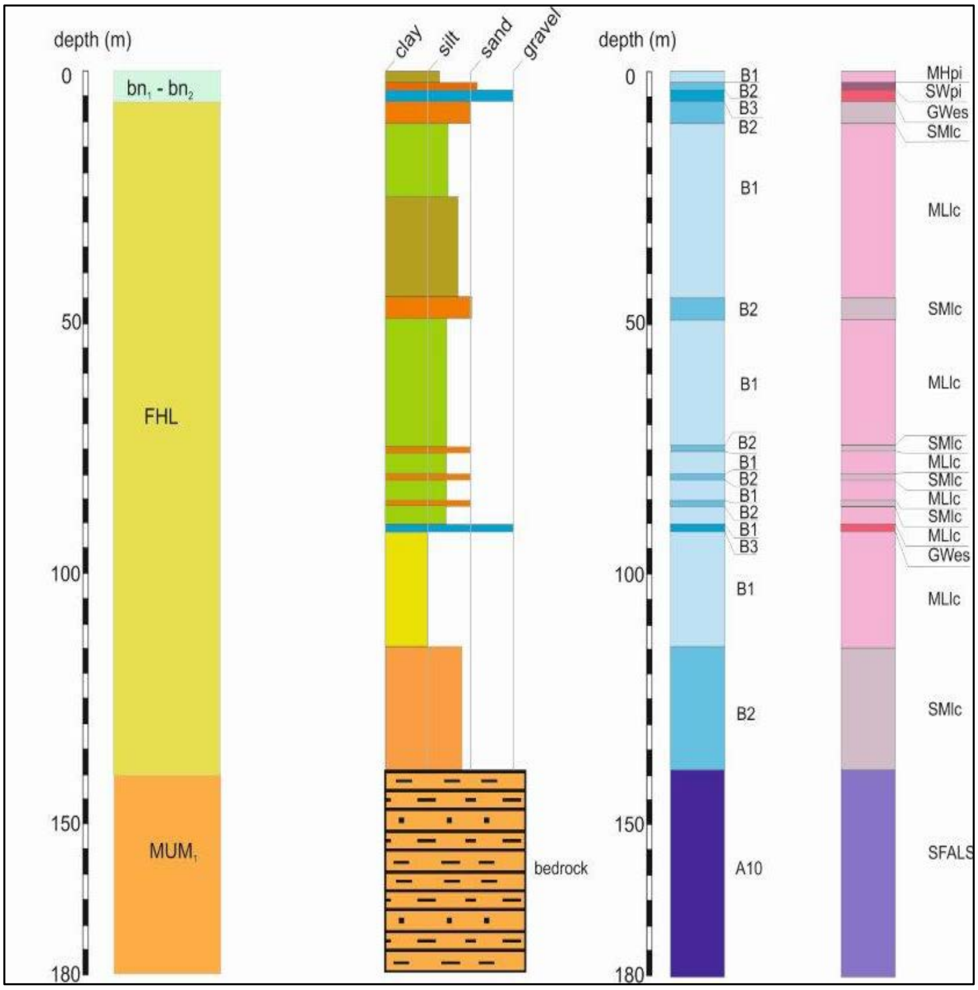


Figure 12 – Geological situation on the ground vertically below the seismic station. From the left: Stratigraphy column; Column with granulometric profile in terms of clay, silt, sand and gravel content; Lithological column according to the Lithological map of Italy 1: 100,000 (ISPRA - Geological Survey of Italy); Lithotecnical column according to the rules of Seismic microzonation (version 4.0b).

LITHOSTRATIGRAFIC AND LITHOTECHNICAL CHARACTERIZATION

In Figure 13 the map of the lithological units is drawn, following the classification used in the Lithological map of Italy 1:100.000 (ISPRA - Geological Survey of Italy).
In Figure 14 the map of the lithotechnical units is drawn following the rules of the Seismic microzonation (revision 4.0b).
In Table 2 are listed the correspondences between the CARG acronyms, the lithological units and the lithotechnical units.

Lithostratigraphic unit (ISPRA, Geological map)	Lithological unit (ISPRA, Lithological map)	Lithotechnical unit (Guidelines 4.0b_MS, 2015)
h	N2	RI_{zz}
b	B3	GW_{es} – SM_{es}
bn1	B4	MH_{pi} – SM_{pi} – GP_{pi}
b2	B4	MH_{ec}
bn2	B4	SW_{pi}
MTC3	B4	GC_{ec}
FHL	B1-B3	CHl_{c} – GW_{es}
MUM1	A9-A10	SFALS

Table 2 – Classification of geological units

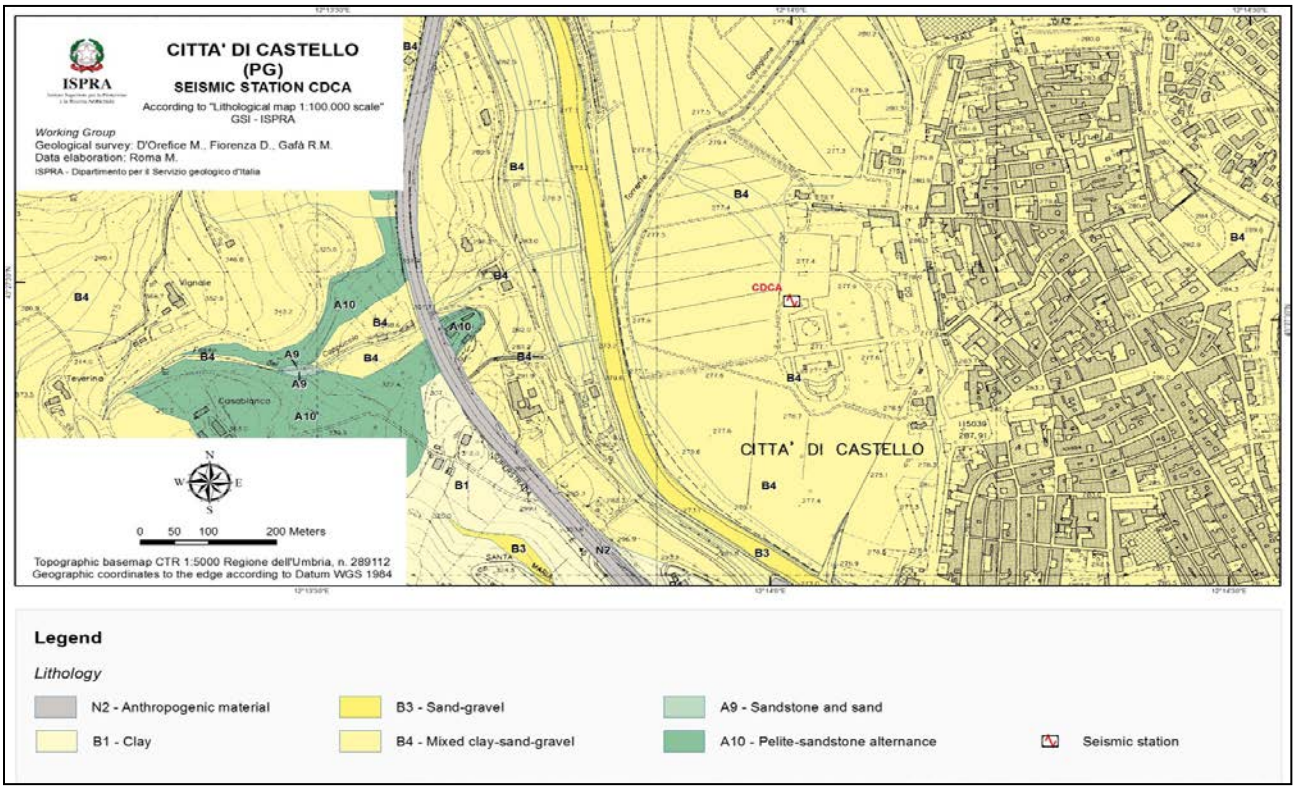


Figure 13 – Lithological map.

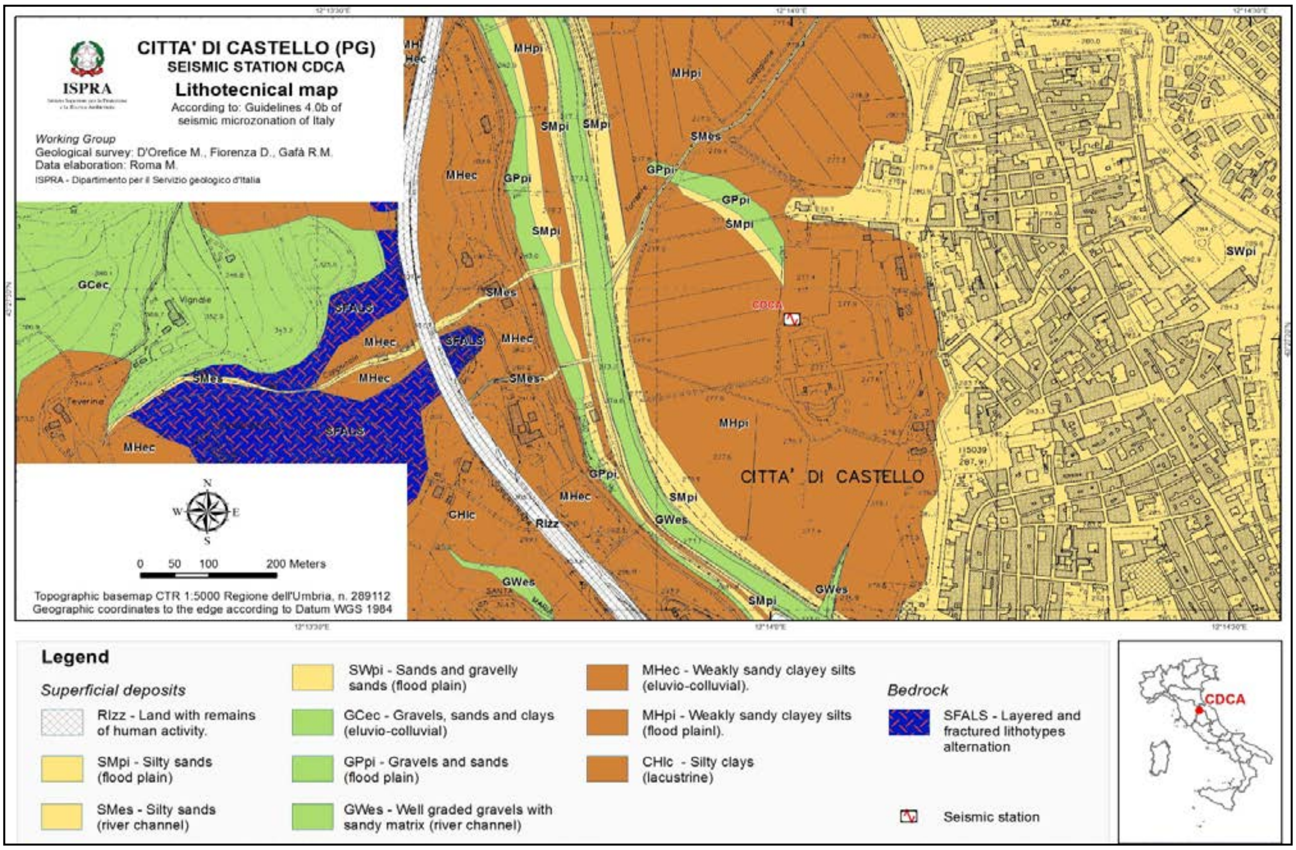


Figure 14 – Lithotechnical map.

LAV9 SEISMIC STATION

GEOLOGICAL SETTING

The LAV9 seismic station is located above a portion of the Volcanic District of the Colli Albani Hills, a composite volcano whose activity ranges from 600 ky to 5.8 ky BP. It was mainly characterized by an explosive caldera-forming activity with some distinctive eruptive stages during which originated also several volcanic edifices.
Lanuvio Village lies above a prevailingly pyroclastic hill (the Colle San Lorenzo, 376 m asl high), referable to a scoria cone activity. This cone represents one of the eccentric peri-calderic apparatuses constituting the Tuscolano-Artemisio lithosome. The volcanic activity producing this lithosome ranges approximately from 355 to 180 ky (named Tuscolano-Artemisio stage), and followed the caldera-forming eruptions (Vulcano Laziale stage, ranging approximately from 600 to 355 ky) which emplaced the ignimbrite plateau of the Villa Senni formation.
During the Tuscolano-Artemisio stage, cinder/scoria cones and lava flows were erupted from peri-caldera and extra-caldera eruptive fissures, emplacing alignments of coalescing monogenetic centers, concentric to the caldera. Lava flows, associated fall out and minor pyroclastic flow deposits are grouped into the Madonna degli Angeli composite formation (DE RITA & GIORDANO, 2009; FUNICIELLO & GIORDANO Eds., 2010). These products overlie the thick and widespread ignimbrite plateau of the Vulcano Laziale. The specific eruptive fissure feeding the alignment of the scoria cones, one of which is the Lanuvio cone, is an about 6.5 km long NNE-SSW oriented fracture (FUNICIELLO & GIORDANO, 2010). The Lanuvio scoria cone has an about 2 x 1 km squared elliptical form, with the main axis oriented as the feeding fissure.
The most recent eruptive stage is referable to a phreatomagmatic maar- and tuff cone-forming activity, partially overlying the preceding deposits on the western and northern flanks of the volcanic edifice (Maar field Via dei Laghi stage, ranging approximately from 200 to 5.8 ky BP). In the study area, this stage built the Nemi maar whose products are cropping out on the western side of Lanuvio cone.

GEOLOGICAL FIELD DATA AND SUBSURFACE DATA

The geological surveying has been made at 1:5.000 scale on the topographic map of the Latium Region; it covered the surrounding area of the seismic station site, placed inside the Municipal Library of Lanuvio (Fig. 1)

Figure 1 – LAV9 station

The few outcrops still preserved and not covered by the urban and anthropogenic manifactures show three main lithologies, linked to three recognizable lithofacies: fallout pyroclastics, lavic flows and surge ashes, the first two of which are referable to the real scoria cone. Lanuvio fallout pyroclastics crop out as altered deposits, and are often pedogenic; many outcrops on the road cuts evidence deposits with such features quite constantly. At places, can occur as scarcely matrix-sustained very welded scorias (like in Borgo S. Giovanni outcrop, *out of sketch*).
In the garden close to the Library, the recent archeological excavations highlighted the subsurface stratigraphy of the station grounds. The first level (Fig. 2) is a volcanoclastic and scarcely coherent deposit made of sub-cm to cm–sized lapilli scoria loose in abundant ashy-matrix containing analcimized leucite (Lc) and pyroxenes (Px) crystals, with a maximum thickness of 1,5 m, overlying a dark pedogenic level (Fig. 3), cropping out for an about 2 m height.

Figure 2 – Outcrop of a scarcely coherent volcanoclastic deposit close to the LAV9 station.

Figure 3 – Outcrop of a paleosoil at archeological excavations close to the LAV9 station.

In Giacomo Matteotti boulevard (on the western side of Lanuvio cone), at about 345 m a.s.l., an altered, partially pedogenic and reworked ash tuff, yellowish to brick red in colour, poorly coherent, massive, large analcimized Lc crystals bearing, 3-4 cm-sized Px, light micas and rare grey-purplish small scoria (Fig. 4) crops out. At about 330 m a.s.l., a pyroclastic succession made up of alternating ash-sustained scoria levels, analcimized Lc cristals and Px bearing, and pedogenic levels occurs for about 3 m of thickness; at the base of it, a level rich of up to 8 cm-sized scoria and frequent lava lithics crops out (from the field survey notes of S. TAVIANI).

Figure 4 – Outcrop of an altered and reworked ash tuff at G. Matteotti boulevard.

In Vagnere road, below to the cemetery, at an altitude of about 320 m a.s.l., a semi-lithoid ash-tuff matrix-supported crops out, more than 2 m thick, including cm-sized Lc-bearing lava clasts, reddish scorias Lc-bearing, with loose Px and Lc crystals, pumice and grey Lc-scorias.
In Vagnere locality, at about 280 m a.s.l., an excavation for new buildings put in evidence a poorly coherent ash-tuff, ochre in colour, showing a developing pedogenesis, with small grey-purplish mm-sized scoria (white when altered), analcimized Lc cristals, large Px and small lavic clasts. The deposit occurs with the same features until an altitude of about 260 m a.s.l.
In Antonio Gramsci road, on the western flank of the cone, at an altitude of about 288 m a.s.l., an escarpment about 5 m high shows a pyroclastic succession, with a 10-30 cm thick bedding, made of mm-sized fallout black scoria, yellow when altered, with a scarce ashy matrix containing micas, Px and analcimized Lc (Fig. 5).

Figure 5 – Outcrop of a scoria fallout at A. Gramsci road.

All the fallout pyroclastic lithofacies previously described has been mapped as FKB_{i5b}.
In many road cuts of the village the pyroclastics are reworked and altered, and crop out as soils with a developed pedogenesis, dark-reddish in colour, that can exceed 2 m of thickness. Such features were observed for example, close to the Giunone Templum, at about 365 m a.s.l. (Figg. 6 and 7), where the soil contains sub-cm to cm-sized lapilli-scoria, small tuffaceous lithics, loose Bt crysts, and crops out as a weakly cohesive sandy-silt deposit.

Figure 6 – A developing volcanic soil cropping out at Giunone Templum road.

Figure 7- The volcanic soil in detail.

The lavic lithofacies (FKB_{i5a} in the geological map) is presumably intercalated as several levels to the pyroclastic succession representing the scoria cone, and it was surveyed at altitudes of 345, 285, 240, 195m a.s.l. (the last two outcrops out of the mapped sketch).

In Giovanni XXIII road, opposite to the cemetery, at an altitude of about 345 m a.sl., the lava flow occurs as a lithoid, compact and recent deposit, aphyric and with sharp edges, interbedded by brecciated, at places scoriaceous levels (Fig. 8). The brecciated portions of the deposit are generally altered by a withish patina. In Conicella road (at about 280 m a.s.l.), the lava cropping out at the grounds of some buildings, is more scoriaceous and altered than the previous one.

Figure 8 - Outcrop of the lavic lithofacies in Giovanni XXIII road

In outcrops out of the sketched map, close to the football stadium of Lanuvio, at about 175 m a.s l. and at Vigne Vecchie locality (at about 190 m), it is possible to follow for some tens of meters a surge pyroclastic succession, up to 8-10 m thick, made up of ash-tuffs with accretionary lapilli and showing a cross and plane bedding. These deposits (NEM in the geological map) occur very close to the scoria cone products and are referable to the more recent eruptive stage that built the Nemi maar.

Field surveying together with data from 388 geological Map "Velletri" (in working, ISPRA – Geological Service of Italy), allowed us to elaborate a geological map at 1:5.000 scale of the examined area (Fig. 9) and a geological profile (Fig. 10).

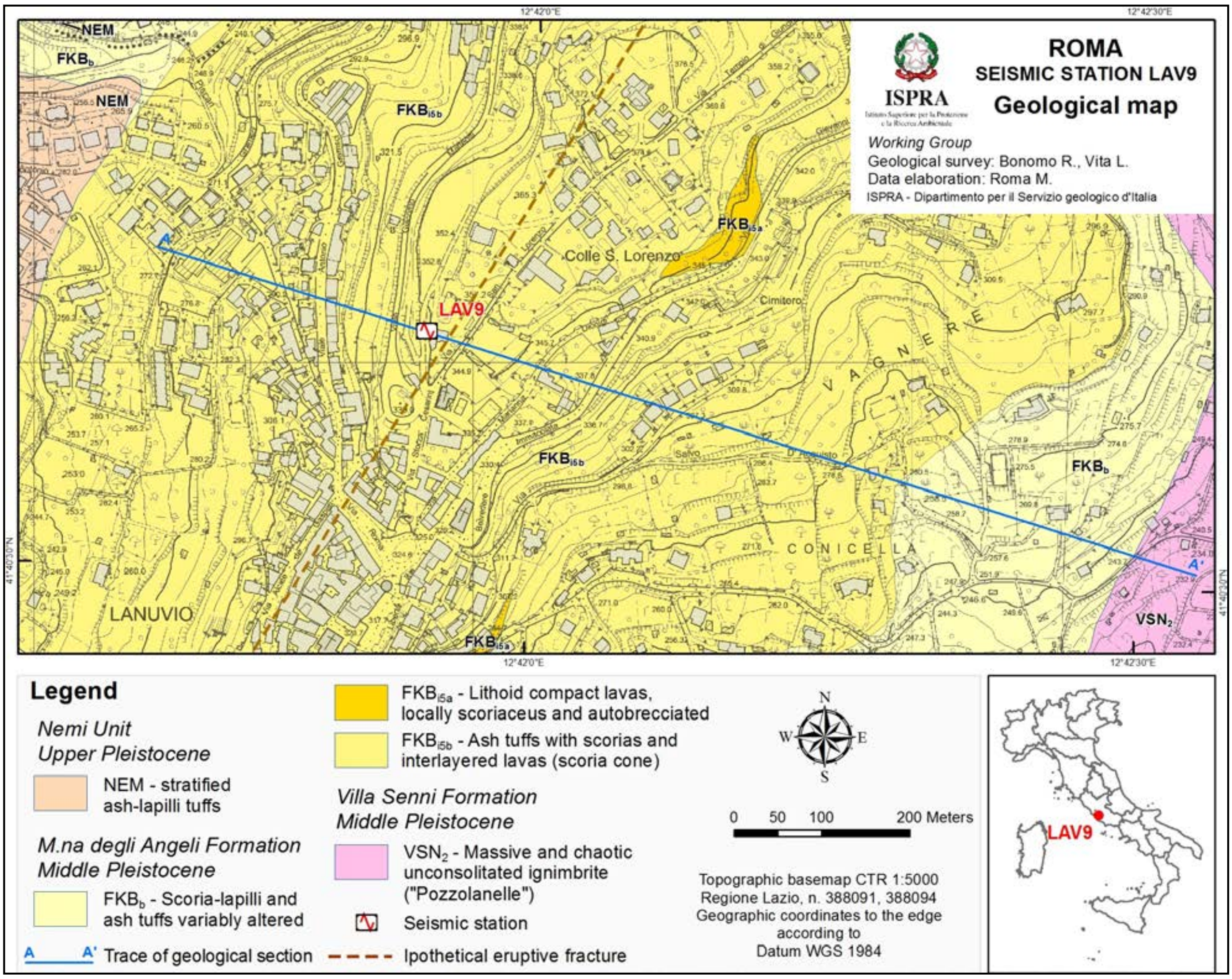


Figure 9 – Geological map after field work.

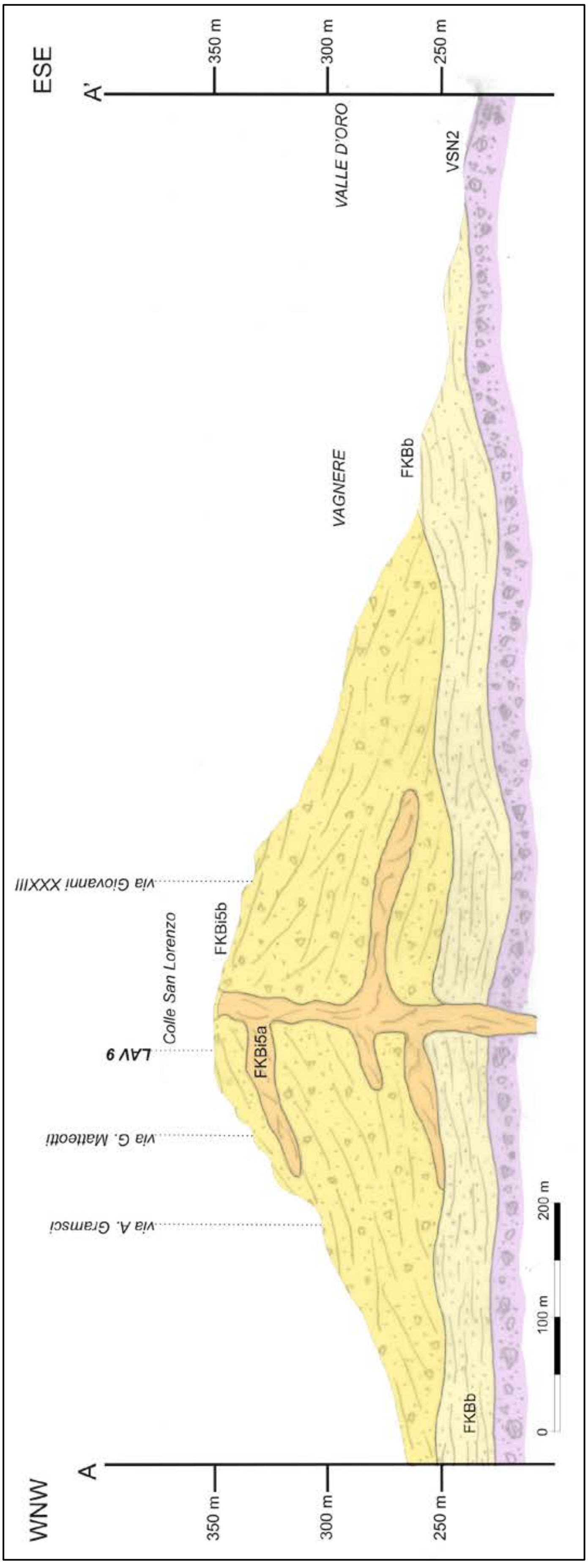


Figure 10- Geological profile WNW-ESE oriented, crossing the LAV9 Seismic Station; vertical exaggeration 2x.

LITHOSTRATIGRAPHIC MODEL

To obtain a quantitative reconstruction of the stratigraphic model of the substratum, a drilling survey should be leaded to a depth of at least 150 m aimed to detailed geodata, as requested by the INGV, unfortunately non available for the moment. Nevertheless, field surveying and data coming from published works interesting the study area, added to the knowledge of what was the style of the activities of the eruptive centres that emplaced the cropping out deposits, allowed us to assume a qualitative and general stratigraphic model representative of the site of the seismic station LAV9.

The surveyed area is wholly located above the Lanuvio scoria cone, made up of alternating scoria levels and lava flows, representative of the Madonna degli Angeli formation. In detail, the published geological map of Colli Albani Volcano (FUNICIELLO & GIORDANO, 2010) names this succession as Monte Due Torri succession (FKB_{i5}), deriving from monogenetic apparatuses; lavas are grey to dark-grey in colour, from aphyric to sub-aphyric to Lc- and Cpx-porphyritic. Their chemical composition is K-foiditic; the maximum thickness reported is locally of 20 m; the age of these lavas is about 178 ± 24 ka. The pyroclastics are referable to a scoria cone occurring as poorly sorted to sorted, poorly stratified to bedded, incoherent to welded, bomb- to lapilli-sized scoria with block and lapilli lava xenoliths. Scoria vary from Lc- and Cpx-porphyritic to aphyric. Maximum thickness reported is 350 m (FUNICIELLO & GIORDANO Eds., 2010).

In the surveyed area its minimum thickness, recognizable analyzing the morphologies of the Lanuvio cone, could reach at least 125 m. The geophysical behavior of the deposits vary from each level to another, due to its different lithological composition, and for the same lithology, because their different alteration and textural features. Hence, to better recognize how many and how much thick are the levels that behave differently, fitting in a seismic-stratigraphical model, a drilling survey would needed, as above said. However, on the base of the dispersal pattern and the emplacing ways of the deposits, it is possible to make some considerations useful to reconstruct the best realistic model. The eruptive style of a scoria cone is explosive with low energy eruptions and a roughly radial dispersion pattern of the pyroclastics around the vent; instead the lavas have preferential axes of flowing, depending on how deeping are the directions around the vent. Hence it is not possible to know surely how wide the 4 lavic outcrops, that obviously behave very differently from the pyroclastics, extend in the inner parts of the cone. It is maybe easier to assume that other lavic lithosomes, not cropping out, are present at different heights inside the body of the cone, but only along some lines that we cannot prior know. Indeed, the Casa Marini borehole (from the ISPRA - Geological Survey of Italy - THE NATIONAL SUBSOIL SURVEYS DATABASE (ACCORDING TO LAW N.464/84): http://sgi.isprambiente.it/indagini/scheda_indagine.asp?Codice=160014), though about 2 km far from the site, evidences the probable occurrence of other lavic units differently distributed also under the Lanuvio cone.

For the above wrote considerations, the whole reconstructed lithostratigraphical succession below the LAV9 seismic station of Lanuvio must be considered speculative and characterized by high uncertainty.

The qualitative stratigraphic model we are able to reconstruct on the base of the field survey, from published data and from boreholes stratigraphies, is the following.

The study area where the LAV9 station is placed, has an elliptical morphology (about 2 x 1 km squared), mostly corresponding to a scoria cone, referring to the well known volcanic succession of Madonna degli Angeli formation (FKB); the lithologies of the surveyed deposits can be summarised as:

- **FKB_{i5b}**) incoherent to semi-welded, generally unstratified, locally bedded, scarcely sorted ash tuffs with scoriaceous lapilli. They lie stratigraphically above:

- **FKB$_b$**) alternating scoria-lapilli and ash fallout beds and layers, variably altered to paleosoils referable, as the preceding, to the same formation and locally up to 35 m thick;
- ***p***) the preceding pyroclastic succession can crop out as reworked and altered volcanoclastic and/or as soils with a developed pedogenesis, dark-reddish in colour, that can exceed 2 m of thickness;
- **FKB$_{i5a}$**) lithoid, dark grey in colour, compact and with a recent aspect, frequently aphyric, with sharp edges lavas, intercalated to the tuffs (FKBi5b); at places they can be scoriaceous and present autobrecciated levels, until to seem autoclastic lavic breccias. The autoclastic portions of the breccias sometimes are altered. Field data are not enough to exactly define how many lavas are intercalated to the pyroclastic lithofacies, and how much thick each lavic unit could be; an useful help to interprete their thickness could come from the stratigraphical analyzing of the Casa Marini borehole, where the lava levels interbedded to the pyroclastic succession can show thicknesses of some meter up to 19 m.

The Madonna degli Angeli succession lies above:

- **VSN$_2$**) Villa Senni formation, referable to the last large ignimbrite-type eruption of the Vulcano Laziale. In detail, it occurs as the Pozzolanelle unit (VSN$_2$) mostly in the fluvial lines of the study area. It is a tephri-phonolitic to phono-tephritic massive and chaotic unconsolitated, dark purple, coarse ash and lapilli-sized scoria and xenolith rich ignimbrite (FUNICIELLO & GIORDANO Eds., 2010). The cropping out thickness is about 20 m; close to Lanuvio and above the top of the Pozzolanelle ignimbrite, could be present also some fallout ash deposits associated to the eruption ignimbrite forming. This cover is some meter thick and is similar to a lapilli tuff .

Conclusive remarks: if the scoria cone, as well the ash banks below it, is assumed to be emplaced when the paleomorphology was controled by the flat ignimbrite plateau of the Vulcano Laziale represented by the Villa Senni formation, then the morphological evidences reveal that FKB constituting the cone body could reach 125 m of thickness below to the site of the seismic station LAV9.
Hence, the whole thickness of such a succession (FKB+VSN$_2$) could here reach and exceed 145 m (fig. 11).

LITHOSTRATIGRAPHIC AND LITHOTECHNICAL CHARACTERIZATION

Basing on the geological and textural features, the recognized units (see Geological Map) have been classified as lithological units (Tab 1), referable to the ISPRA Lithological map of Italy 1:100.000, and as lithotechnical units referable to the Standards for the Seismic Microzoning drafted by the Technical Committee (art. 5, c. 7 OPCM 2010, 4.0 b version).
For the great variability of the grainsize distribution and of the textural features of the different volcanoclastic lithotypes that a geological formation could show, we summarized some geological unit as the best, even though not entirely fitting class of the MS Standards.
Moreover we categorized as cover units those pyroclastic units that for their specific textural features or because frequently altered, occur often as loose granular deposits or with very low welding. Note besides that the Lithotechnical classification of FKBi5b (namely GMsc), does not count on the occurrence into the body of the scoria cone, of alternating lava levels (FKBi5a), which are classified apart only when cropping out.

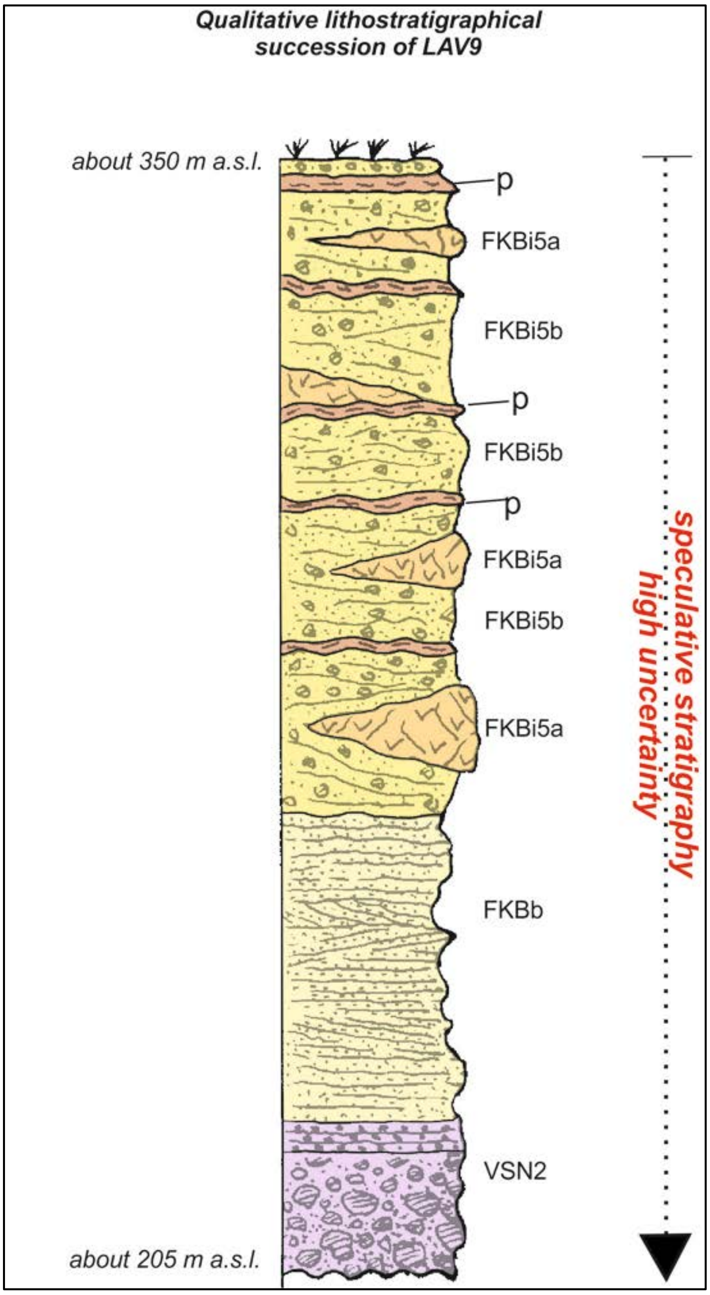


Figure 11 – Qualitative lithostratigraphical succession of ROM9

Lithostratigraphic unit (ISPRA, Geological map)	Lithological unit (ISPRA, Lithological map)	Lithotechnical unit (Guidelines 4.0b_MS, 2015)
NEM	D5	GMig
FKBi5a	D3	SFLP
FKBi5b	D6	GMsc
FKBb	D7	GCsc
VSN2	D8	GMig

Table 1 – Classification of geological units

The table 1 was utilized to elaborate the Lithological Map (Fig. 12) and the Lithotechnical Map (Fig. 13) of the sketched geological map of Lanuvio seismic station site (LAV9).

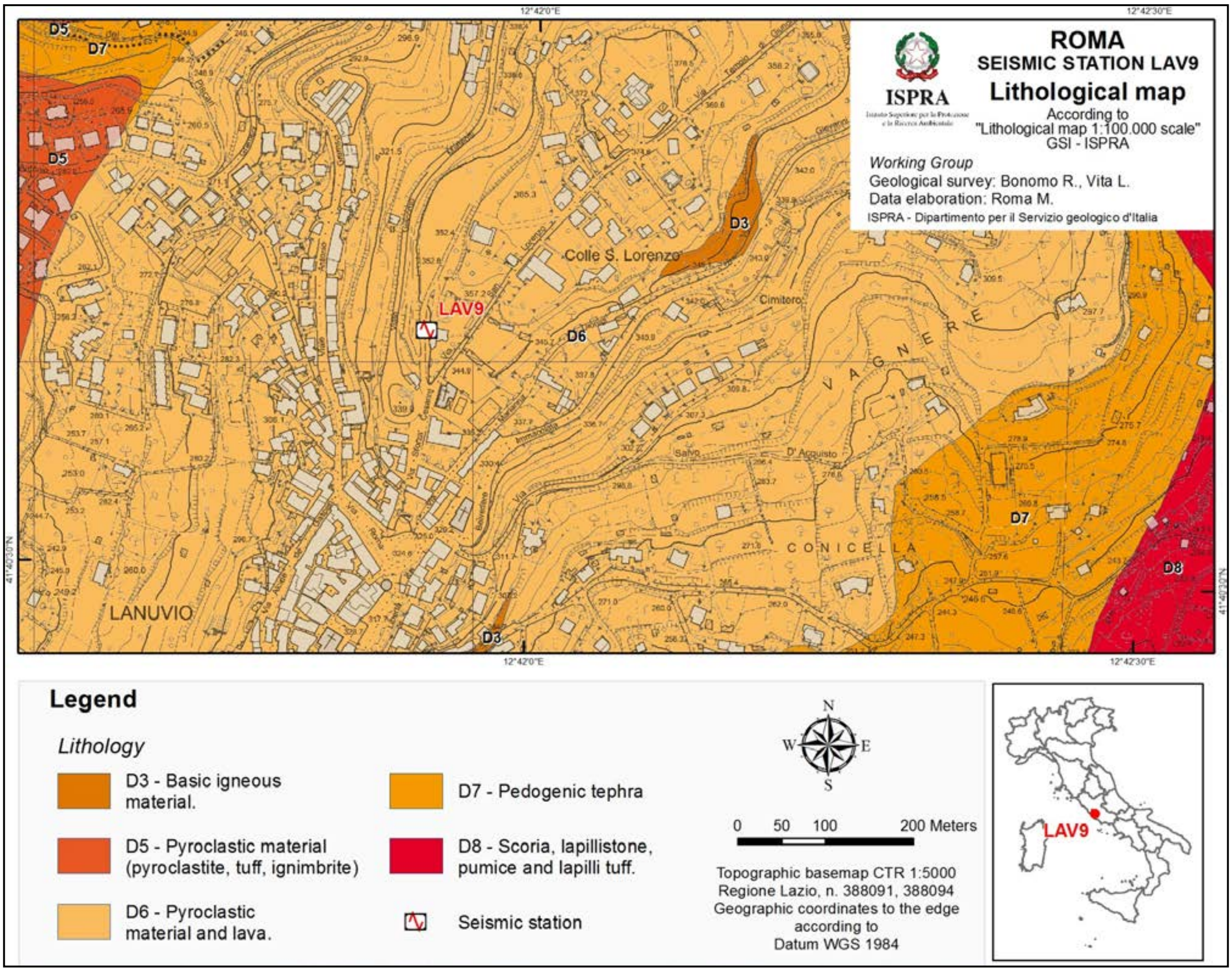


Figure 12 – Lithological map.

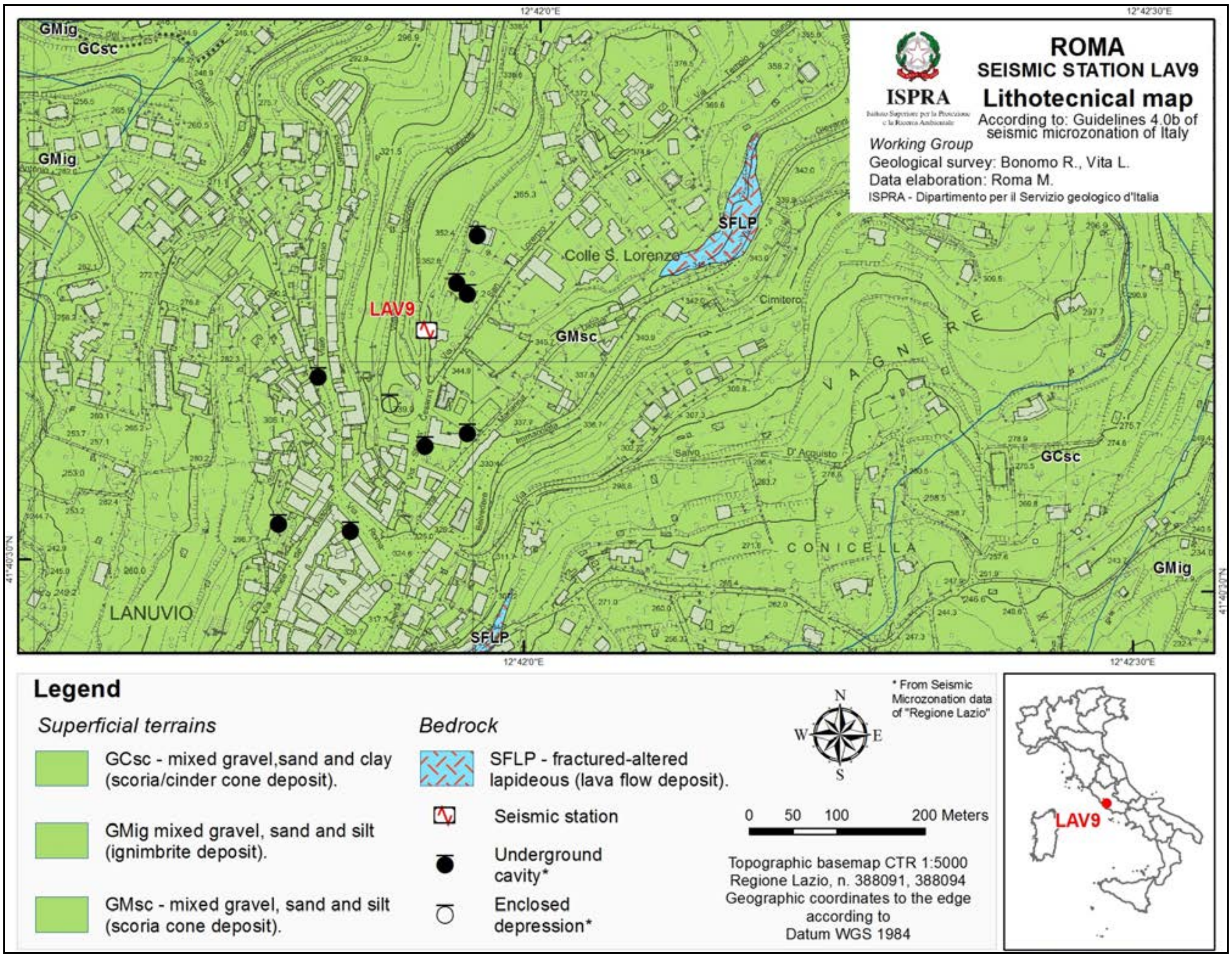


Figure 13 – Lithotechnical map.

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