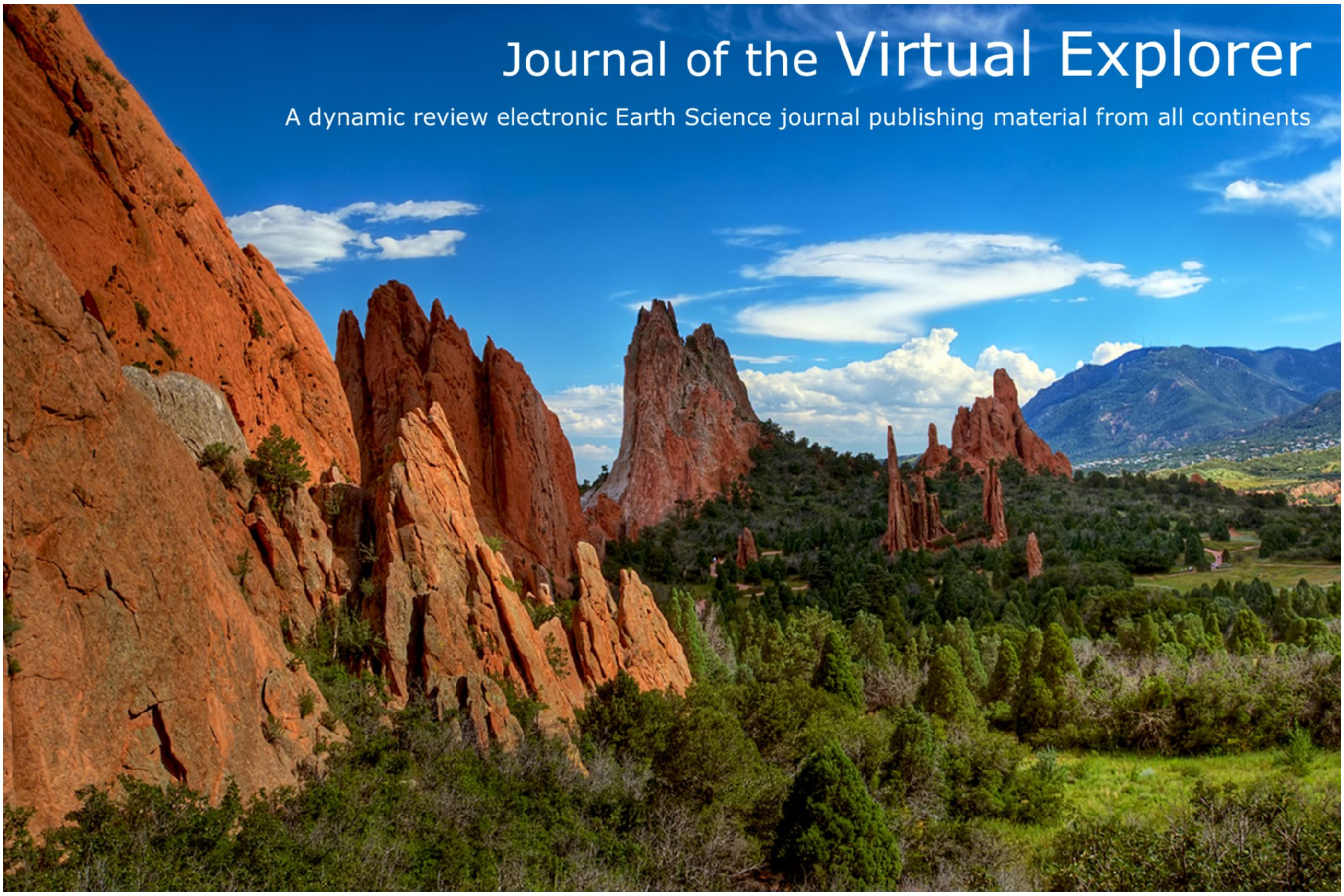


# The Geology of Rome and Urban Areas: the legacy of Prof. Renato Funiciello

*Guido Giordano, Roberto Mazza*

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# The Geology of Rome and Urban Areas: the legacy of Prof. Renato Funiciello

**Guido Giordano**
Dipartimento Scienze Geologiche, Università Roma TRE, Italy. *Email: giordano@uniroma3.it*

**Roberto Mazza**
Dipartimento Scienze Geologiche, Università Roma TRE, Italy.

**Abstract:** This paper presents an overview on the geology of the city of Rome and illustrates how the city and its evolution have been significantly affected by the active interaction with the geological environment both in terms of resources and hazards. Roma, with its 3,000 years of history, represents a unique case - a laboratory for urban geology. The city is still being exposed to several hazards and the knowledge of geology is mandatory to mitigate and prevent the effects of future events such as earthquakes, volcanic gas emission, floods and landslides. At the same time, the correct management of the water and land resources needs careful planning in consideration of the very high level of anthropic pressure on the local environment. The study of the geology of Roma and its intimate relationships with the urban development of the city have been strongly influenced by the ideas of Renato Funiciello, recently passed away, to whom this paper is dedicated.

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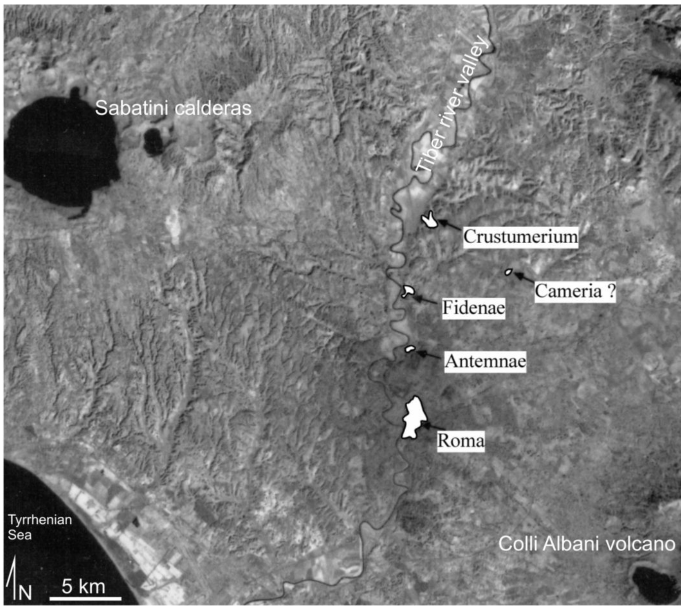
## Introduction

It is not an exaggeration to say that the discipline of Geology of Urban Areas, today widely accepted in the scientific community, was begun in large part because of the innovative and creative work of professor Renato Funiciello, who unveiled the relationships between geology and urban development, bounding linkages across disciplines, which involve engineering, architecture, archaeology, urban planning, civil protection and more. Renato Funiciello (1939-2009) had a precise idea of the role that geology has and can play as a social discipline. Geology was, for Funiciello, the center of a continuum where there is no distinction between exact sciences, natural sciences and social sciences. This is because, for Renato Funiciello, planning and management of a modern society made up of complex systems like those of urban areas are not possible without the complete reading of the relationships between natural and human environment in space and time.

Figure 1. Location of archaic pre-Roman villages along the Tiber river valley at the beginning of the II millenium B.C.E.




Rome, a city much loved by Funiciello, has been the place to discover and unveil those relationships. For anyone who has had the great pleasure, it was an exciting discovery to listen Renato Funiciello depicting the relationships between the development of the city and the geological history, ranging from the description of the first geological map of a urban area prepared by Brocchi for Rome in 1820, to the disputes between Neptunists and Plutonists for the interpretation of volcaniclastic deposits, to the urban stratification linked to earthquakes, floods of the Tiber, and landslides, to the current plans for the underground transport network.

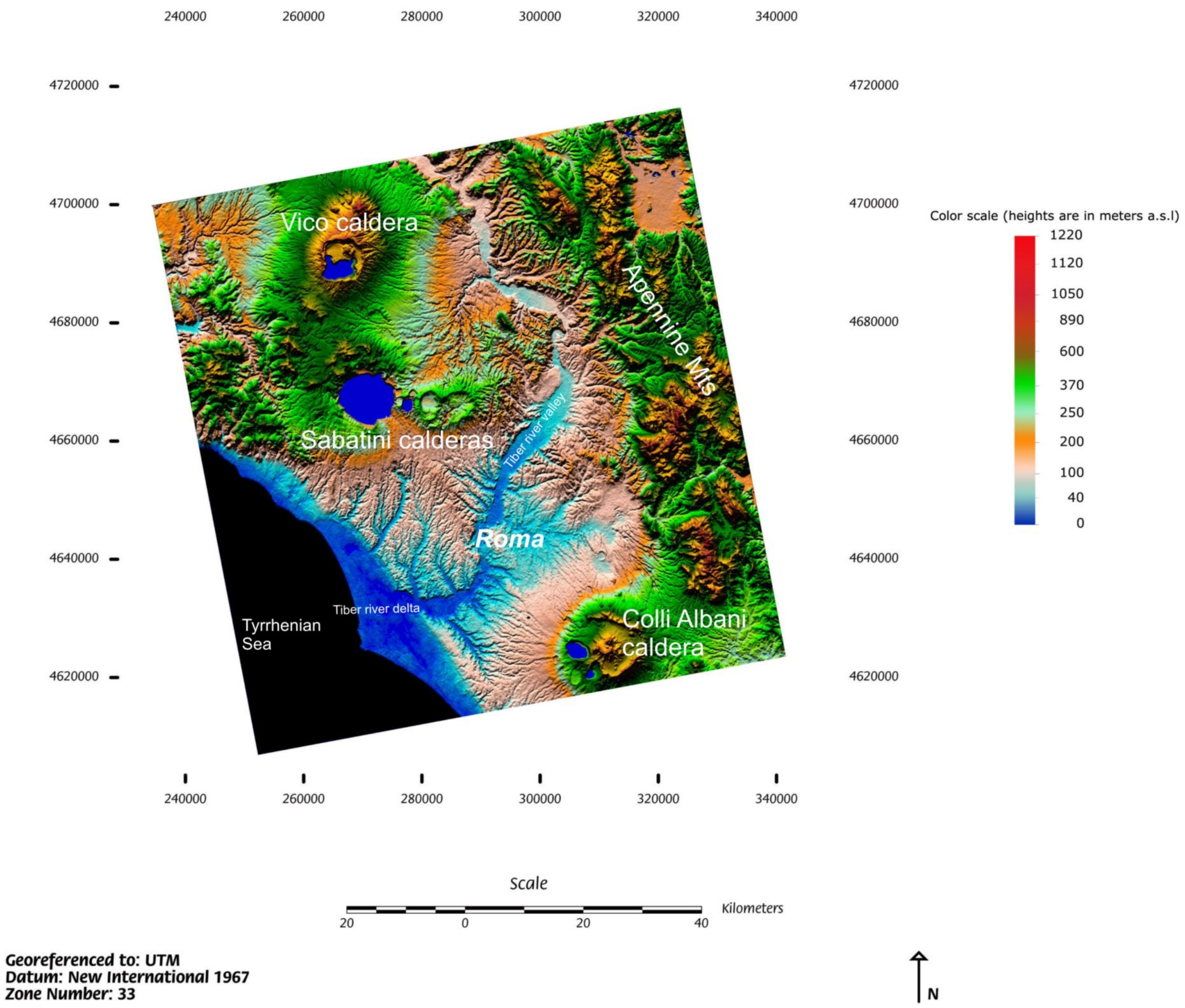
Syntheses of this vision and knowledge are contained in two monumental monographs devoted to Rome and its municipalities (Funiciello, 1995; Funciello *et al.*, 2008), prototype and model for any study of urban areas. Developing this type of systemic approach, where the Geology of Urban Areas becomes a driving force for multidisciplinary interaction, with the aim to serve society, is the legacy of Renato Funiciello.

The geology of the Roman area is one of the most studied for the excellent exposures of the sedimentary succession, and the interconnections with the 3,000 years of history of the city. The characteristics of the environment have played a major role in promoting the excellence of Roma as a political, economic and administrative power, the so called *Caput Mundi.*

Aside from the anthropological and ethnological factors, the positive geological and geomorphological settings have favoured the settlement of several arcaic villages along the left bank of the Tiber River since the beginning of third millennium B.C. These ancient villages constituted the proto-Roma and were built in very close succession and space from north to south from the arcaic site of Crustumerium, Fidenae, Antemnae and finally to the site of Roma (Fig. 1). The sites were strategically located, at the northwestern edge of the Colli Albani volcano ignimbrite plateau (Fig. 2), where tuffs are cut through by the nearby Tiber river fluvial network, leaving isolated tuffaceous cliffs dominating the alluvial plain. Such setting was also favourable for the abundance of spring waters and the large availability of building stones, which promoted a quick technological development of building and infrastructures to the growing town. The strategic location along with the good microclimate also had the capability to avoid the negative influence of the malaric plains distributed along the Tyrrhenian coastline in the past times.

One of those proto-historic villages prevailed progressively over the others, extending its power over the entire Latium region, and later over Italy, Europe and the Mediterranean: Roma.

Figure 2. Digital Elevation Model for the Roman area




## Geological setting

Roma and its hinterland are part of a portion of the western coast of Central Italy between the Apennine chain and the Tyrrhenian sea (Fig. 2). The Apennine chain is a complex structural unit thrusting toward E and NE mainly between Upper Miocene and Lower Pliocene (Mattei *et al.*, 2008 and references therein). The inner side of the chain has progressively been extended westward to form the back-arc Tyrrhenian basin, whereaside, from Tuscany to Sicily, a complex volcanic belt, mostly K-rich in composition, developed from Lower Pleistocene to Present (e.g. Barberi *et al.*, 1994; Conticelli *et al.*, 2002; Mattei *et al.*, 2010 and references therein).

The open and planar landscape of the Campagna Romana is mainly related to its Quaternary tectonic and volcanic evolution. During Lower Pleistocene the coast attained approximately its present configuration with the regression from open marine to continental environments (Funiciello and Giordano, 2008a,b; Parotto, 2008). Since the Middle Pleistocene, four main volcanic districts have been active along the Tyrrhenian margin between Tuscany and Latium, which are from north to south the Vulsinian Latera and Bolsena calderas, the Vico stratovolcano, the Sabatinian Bracciano and Sacrofano calderas and the Colli Albani caldera complex. These volcanoes erupted thousands of cubic kilometres of magma and emplaced large volume ignimbrite sheets confering to the region its gentle morphology (e.g. Giordano *et al.*, 2006, 2010). The ignimbrite plateau has been deeply eroded during the last glacial age by the Tiber river fluvial network and delta. During the subsequent rise of the sea level, the fluvial network has been backfilled with alluvial Holocene deposits, consisting of unconsolidated clayey-sandy sediments.

Figure 3. The bedrock of Roma


A. Panoramic view of Monte Mario viewed from the summit of S. Pietro basilica; B. Close up showing the reconstructed unconformity which separated the Pliocene Monte Vaticano Fm. (circalittoral grey clays; MVA) from the overlying Lower Pleistocene Monte Mario Fm. (infralittoral to transitional yellow and grey sand; MTM), here underlined by the Farneto member (infralittoral grey silt and sand, MTM1); C. The same contact as it could be seen at Fornace Veschi, near Valle Aurelia (now covered by back-fill); D. Stratigraphic conformable contact between the Farneto member and the yellow sands of the Monte Mario Fm. during the excavation of the Galleria Giovanni XXIII; E. Typical cross stratified and unconsolidated appearance of the yellow sands of the Monte Mario Fm.

The deep structure of the Campagna Romana is constituted by extensional highs and lows mainly overprinting pre-existing NW-SE thrusts, which piled up the Mesozoic-Cainozoic carbonatic and terrigenous succession during the Apennine orogeny (Funiciello and Parotto, 1978; Mattei *et al.*, 2008; Danese and Mattei, 2010).

The pre-orogenic Mesozoic-Cainozoic sedimentary succession is composed by limestones and marls deposited in the Tuscan and Sabinian basins of the Thetys sea, overlain by an allochtonous terrigenous cover, the "Ligure flysch", emplaced gravitationally during the early phases of the orogeny. This succession is structurally organized in a sequence of ramps and flats and it has been encountered in several deep bore-holes in correspondence with structural highs at variable depths from a minimum of few hundreds of meters below surface (Cristoforo Colombo GRA) to more than 1300 m below surface (Cesano, Circo Massimo) (Funiciello and Parotto, 1978; Barberi *et al.*, 1994; Funiciello and Giordano, 2008a,b).

Figure 4. The volcanoes of Roma

A. The Colli Albani volcano profile seen from the Capitolium hill with the Coliseum and the Forum in the foreground


B.. The Sabatini calderas seen from the airplane, landing at Fiumicino airport. The Bracciano caldera in the foreground is largely covered by clouds, then toward the east we see the Martignano maar lake, then the Baccano caldera and the Sacrofano caldera. In the background the Apennine Mountains.

The post-orogenic terrigenous marine sedimentation along the Tyrrhenian margin started diachronously during the Messinian-Lower Pliocene overlying the deformed Mesozoic-Cainozoic basement. The pre- and syn-depositional development of structural highs and lows, together with the isostatic rebound of the Tyrrhenian margin accompaining the transition from the orogenic to the post-orogenic phases, determined different sedimentary basins, mostly NW-oriented (e.g. Barberi *et al.*, 1994; Buonasorte *et al.*, 1991).

The post-orogenic stratigraphic succession outcrops discontinuously along the margins of the Apennine chain, in correspondence of structural highs and of shallow intrusions of magmatic bodies. Roma is located along one of the NW-trending structural highs, the Monte Mario high (Fig. 3), where the Pliocene-Pleistocene sedimentary succession shows the transition from open marine (grey clay and yellow sand) to continental facies (fluvial-deltaic conglomerate and sand).

After the Brunhes-Matuyana reversal, approximately at 780 ka, the Sabatini volcano and the Colli Albani volcano (Figs. 2 and 4a,b), respectively to the NW and to the SE of Roma, started their activity, which lasted till the Upper Pleistocene for the Sabatini and till the Holocene for the Colli Albani from the eccentric Albano maar (Funiciello *et al.*, 2003; Giordano *et al.*, 2006, 2010; De Benedetti *et al.*, 2008, Anzidei *et al.*, 2008). During this time span, the interplay between volcanism, tectonism and climate changes has produced the alternation of depositional and erosive phases, recorded by the complex arrangement of the Middle-Upper Pleistocene fluvial terraces along the course of the Tiber river.

The sequence of block diagrams of Fig. 5 illustrates the paleogeographic evolution of the Campagna Romana since Pliocene.

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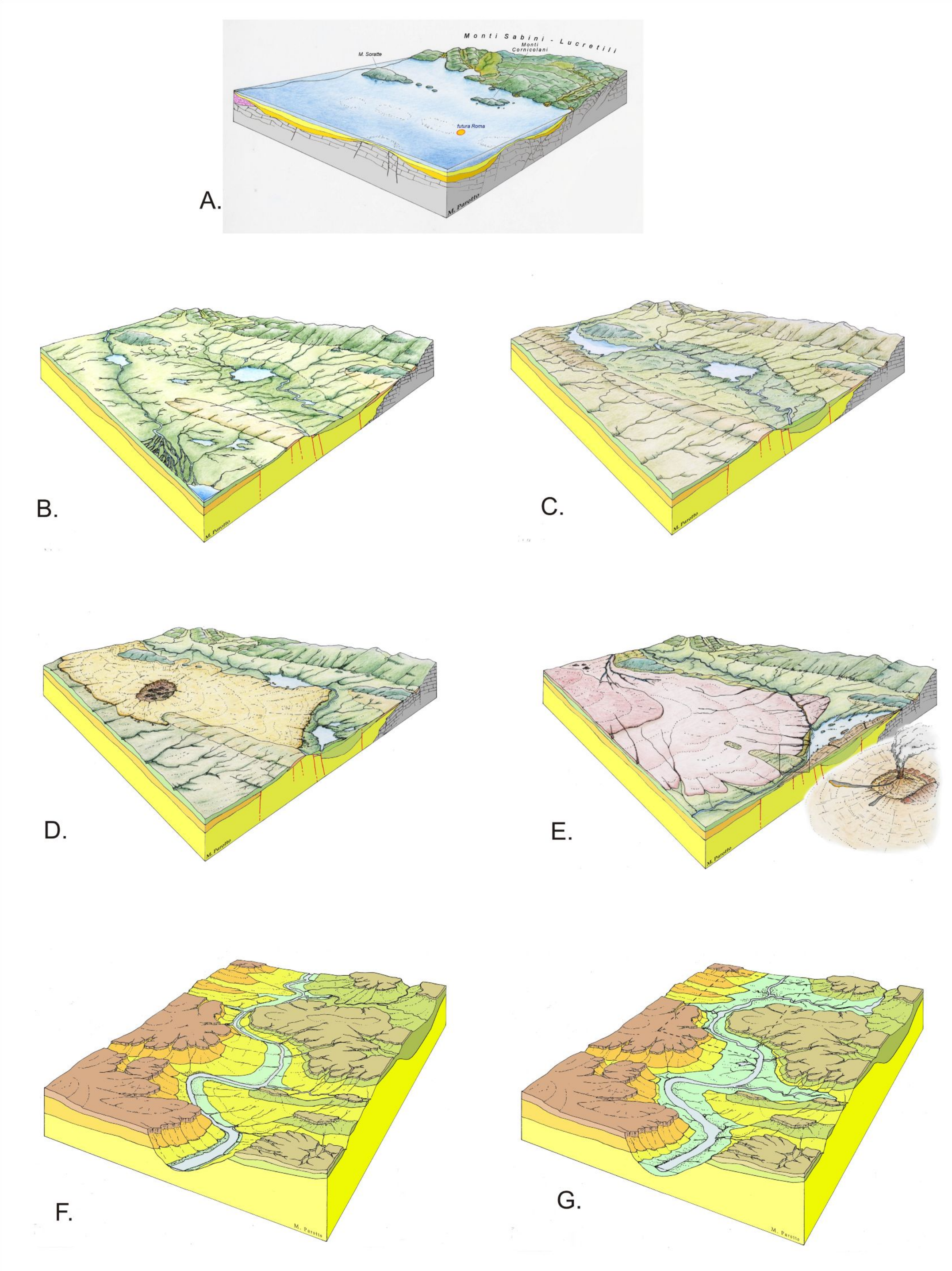
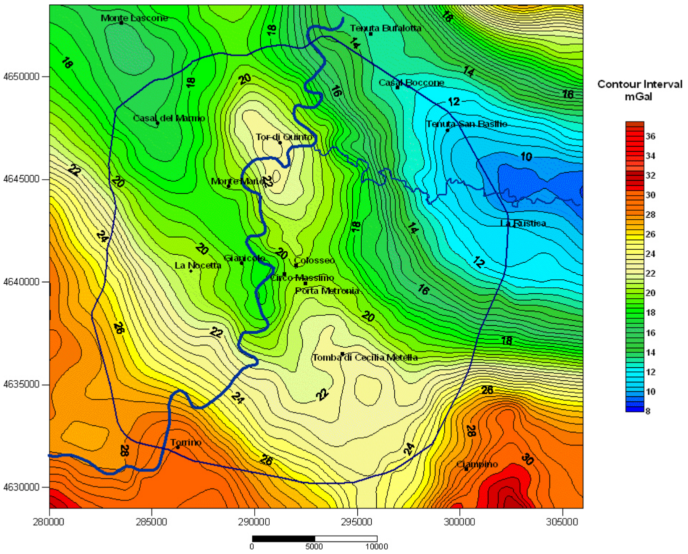
Figure 5. Paleogeographic Evolution of the Roman area (from Parotto, 2008)




A. Pliocene (post-orogenic deep marine sedimentation); B. Lower-Middle Pleistocene (marine regression and paleo-Tiber river delta formation); C. Middle Pleistocene (Monte Mario horst uplift); D. Middle Pleistocene (formation of the ignimbrite plateau of the Sabatini volcanic district); E. Middle Pleistocene (formation of the ignimbrite plateau of the Colli Albani volcanic district; the small black box indicates the area illustrated in the next two block-diagrams); F. Upper Pleistocene (incision of the last glacial age fluvial network); G. Holocene (formation of the alluvial plains).

Figure 6. Map of the Bouguer anomalies of Roma (from Cesi *et al.*, 2008)

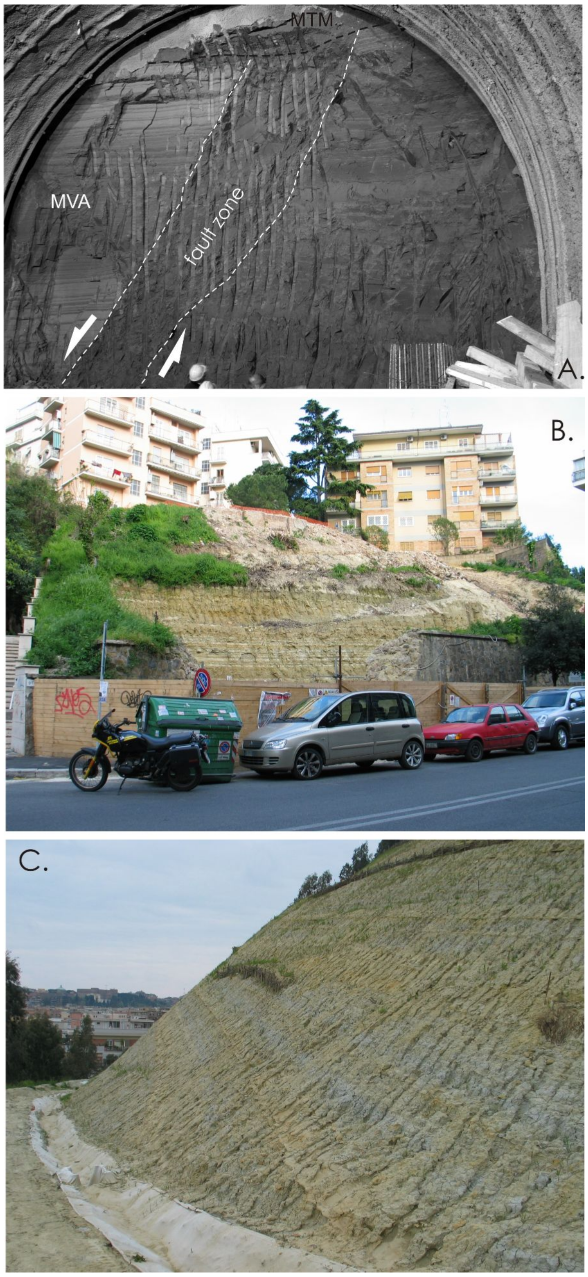



Some localities are indicated for geographic reference, as well as the trace of the Tiber river and the outer-ring GRA freeway.

**Pliocene** (Fig. 5a) - The area corresponding with the future Campagna Romana was submerged by the Tyrrhenian sea and formed an articulated continental platform from which isolated blocks emerged to form islands (Monte Soratte and Monti Cornicolani). The marine open-marine shales were deposited during the Pliocene, presently form the hundreds of meters thick bedrock of the area with very low permeability and over-consolidated characteristics (Capelli and Mazza, 2005; Cosentino *et al.*, 2008). These shales are named Monte Vaticano Fm. (MVA; Funiciello and Giordano, 2008a,b). At the transition Upper Pliocene-Lower Pleistocene, an episode of tectonic uplift occurred favouring a temporary emersion of structural highs, and namely of the Monte Mario high (Fig. 6) (Cesi *et al.*, 2008), where the Monte Vaticano Fm. is eroded at the top by a planar erosional surface (Fig. 7) (Cosentino *et al.*, 2009).

**Lower Pleistocene (Santernian-Aemilian)** (Fig. 5b). After the episode of tectonic uplift and emersion, the Roman area was again submerged. The Pliocene Monte Vaticano Fm. is overlain, above a subhorizontal erosional unconformity, by Lower Pleistocene (Santernian) infralittoral sandstone and siltstone which form the Monte Mario Fm. (MTM) (Figs. 7 and 8). These rocks culminate along the NW-trending Monte Mario structural high and mostly outcrop along the right bank of the Tiber river valley (Fig. 3).

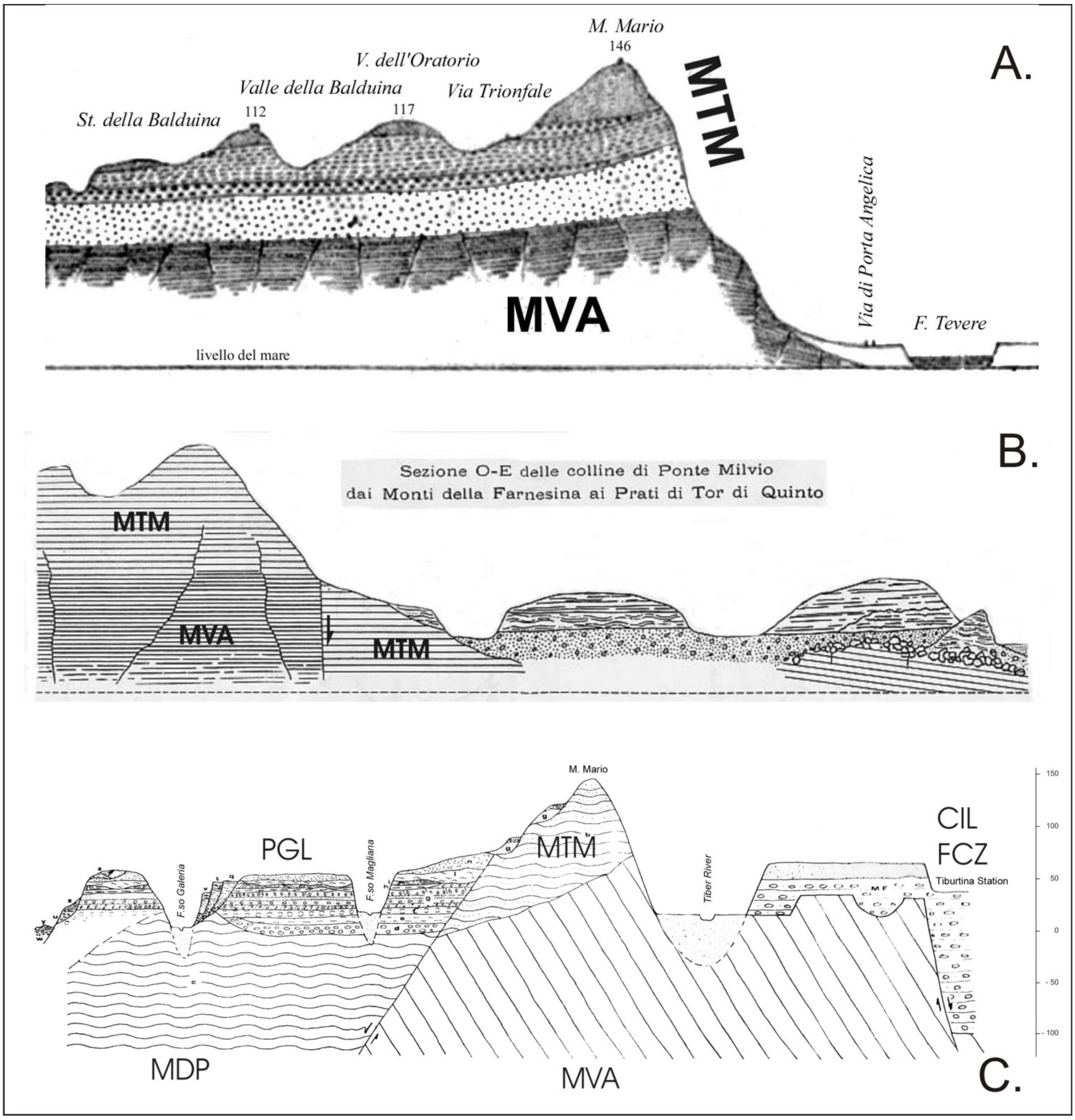
Figure 7. The Pliocene Monte Vaticano Formation




A. The unconformity between the Pliocene marine clays (MAV) and the Lower Pleistocene silts and sands (MTM) exposed during the excavation of the Galleria Giovanni XXIII through Mt. Mario. Note the tectonic deformation sealed by MTM; B. The MAV clays and sand crop out along the Mt. Mario slopes, seldom causing landslides (Via Labriola); C. Excavation of the MAV clays at Via di Donna Olimpia for the construction of an underground parking, needs special care for the presence of nearby housings.

The Monte Mario structural high was formed along a prolonged period of time. An early phase of uplift was responsible for the shifting toward the west of the depocentre of deposition, where, during the late Lower Pleistocene (Emilian) open marine clay, with Hyalinea Baltica, were sedimented (Monte delle Piche Fm. – MDP; Funiciello and Giordano, 2008a,b).

Figure 8. Geological cross-sections across Mt Mario



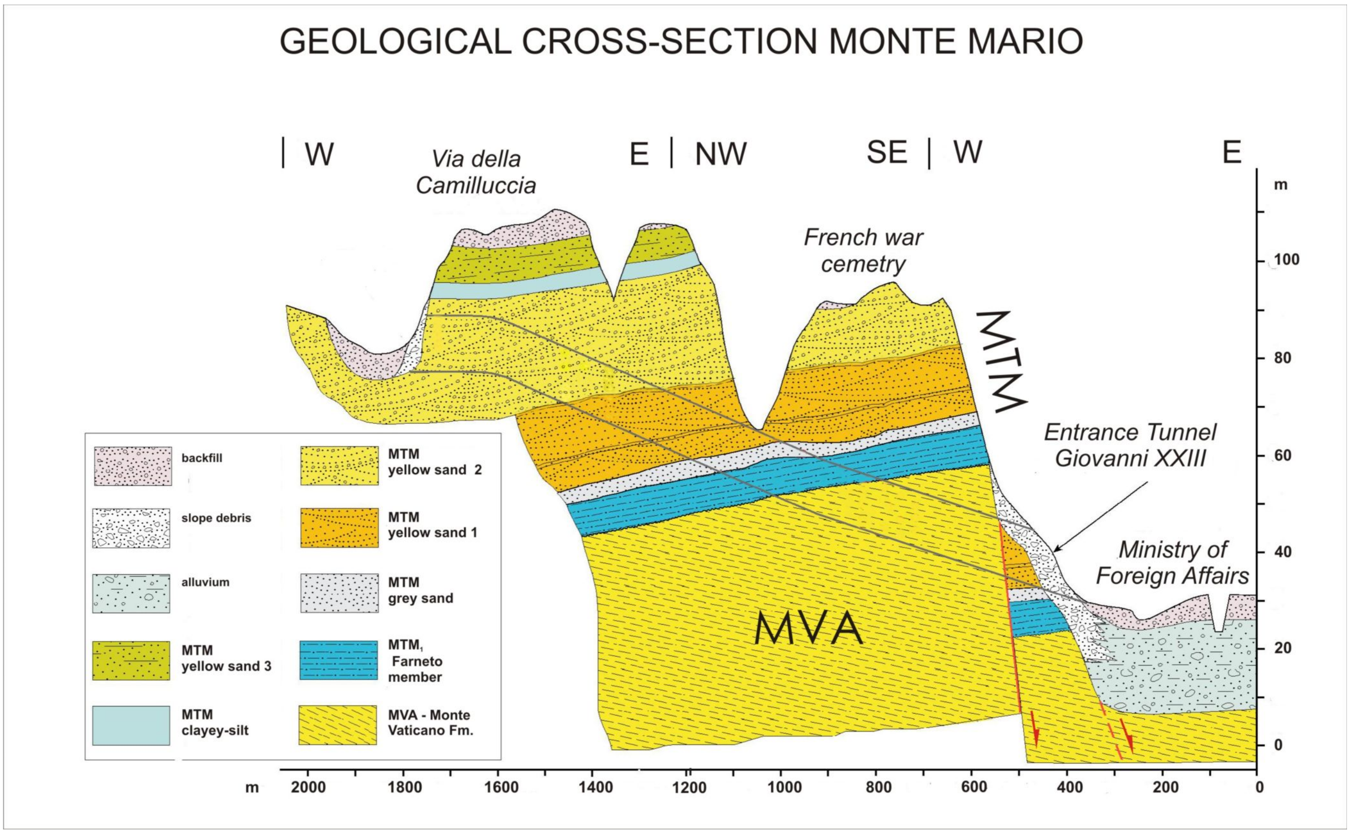

The three sections show the tectonics and the unconformity relationships between the Pliocene Monte Vaticano Fm. and the Lower Pleistocene Monte Mario Fm. A. Tellini (1896); B. Verri (1915); C. Conato *et al.* (1980).

**Lower (Sicilian/Villafranchian)-Middle Pleistocene p.p.** (Fig. 5c,d) - The marine domains extinguished progressively from east to west for the regional uplift of the area. The complete transition from marine to continental environments occurred between the late Lower and the early Middle Pleistocene, approximately between 850 and 700 ka, when the Roman area hosted the deltaic sedimentation from a paleo-Tiber river (Fig. 5c and 16 Ponte Galeria Fm. – PGL; Funiciello and Giordano, 2008, a,b).

The last phase of uplift of the NW-trending Mt. Mario structural high (Fig. 9), isolated the deltaic sedimentary wedge and forced the paleo-Tiber toward the south-east, parallel to the coast, inside a NW-trending subsiding valley wherein a thick succession of fluvial conglomerates was deposited (Manfredini, 1990; Feroci *et al.*, 1990; Giordano *et al.*, 2002), named the Fosso della Crescenza Fm. (Fig. 5d; FCZ; Funiciello and Giordano, 2008, a,b). The fluvial conglomerates of the Fosso della Crescenza fm. are found as deep as -100 m below sea level.

**Middle p.p.-Upper Pleistocene (700-125 ka)** (Fig. 5e,f) - As a consequence of the Tiber river diversion parallel to the coast, a large lake or swamp probably developed in the Colli Albani area, bearing an influence upon the early phreatoplinian activity of the volcano which started at about 600 ka (Pisolitic Tuffs succession; De Rita *et al.*, 2002; Giordano *et al.*, 2006, 2010). The growth of the Colli Albani volcano to the south (Fig. 10), and especially the early emplacement of the large volume ignimbrite sheets (600-355 ka; Giordano *et al.*, 2006, 2010), progressively shifted the river back northward (after ca. 550 ka) approximately where the present day river has its course, where it cross-cut the Monte Mario-Gianicolo horst (likely captured by a minor valley cut on the west flank of the Monte Mario rise) to find its way to the reach the sea.

Figure 9. Geological cross-section across Monte Mario (from Cosentino *et al.*, 2009)

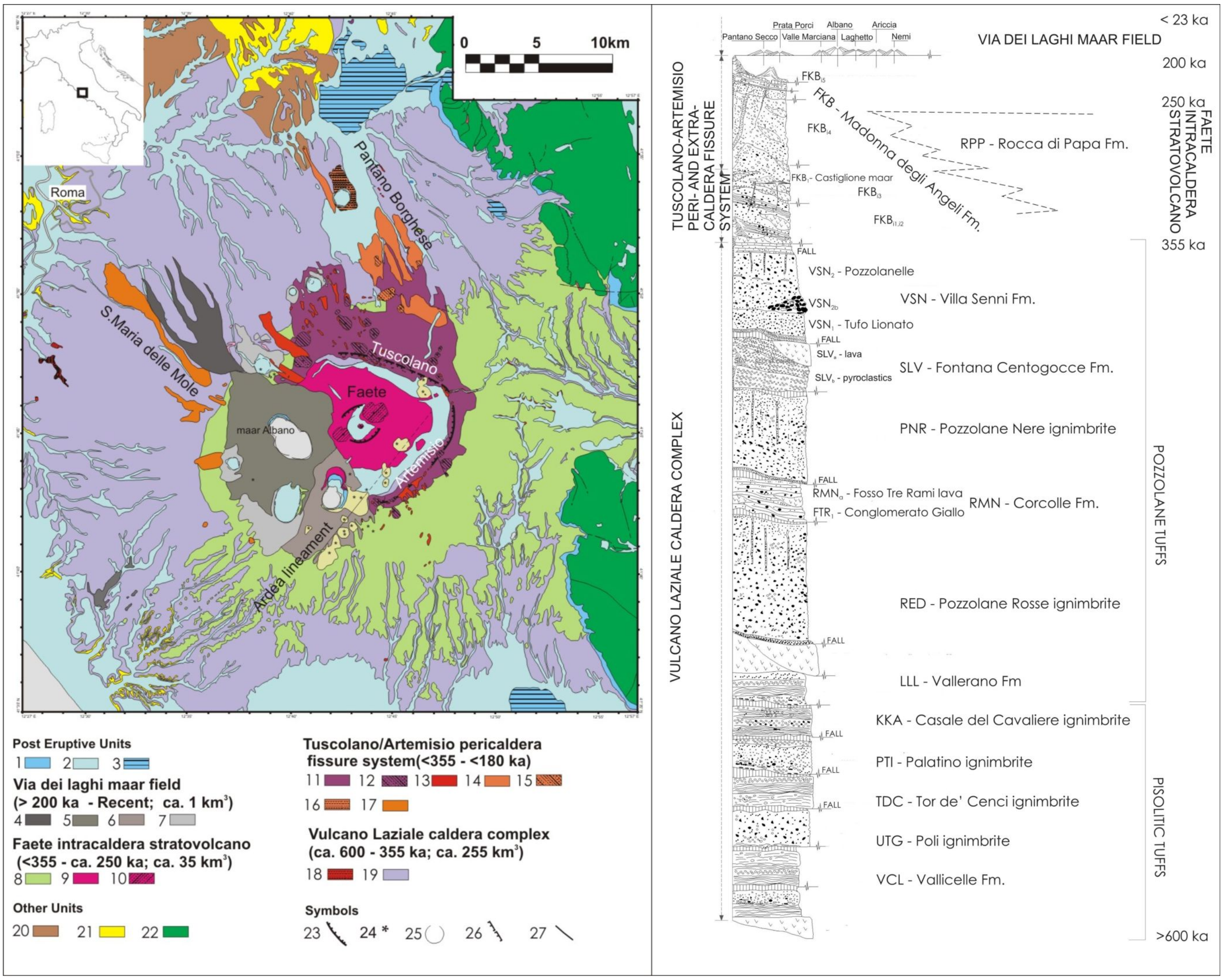



This section was reconstructed from direct observation during the excavation for the Galleria Giovanni XXIII.

Contemporaneously, the Sabatini volcanoes to the north emplaced large volume ignimbrites, pushing the course of the Tiber river eastward near the Apennines (Funiciello and Giordano, 2008a,b; Parotto, 2008).

**Last Glacial Age** (Fig. 5g) - The volcanic activity at the Colli Albani and Sabatini volcanoes during this period was essentially phreatomagmatic forming several maars (Giordano *et al.*, 2006, 2010; Giordano, 2008 and references therein). The progressive reduction of the erupted volumes, with the consequence of reducing considerably the production of volcanic debris, allowed the climate changes to have a stronger influence on the landscape evolution. During the last low stand of the sea level related to the Wűrmian glacial age, the Tiber river valley deeply eroded the volcanic and pre-volcanic rock succession down to the Pliocene clay units. The Campagna Romana assumed the present configuration with perched relics of the tabular volcanic plateau, which represent the present day topographic reliefs of Roma.

Figure 10. The Colli Albani volcano

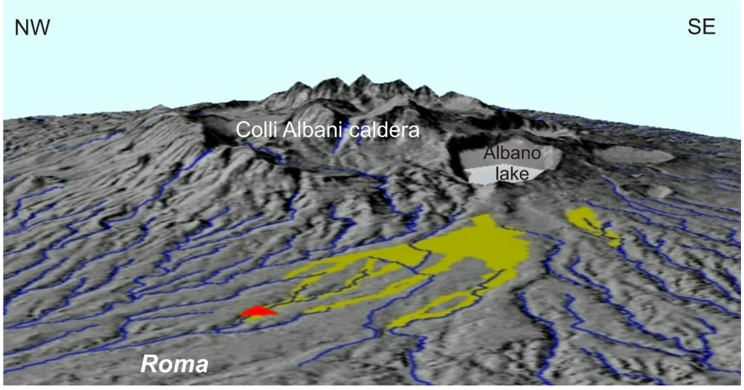



A. Geological map of the Colli Albani (modified after Giordano *et al.* 2010); B. Schematic stratigraphic column of the Colli Albani volcanic products.

**Holocene** (Fig. 5h) - The rise of the sea to the present level has induced the progressive filling of the Tiber river valley with its alluvial deposits, forming the alluvial plain closed to the west by the Monte-Mario-Gianicolo ridge, and, to the east, by the relics of the margin of the volcanic plateau, the famous Seven Hills of Roma (Fig. 4a,b).

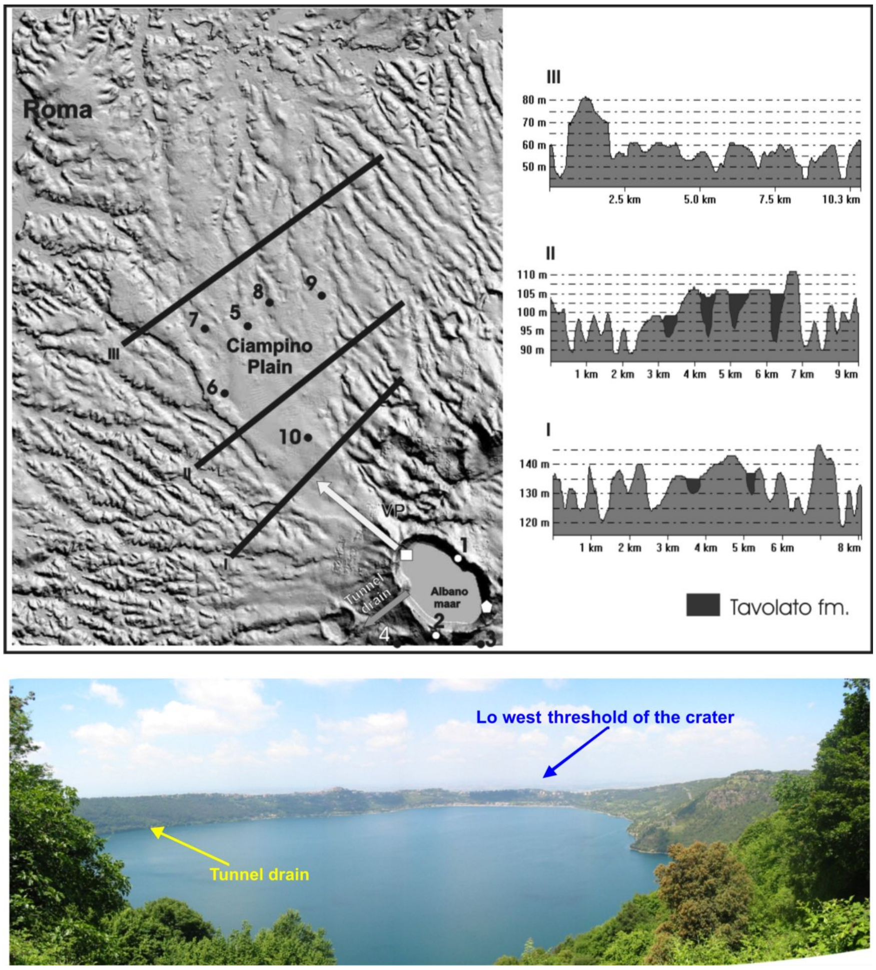
Recent studies have revealed that the large flat plain that extends northwestward from the Albano maar lake in direction of Roma, the Ciampino Plain, is been formed by the deposition during the Holocene of phreatomagmatic and lahar deposits from the most recent activity of the Albano maar (Fig. 11; Funiciello *et al.*, 2002, 2003; Funiciello and Giordano, 2008a,b; Giordano *et al.*, 2005, 2006, 2010; De Benedetti *et al.*, 2008). The last episode of lake overflow occurred in the IV cent. B.C.E. (before common era) and induced the Romans to dig a tunnel to drain the lake which still today regulate the lake level 70 m below the crater rim (Fig. 12b). The Ciampino Plain has been later used as the path for all Roman aqueducts, changing forever the social perception of that area from the source of disastrous floods in the main water way to the city (Fig. 13).

Figure 11. The Ciampino laharic plain




3D perspective of the flat Ciampino plain, showing in green the distribution of the Holocene lahar deposits originated by the overflows of the Albano maar lake (picture courtesy of Antonia Arnoldus-Huyzendveld).

Figure 12. The Tavolato Formation and the historical overflows of the Albano maar lake




A. profiles across the Ciampino plain show the Holocene infilling of the Last-Glacial fluvial network by the lahar deposits of the Tavolato Fm. (from De Benedetti *et al.*, 2008); B. View of the Albano lake with the location of the tunnel drain buikt by the Romans to keep the lake level 70 m below the lowest threshold of the crater rim, in order to prevent further overflows, the last having occurred in 398 B.C.E.

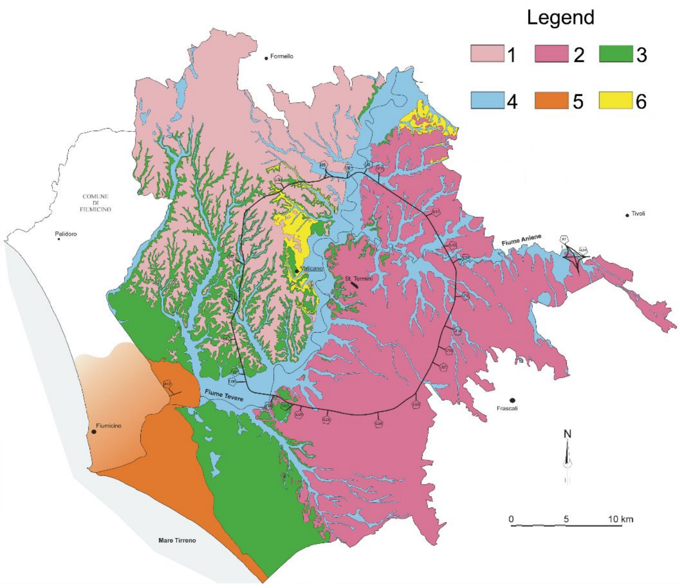
Figure 13. The flat top of the Tavolato Fm.


Note the aqueducts in the background, built by the Romans to use the top gently sloping toward the city (Via Appia-G.R.A.).

## Water and building stones resources

Five hydrogeological units can be defined in the territory of Rome. These units overlie the hydrogeological complex of the Pliocene clayey-marly deposits that, given the considerable thickness, always larger then hundreds of metres, and the very low permeabilities, act as regional aquiclude (Fig. 14) (Capelli and Mazza, 2005). The local structural setting and the type of water exchange between units affect the hydrogeological setting and the scheme of movement of groundwater in the town area. The most interesting hydrogeological complexes are those characterized by high permeability and include the Ponte Galeria Fm., the Fosso della Crescenza Fm. and the S. Cecilia Fm. In addition to these, also the deposits of the Vulcano Laziale activity host important aquifers, especially in the south east, where such deposits, significantly extensive, have thicknesses of several tens to hundreds of meters. The morphological evolution following each main eruptive phase both from the Colli Albani and Sabatini volcanoes, has led to formation of alluvial successions presently terraced, in outcrop along the system of valleys which have been eroded during the Pleistocene low standing of the sea level. These deposits contain, generally at the base, gravel aquifer facies, confined above by mainly pelitic terms. These bodies, however extensive, do not constitute a single aquifer and their recharge is still object of study. During the twentieth century a thick and extensive layer of filling, due to the urbanization of the city of Roma, covered the natural rock-formations. These deposits host little aquifers linked to the zenithal recharge and the leakage of underground utilities.

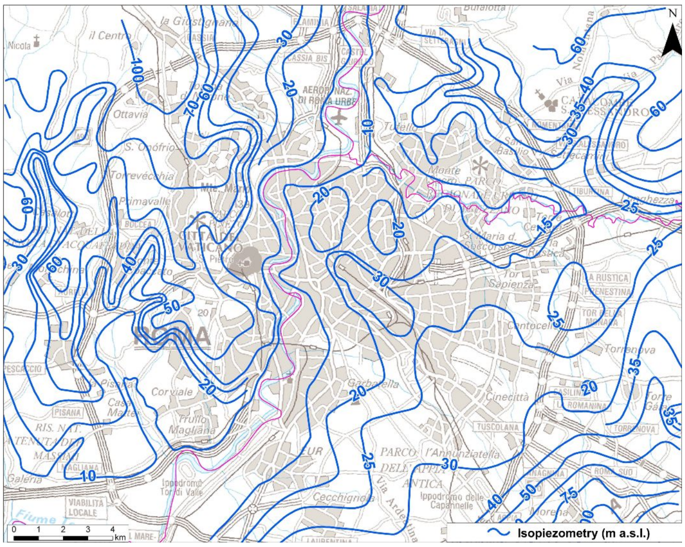
Figure 14. Map of the hydrogeological units of the Roman area (from Capelli & Mazza, 2005).




Legend: 1 - Sabatini Mts. hydrogeological unit; 2 – Colli Albani hydrogeological unit; 3 - Ponte Galeria hydrogeological unit; 4 - Hydrogeological unit of Recent and present alluvial deposits; 5 - Tiber river delta hydrogeological unit; 6 - Hydrogeological system of low permeability clayey-marly deposits.

The Hydrogeological Map of Roma (Fig. 15) (Capelli *et al.*, 2008b), allows to evaluate the relations between groundwater, and the drainage network, both natural and artificial, the latter consisting mainly of the sewer network that replaced the pre-existing river branches. Furthermore, the isophreatic lines, in addition to the identification of the main directions of groundwater flow, can identify the different gradients that characterize the groundwater circulation in different areas of the city. In the western area of the territory, to the west of the Tiber, the clayey structural high of Monte Mario, oriented NW-SE, affects the pattern of groundwater flow. The groundwater drainage of Monti Sabatini Hydrogeological Unit aquifer is affected by this structure, which acts as groundwater divide and splits the drainage partly to the south-west, towards the river Arrone, and partly to the west, towards the basins of the Fosso della Mola - Cremera Valchetta. The recharge of the Galeria and Magliana streams and the smaller basins is mainly due to the pre-volcanic sandy-gravel aquifers, belonging to the Ponte Galeria Fm.

Figure 15. Map of the isopiezometric lines of Roma (from Capelli *et al.*, 2008).




To the east of the Tiber, the hydrogeological setting is different. There, the Colli Albani aquifer is less affected by the morphology of the clay substrate, which is more flat and deeper. The Colli Albani aquifer feeds copiously all stream valleys eroded down to the roof of the regional aquifer.

Essentially, the territory to the west of Tiber river is characterized by discharges of the streams mainly due to the surface runoff, whereas to the east of the Tiber, the river network is supported by base flow from the Colli Albani groundwater aquifer. Moreover, in the western part of the city the territorial changes resulting from urban changes have not determined the total disappearance of the river network, whereas in the eastern part, longly urbanized, the flillings and the transformation of talwegs in the sewerage network, led to the disappearance of valleys.

Surface waters have played in ancient times of Roma, and are still playing, a major role both as essential resource and hazard, because of recurrent floodings and the related unhealthy marshes and swamps.

The availability of surface water is related to the hydrogeological setting of Roma and its surroundings (Corazza and Lombardi, 1995; Capelli *et al.*, 2005; Corazza *et al.*, 2006; Capelli and Mazza 2008a; Capelli *et al.*, 2008a;). To the west of Roma, the Apennine chain provides several high discharge springs associated with the highly permeable Mesozoic-Cainozoic limestone blocks thursted over the impervious Miocene terrigenous flysch (e.g. Boni *et al.*, 1988).

The importance of surface waters for Roma is recorded in its foundational legend, when Romolo and Remo landed in the site of the future Roma in a basket, which had floated over the Tiber river. This legend must reflect the lively relationship between human settlements and water.

During the Empire, the 2 millions citizens of Roma had an amount of drinkable water per person per day equal to that of the most efficient (and lucky) modern cities. All the major springs along the Apennine mountains were captured and delivered to houses, thermae and fountains of Roma, with the edification of perched aqueducts hundreds of kilometres long, likely the most spectacular engeneering construction of that time. After the fall of the Empire, Roma experienced a rapid demographic decline and lost the technical expertise to keep in function the aqueduct network, which was restored only one thousand years later.

Figure 16. Ponte Galeria Formation


The Ponte Galeria Fm. (PGL) shows transition from pro-delta conglomerate and sand (PGL3a), to lagoonal clay (PGL3b), to aeolian sand (PGL3c). Here PGL is overlain by the S. Cecilia Fm. (CIL) bearing the first volcaniclastic deposits (> 600 ka).

Figure 17. Lithified ignimbrites as building stones


A. Quarries of the lithified ignimbrite Tufo Lionato (355 ka, erupted from Colli Albani) along the Aniene river. B. the use of blocks of lithified ignimbrites allowed the great development of Ancient Roman architecture; here the Servian walls and successive modifications at Roma Termini train station.

Aside water, the availability of a vast range of local building stones has certainly played a major role in promoting the excellence of Roma in history (Giampaolo *et al.*, 2008 and references therein). A review of the geotechnical characteristics of the rocks of the Roman area can be found in the explanatory notes to the new 1:50.000 scale geological maps of Roma (sheet n. 374; Funiciello & Giordano, 2008a) and Albano (sheet n. 387; De Rita & Giordano, 2010) (see Bozzano 2008; Lanzini 2008, Diano, 2010)

The Pliocene shales of the Monte Vaticano Fm. have been longly quarried to produce bricks (Fig. 8), alongside, at least in early Roman times, with the clay from the Holocene alluvial deposits.

The conglomerate and sand of the Ponte Galera Fm. are still largely quarried (Fig. 16) for concrete.

The lithifed ignimbrites, both from Colli Albani and Sabatini (namely, the Tufo Giallo della Via Tiberina, the Tufo Giallo di Porta and the Tufo Rosso a Scorie Nere from the Sabatini, and the Unità di Tor de Cenci, Unità del Palatino, Tufo Lionato and the phreatomagmatic Peperino Albano from the Colli Albani; see Funiciello & Giordano, 2008b), have provided tuff blocks for walls (Fig. 17). The unconsolidated ignimbrites, mostly the Pozzolane Rosse, the Pozzolane Nere, and the Pozzolanelle units from the Colli Albani (Fig. 18; see Giordano *et al.*, 2010), have been used mixed to cement to produce the hydraulic cement, a discovery which allowed the Romans, first in history, to build concrete peers in harbours.

Figure 18. The Pozzolane Tuffs succession


Succession of the main pozolanaceous ignimbrites of the Colli Albani, the Pozzolane Rosse (RED, 460 ka), Pozzolane Nere (PNR; 407 ka) and Pozzolanelle (VSN2; 355 ka) at Cava Bulgarini.

Both the lithified and the unconsolidated ignimbrites have been largely quarried underground (Fig. 19), producing a vast and still largely unexplored network of catacombs and undergound tunnels, which occasionally collapse affecting the edifices and infrastructures (Mazza *et al.*, 2008 and references therein).

Figure 19. Roma underground


A. Tunnel excavated in the Tufo Lionato at Monteverde originally to extract building stones, have been re-inforced and longly used. Note also the vertical pole-foundation which have penetrated the tunnel from overlying constructions; B. Underground cavities used for mushroom-growing.

The K-foiditic to tephritic lavas have been quarried to form foundation of buildings and to pave roads, for their fine grained and compact texture which allows excellent resistance to compression and to friction (Fig. 18; see Diano, 2010).

The partly welded scorias from the Colli Albani scoria cones have been quarried for presenting similar characteristics to lava but in a less dense material (Fig. 20). This rock has been largely used in the Colosseum.

Figure 20. Building stones

Roman quarry at Tuscolo (Colli Albani caldera) where welded scorias (local name « sperone ») were quarried for buildings.

Finally the carbonatic rocks from the nearby Apennines, but most importantly the Tivoli travertine have been quarried since Roman times both as building and ornamental stones (Fig. 21).

Figure 21. The Tivoli travertine

The quarries of Tivoli travertine have left a superelevated strip on which runs the Tiburtina road.

## Geological hazards

### *Brief history of urban development (by Andrea Bollati)*

Roma has developed over almost 3000 years. Accurate reconstructions of the urban evolution of Roma have allowed to trace the history of the city (Muratori *et al.*, 1963). The transition from the Archaic village to the Republican age town then to the Imperial Age capital city had been accompanied by an impressive urban development, which culminated between the 1st and the 4th centuries C.E. (common era), when the city hosted more than 2 millions people (Fig. 22). In the Medioeval time, under the temporal power of the Catholic church, the city experienced a drastic decline (Fig. 22), oscillating around some tens of thousands people, a number which did not rise through the Renaissance till the XIX century (Fig 22a,f). The Tiber alluvial plain and its tributary valleys have been intensively urbanised mostly in the last 150 years, after the unification of Italy under the kings of Piedmont. Roma became the capital city after 1870 and developed quickly. The advantages of the regular and flat morphology have been preferred, disregarding the hazards which kept these alluvial areas largely un-settled for millennia.

*From the origins to the Hellenic city (12th – 2nd centuries B.C.) – Fig. 22a*

The first settlements developed between the 13th and the 12th century BC; they were distributed on the heights converging towards the River Tiber.

Many favourable factors make this site a good choice: ships can sail up the river which constitutes an important communication route, the proximity of the mouth to the heights representing the first landing point for merchant ships sailing towards the interior of the territory, the abundance of affluent rivers and springs, the position of the hills converging towards a bend of the river, the configuration and elevation of the hills permitting to control and defend the territory below as well as the river crossings, the morphology of the heights with mainly flat summits and the existence of a plateau embracing all the hills, allowing easy connections between the different settlements (Bollati R.; in Muratori *et al.*, 1963).

In the 11th and 10th centuries the settlements developed downstream, towards the intersection between the heights and the bottom or the valley; in the 9th century on each hill-top, the initial settlements merged into unitary systems surrounded by the first defensive works; in this period the population numbers approx. 5,000.

The groups of hills join in confederations (7th century); hence they merge (8th and 7th century) in a single unit (defended by fences linking the various systems) gravitating towards a common forum. The population increases from approx. 10,000 to 20,000. During the 4th and 5th centuries the initial unit is commonly administered and delimitated by continuous fortifications.

Under the government of the Etruscan dynasties the population reaches 80,000 inhabitants.

During the 5th century the building expansion outgrows the “pomeriali” boundaries (sacred land beyond the city walls, where building was forbidden). During the period of conflicts against the neighbouring populations, until the Gallic invasion, the population reaches 100,000 inhabitants. In the 6th century the first reconstructions are performed under the pressure of renewing urban needs (period of the Sannite wars and expansion to the South). In the 3rd and 2nd B.C.E. (Punic wars period) the town undergoes a specific urban planning by sectors: the heights and their spurs are occupied by exclusive neighbourhoods, the valleys are occupied by high density residential and commercial quarters, the sites along the Tiber house the naval and provision quarters while the areas beyond the wall are occupied by military quarters and commercial activities. Towards the end of the 2nd century B.C.E. the population adds up to about 300,000 people.

*The imperial city: from the conquest of the supremacy in the Mediterranean area to the fall of the Empire (1st B.C.E. – 4th C.E. centuries) - Fig. 22b*

Between the 1st century B.C.E. and the beginning of the 1st century C.E. (period of the emperors Silla, Caesar and Augustus) the urbanization of the city is realised by three different interventions: new fortifications are built, the “pomeriale” perimeter spreads out (also in the transtiberial area) and a long series of renovations begins, including the creation of huge architectural structures and the tracing of new main roads (Marinucci G.; in Muratori *et al.*, 1963). The city plan at the beginning of the 1st cent. C.E. is organised in: the imperial quarters on the Colle Palatino, the patrician quarters on the Esquilino, the plebeian quarters on the Aventino, Celio and Trastevere, the artisan – commercial quarters are hosted in the river valley, the suburbs along the consular roads, the military quarters are located in the “extrapomeriale” areas.

In the 1st century a.d.(period between the emperors Tiberius and Nerva) the urban expansion includes monumental complexes in the north-west and south-east sectors; private buildings support this expansion process with the creation of houses interposed between the above-mentioned complexes and with the edification of new houses located in peripheral lots. In this period the population exceeds one million inhabitants.

Between the 2nd and 3rd century (period between the emperors Trajan and Constantine) the imperial planning is completed, followed by the last phase of urban development and the final asset of the city boundaries, coinciding with the Aurelian walls; in this period the first Christian cult sites spring up and the city is divided in 7 ecclesial regions with a new interpretation of the city structure. Between the end of the 3rd century and the beginning of the 4th the large central establishments are abandoned, following the removal of the imperial court from Rome.

*The medieval city (5th - 14th centuries) - Fig. 22c*

In the 5th century the grand political and military buildings are abandoned, a contraction of the collective provision systems takes place, the homogeneity of the urban fabric declines; additionally the pagan temples close and the basilicas develop together with the pertinent connecting paths. At the end of the Roman Empire the population adds up to less than a half million inhabitants.

During the 6th century the destination of the structures progressively changes: still maintaining the architectural unity they are subdivided or grouped for the new functions (pilgrim and foreigner hospices, hospitals, monasteries and fortifications); so, the beginning of the centralisation process takes place in the city, which progressively loses its secondary peripheral structures (Bollati S.; in Muratori *et al.*, 1963).

In the 7th century the diagonal north-west south-east trend starts in relation with the political-religious interests around the Lateran, Forum and Saint Peter areas. During the Byzantine period the inhabitants of Rome are around 100,000.

In the 8th century the residences on the heights become progressively isolated; the ancient public buildings in the Campo Marzio begin to change into religious and residential complexes.

The 9th century sees the birth of the “contradas”, the residential fabric along the river valley decreases while in the next century the city districts (rioni) begin to develop. Between the 8th-9th and 10th centuries the population declines from about 50,000 (Carolingian period) to 30,000 (Othonian dynasty).

During the 11th century a new growth phase starts, with the formation of an urban strucure connected with the old religious interests and the new civil interests; the 12th century sees the establishment of the City-State, the definition of isolated centres organised around the elements of churches and fortresses, the birth of craftwork distrists and the specialisation of collective centres in markets, craft and commercial streets.

In the 13th century the residential isolated areas progressively merge together following the new street network of the future Renaissance city.

The population remains around 35,000 inhabitants, still with up and down events: periods of decline coincide with the Norman invasion (second half of the 11th century) and the transfer of the Papal court to Avignone (during the 14th century).

*The Renaissance city and the modern city (15th–20th centuries) - Fig. 22d,e,f.*

Between the years 1400 and 1550 the city is renovated (coinciding with the return of the Papal court) with restorations and the first suburban planning, the drawing of city plans in the central sectors (new specialised hubs like piazza Navona and Campo de’ Fiori develop), extension of suburban areas, building growth in the new and ancient sectors and completion of defensive works (Bollati R.; in Muratori *et al.*, 1963). During this period the population increases from 30,000 to 60,000 inhabitants.

Between the year 1550 and 1748, the city develops according to the building policy of the popes: suburban planning and drainage, the first straight roads outside the ancient centre (1550-1572); connection between the suburbs and growth of new suburbs, especially in the eastern area, with the epicentre corresponding to the basilica of S.M Maggiore (1572-1605); completion of the minor internal road axis and the development of the great baroque structures, including churches with important façades, big fountains and architectural arrangement of natural elements such as the stairs of Trinità dei Monti (1605-1748). At the end of the 18th century the population grows to the 150,000 inhabitants.

From the year 1800 to 1870 (year in which Rome becomes the capital of Italy) a new city develops alongside the ancient one; the new urban plant develops in the hilly areas of Quirinale, Viminale and Esquilino, gravitating towards the new axis of via Nazionale.

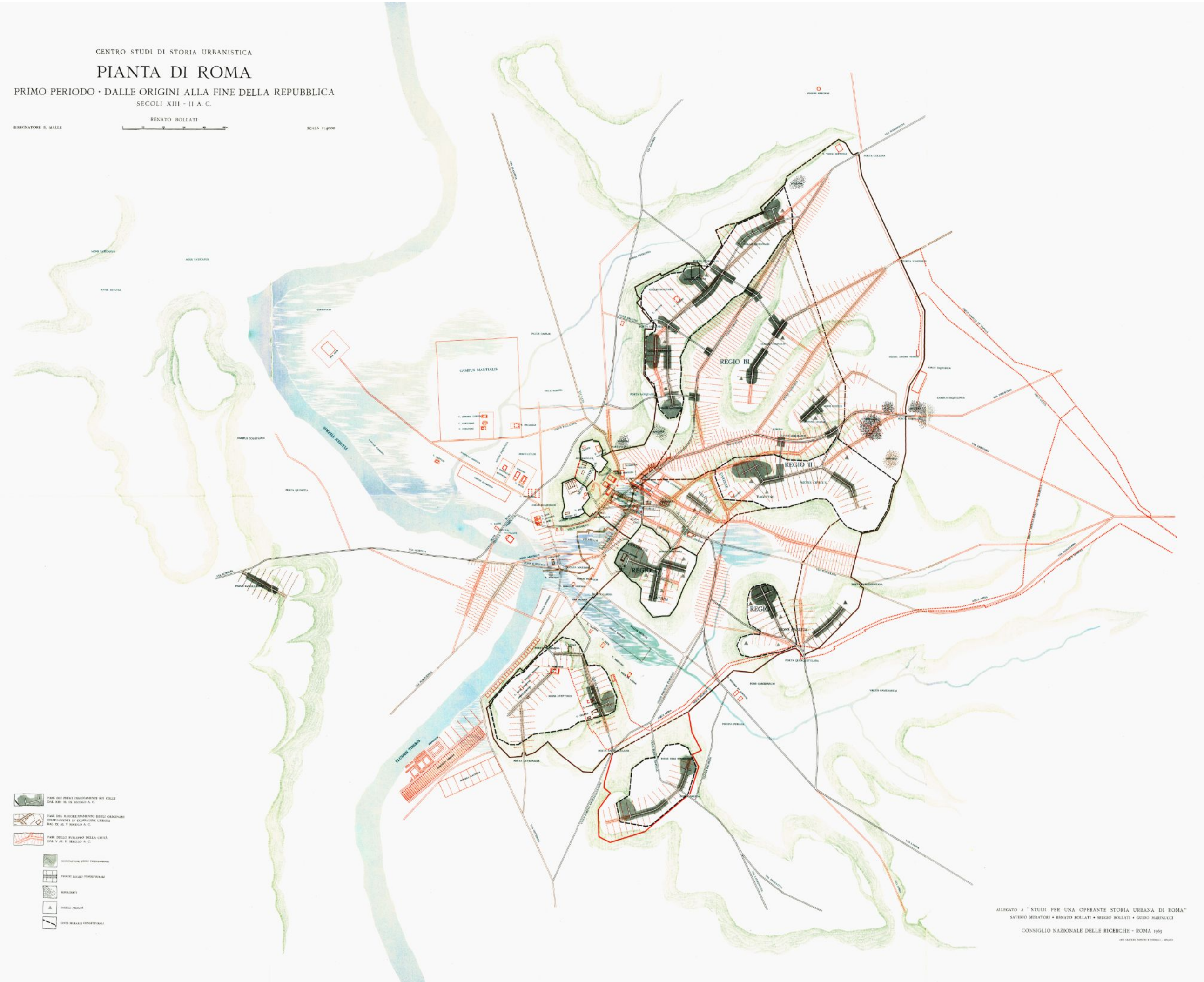
The plan of A. Viviani dating 1873 suggests the realisation of Via Nazionale, the drawing of Prati district and of all those within the Aurelian walls, pivoting around the axis S. M. Maggiore-Porta Maggiore, while piazza Vittorio Emanuele becomes the centre of the new capital between the old area and the Termini Railway Station.

The Urban Plan of Santjust di Teulada of 1908 includes the urban developoment of all the Eastern area between via Tiburtina and Prati up to the new district of Piazza d'Armi beyond the Tiber and extending to West and South with the Gianicolo and Archeological Parks up to the Vittorio Emanuele Monument.

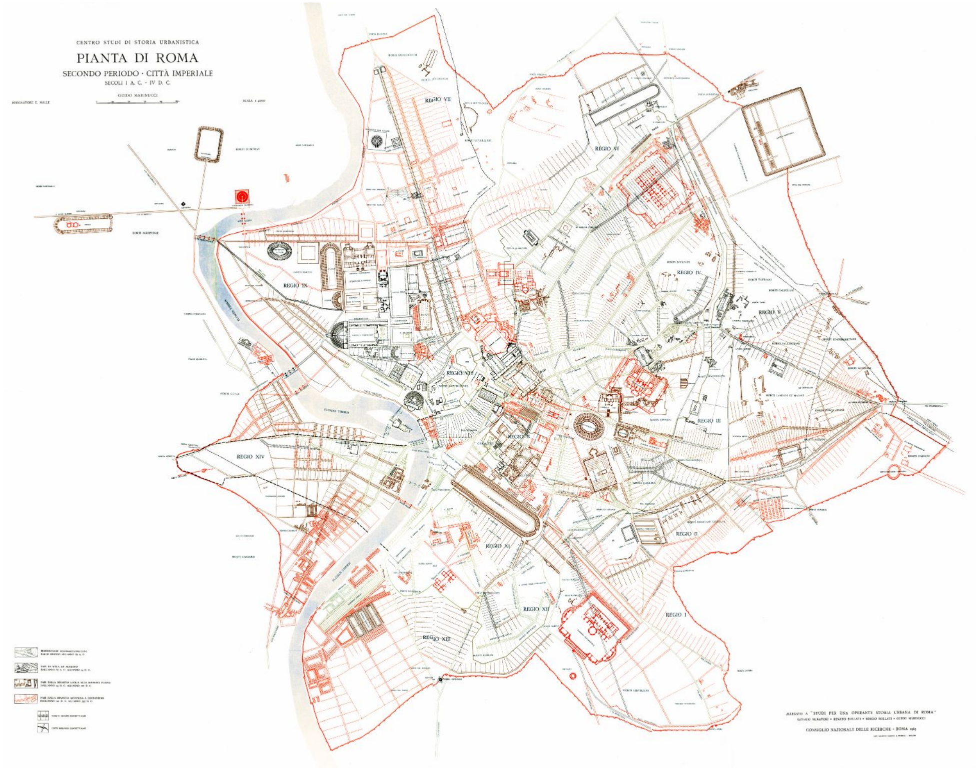
The 1931 plan brings drastic demolitions (eg. Augustean Area, Corso Rinascimento, via dell'Impero and della Conciliazione.

New suburbs grow in suburban areas and the monumental EUR District is created.

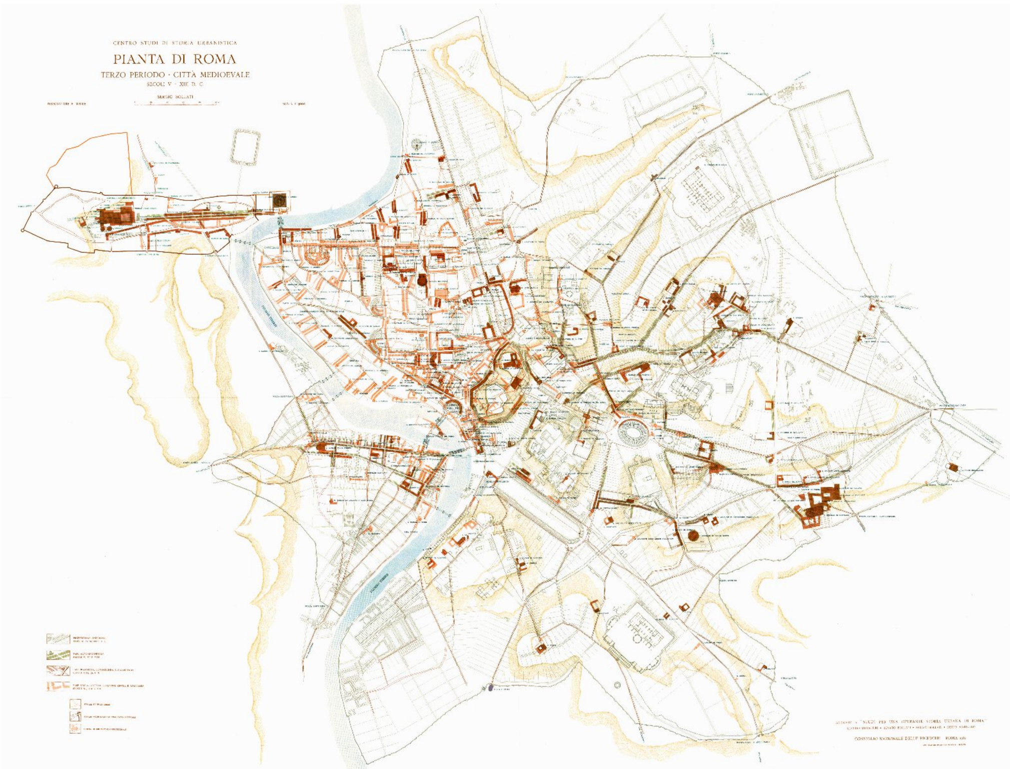
Figure 22. The urban evolution of Roma




The maps reposted in this figure are by Muratori, S., Bollati, R., Bollati, S., Marinucci, G. (1963) and show the urban evolution of Roma from the early settlement to modern times; a) XIII-II centuries B.C.E.

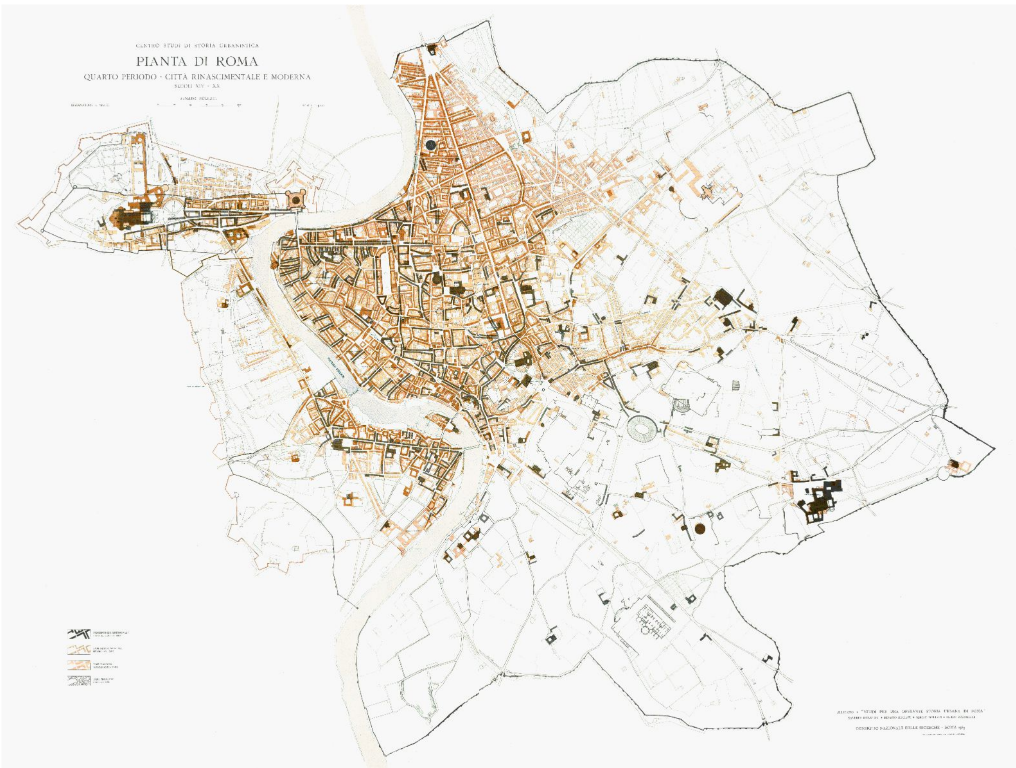



b) I cent. B.C.E.-IV cent. C.E.

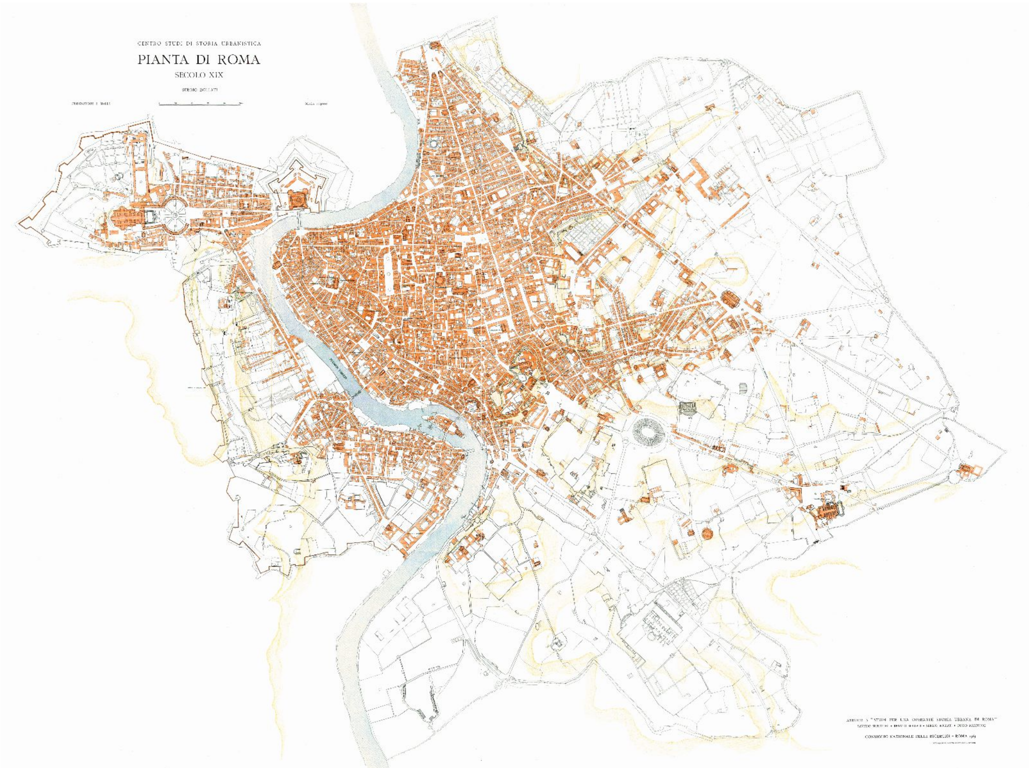



c) V-XII century

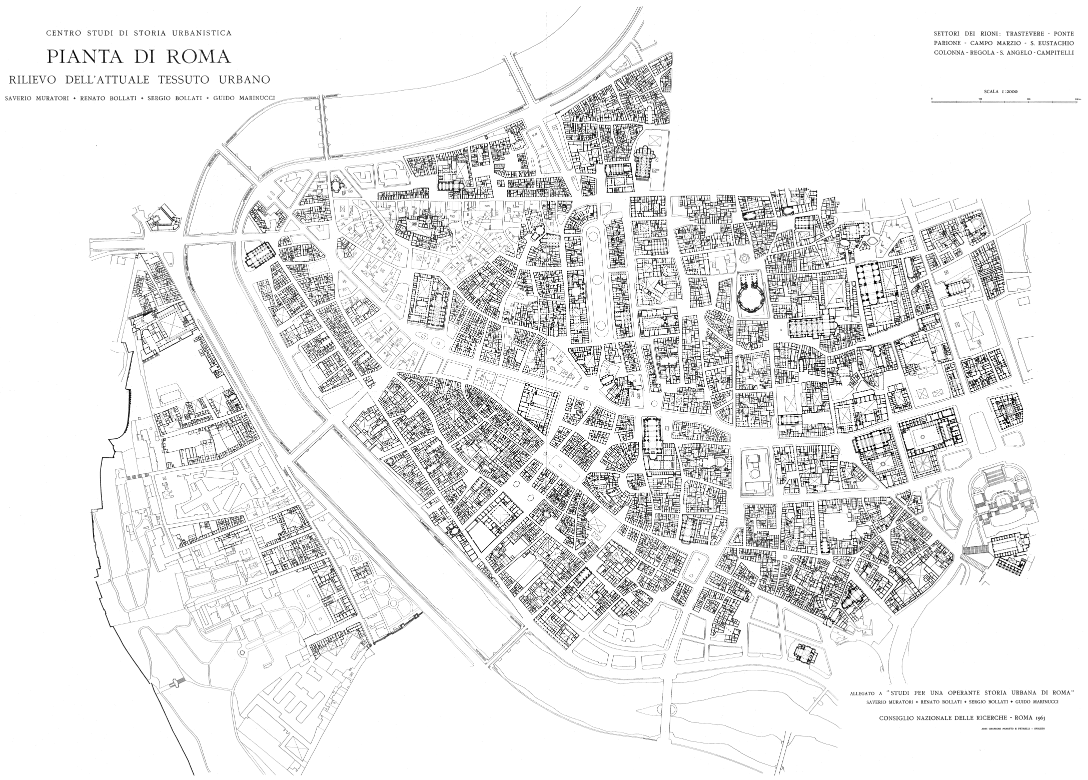

d) comparison of the city during the Imperial time in the IV century and the city in the XIX century




e) comparison of the city during the Renaissance time in the XV century and the city in the XX century




f) XIX century




g) present day urban setting of the city centre

### Overview on main geological hazards

Roma capital city is exposed to several geological hazards (Table 1), which are different as intensity, recurrence time and affected areas (Funiciello and Cologgi, 2008).

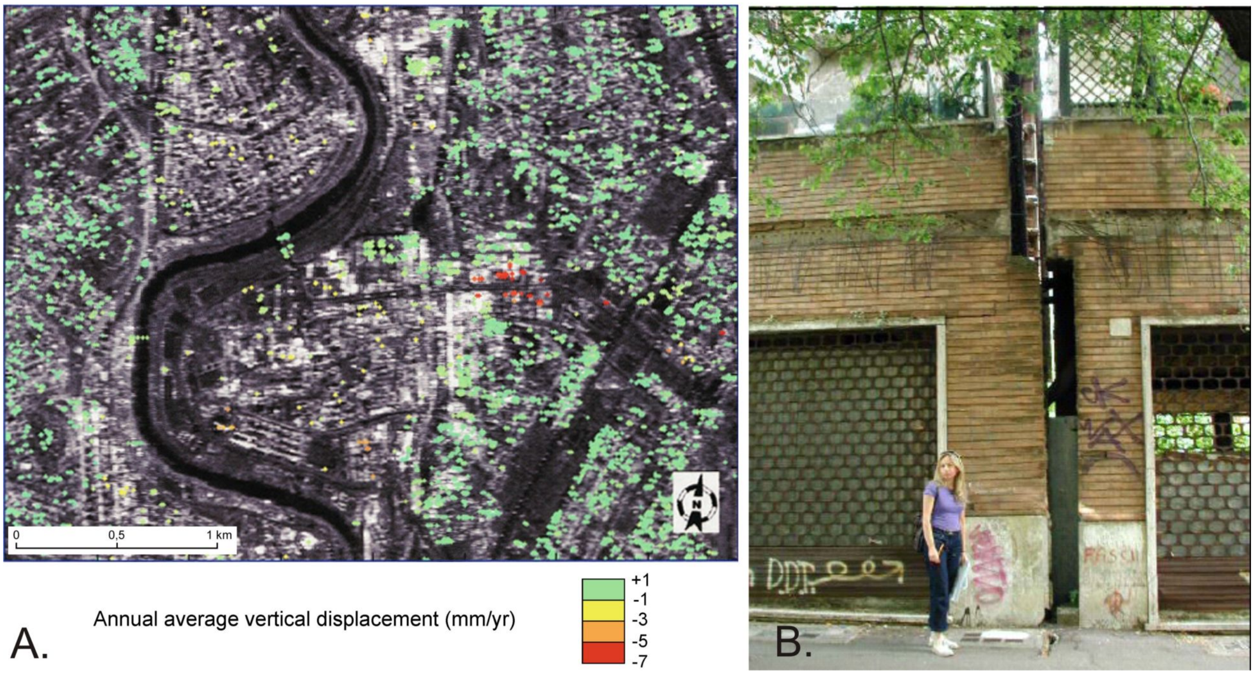
Table 1. Main Geological Hazards

| **Hazards** | **recurrence times** | **areas affected** |
|---|---|---|
| Subsidence | continuous process | alluvial areas (less in the city historical centre) |
| Landslides | 100 yrs | West flank of Tiber valley |
| Rock fall, roof collapses of underground tunnels | 2 yrs | East flank of Tiber valley and Colli Albani ignimbrite plateau |
| Floods | 30 yrs | alluvial plains |
| Extreme climatic events | 1 yr | ubiquitarian |
| Hurricanes, tsunamis | 1 yr | coast |
| Groundwater pollution and salinization | continuous process | ubiquitarian |
| Groundwater depletion | continuous process | ubiquitarian |
| Local amplification of earthquakes | 100/30 yrs | mostly alluvial plains |
| Gas emissions ($CO_2$, $H_2S$, Radon) | continuous process | Colli Albani area |
| Volcanic eruptions | 10,000 yrs | Colli Albani area |

*Subsidence.* The Tiber Holocene alluvial deposits downtown Roma are up to 60 m thick, filling the Wűrmian valley, which deeply cuts the Pliocene clay basement. The stratigraphy of the alluvial deposit is complex and locally depends on the paleocourse of the river and the presence and dimension of tributaries (Corazza *et al.*, 1999; Campolunghi *et al.*, 2008a). The stratigraphy is a fining upward sequence with a basal conglomerate overlain by sand, silt and clay with peaty levels. The succession is topped by 1-10 m of anthropogenic backfill. The sediments are unconsolidated and the topmost 20 m are the most prone to compaction, because of the fine grainsize and the presence of peat, which in many cases have produced severe to irreversible damages to buildings, such as the case of Via Giustiniano Imperatore (Campolunghi *et al.*, 2008b). Over ten years of interferometric remote sensing data have revealed that buildings along the Tiber alluvial plain are subject to a general subsidence (Fig. 23). At the scale of the city areal subsidence is most evident away from the city centre. This is because downtown buildings and large structures have existed from more than 2000 years and sediments have already undergone to compaction, whereas the recent city is still loading up the alluvial sediments over which is built. This is demonstrated by the high values of resistance to penetration that shallow sediments show in the city centre.

*Seismic hazard.* The poor geotechnical characteristics of the alluvial sediments also determine anomalous ground acceleration during earthquakes, and differential shaking at the contact with the consolidated bedrock. Strong earthquakes from the Apennine region may produce significant damages, essentially within the Tiber river tributaries alluvial plains (Donati *et al.*, 2008). Severe damages to monuments, such as the collapse of the Colosseum in 1349, are associated with this type of seismic events, whereas more limited and localised effects may be produced by the shallow seismicity of the Colli Albani volcano and the occasional seismicity of the Roma area (Rovelli *et al.*, 1995).

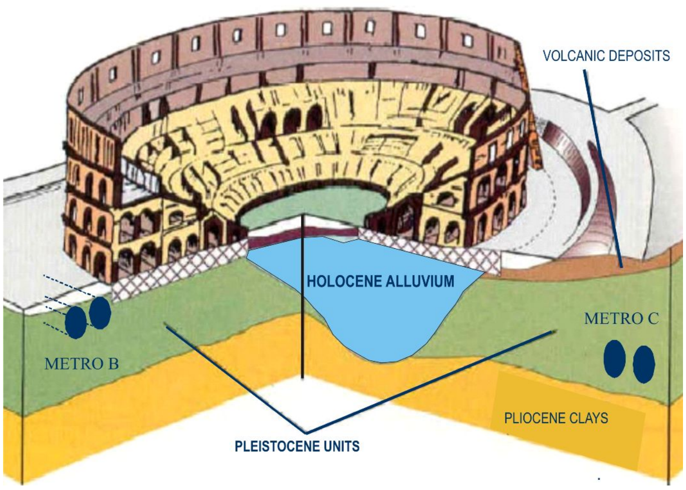
Figure 23. The problem of subsidence




A. Estimate of vertical displacement of building from multi-image radar map analysis (from Giordano, Mazza *et al.*, 2004). At present, several edifices built over unconsolidated clays are monitored from selective subsidence. This image is a courtesy of F. Ferrucci and has been obtained by comparing 10 years of satellite images. B. Evidence of differential subsidence on the structure of buildings.

The Colosseum was half built on the bedrock, there constituted by pre-volcanic conglomerate and sand, and half on the Fosso Labicano talweg; the contrast of seismic impedance between the bedrock and the unconsolidated sediments of the Fosso Labicano produced with times the main damages and partial collapses of the outer wall of the monument when in 1349 a strong earthquake in the Apennine region struck Roma (Funiciello *et al.*, 1995). Experimental analogue and numerical modelling have shown that the resonance frequencies of both the monument and the alluvial sediments filling the Tiber river valley have the same value of 2 Hz. This coincidence explains why the shaking of the alluvial sediments produces an amplification of the shaking of the monument, and therefore damages (Fig. 24).

Figure 24. The Coliseum and the effects of local amplification of seismic waves




Block diagram of the Coliseum showing the underlying geology and the occurrence of unconsolidated Holocene alluvial deposits which have caused the collapse of half of the external walls due to differential shaking during the 1349 earthquake (Funiciello *et al.*, 1995).

The recent introduction of the Roma municipality among those required to comply to anti-seisimic engeneering of new constructions (though, as appropriate, in categories with more limited requirements) is a great success of 20 years of geological studies, but does not solve the case of damaged buildings in the historic center of the City for which, especially for those on Recent alluvial areas, it should be considered to give urgent intervention to evaluate static conditions.

*Rotational landslides* are characteristics of the reliefs overlooking the Tiber valley associated with the Plio-cene-Quaternary clay and sand of the Monte Mario-Gianicolo structural high (areas of Belsito, Monte Mario, Vatican Hill and the ridge Gianicolo-Monteverde; Amanti *et al.*, 1995) (Fig. 25).

Figure 25. Landslides in Roma (I)


Landslides along the left side of the Tiber river valley, due to slow movement of the Pliocene clays . A. The external wall of Villa Sciarra collapsed in 1990. B. The edifices at the base of Monteverde hill have been built with horizontal arcs to prevent the effects of decompression of the overconsolidated Pliocene clays.

*Rock-falls* forms more frequently along the left flank of the Tiber valley, where the volcanic plateau is deeply cut through (Pincio hill, Capitoline Hill) and both lithoidal continental and volcanic Quaternary rock-formations are exposed along vertical cliffs dissected by fractures (Tufo Lionato, Valle Giulia travertines). These processes are very localized and may be enhanced by human interaction, such as the excavation of tunnels, such it was the recent case occurred along the western slope of the Monti Parioli, in December 2007 (Amanti *et al.*, 2008) (Fig. 26).

*The river floods* have been one of the most damaging and dangerous natural processes for the city. The flow rate of the Tiber river system can increase in very short times from a few hundred to more than 2000 $m^3$/sec, and every two hundred years it may reach exceptional values of up to 4000 $m^3$/sec.

Extreme weather events are mainly represented by several consecutive days of rainfall typical of autumn and winter. Parts of the city where the underground drainage systems are not fully efficient and with very flat morphology are those subject to greater risk, as well as areas where dense constructions and diffused paved roads induce a severe land-impermeabilisation.

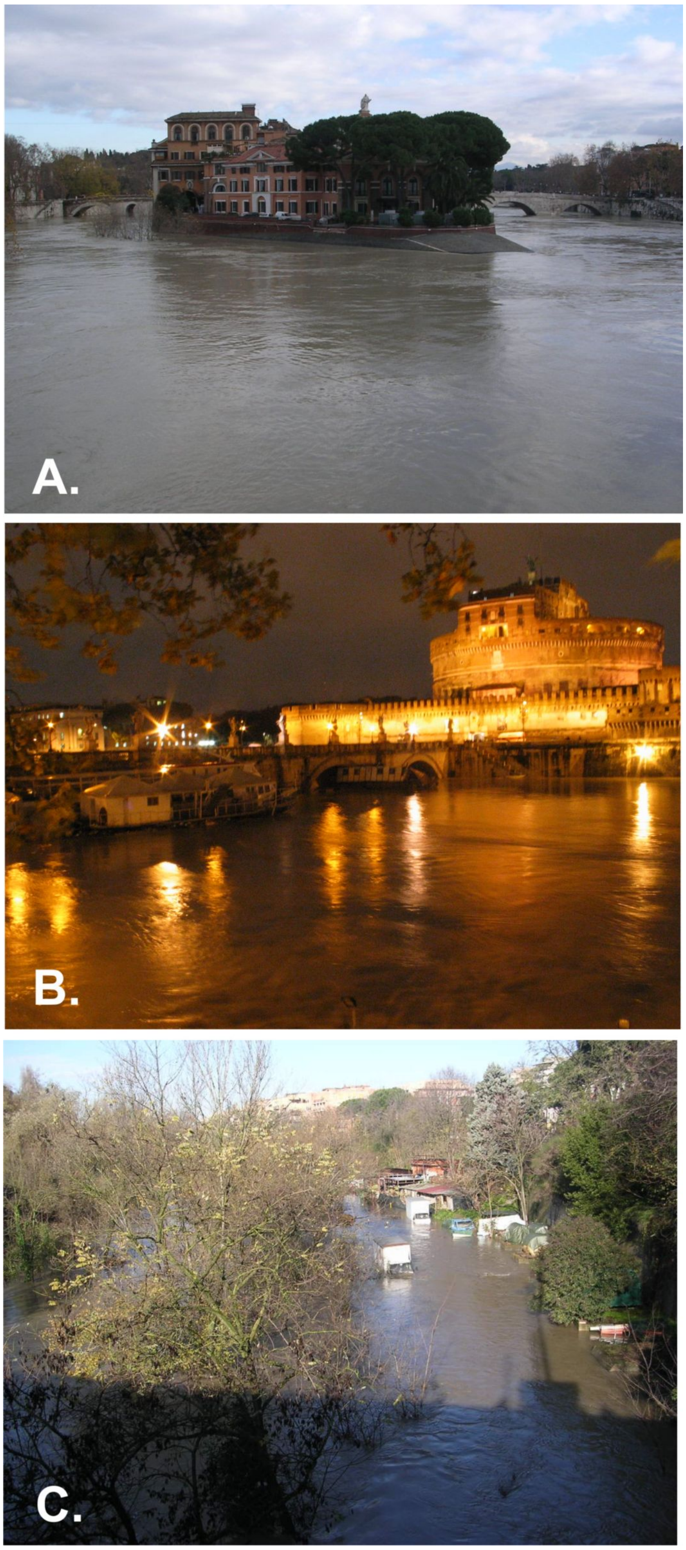
Embankments were built to protect the natural alluvial plain from floodings (Fig. 27) and the Tiber river has been progressively regimated with the construction of dams along its course. Floods since 1950 have reduced in number and intensity. The most remarkable side effect to the dam costruction is the dramatic reduction of solid transport of the Tiber, which is inducing a severe retreat of the coast and damages to the economy of the Roman shores (Praturlon, 2008), similar in magnitude to the progradations and regressions experienced by the Tiber river delta several times during the Holocene both for climatic variation and oversedimentation during volcanic activity of the Albano maar.

Figure 26. Landslides in Roma (II)

Travertine sands of the Middle Pleistocene Valle Giulia Fm. collapsed in 2007.

*Hydrogeology*. The construction of the embakments, underground infrastrucutres (metro lines, parkings etc.) and the backfilling of many tributaries within the urban area have drastically changed the local hydrogeology of Roma. Downtown the groundwater table has rose by metres because the natural drainage to the Tiber is obstacled by the embankments, interfering with the basements of many buildings, and worsening the geothecnical properties of the unconsolidated sediments. Frequent water losses from the underground aqueducts and surges also contribute to changing the local balance.

Figure 27. The 2009 flood in Roma




A. Tiberina island. B. Boats against S. Angelo Bridge. C. the flood along the Aniene River.

In the periphery of the city, by contrast, the dramatic increase of groundwater extraction has induced a drawdown of the water table by several tens of metres and up to 60 m, with a demonstrated subsidence in the areas most exposed to this problem (Capelli and Mazza, 2005). The coastal areas are subject to a progressive depletion and salinization of the aquifers with serious danger to the relevant local flora (pine forests and parks) and need for continuous monitoring (Capelli and Mazza 2008b).

Figure 28. Gas hazard associated to the quiescent Colli Albani volcano

The lake near La Zolforata, is acidic for the upwelling of CO2 and H2S rich gas which pose serious hazard issues.

Parameters such as the effective infiltration has also drastically reduced by means of not pervious human fill of the urbanised areas, as much as the loading of unconsolodated terrains is also varying with time their permeability due to the ongoing compaction. All the above mentioned factors contribute to fastly change the local hydrogeology, i.e. the flow rates and the flow paths, as well as the volumes of rocks interested by groundwater flow.

*Groundwater pollution* is mainly local, but no less harmful as a consequence of uncontrolled discharges (waste oil, sludges etc.). It is ultimately the loss of a strategic resource that could, in the near future, be crucial to the city.

*Gas Hazard.* The proximity of Roma to the quiescent Colli Albani volcano, exposes several areas geologically and structurally prone to anomalous gas emissions (mainly $CO_2$ and $H_2S$ and secondarily radon), especially to the southeastern outskirts of the city (Carapezza *et al.*, 2003; 2010; Carapezza and Tarchini 2007) (Fig. 28). The gas hazard can be prevented by systematic requirements in construction (especially for underground environments) and presciptions for the execution of drillings, excavations and trenches in areas of potential hazard.

## The low enthalpy geothermal resource

Significant savings in the fossil fuel and electric energy consumption and a strong reduction of the atmospheric pollution can be obtained by using low enthalpy geothermal resources, with temperature near or even below 20 °C for indoor heating and conditioning. Recent studies indicate that the aquifer contained in the basal gravels of Tiber river represents an important geothermal resource for this kind of direct heat utilization in the city of Rome (Barberi *et al.*, 2008), as well as potentially many other productive aquifers in the area (Capelli *et al.*, 2005, 2008a). Aquifers with interesting temperatures for low enthalpy geothermal energy can be found at shallow depths, in the order ot 10’s of meters from the ground. These values indicate that the geothermal water can be easily extracted with low-cost wells, provided the re-injection of the water in the same aquifer, and the execution of thorough tests on the aquifer production, and on the interaction with the chemical-physical balance of the aquifer.

The most studied case is that of the basal gravels of Tiber river from Barberi *et al.*, 2008, summarised below. The thickness of the basal gravels is usually around 15 m, but is rises to up to 30 m in the river northern sector. There is an excellent continuity of the aquifer along the river course, that ensures a good longitudinal water recharge, that is increased by lateral contribution from zones where gravels are in contact with permeable rocks. The aquifer is confined downward by the Monte Vaticano pliocenic shales and upward by impervious Tiber silt deposits. The latter prevent vertical percolation of rain and river waters and protect the basal aquifer from both pollution and seasonal thermal effects. Physico-chemical parameters measured in 17 wells indicated a water temperature (T) ranging from 16 to 21.6 °C, but usually around 18-19 °C, values that are ideal for direct heat utilization. The pH is mostly neutral and slightly acid in some zones, whereas electrical conductivity is locally rather high with values slightly exceeding 5000 μS/cm. It has been estimated that 20 l/s of a geothermal water with a T of 17-18 °C are needed for winter heating and summer cooling of a 40,000 $m^3$ space. The Tiber basal aquifer can easily provide such a resource in several zones of Rome city considering that the water, after its utilization, will have to be reinjected into the provenance aquifer.

## Conclusions

This paper presents an overview on the geology of the city of Roma and illustrates how the city and its evolution has been significantly affected by the active interaction with the geological environment both in terms of resources and hazards. Roma, with its 3000 years of history, represents a unique case, a laboratory for urban geology. The city is still currently exposed to several hazards and the knowledge of geology is mandatory to mitigate and prevent the effects of future events such as earthquakes, volcanic gas emission, floods and landslides. At the same time, the correct management of the water and land resources need a careful planning in consideration of the very high level of anthropic pressure on the local environment. The study of the geology of Roma and its intimate relationships with the urban development of the city have been strongly influenced by the ideas of Renato Funiciello, recently passed away, to whom this paper is dedicated.

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