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DEVELOPMENT OF A GEOLOGICAL MODEL USEFUL FOR THE STUDY OF THE NATURAL HAZARDS IN URBAN ENVIRONMENTS: AN EXAMPLE FROM THE EASTERN SECTOR OF ROME (ITALY)[°]

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EXTENDED ABSTRACT

La gestione del rischio di un'area urbana con la diffusa presenza di elementi di valenza storico-archeologica richiede, anche nel caso di basse pericolosità geologiche, come nel caso di Roma, una conoscenza accurata del sottosuolo. Infatti, l'elevato valore esposto dei beni storici e la loro maggiore vulnerabilità, tenuto conto della loro vetustà e delle tecniche costruttive talora inadeguate, ad ogni evento e per qualunque intensità, rispetto a beni di recente costruzione, determinano livelli di rischio elevati anche per bassi livelli di pericolosità. Lo studio delle pericolosità geologiche locali presuppone pertanto la preventiva ricostruzione di un modello geologico adeguato agli scopi, dal momento che una loro stima, ancorché eseguita con le più avanzate metodologie e i migliori strumenti disponibili, qualora ottenuta da una base dati geologica inadatta, porterebbe a valutazioni errate. Con tali fini, si è inteso valutare se e in che misura l'esame integrato dei dati geologici con quelli archeologici e storico-archivistici, opportunamente coadiuvato da idonee metodologie di analisi, potesse consentire di approfondire il quadro delle conoscenze geologiche e di individuare specifiche criticità, rispetto al territorio in esame. Al riguardo, occorre infatti considerare che il patrimonio storico e le emergenze archeologiche, ancorché beni di elevato valore esposti al rischio, costituiscono una "risorsa", se intesi come elementi che possono accrescere lo stato delle conoscenze, anche geologiche, del territorio.

Il presente studio, basato sull'esame critico della letteratura e su un processo di analisi integrata dei dati geologici acquisiti, principalmente derivanti dalle stratigrafie di sondaggi, visto il contesto urbano, con quelli archeologici e storico-archivistici, ha consentito di approfondire il quadro delle conoscenze geologiche. L'esame di questi dati è stato inserito in un geodatabase e analizzato tramite la piattaforma GIS implementata, mentre altri dati, tra cui le foto aeree storiche, sono stati analizzati con le tradizionali tecniche, ma confrontati con i precedenti. Per quanto riguarda i risultati, l'esame e il confronto dei più completi studi monografici sulla geologia di Roma eseguiti negli ultimi decenni hanno innanzitutto evidenziato che sia l'organizzazione stratigrafica sia le rappresentazioni cartografiche sono molto diverse tra loro. Inoltre, i riscontri stratigrafici forniti dai sondaggi e dagli altri dati acquisiti in questa sede hanno evidenziato una maggiore complessità stratigrafica anche rispetto alla più recente monografia, confermando le indicazioni fornite dalla recente letteratura. Ciò, unitamente ai vincoli radiometrici forniti da alcuni autori nell'ultimo ventennio, ha permesso di rilevare alcune incongruenze stratigrafiche, pur se la scala del presente studio è stata di maggior dettaglio in confronto ai rilievi eseguiti per la recente cartografia geologica. Rispetto ad essa, per altri versi, l'analisi multitemporale dei diversi strati informativi acquisiti ha evidenziato anche delle discrepanze in termini di distribuzione spaziale delle unità presenti. Tra i risultati di maggior rilievo, infatti, va anche menzionato il riconoscimento di morfologie vallive sepolte, solo in parte note in letteratura, la cui esistenza condiziona la geologia e pone ulteriori elementi di attenzione. Infatti, dette incisioni sono in tutto o in parte celate da consistenti spessori di terreni di riporto.

Pertanto, l'utilizzo di originali metodologie di analisi e di gestione dei diversi dati ha permesso di ricostruire un modello geologico di maggior dettaglio e che tiene inoltre conto delle notevoli modificazioni derivate, in questo settore urbano, dai diversi usi del territorio occorsi in circa tremila anni di storia. I risultati ottenuti suggeriscono la necessità di una parziale revisione delle rappresentazioni cartografiche e della stratigrafia di Roma, tenuto conto che in alcuni casi gli elementi scaturiti hanno una validità anche per altre zone dell'area romana. Per altri versi, questo studio ha definito un approccio metodologico valido anche per altri contesti urbani storici e fornito elementi utili per analisi con finalità applicative. Infatti, l'individuazione di aree di "maggiore attenzione", caratterizzate dalla presenza nel "volume significativo" del sottosuolo di spessori mediamente elevati di materiali dalle scadenti proprietà geotecniche, quali i terreni di riporto e, in altri casi, le alluvioni, rileva la necessità di valutare attentamente questi settori in sede di stima delle pericolosità geologiche. Infatti, vanno considerati i possibili effetti locali, sia in condizioni statiche che dinamiche, quali possibili cedimenti differenziali del terreno e amplificazioni sismiche locali.

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ABSTRACT

Detailed knowledge of the subsoil setting is an extremely important issue for a correct risk reduction policy, especially when dealing with urban areas hosting cultural heritage, which enhance risk conditions even at low geo-hazard levels, as in the case of Rome. In general, the reliability of risk assessments related to geo-hazards is strictly dependent on the resolution of the reference geological model. The study presented here exemplifies an integrated methodology aimed at refining the knowledge of the geological setting in unique urban environments, such as the city of Rome, where canonical approaches are limited by the scarcity of outcrops and ad-hoc geognostic surveys may be expensive and time-consuming. The methodology used in the study is based on a critical review of available geological, stratigraphic, archeological and historical-archival data. The integration of such data, properly stored, managed and analysed in a GIS environment, made it possible to: i) better frame the geological setting of a wide sector of the eastern part of Rome; and, in particular, ii) focus on buried natural morphologies (i.e. valleys) strongly modified by progressive urbanisation that determined their filling with huge thickness of backfills, which often represent a critical geotechnical issue. A detailed geological model was thus developed. The model shows slight but significant differences with respect to already available official maps, emphasising the need for carrying out in-depth analyses of already existing data from different sources, in order to collect thematic data to be used for effective land management policies.

Keywords: Rome (Italy), urban geology, human activity, geo-hazard, borehole log, engineering-geological model

INTRODUCTION

Managing geological risks in an urban area with plenty of historical-archeological heritage, like Rome, requires a deep understanding of the subsoil, even when geological hazards are low. Historical buildings have a high risk-exposed value and, given their ancient age and mode of construction (frequently, non-reinforced masonry), they are more vulnerable to events of a given type and intensity than recent buildings. Hence, even if the level of hazard is low, the level of risk is high.

A natural hazard, which may anyway recur, is defined as the likelihood of occurrence of an event in a given area, within a given timeframe and with a given intensity (UNDRO-UNESCO, 1978). Estimating geo-hazards, as well as other natural phenomena, is crucial to assessing geo-risks. The latter may be defined as the likelihood of occurrence of adverse effects on health, property and society arising from exposure to a hazard of a given type and of a given intensity, within a given timeframe and in a limited area. More directly, risk assessment is related to the economic value of the elements damaged by a phenomenon of a given intensity in a given area. In addition to the level of hazard (Hi) of a specific phenomenon of a given intensity (i), the factors that, in simplified terms, come into play in calculating the relative specific risk (RS), i.e. the expected damage to a specific vulnerable element (e), are: the vulnerability (Vi) of the exposed element and its related economic value (€). For each category of elements exposed to a phenomenon of a given intensity, the specific risk (RS) is:

$$RS = H(i)\ V(i)\ e\ [€] \quad (1)$$

On 27 February 2004, the President of the Italian Council of Ministers issued a directive that defined the concept of "deferred-time" geo-risk management (prevention), i.e. to activities of study, planning, design and implementation of actions to protect human lives and property. Therefore, especially in historical urban centres, adequately assessing geo-hazards has a paramount importance. Failure to plan and implement actions to mitigate the effects of expected "catastrophic" events or wrong estimations of their intensity or return in a given area increase the likelihood of losses of human lives and the costs to be incurred to repair the damage caused by these events and to manage "real-time" (emergency response) activities (Prestininzi, 2011).

Defining a geological model that is reliable and adequate to the scale of the study is key to adequately assessing geo-hazards. If the levels of hazard for each type of geological event are estimated by resorting to the most advanced approaches, to the best available tools, but to an "unreliable" geological model, the resulting estimations are poorly significant.

The study described in this paper was focused on urban geology issues, namely those arising from the presence of historical and archeological heritage elements. Although these elements have a high risk-exposed value, they represent a "resource", not only in economic terms, but also in the sense that careful reading of archival documents and archeological reports can help shed more light on a given urban area.

The case-study area is the highly urbanised sector of Rome that extends from the Termini station towards NE as far as the Aniene river, between via Nomentana and the railway ring (Fig. 1). This important area was selected because it lies in part in the historical centre, within the Aurelian Walls, and in part externally to them. Its SW portion, within the Walls, was intensely urbanised in Roman times and particularly during the Roman empire. Its central and NE portions, then suburban, had a more rarefied urban fabric (gardens and farmland), but kept a strong continuity with the city (Witcher, 2005). In Medieval times, all of the area under review was practically abandoned. Subsequently, it remained mostly rural or hosted villas and gardens, as shown by numerous historical maps (Frutaz, 1962). In 1870, Rome was annexed to the Kingdom of Italy and, shortly afterwards, it became the capital city. This fact gave strong impetus to building construction in the following decades.

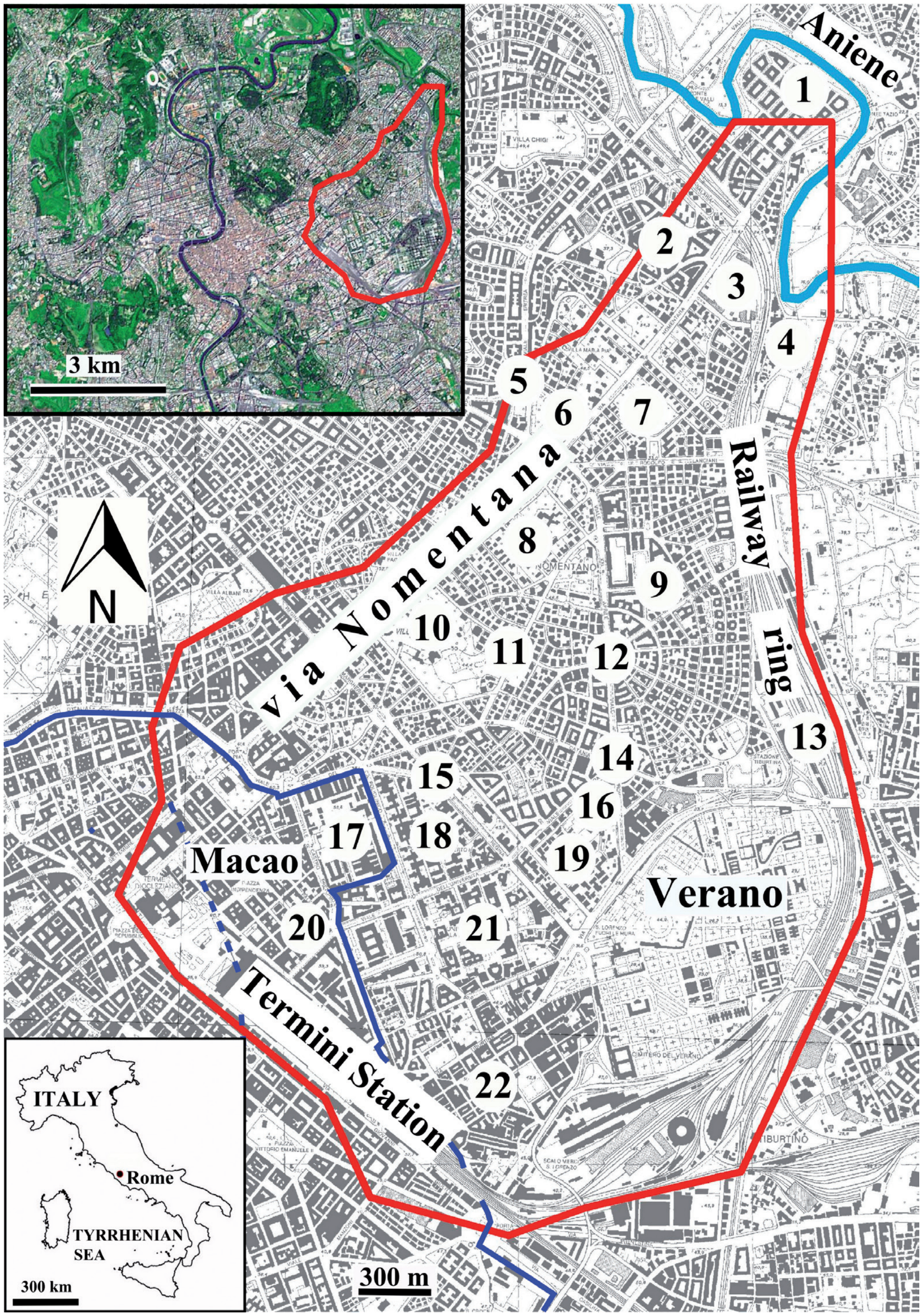


Fig. 1 - *Boundary of the study area (red line) over the topographic map and the satellite image from NASA, 2003 – modified (upper left box), and location of the main cited sites: 1 – Saccopastore, 2 – Sedia del Diavolo, 3 – Batteria Nomentana, 4 – via di Pietralata, 5 – piazza Annibaliano, 6 –Sant'Agnese/Santa Costanza Complex, 7 – Villa Blanc, 8 – Villa Mirafiori, 9 – piazza Campidano, 10 – Villa Torlonia, 11 – via di Villa Massimo, 12 – piazza Bologna, 13 – Tiburtina Station, 14 – piazzale delle Province, 15 – piazza Sassari, 16 – via Zacchia, 17 – Castro Pretorio, 18 – Policlinico, 19 – Castro Laurenziano, 20 – via Varese/via Milazzo intersection, 21- Città Universitaria, 22 – San Lorenzo. The solid blue line highlights the layout of the Aurelian Walls, while the dashed blue line identifies the known layout of the Servian Walls*

One of the targets of the study was to determine whether a critical review of available data and a process of integrated analysis of geological data, archeological data and historical archives, supported by suitable methodologies, could improve the general understanding of the study area and highlight specific critical issues. Taking into account the urban setting under review, lacking outcrops but rich of information, a set of geological-stratigraphic data was extracted from available direct investigations, mostly from borehole logs. In historical urban settings, archeological stratigraphy and geological stratigraphy are closely related (Edgeworth, 2014). Thus, data collected from archeological sources and historical archives (historical maps and photos, archival documents mostly obtained from municipal archives, but also from notarial documents), contributed to creating a geological-stratigraphic database.

GEOLOGICAL SETTING OF THE CITY OF ROME

Rome's urban area lies in a wide hilly sector, SW of the Apennines, whose reliefs are interrupted by the alluvial and deltaic plain of the Tiber river. The central urban area is located after the confluence of the Tiber with the Aniene river, its main tributary (Fig. 2). Rome's geological setting originates from repeated sedimentary and volcanic depositional events, alternating with erosional stages, during the Plio-Pleistocene (Conato *et alii*, 1980; Marra & Rosa, 1995a; Milli, 1997; Marra & Florindo, 2014). The Units mentioned below, based (unless otherwise specified) on the nomenclature adopted by Funiciello & Giordano (2008a), belong to the central urban sector (Fig. 2). For the sake of shortness, the Units occurring in the peripheral sectors of the municipal area were excluded.

In Rome, the Apennine bedrock is tectonically downthrown and covered by marine, circalittoral to upper bathyal, neoautochthonous sediments, of Pliocene age, dominantly consisting of clayey silts and marly clays (Marra & Rosa, 1995a). These sediments belong to the *Monte Vaticano Formation* Auct., whose thickness is more than 900 m at Circo Massimo (Signorini, 1939), but half or less in other sites close to the city, demonstrating the strong structuration of the bedrock due to extensional tectonic movements (Funiciello & Giordano, 2008a). In the lower Pleistocene, a new marine sedimentary cycle led to the deposition of the coarser sediments of the *Monte Mario Formation*, which overlie the previous sediments with a slight angular unconformity (Bonadonna, 1968). The following *Monte Ciocci Formation* (Karner *et alii*, 2001a) includes the *Monte Ciocci Unit* (Marra, 1993) and the *Monte delle Piche Unit* (Conato *et alii*, 1980), highlighting a first continentalisation of Rome's SW sector (Florindo *et alii*, 2007; Marra & Florindo, 2014). Littoral, transitional and continental facies in the same area testify the final retreat of the sea. Ambrosetti & Bonadonna (1967) ascribed these facies to the *Ponte Galeria Formation*. Subsequently, other authors (Marra *et alii*, 1998a; Florindo *et alii*, 2007) attributed these facies to two distinct depositional sequences, mostly made up of gravel and sand and occurring between the end of the lower Pleistocene and the middle Pleistocene. At the same time, an Apennine-trending tectonic sinking took place in the NW NE portion of the current central urban sector, comprising the study area. This tectonic depression, where a dominantly fluvial and palustrine sedimentation occurred (Marra & Rosa, 1995a), is known as *Paleotiber graben.* Two successions were deposited into this graben. The successions, correlated with the *Marine Isotope Stages* (MIS) 19 and 17, are defined as *Paleotiber 2* and *Paleotiber 3*, respectively (Florindo *et alii*, 2007; Marra & Florindo, 2014).

Tectonic, sedimentary, volcanic and eustatic events had a more complex interaction with one another starting from the end of the lower Pleistocene and throughout the middle Pleistocene (Cavinato *et alii*, 1992; Marra *et alii*, 1998b; Karner *et alii*, 2001a; Marra & Florindo, 2014). The effects of these events on the Roman stratigraphy are a succession of fluvio-palustrine and fluvio-lacustrine continental sediments, alternating with volcanic deposits, chiefly pyroclastic fall and flow deposits and, subordinately, lavas. This succession was reconstructed by using the paleomagnetic and geochronological constraints provided by interbedded tephra (Karner & Marra, 1998; Karner & Renne, 1998; Marra *et alii*, 1998a; Karner *et alii*, 2001a, 2001b; Marra & Florindo, 2014). The succession is missing or incomplete on the right bank of the Tiber, where marine and early continental sediments were dislocated into the structural high of Monte Mario.

The first volcanic eruptions emplaced levels of volcanic fall deposits onto the Paleotiber sediments (Marra *et alii*, 1998a; Florindo *et alii*, 2007; Marra *et alii*, 2014b). The deposits of the following sedimentary succession, the *Santa Cecilia Formation* which was correlated with the MIS 15 (Marra *et alii*, 1998a), are more frequent and thicker in the SW area of Rome (Marra & Florindo, 2014). The first volcanic products to reach the urban area with huge volumes are the Colli Albani Volcanic District's (CAVD) *Tufo Pisolitico di Trigoria*, and the Monti Sabatini Volcanic District's (MSVD) *Tufo Giallo della via Tiberina* (Karner *et alii*, 2001b). These deposits are overlain by generally fluvial and locally palustrine sediments, which were referred to as the *Valle Giulia Formation* and correlated with the MIS 13 (Marra & Rosa, 1995a; Karner & Marra, 1998); these sediments are also exposed in the historical centre, near the Tiber. During their long depositional interval (Karner *et alii*, 2001b; Marra *et alii*, 2009; Marra *et alii*, 2014b), a second eruptive cycle of the CAVD emplaced pyroclastic deposits, which are diffuse in the historical centre and known as *Tufo del Palatino*. These deposits were temporally followed by the MSVD's *Tufo Giallo di Prima Porta*, *Grottarossa Pyroclastic Sequence* and *Tufo Terroso con Pomici Bianche* that are encountered also in the central urban

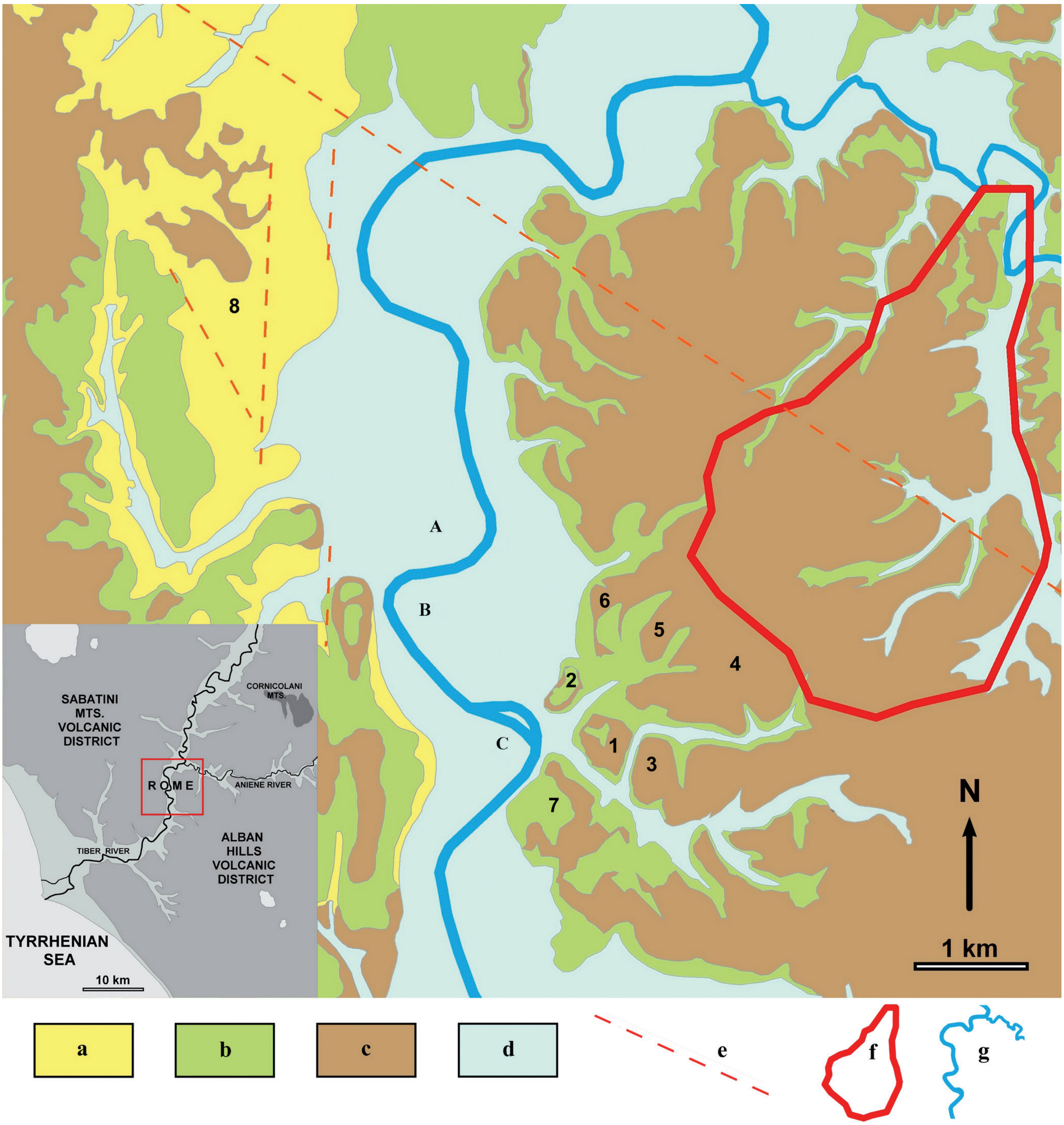


Fig. 2 - Geologic sketch of the central urban area of Rome (red square-frame in the lower-left box). Backfills are not mapped. Legend - a: marine sedimentary deposits (Pliocene-early Pleistocene); b: transition and continental sedimentary deposits (early Pleistocene–upper Pleistocene); c: volcanic deposits (middle Pleistocene–upper Pleistocene); d: "Post-Wurmian" alluvial deposits (upper Pleistocene–Holocene); e: main tectonic lineaments, inferred, buried (the Apennine-trending fault marks the SW border of the Paleotiber graben); f: boundary of the study area; g: rivers. Main reliefs: 1 – Palatino, 2 – Campidoglio, 3 – Celio, 4 – Esquilino, 5 – Viminale, 6 – Quirinale, 7 – Aventino, 8 – Monte Mario. Cited toponyms: A – Prati di Castello, B – Campo Marzio, C – Trastevere

area (Karner *et alii*, 2001b). Subsequently, huge volumes of volcanic deposits (especially pyroclastics) reshaped Rome's paleomorphology, emplacing deposits that flattened the paleovalleys and, at times, inverted their relief (Karner *et alii*, 2001b). The *Pozzolane Rosse* Auctt., emitted by the CAVD, occur on the left side of the Tiber; they were temporally followed (Karner *et alii*, 2001b; Marra *et alii*, 2014b) by deposits from the MSVD. These deposits, mostly located in the NW sector of Rome, on the right bank of the Tiber, are known as *Tufo Rosso a Scorie Nere*; they are dominantly lithoid owing to zeolitisation (Funiciello & Giordano, 2008a). A long period of continental sedimentation (Marra *et alii*, 2014b) partially reworked the *Pozzolane Rosse* in layers alternating with primary fall and flow deposits, originally indicated as *Conglomerato Giallo* and corresponding to the MIS 11 *San Paolo Formation* (Marra & Rosa, 1995a). These deposits were immediately followed by pyroclastic deposits from the CAVD, the *Pozzolane Nere* Auctt. (Karner *et alii*, 2001b). At the same time, the MSVD began a long stage of emission of fall products (Marra *et alii*, 2014b), corresponding to the *Tufi Stratificati Varicolori di La Storta,* after which the CAVD had a single eruptive sequence (Marra & Rosa, 1995a). This sequence involved a first pyroclastic flow - the *Tufo Lionato* Auctt. - with a prevailingly lithoid facies due to zeolitisation, and then a second flow upwards - the *Pozzolanelle* Auctt. - with a generally incoherent facies (Karner *et alii*, 2001b). The related deposits are found in some central sectors, including the hills of the first Roman settlements (Fig. 2). This massive eruptive stage was followed by the collapse of the Tuscolano-Artemisio volcanic edifice and by the resumption of the erosional activity. This activity was followed by the deposition of MIS 9 fluvio-lacustrine sediments that are known in the literature as *Aurelia Formation* (Conato *et alii*, 1980). Limbs of this formation now occur on Roman hills, including historical ones near the Tiber. Locally, in particular at Batteria Nomentana, close to the Aniene river (Fig. 1), temporally subsequent sediments were identified. These sediments, called *Via Mascagni Succession* (Marra *et alii*, 2014a), are covered by thin levels of *Tufo Giallo di Sacrofano* (Karner *et alii*, 2001b). Limited limbs of the subsequent *Vitinia Formation* (Conato *et alii*, 1980), consisting of MIS 7 fluvio-lacustrine deposits (Karner & Marra, 1998), are supposed to be present in the urban area, e.g. at Saccopastore, where Marra *et alii* (2015b) ruled out the correlation of these deposits with the MIS 5. The *Lava di Capo di Bove* flow, resulting from the activity of the CAVD, elongates from the SE peripheral sector to the margin of the central urban area (Marra *et alii*, 2003). The Sabatini and Albani volcanic activities ended in the upper Pleistocene (Giaccio *et alii*, 2009; Sottili *et alii*, 2010).

During the latest glacial stage, erosional processes triggered by the lowering of the base level completed their effects. They incised the present hydrographic network and, from the end of the upper Pleistocene through the Holocene, they deposited generally alluvial sediments, whose thickness is 60-70 m in the Tiber valley (Bozzano *et alii*, 2000; Mancini *et alii*, 2013; Marra *et alii*, 2013). Finally, in the last 2,500 years, numerous human activities contributed to remodelling the urbanscape, especially by excavating slopes and filling valley depressions with backfills (Del Monte *et alii*, in press).

THE GEO-HAZARDS OF THE CITY OF ROME

Rome is exposed to all geo-hazards, including coastal ones (erosion, marine ingression, tsunamis), the latter only pertaining to the area of Ostia and of the Tiber delta (Fig. 2). The urban centre is subject to natural events with a low frequency but, at times, a high intensity of occurrence. Nevertheless, the high risk-exposed value of ancient heritage elements and their higher vulnerability than recently built ones entail high levels of risk. In addition to hazard factors that may recur, there are danger factors that may cause an event in a specific site, through processes that may span a long timeframe.

Among the latter factors, numerous authors (including Crescenzi *et alii*, 1995; Lanzini, 1995; Bianchi Fasani *et alii*, 2011) mentioned the danger of collapse of the covers overlying the roofs of underground quarries, especially in Rome, which has a dense network of hypogeal man-made cavities mainly due to extracting activities and favoured by its geological setting (Ventriglia, 1971; Amanti *et alii*, 1995b; Ventriglia, 2002).

The danger of subsidence in Rome's urban area generally depends on overloads, e.g. stresses induced by the construction of buildings on highly compressible alluvial terrains (Prestininzi *et alii*, 1990) or by water abstraction. The occurrence of peat levels enhances this phenomenon (Campolunghi *et alii*, 2008; Stramondo *et alii*, 2008; Zeni *et alii*, 2011; Caserta *et alii*, 2012; Sbarra *et alii*, 2012). Satellite interferometry data from the Portale Cartografico Nazionale (MATTM, 2009) show the general stability of the ground in the study area.

As to landslide hazard, numerous falls/topples, slides and flows were inventoried in Rome, although complex phenomena and areas prone to diffuse shallow landsliding are dominant (Amanti *et alii*, 2008; ISPRA, 2014). Recent events (at the beginning of 2014), which affected above all the slopes on the right bank of the Tiber, showed some anomalies with respect to historical records, in terms of spatial distribution and statistical data of the lithotypes involved. These anomalies were correlated with the exceptional rainfall event that occurred at the time and with the fact that areas of instability have more differences in height and accommodate non-volcanic clastic deposits (Alessi *et alii*, 2014). The intensity (albeit variable) of the individual phenomena, during the above event and historically, was generally low in terms of velocity and volume of mobilised materials. On the left bank of the Tiber, gravitational phenomena are less frequent owing to lithological conditions, lower energy relief and also more intense urbanisation (Del Monte *et alii*, in press). In the study area, no landslide events were inventoried, except one case of risk of erosion-induced collapse of the Aniene river banks, near via di Pietralata (Fig. 1), in 1959 (ISPRA, 2014).

Hydraulic hazard is related, above all, to the Tiber and Aniene rivers. In occasion of high hydrometric levels, repeated floods occurred in large sectors of their alluvial plains and, in the centre of Rome, at Campo Marzio, Prati di Castello and Trastevere (Fig. 2). Numerous historical sources starting from the 5th century B.C. testify frequent floods. The latest flood of the city leads back to 29 December 1870. After this event, massive embankments (*muraglioni*) were built in the urban section of the Tiber to prevent flooding of the historical centre. Since 1953, flood control structures have been built along the Tiber, e.g. the Corbara hydropower dam, 90 km N of Rome, and the Castel Giubileo breakwater. These structures further decreased the likelihood of flooding. In the study area, flooding of the railway ring (Fig. 1) close to the confluence of the Fosso della Marranella with the Aniene river is possible but with a low level of hazard (Autorità di bacino del fiume Tevere, 2013).

Various studies (including Karner *et alii*, 2001b; Marra *et alii*, 2004; Giordano, 2008) defined volcanic hazard in Rome as non-negligible. A study by De Benedetti *et alii* (2008) assumed that *lahar* phenomena had recently occurred, based on the assessment of prehistorical and historical events. Subsequent studies (Giaccio *et alii*, 2009) indicated a minimum age of about 37 ka for the distal portions of these deposits. In spite of this, further volcanic hazard studies on the Alban district are deemed necessary (Marra *et alii*, 2004).

Seismic hazard in Rome is not negligible, since numerous classical and historical sources report felt intensities often above the damage threshold. The maximum felt intensity recorded in Rome is VII-VIII MCS. Most of the damage from historical earthquakes was concentrated in alluvial areas (Molin *et alii*, 1995; Tertulliani & Riguzzi, 1995; Guidoboni *et alii*, 2007). The availability of a large number of data for the seismic sequences of Umbria-Marche in 1997 and 1998 (Donati *et alii*, 2008) and of L'Aquila in 2009 (Bozzano *et alii*, 2011) confirmed that the areas with the highest felt intensities were those resting on alluvial deposits, but also areas with volcanic deposits had a high concentration of damage. In the latter areas, seismic amplification - albeit lower than in alluvial deposits - was evident and particularly intense (just as for alluvial plains), with frequencies of around 1 Hz (Caserta *et alii*, 2013). With regard to the L'Aquila earthquake of 2009, the analysis of the macroseismic intensity residual, calculated on the main shock and on the four aftershocks, pointed to the occurrence of an area of particular amplification within the *Paleotiber graben* (Sbarra *et alii*, 2012), which encloses part of the study area (Fig. 2).

MATERIALS AND METHODS

A geodatabase was developed in a Geographic Information System (GIS) environment to catalogue, manage, analyse and process the data. Data with no explicit or clear geographic content or references were catalogued and archived, where practicable, in digital form outside the GIS platform. These data, which were analysed in a different manner, gave an indirect contribution to the implementation of the geodatabase. Aerial photos were analysed with conventional photointerpretation methods and compared with the data stored in the geodatabase. Then, the results of the analyses were fed to the data layers being processed.

Borehole logs were obtained in part from the literature (mainly from Ventriglia 1971, 2002), and in part from unpublished reports made available by public and private entities and, to a lesser extent, by professionals. As regards the geological literature, the most detailed and most recent maps were selected. Smaller-scale (up to 1:100,000) and historical maps were also considered. Table 1 displays the maps that proved to be most useful for the integrated process of analysis described below. Geological surveys of the locally rare and limited outcrops gave a further contribution to defining the geological-stratigraphic setting of the study area.

For archeological data, reference was made above all to the *Forma Urbis Romae* by Lanciani (1893-1901), an archeological map which overlays data about different historical periods, that still today represents an absolutely necessary tool to study Rome's historical centre, and to the archeological map of Rome (*Carta Archeologica di Roma*) (Min.BB.CC.AA, 1977).

With regard to historical maps, a fundamental guide for the city of Rome is the collection of maps of Frutaz (1962). From these maps, the *Pianta grande* of Nolli (1748), limited to Rome's historical centre, was selected for the geodatabase. For suburban areas, use was made of the following maps: the *Carta del Censo* (Presidenza del Censo, 1839), a topographic map based on census data; the topographic map of Moltke (1852); the first edition of *Tavolette* (IGM, 1873), i.e. the first topographic maps with elevation data; and the *Piano Topografico di Roma e Suburbio*, a topographic map of Rome and its suburbs surveyed for the Rome's Urban Master Plan (Sanjust di Teulada, 1908) and later updated (IGM, 1924). As regards historical aerial photos, the first document to be used was the photomosaic by Nistri (1919), although consisting of non-overlapping photo frames and thus not usable for stereoscopic viewing. The SARA-Nistri (1934) and the MAPRW (1943-1944) flights, specifically performed for stereoscopic view, were the fundamental references for the study of the area under review, at a time when its urban development had not yet been completed (Fig. 3). Results from analogical analysis were compared with other data present in the geodatabase and then fed to the data layers being processed on the GIS platform.

Historical photos, iconographic documents and, in some instances, archival documents - often lacking references for tracing

Author/s	*Title*	*Year*	*Scale*	*Type of map*
FUNICIELLO & GIORDANO	*Carta geologica del Comune di Roma*	2008	1:10,000	Geological map
LA VIGNA, CAPELLI & MAZZA	*Carta idrogeologica del settore romano del fiume Aniene*	2008	1:20,000	Hydrogeological map
FUNICIELLO & GIORDANO	*Foglio 374 "Roma" Progetto CARG*	2008	1:50,000	Geological map
VENTRIGLIA	*Carta litostratigrafica del territorio del Comune di Roma*	2002	1:20,000	Geological "lithostratigraphic" map
VENTRIGLIA	*Carta delle cavità sotterranee*	2002	1:20,000	Map of underground cavities
ROMA METROPOLITANE (COMPANY)	*Progetto Linea Metropolitana B1*	2000's 1990's	1:200 1:1,000	Metro design and geothematic maps
MARRA & ROSA	*Carta geologica del centro storico di Roma*	1995	1:10,000	Geological map
CORAZZA & LOMBARDI	*Carta idrogeologica del centro storico di Roma*	1995	1:10,000	Hydrogeological map
CORAZZA & MARRA	*Carta dello spessore dei terreni di riporto*	1995	1:10,000	Anthropogenic filling material thickness map
MARRA & ROSA	*Carta delle isobate della superficie di tetto dell'Unità di Monte Vaticano (substrato Pliocenico)*	1995	1:10,000	Isobath map of the roof surface of the Monte Vaticano Unit (Pliocene bedrock)
MARRA & ROSA	*Carta delle isobate della superficie di base dei depositi vulcanici*	1995	1:10,000	Isobath map of the bed surface of the volcanic deposits
MARRA & ROSA	*Carta della superficie di letto delle alluvioni recenti*	1995	1:10,000	Map of the bed surface of recent alluvial deposits
INTERMETRO (COMPANY)	*Progetto Linea Metropolitana B Termini-Rebibbia*	1980's 1970's	1:200 1:1,000	Metro design and geothematic maps
VENTRIGLIA	*Carta geologica della città di Roma*	1971	1:20,000	Geological map
VENTRIGLIA	*Carta delle cavità sotterranee*	1971	1:20,000	Map of underground cavities
VENTRIGLIA	*Carta dello spessore delle formazioni affioranti*	1971	1:20,000	Map of outcrop unit thickness
VENTRIGLIA	*Carta dello spessore dei riporti*	1971	1:20,000	Anthropogenic filling material thickness map
ALBERTI, BENEO, DRAGONE, FORNASERI, LIPPARINI, MANFREDINI, SCHERILLO, SEGRE & TILIA	*Foglio 150 "Roma", Carta geologica d'Italia, II Ed.*	1967	1:100,000	Geological map
VERRI	*Carta geologica di Roma*	1915	1:15,000	Geological map
SANJUST DI TEULADA	*Piano Regolatore di Roma 1908*	1908	1:5,000	Morphological maps
ZEZI, PERRONE, CORTESE & MODERNI	*Foglio 150 "Roma"*	1888	1:100,000	Geological map

Tab. 1 - List of the main geological, geothematic and design maps added to the geodatabase and analysed in the GIS environment (full references in: LUBERTI, 2015)

Fig. 3 - Top: present-day satellite image (source: Google Earth, 2013) of a portion of the study area (grey-highlighted rectangle within the red-line bordered study area). Bottom: the corresponding sector in 1934, before final urbanisation, aerial photo (SARA-Nistri, 1934, frame 150_103_39_124973_0. Source: Istituto Centrale per il Catalogo e la Documentazione, Aerofototeca Nazionale. Further reproduction is prohibited)

them geographically - were compared with other data and documents with a geographic location known with certainty, in order to utilise their data. Geological surveys covered all accessible areas were performed, taking into account the difficulties arising from an intensely built urban environment and from the presence of numerous inaccessible private areas. In other cases, e.g. at Verano, monument protection rules did not permit test excavations or sampling.

ANALYSES AND RESULTS

The GIS platform facilitated the comparison and examination of different data, aiming at the definition of the local stratigraphic succession, of stratigraphic relationships and of the spatial distribution of the geological units. In this connection, it is worth noting that, both stratigraphic organisation and maps, as defined in the latest monographic studies on Rome (Ventriglia, 1971; Marra & Rosa, 1995a, 1995b; Ventriglia, 2002; Funiciello & Giordano, 2008a, 2008b) are very different between them and this is due not only to the names of the units and to the groupings adopted by the various authors (Tab. 2). For instance, in the geological maps of Ventriglia (1971, 2002), the *Complesso delle Pozzolane inferiori*, including both the *Pozzolane Rosse* and the *Pozzolane Nere* of Marra & Rosa (1995a) and Funiciello &

Ventriglia (1971) "Carta geologica" scale 1:20000	**Ventriglia (2002) "Carta litostratigrafica" scale 1:20000**	**Marra & Rosa (1995) "Carta geologica" scale 1:10000**	**Funiciello & Giordano (2008) "Carta geologica" scale 1:10000**
	Quarry waste deposits, river levees **da**	Waste deposits and archaeological ruins **1**	Historical deposits **h** Quarry backfill **h_1**
Tiber alluvial deposits **al**	Recent alluvial deposits **qa**	Recent and active alluvial deposits **2**	Alluvial deposits **SFT_b** and lacustr. d. **SFT_e**
			Saccopastore Unit **SKP**
		Pyroclastic flow dep. with pumice and sanidine **3**	Via Nomentana Unit **NMT**
Formazione Fluvio-lacustre **fl** (fluvial-lacustr.)	Formazione Fluvio-lacustre **fl** (fluvial-lacustrine deposits)	Vitinia Unit and Aurelia Unit **4**	Vitinia Formation **VTN** Aurelia Formation **AEL**
Pozzolane superiori **ps**	Tufo Villa Senni **Avs** Pozzolana grigia **Aps**	T. Villa Senni **5**	Villa Senni Formation: Pozzolanelle **VSN_2** Tufo lionato **VSN_1** Gravel and sand Litofacies **VSN_a**
Tufo lionato **tl**	Tufo lionato **Atl**	Tufo lionato **6**	
Complesso Pozzolane inferiori **pi:** Pozzolane medie	Compl. Pozzolane inferiori **Api** : Pozzolane medie or nere or delle Tre Fontane		Pozzolane nere **PNR**
T. antichi **ta**: compl. t. terr.	Tufo de La Storta **Sg**[1]		Tufi stratificati varicolori di La Storta **LTT**
Tufi antichi **ta**: t. rosso s.n.	Tufo rosso a scorie nere **Vv**[4]		Tufo rosso a scorie nere sabatino **RNR**
Compl. Pozzol. inf. **pi:** Conglomerato giallo	Compl. Pozz. Inf. **Api**: Conglomerato giallo	S. Paolo Unit **8** Pyroclastic fall deposits **7**	Fosso del Torrino Formation **FTR:** Conglomerato giallo **FTR_1**
Com. Pozz. inf. **pi:** Pozz. inf.	Compl. Pozz. Inf. **Api**: Pozz. rosse o S. Paolo	Pozzolane rosse **9**	Pozzolane rosse **RED**
Tufi antichi **ta:** Complesso dei tufi terrosi	Tufo di Sacrofano **Sl**[3]		Tufi stratificati varicolori di Sacrofano **SKF**
			Casale del Cavaliere Unit **KKA**
			Prima Porta Unit **PPT**
			Palatino Unit **PTI**
Tufi grigi litoidi (ancient tuffs) F. Fluvio palu-stre **fp** (fluvial palu-strine dep.)	Tufi antichi **Ata**: tufi grigi granulari e pisolitici (ancient tuffs) F. Fluvio palustre **fp** (fl. pal. d.)	Valle Giulia U. **10** Palatino pyroclastic Unit **13**	Valle Giulia Formation **VGU**
	Tufo giallo della via Tiberina **Sn**[1]	T. giallo via Tiberina **11**	Via Tiberina Unit **TIB**
	Peperino via Flaminia **SO**[2]	Peperino via Flaminia **12**	
			Tor de' Cenci Unit **TDC**
Clay, Sand and Gravel Complex **si** (transitional and continental deposits) Siciliano	Clay, Sand and Gravel Complex **qt** (transitional and continental deposits)		S. Cecilia Formation **CIL**
		Paleotevere 2 Unit b **14** Paleotevere 2 Unit a **15**	Fosso della Crescenza Formation **FCZ**
		Ponte Galeria Unit (Paleotevere 1 Unit) **16**	Ponte Galeria Formation **PGL**
		Monte Ciocci Unit **17**	Monte delle Piche Formation **MDP**
Marine sand and clay dep.: **cs** (transitional clay and marine sand deposits) and **ca** (marine clay dep.) Calabriano	Grey-blue clayey sand, yellow or red coarse sand, green grey sandy clay and yellow marl deposits with conglomerate layers **Psi** Siciliano-Calabriano	Monte Mario Unit **18**	Monte Mario Formation **MTM**
Blue clay **pl** Pliocene	Blue clay, marly clay and grey-blue marl deposits with gypsum crystal **Pm** Piacenziano	Monte Vaticano Unit **19**	Monte Vaticano Formation **MVA**

Tab. 2 - *Match between the stratigraphic units of Rome, as defined in the main recent geological monographs (Ventriglia, 1971; Marra & Rosa, 1995a; Ventriglia, 2002; Funiciello & Giordano, 2008a) and related maps. The stratigraphic order is given according to the last contribution. In bold, the unit initials adopted in each map. The stratigraphic succession is limited to the units that are present, according to each map, within the railway ring. The table reports the names of the units and their concise description. Units highlighted in yellow are those that are present within this study area, according to the maps and sections of the respective authors*

Giordano (2008a), is assumed to outcrop extensively (disregarding backfills) at Macao, Castro Pretorio and Policlinico, close to the Aurelian Walls (Fig. 1). However, Marra & Rosa (1995b) suppose that these pozzolanas do not outcrop in this sector, while Funiciello & Giordano (2008b) mention the occurrence of *Pozzolane Rosse* only within very narrow belts. The *Pozzolane Nere* are completely missing throughout the historical centre according to Marra & Rosa (1995b), within the boundaries indicated in their maps, and also according to Funiciello & Giordano (2008b), within the same boundaries. Discrepancies arise in connection with many other units of the Roman stratigraphic succession in the investigated sector (Luberti, 2015). This infers that the study of urban geology may be extremely challenging, when outcrops are scarce and reference is to be made to borehole data, whose different interpretation may lead to very different results.

The examination of borehole logs is problematic (Amanti *et alii*, 1995a), first of all because of the uncertainties revolving around their plano-altimetric location (Luberti, 2015). Furthermore, the lack of temporal data does not permit to refer the logs to the topography of the time, with consequent uncertainties about the actual planimetric position of the borehole and the elevation of its head. The uncertainty is even more significant when the area under review has undergone major changes. For instance, urban expansion in the 140 years following the unification of Italy significantly changed the topography of the study area (Fig. 4). So, this problem concerned above all the borehole data retrieved from the publications of Ventriglia (1971, 2002). Here, in many cases, differences of many metres were observed between the elevation of the head of the borehole, specified in the text, and the elevation of the corresponding point, in the topographic base used in this study. Moreover, the planimetric position of some boreholes proved to be not very accurate (errors of up to tens of meters), which heightened the uncertainty. As to borehole logs obtained from institutions and professionals, uncertainties frequently arose from failure to indicate the elevation of the head of the borehole in the log, lack of geographic coordinates and use of design-layout detailed scale maps (1:1,000 or above) for the location of boreholes, without accurate topographic references identifiable in the base map of the GIS platform.

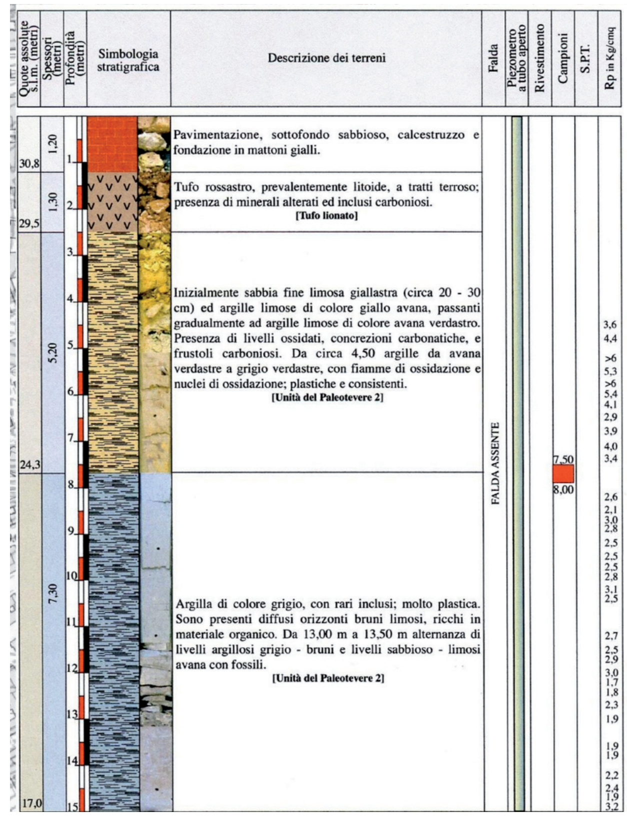
The interpretation of borehole logs was also made problematic by the stratigraphic data accompanying them, which are very often of a lithological rather than geological nature, in accordance with clients' requirements. Textural data were often insufficient and, for sedimentary and pyroclastic units, sedimentological data (grading, sphericity, rounding and size range of clasts) were completely missing. The specification of the minerals identified in the stratigraphies may usually help ascribe lithotypes to specific geological formations. However, in the case under review, the frequent identification of leucite, at times altered to analcime, did not help, because this mineralogical species occurs in many Roman pyroclastic units (Karner *et alii*, 2001b).

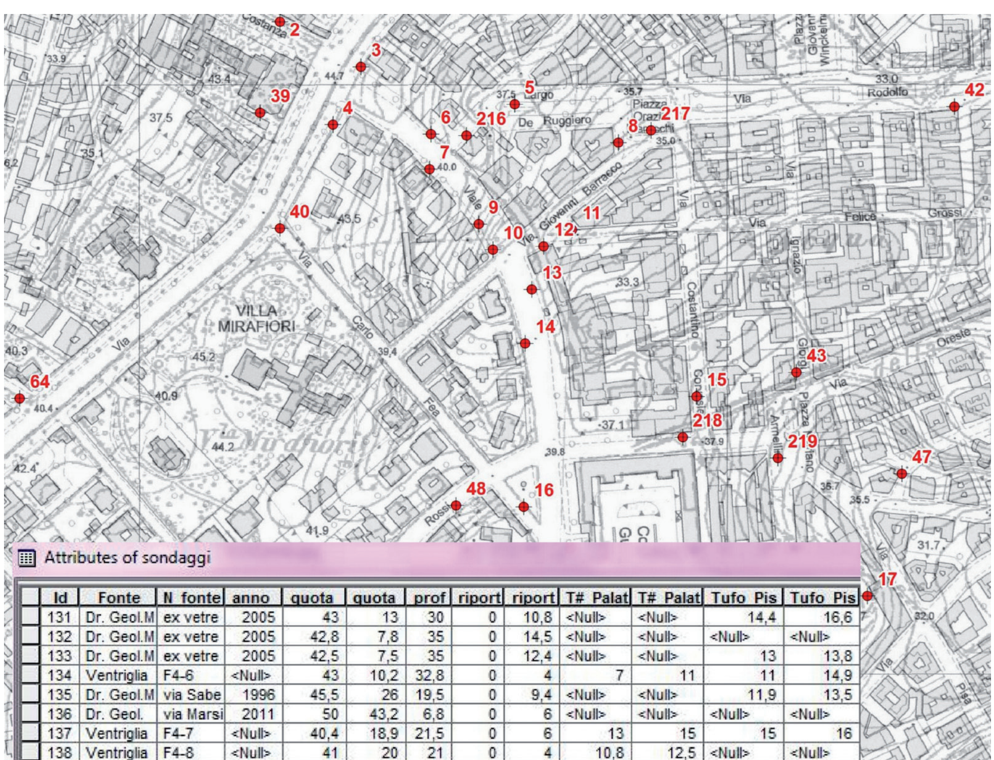
Borehole logs were incorporated into the geodatabase with the following data: source, original number of the borehole and year of boring, elevation of the borehole head and bottom above sea level (a.s.l.), water table elevation, depth of the roof and bed of each unit from ground level, or level reached by the borehole bottom, and possibly intercepted cavities (excerpt in Fig. 4). To interpret each of the logs, reference was initially made to the stratigraphic organisation defined by Funiciello & Giordano (2008a) and to the enclosed map to a scale of 1:10,000 (Funiciello & Giordano, 2008b). These data were compared with those of previous geological and geothematic maps, including the ones listed in Table 1. Some difficulties of interpretation emerged from a first examination of the stratigraphies. These difficulties concerned, on one hand, the succession and its stratigraphic relationships and, on the other hand, the spatial distribution of the units in the related map, as defined by Funiciello & Giordano (2008a, 2008b). Further studies on the previous and subsequent literature (including Marra & Rosa, 1995a; Karner *et alii*, 2001b; Florindo *et alii*, 2007; Marra *et alii*, 2009; Marra & Florindo, 2014; Marra *et alii*, 2014b; Marra *et alii*, 2015a, 2015b) revealed a number of inconsistencies of that stratigraphic succession, providing however, at the same time, more rational explanations to understand and interpret the borehole logs. The need thus arose for revising the local stratigraphic succession and relationships and for updating the borehole database accordingly. Together with the definition of the local stratigraphy, a methodology was developed to pinpoint topographic and stratigraphic constraints: the former provided by current and previous topography, and the latter given by outcrops and stratigraphic data interpreted with certainty from boreholes with a position known with certainty. These constraints may be used to more accurately determine the plano-altimetric location of boreholes for which the source provides poorly accurate data or to verify stratigraphies when they are too concise or lack elements for an adequate interpretation. For instance, if a borehole indicates 2 m of filling materials and, in the map provided by the source, it lies at a point whose current elevation is 8 m higher than shown in historical maps, then the position of the borehole must be incorrect. This position may be redetermined by relying on stratigraphic data known with certainty from the same borehole or boreholes placed at reasonable distance from it. In other cases, a borehole whose position is certain but whose stratigraphy is inaccurate may be correctly interpreted if, at short distance, there is a borehole with a detailed stratigraphy or an outcrop or a section, described in an excavation report or retrieved from the historical literature, referring to periods prior to the urbanisation of the investigated sector.

Archeological data proved to be very useful, especially to accurately determine the thickness of backfills and to single out major anthropogenic changes, at the study scale, affecting the local shallow stratigraphy. This is the case of the military moat outside the *agger* of the Servian Walls, built during the Roman Republic and occurring at Termini and Macao (Fig. 1). Moreover, historical and archival documents, often with no references for an accurate geographic contextualisation, were compared with other data and documents, thus improving the understanding of the study area. This is the case of a pozzolana quarry, which was used between 1759 and 1788, based on notarial documents. The quarry was located near Villa Rondanini, in the Termini area, at the boundaries with the De Vecchis and Quarantotti estates. As these estates are reported in the map of Nolli (1748), the location of the quarry was determined near the intersection between via Varese and via Milazzo (Fig. 1).

In some cases, the examination of historical topographic maps (in particular: IGM, 1924) and the stereoscopic analysis of historical aerial surveys (SARA-Nistri, 1934; MAPRW, 1943-44) made it possible to: i) extrapolate the boundaries between the units, based on the identified landforms and on the stratigraphic constraints provided by boreholes; and ii) build a geological model consistent with the topography prior to recent morphological urban-planning changes.

Thanks to the analyses carried out with the described multidisciplinary and multi-temporal approach, a detailed geological model was built. The model is shown in the geological map (scale 1:10,000) and in the two cross-sections of Plate I, of which the





	Id	Fonte	N fonte	anno	quota	quota	prof	riport	riport	T# Palat	T# Palat	Tufo Pis	Tufo Pis
	131	Dr. Geol.M	ex vetre	2005	43	13	30	0	10,8	<Null>	<Null>	14,4	16,6
	132	Dr. Geol.M	ex vetre	2005	42,8	7,8	35	0	14,5	<Null>	<Null>	<Null>	<Null>
	133	Dr. Geol.M	ex vetre	2005	42,5	7,5	35	0	12,4	<Null>	<Null>	13	13,8
	134	Ventriglia	F4-6	<Null>	43	10,2	32,8	0	4	7	11	11	14,9
	135	Dr. Geol.M	via Sabe	1996	45,5	26	19,5	0	9,4	<Null>	<Null>	11,9	13,5
	136	Dr. Geol.	via Marsi	2011	50	43,2	6,8	0	6	<Null>	<Null>	<Null>	<Null>
	137	Ventriglia	F4-7	<Null>	40,4	18,9	21,5	0	6	13	15	15	16
	138	Ventriglia	F4-8	<Null>	41	20	21	0	4	10,8	12,5	<Null>	<Null>

Fig. 4 - A portion of the study area (corresponding to the one of Fig. 3) in the GIS environment, showing the present-day topographic map on the historical topographic map IGM (1924), the location of boreholes (red points) and their Id number. In the lower sector of the figure, part of the borehole table, consisting of 288 selected logs. Up, one of the logs linked to the table (full table and borehole location map in: Luberti, 2015)

main elements are described below.

In accordance with the literature (Marra & Rosa, 1995a), the roof of the *Marne Vaticane Formation* is extremely structured. This roof is found at elevations close to sea level (Section D-E-F in Plate I) in the districts of Macao, Castro Pretorio, Policlinico and farther S, not beyond San Lorenzo (Fig. 1). However, NE of a line passing through Villa Torlonia and piazzale delle Province (Fig. 1), the roof of the formation occurs at progressively lower elevations. This fact suggests that, in agreement with Florindo *et alii* (2007) and Marra & Florindo (2014), the fault bordering the *Paleotiber graben* (Fig. 2) lies in that position and therefore the graben extends towards the NE sector of the study area (Plate I). Nonetheless, it is worth pointing out that, in two boreholes located between Policlinico and Castro Laurenziano (Fig. 1), SW of the above fault, the roof of the *Marne Vaticane Formation* was identified at -25 m and -42 m a.s.l., respectively. Hence, the structural setting may be, at least locally, more complex, with a small graben bounded by two anti-Apennine-trending faults, corresponding to the eastern portion of *Fosso della Città Universitaria* (Plate I and Fig. 5). Based on borehole logs alone, other faults active at least until the middle Pleistocene were hypothesised (Plate I).

The marine deposits are overlain by the continental sediments of the Paleotiber. In place of the *Fosso della Crescenza Formation* (Funiciello & Giordano, 2008a, 2008b), it was necessary to distinguish two units, correlated with the MIS 19 and the MIS 17 and defined *Paleotiber 2* and *Paleotiber 3*, respectively (Florindo *et alii*, 2007). This distinction was facilitated by the fact that the related sediments are easily identifiable in borehole logs. In effect, the deposits of the *Paleotiber 2* dominantly consist of calcareous gravel with a poor silty-clayey matrix; they host the main aquifer and are followed by grey-blue clays upwards. Conversely, the deposits of the *Paleotiber 3* are made up of yellow and havana-brown variegated silts and weakly clayey sands interbedded with travertine lenses and levels. The roof of the *Paleotiber 2* deposits usually lies at an elevation of 20 to 10 m a.s.l. along via Nomentana as far as the Aniene river (Plate I) and at lower elevations (even below sea level) in Fosso della Marranella and in the middle portion of Fosso di Sant'Agnese, at piazza Annibaliano (Section A-B-C in Plate I). This infers that the significant diversification of the *Paleotiber 2* roof elevation is only in part due to erosional processes, as it can also be ascribed to tectonic dislocations; these dislocations must have been active at least after the time interval of deposition of this unit and of the *Paleotiber 3* and perhaps, during the deposition of the first volcanic deposits, until the emplacement of *Tufo del Palatino*. The deposits of the *Paleotiber 3* are completely missing between Sedia del Diavolo and Batteria Nomentana, in some sections of Fosso della Marranella and from the Tiburtina Station towards the valley depression and piazzale delle Province (Fig. 1). Boreholes indicated that pyroclastites or, in some cases, *"Post-Wurmian" alluvial deposits* are directly in contact with the *Paleotiber 2*, suggesting that the sediments of the *Paleotiber 3* must have been eroded during the glacial stages of the Pleistocene. At piazza Campidano (Fig. 1), at the head of Fosso di via Salento (Fig. 5), the thickness of the deposits correlated to the *Paleotiber 3* reaches an exceptional value of nearly 30 m. Moreover, the lower part of the succession contains a 1 m-thick level of yellowish grey cineritic pyroclastic material with small pumices, altered in their top part. Even the most recent literature (Marra & Florindo, 2014) does not report this volcanic level interbedded into the *Paleotiber 3* deposits.

The *Paleotiber 4* deposits sensu Florindo *et alii* (2007) - correlated with the MIS 15 and corresponding to the *Santa Cecilia Formation* of Funiciello & Giordano (2008a) - are very discontinuous in the study area (see sections in Plate I) and with a very variable thickness (generally of a few metres and exceptionally exceeding 10 m). Their geometries seemingly indicate that they were thicker in the paleovalleys and that they were finally buried by the pyroclastites, as in the case of via Nomentana, in the section between Villa Mirafiori and the Sant'Agnese/Santa Costanza Complex (Fig. 1).

The most ancient volcanic deposits reaching the study area with substantial volumes are the *Tufo Pisolitico di Trigoria* and the *Tufo del Palatino* (Karner *et alii*, 2001b), corresponding to the *Unità di Tor de' Cenci* and *Unità del Palatino* respectively (Funiciello & Giordano, 2008a). These deposits are exposed in the Verano area, near piazzale delle Province and on the man-made slope underlying via Zacchia (Fig. 1 and Plate I).

The *Valle Giulia Formation* was deposited in a long time interval including the MIS 13 (Marra *et alii*, 2014b). Deposits correlated with this formation were identified in boreholes in the area of Castro Laurenziano as far as Villa Torlonia (Fig. 1), mostly between the *Tufo Pisolitico di Trigoria* and *Tufo del Palatino*, but also above the latter (Plate I). Deposits of the *Lower Valle Giulia Formation* were reported at via di Villa Massimo (Fig. 1) by Florindo *et alii* (2007) and Marra & Florindo (2014). In this area, they reach an exceptional thickness of over 20 m, suggesting that they filled a paleoriver bed. Their depositional facies is indicative of slope debris with moderate transport in water (Marra F., pers. comm., 2014); therefore, their facies is very different from the palustrine one that is typical of the unit. Deposits of the *Upper Valle Giulia Formation* with a fluvial, palustrine and lacustrine facies were found above *Tufo del Palatino* and beneath the units that are associated here with the *Tufi Stratificati Varicolori di Sacrofano complex* (see later on), NE of Villa Torlonia and at Villa Blanc (Fig. 1 and Plate I). In this latter site, geognostic investigations recently conducted in the area acquired by the LUISS university (Lanzini M., pers. comm., July 2015) revealed deposits belonging to the above unit at the SE margin of the above property, beneath 2-7 m of backfills. Indeed, these sediments lie under

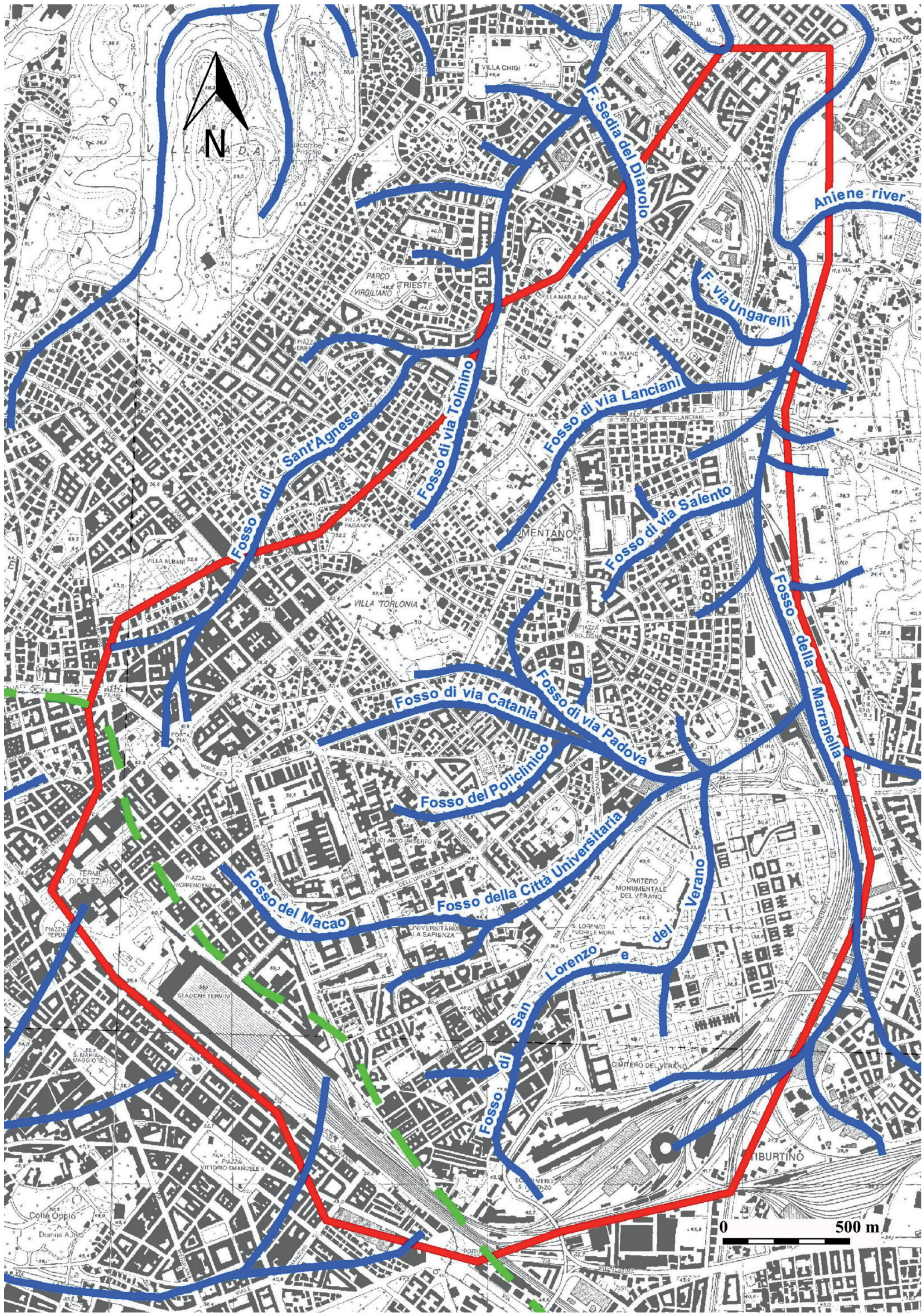


Fig. 5 - Reconstruction of the watershed drainage lines of ancient stream valleys (each called "Fosso" in accordance with the local terminology), before their partial or total burial, due to anthropogenic processes mainly connected with the recent urbanisation process. The study area is bordered in red. Names are given according to present-day toponyms. The green dashed-line marks the divide between Aniene and Tiber river hydrographic basins, NE and SW, respectively

the fall pyroclastites ascribed to the *Tufi Stratificati Varicolori di Sacrofano complex,* as they underlie the *Pozzolane Rosse*.

In some sites between Termini, piazza Sassari and piazza Bologna (Fig. 1), some particularly accurate borehole logs made it possible to discriminate the *Tufo Giallo di Prima Porta* and the pyroclastites of the *Grottarossa Pyroclastic Sequence* from the *Tufo Terroso con Pomici Bianche* (Karner *et alii*, 2001b), based on their stratigraphic relationships with other units. The latter two units correspond to the *Tufi Stratificati Varicolori di Sacrofano* of Funiciello & Giordano (2008a). However, as the three units were generally undistinguishable in borehole logs, they were merged with the informal unit introduced here, the *Tufi Stratificati Varicolori di Sacrofano complex*; this unit extensively occurs in the study area except in the sector from Batteria Nomentana to the Aniene river (Fig. 1).

The *Pozzolane Nere* were identified to occur at least in the Termini area and probably as far as Villa Torlonia and piazza Bologna (Fig. 1), based on the examination of the historical literature (De Angelis D'Ossat, 1948) and in agreement with the recent interpretation proposed by Marra *et alii* (2015a). In this case, too, the units are thin and not easily distinguishable, in many other stratigraphies, from the *Pozzolane Rosse*. Consequently, they were mapped together with the portion of the Sabatini fall pyroclastites that they embed (see later) as an informal unit, here called *Pozzolane inferiori complex*.

Fall pyroclastites whose facies and stratigraphic position correspond to the *Tufi Stratificati Varicolori di La Storta* can be found above and below the *Pozzolane Nere*. This is suggested by the radiometric ages of the Sabatini fall pyroclastites, indicating a long time interval of emission. The upper portion of these pyroclastites, recently referred to the *Successione di San Abbondio* (Marra *et alii*, 2014b), overlaps the *Pozzolane Nere*. In this study, an informal unit (*Upper Tufi Stratificati Varicolori di La Storta*) was introduced to accommodate these fall pyroclastites overlying the *Pozzolane inferiori complex*. Moderately thick levels of this informal unit are diffuse in the central-southern sector of the study area (Plate I). In the same sector, above this unit, are thin limbs of *Tufo Lionato* and *Pozzolanelle*. *Tufo Lionato* extensively occurs farther N towards the Aniene river (Plate I and Section A-B-C). Here, *Tufo Lionato* has a thickness of 10-20 m in sites where historical maps (IGM, 1924) show open-pit tuff quarries, e.g. at Sedia del Diavolo (Fig. 1) where it is still exposed.

Recent geognostic surveys in the Villa Blanc area (Fig. 1) revealed the absence of *Tufo Lionato* and the presence of outcrops of the *Aurelia Formation* (disregarding 1-3 m-thick backfills).

Recent studies conducted by Marra *et alii* (2015b) suggested that the deposits attributed to the *Vitinia Formation* by Funiciello & Giordano (2008b) along via Nomentana, between Villa Blanc and Batteria Nomentana (Fig. 1), are to be correlated to the *Via Mascagni Succession* (Plate I). This succession outcrops at the same elevation as the homonymous site located about 1 km NW of it. Conversely, the fluvial deposits of Saccopastore (Fig. 1), near the Aniene river, which Funiciello & Giordano (2008a) attributed to the *Saccopastore Unit*, do not correlate with the MIS 5 "Tyrrhenian" deposits, but with those of the MIS 7. Hence, they belong to the *Vitinia Formation,* as demonstrated by Marra *et alii* (2015b). Small limbs of *Tufo Giallo di Sacrofano* (Karner *et alii*, 2001b), corresponding to the *Unità della Via Nomentana* of Funiciello & Giordano (2008a), occur between Batteria Nomentana and Sedia del Diavolo (Fig. 1 and Plate I). Based on the radiometric ages provided by Karner *et alii* (2001b) and on the stratigraphic relationships recently redetermined by Marra *et alii* (2014a; 2015b), the *Tufo Giallo di Sacrofano* is to be stratigraphically positioned above the *Aurelia Formation* and the *Via Mascagni Succession*, but below the *Vitinia Formation* (Plate I).

The *"Post-Wurmian" alluvial deposits* reach a considerable thickness, of at least 6-7 m in minor stream valleys, such as Fosso di San Lorenzo (Section D-E-F in Plate I and Fig. 5). In Fosso di Sant'Agnese, at piazza Annibaliano (Fig. 1), the maximum thickness of the alluvial deposits intercepted by the boreholes is 16 m. In Fosso della Marranella, near the Tiburtina Station (Fig. 1), the intercepted thickness exceeds 20 m (Section A-B-C in Plate I) and, farther downslope, 30 m, corroborating the assumptions made by Marra & Rosa (1995c).

As exhaustively explained by Luberti (2015), the top portion of the *"Post-Wurmian" alluvial deposits* was placed in heteropy with the *Ancient Backfill materials*, distinguishing the latter from the *Modern Backfill materials*, whose age was conventionally assumed to start about 140 years ago. The backfills are not represented in the geological map, otherwise they would practically cover most of the study area, as indicated by Luberti (2015) in the *"Carta delle Unità affioranti"*. The considerable lateral changes of the backfills can instead be recognised in the geological sections (Plate I), where the modern portion can be distinguished from the ancient one. The latter distinction is not reported in the table of boreholes, since the two units cannot be distinguished in the related stratigraphies. Plate I shows a sketch of the local stratigraphic relationships of the above-described units.

The multi-temporal analysis of historical topographic maps and aerial photos, as well as the topographic constraints provided by borehole logs, also suggested a topographic setting that was significantly changed by anthropogenic processes. These processes, which took place in about three millennia, were particularly intense in the study area in the past 140 years. These changes inevitably affect the local shallow geology. In particular, in-depth investigations disclosed the occurrence of valleys, whose morphological records were totally or partially obliterated by urbanisation processes. These processes caused their partial or total filling with variably thick and, in places, very thick backfill materials. The historical memory of most of these valleys had been lost and they are not represented at all or are not adequately represented in the geological maps of previous authors (Ventriglia, 1971; Marra & Rosa, 1995b; Ventriglia, 2002; Funiciello & Giordano, 2008b). Each of these valleys was associated with a name starting with "Fosso" (in accordance with the local terminology for the Campagna Romana stream valleys) on the basis of present-day toponyms (Fig. 5), also because they are anonymous (except for Fosso di Sant'Agnese and Fosso della Marranella) in the above-quoted historical topographic maps. These stream valleys are as follows: Fosso di San Lorenzo and its downslope extension towards the Verano area (Luberti, 2014), the former completely buried, the latter with marked morphological evidence; Fosso della Città Universitaria, deeper than the one mapped by Funiciello & Giordano (2008b) and whose head is retreated (probably inside the Macao area) and merges with the local depression called Fosso del Macao; Fosso del Policlinico; Fosso di via Catania, whose head is more retreated than mapped by Funiciello & Giordano (2008b), as better shown in the "Map of the outcrop unit thickness" (Ventriglia, 1971); Fosso di via Padova, distinguished from the latter and deeper than mapped by Funiciello & Giordano (2008b); Fosso di via Salento and Fosso di via Lanciani, in part shown in the "Map of the outcrop unit thickness" of Ventriglia (1971); and Fosso di via Ungarelli. All of the above-mentioned streams are tributaries of Fosso della Marranella. Among the tributaries of the right bank of Fosso di Sant'Agnese - deeper but less wide in its initial section and whose head is more retreated towards the Aurelian Walls than mapped by Funiciello & Giordano (2008b) - it is worth quoting: Fosso di via Tolmino, just hinted at in the maps of Ventriglia (1971, 2002); and Fosso della Sedia del Diavolo, mapped by Funiciello & Giordano (2008b) but more faithfully described in the "Map of the outcrop unit thickness" (Ventriglia, 1971).

The geological map in Plate I adequately depicts another unique feature of the geological model that was built as part of this study: the NNW-SSE-trending lineament that is visible in the Termini and Macao areas (Fig. 1). This lineament corresponds to the military moat located externally to the *agger* of the Servian Walls and to the effect of the excavation of the trench during the Roman Republic on the more shallow pyroclastic deposits. This trench, then filled with backfill materials, carves the volcanic succession almost entirely, as far as *Tufo del Palatino*, based on the interpretation of the section provided by De Angelis D'Ossat (1948).

ENGINEERING-GEOLOGICAL IMPLICATIONS

The detailed geological model highlighted numerous valleys, whose morphological evidence was totally or partially concealed by urbanisation processes, in particular by their total or partial filling with backfill materials having a thickness of up to 20 m.

Based on the descriptions of borehole logs (where present and distinct from those of modern deposits), the ancient backfills in the study area are extremely heterogeneous in terms of grain size and weathering of their volcanic groundmass, and generally poorly cemented (Luberti, 2015). Archeological remnants are frequent: mostly parts of buildings and paving stones, consisting of lapideous materials and bricks (Lanciani, 1893-1901; Min. BB.CC.AA., 1977). Modern backfills are mainly volcanic origin soils re-worked by human activities, heterogeneous in terms of grain size and weathered, and usually poorly cemented. The occurrence of bricks, metals, wood and putrescible materials is possible. Archeological remains are usually absent (Luberti, 2015). The geometries of backfills appear, to a first approximation, to have very significant lateral thickness variations (Sections in Plate I). The stream valley alluvial deposits are mostly made up of silty-clayey levels alternating with sandy levels and vegetable remains, with subordinate minute gravel of volcanic origin at their bottom, as noted in the study area.

Based on literature data for the area of Rome (Bozzano *et alii*, 2000; Ventriglia, 2002; Campolunghi *et alii*, 2008; Raspa *et alii*, 2008), backfills but also recent alluvial sediments have very different mechanical properties, generally poor, which may only be characterised through ad-hoc case-by-case investigations. The highest seismic amplifications (Bard & Riepl-Thomas, 2000) are likely to occur in areas with thick levels of poorly cemented soil, given their very low Vs values; in Rome, in backfills and recent sandy and silty-clayey alluvial soils, these values are generally in the range of 150 to 300 m/s (Rovelli *et alii*, 1995; Bozzano *et alii*, 2008; Caserta *et alii*, 2012). Considering possible seismogenic sources and expected magnitudes, the possible scenarios for Rome indicated that the highest seismic amplifications are likely to occur in particular in the Tevere plain (Olsen *et alii*, 2006), at a frequency of about 1 Hz (Bozzano *et alii*, 2008). This frequency is corroborated by the records of the L'Aquila earthquake in 2009 (Caserta *et alii*, 2013). During this earthquake, most of the damage was recorded near the alluvial plains of the Tiber and its tributaries (Bozzano *et alii*, 2011). In the sector investigated in this study, where these deposits have an average thickness of less than 10 m, soil resonance frequencies at which the above amplifications are possible are usually in the range of 5 to 10 Hz or more; as result, they cannot interact with the eigenfrequencies of buildings (generally of 3-6 floors) that are on average equal to 2-4 Hz (5 Hz only in the rare case of 2-floor buildings). Soil amplification frequencies of below 5 Hz are possible in limited sectors of the area under review, where alluvia and backfills may be more than 10 m-thick, e.g. in correspondence of stream valleys or in case of particularly low Vs values. These frequencies may have "double resonance" effects, amplifying ground motion and applying more stresses to the structures of buildings, many of which are in non-reinforced masonry.

Alluvial and backfill soils may be subject to differential settlements, which may originate from different responses in different sectors of the foundation area to the static load of a building or of nearby buildings (Antonucci, 2012), from the lowering of the water table (Terzaghi & Peck, 1974; Ferretti *et alii*, 2003), and from dynamic stresses (e.g. earthquakes) that may densify loose soils (Martelli, 2009). Differential settlements may also result from the progressive sinking of covers due to the gradual upward migration of underground cavities (Bianchi Fasani *et alii*, 2011). About 50% of the underground cavities (roughly 100) identified in the study area certainly belong (in the case of those recognised through boreholes) or are likely to belong (in the case of other sources and consequent assumptions based on the reconstructed geological model) to the *Pozzolane inferiori complex* and are always (in the case of cavities identified through boreholes) referrable to the *Pozzolane Rosse* or to the *Pozzolane Nere*.

Masonry buildings, which generally have shallow foundations and are common in historical urban centres, are those that mostly reflect the effects of their interaction with the foundation soil. Indeed, these buildings may experience stress-induced damage, when their constituent materials exceed their limit of strength. Although these effects may be due to unstable foundations (designed or built in an inadequate manner, old or subject to overloads due to the addition of floors), differential settlements in foundation soil may cause tensile damage (Mastrodicasa, 1993). Ground motion due to seismic action may densify loose soil as an indirect consequence (vibration induced by seismic waves), and differential settlements may occur due to lateral thickness variations and variable mechanical properties of the foundation soil strata (Martelli, 2009).

In the case of the urban portion investigated in this study, recent alluvial deposits and backfills represent a particularly critical issue. Indeed, depending on their thickness, they have a strong influence on the behaviour of the soil within the "significant volume" (A.G.I., 1977), under both static and dynamic conditions. In the study area, surveys conducted by Luberti (2015) to determine the damage of buildings evidenced a particular concentration of masonry buildings (without added floors), in the Macao and San Lorenzo areas (Fig. 1), with tensile damage reasonably attributable to differential settlements. Therefore, these areas deserve "careful attention" in terms of vulnerability and protection of their built heritage. In an indirect way, the findings from these surveys also seem to infer that these areas may be more geologically complex.

In view of the above, the development of a particularly accurate engineering-geological model is of crucial importance in urban areas, especially in historical centres with plenty of masonry buildings, which are more vulnerable. The accuracy of this model should be particularly enhanced on its shallower portion that certainly includes the "significant volume" and, considering possible effects under dynamic conditions, on the soil volume overlying the seismic bedrock. It should be stressed out that the geological model developed as part of this study with the above-discussed methodologies may certainly be used at the local urban-planning scale. However, for the design of structures or buildings, this model is to be regarded as indicative, since ad-hoc, direct and indirect subsoil investigations are imperative.

CONCLUSIONS

In urban environments, collecting geological data with conventional techniques, usually based on surveys and, where necessary, investigations, is challenging. The study discussed in this paper was expected to determine whether a critical review of available data and an integrated analysis of geological, archeological and historical data - supported by suitable data management methodologies - could improve the geological understanding *sensu lato* of urban areas. The end goal of the study was to gather sufficient data to adequately implement a geological model useful to correctly assess geo-hazards, whose estimation is particularly important in urban areas with high population density and precious historical-archeological heritage.

The examination and, where necessary, re-examination of existing (published and unpublished) geological data may give a valuable contribution to improving the basic geological knowledge needed to develop an engineering-geological model suitable for the urban-planning scale. In urban areas, data from prior investigations and, in particular, from borehole logs can provide a fundamental contribution. Their acquisition requires a process of interpretation based on the comparison with current and historical topographic data and, considering anthropogenic changes of the urban context, with other geological and especially stratigraphic data. With regard to the latter aspect, a review of the historical literature (contributions by authors who described the investigated areas when they were not yet urbanised) may yield important elements of information. Non-geological data may usually give a further contribution to interpreting borehole data in an appropriate way and implementing the geological model. In historical urban settings, the analysis and comparison of archeological data and historical archive files may provide useful insights for geological studies.

In the study area, a more detailed geological model, suitable for urban-planning studies, was implemented. Apart from discrepancies in terms of stratigraphic relationships and nomenclature, the model showed that the succession defined for drawing Sheet 374 "Roma" (Funiciello & Giordano, 2008c) of the official geological map of Italy and the municipal geological map (Funiciello *et alii*, 2008), both to a scale of 1:50,000, was mostly suitable for that scale. However, based on the findings from this study, the succession proved to be unsuitable for more detailed maps (at least in the investigated sector), e.g. the geological map of Rome's urban area (scale 1:10,000) of Funiciello & Giordano (2008b).

As regards geo-hazards and their implications in the study area, it is worth mentioning the occurrence of buried stream valleys, known only in part in the literature. These valleys suggest the presence of recent alluvial deposits, as demonstrated in many cases by boreholes, which also showed very thick levels of backfills, often masking them, put in place from the times of the Roman Empire to the recent urbanisation. Areas deserving "careful attention" were thus demarcated. They correspond to the heads of paleostreams, as well as to sectors with dense networks of underground cavities and delimited buried quarries, and alluvial plains with huge thickness of recent deposits. The presence in the "significant volume" of generally highly compressible materials, extremely heterogeneous and with often poor geomechanical properties whose thickness is averagely high but with sizeable lateral variations, such as alluvial deposits and backfills, suggests that, unquestionably, both deposits represent a critical issue to be carefully taken into account in view of the possible effects (load bearing capacity and local seismic response) on the exposed elements, including residential, strategic and monumental buildings.

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GEOLOGIC MAP OF THE EASTERN URBAN SECTOR OF ROME (ITALY)

Scale 1:10 000

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