ANNALI DI GEOFISICA, VOL. XXXVIII, N. 5-6, November-December 1995

Seismic damage and geological heterogeneity in Rome's Colosseum area: are they related?

Renato Funiciello (1) (2), **Leonardo Lombardi** (3), **Fabrizio Marra** (1) and **Maurizio Parotto** (2)
(1) *Istituto Nazionale di Geofisica, Roma, Italy*
(2) *Dipartimento di Scienze Geologiche, III Università Statale di Roma, Italy*
(3) *Via G. Sacchi 12, Roma, Italy*

Abstract
According to the historical sources, the Colosseum suffered several types of damage related to earthquakes. In particular, the damage is mostly concentrated in the southern portion of the amphitheater where the study of the geological features shows the presence of a Holocene alluvial valley, a situation that is potentially responsible for significant amplification of ground motion during earthquakes. A detailed reconstruction of the subsurface geology in the area of the Colosseum was performed with the purpose of verifying whether the heterogeneity of the damage observed could be associated with the variability of the geological conditions of the site where the monument was built.

Key words *seismic archaeology – site effects – Quaternary stratigraphy – Colosseum – Rome*

1. Introduction

The city of Rome (fig. 1) developed in an area of great geological significance that marks the boundary between the northern portion of the peninsula, which is characterized by a moderate tectonic activity and seismicity and by a high heat flow, and its central-southern portion, which in contrast is responsible for numerous large earthquakes that have struck the urban area throughout history though with generally limited effects.

The historical center of Rome is characterized by the presence of a complex drainage network filled up by recent alluvial deposits and subsequently hidden by the anthropic cover which accumulated during the centuries of urban development.

The role played by recent deposits with poor geotechnical characteristics in inducing significant amplification of ground motion during earthquakes has been demonstrated studying the distribution of damage in the urban portion of cities that have experienced large earthquakes in recent years (such as in the case of Mexico City's downtown area, see Singh *et al.*, 1988; or Santa Cruz, California, see Cranswich *et al.*, 1990). It has also been recently shown that the different levels of seismic damage observed throughout the historical center of Rome are related to differences in the characteristics of the near-surface geology (Ambrosini *et al.*, 1986; Salvi *et al.*, 1991; Boschi *et al.*, 1995). Nearly all the areas of the city where the seismic motion was amplified turned out to overlie Holocene sediments deposited by the complex network of the Tiber River, which has almost completely filled up the deep valleys created by the eustatic changes at the end of the Würmian glacial cycle.

The Anfiteatro Flavio (Flavio amphitheater, also known as the Colosseum) is located directly above the course of the Fosso Labicano,

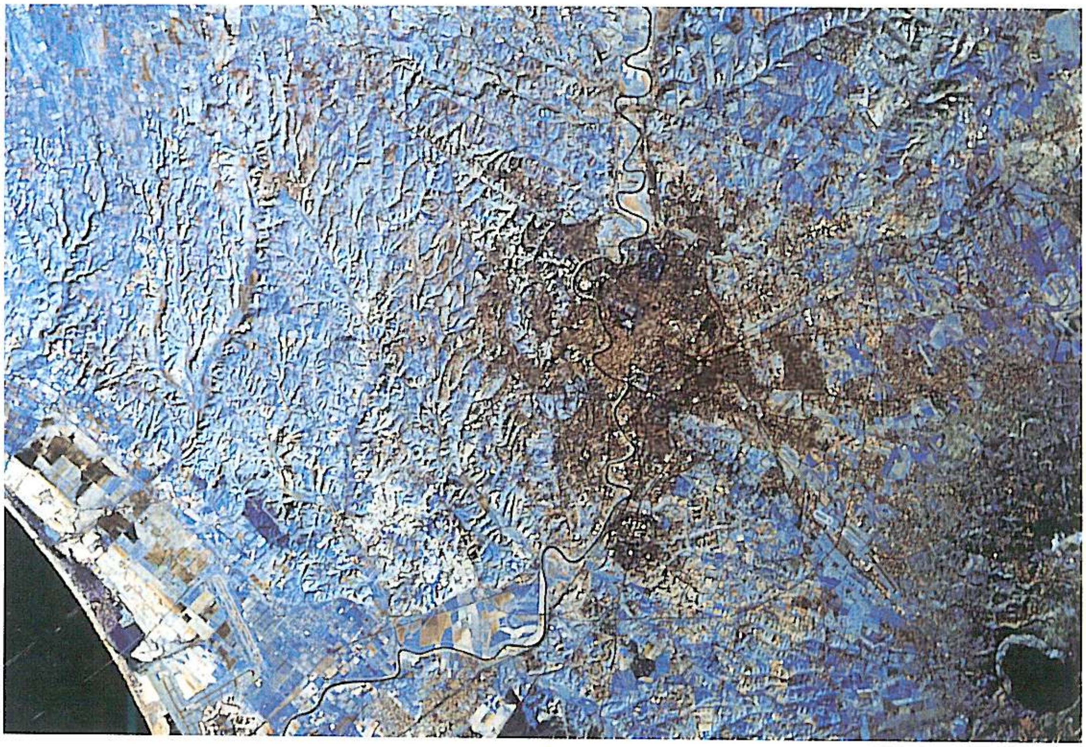


Fig. 1. Satellite image of the area of Rome.

a third order tributary of the Tiber River that was artificially channeled during the Republican period. During the rule of Nero, and up until a few years before the monument was built between 75 and 80 A.D., the valley beneath the Colosseum was occupied by a small artificial lake (or a pool, as some archaelogists state) complete with a tributary and an outlet, the lakeside being fronted by some of the most sumptuous imperial residences of Rome. After at least four hundred years of uninterrupted activity as a circus, the Colosseum became a shelter, a castle, a place of esoteric worship and finally a stone quarry. Only in modern times was the Colosseum finally granted its true symbolic and monumental dignity and, although under the siege of city traffic, partly returned to the role it deserves. The present conditions of the Colosseum, however, still bear traces of the wounds inflicted both by the activity of man and by natural causes.

Table I summarizes the damage suffered by the Colosseum according to the historical sources, showing that the information available is rather heterogeneous particularly for the Middle Ages. On the other hand, data regarding the regional seismicity during this long period of time are especially scarce although it is generally assumed to have been equivalent to that recorded in the periods that followed. Another clear fact is that the damage is mostly concentrated in the southern part of the amphitheater. Indeed the period during which the Colosseum was damaged by earthquakes seems to coincide with that of the most negligence and structural weakness.

For this reason a detailed geological study of the site was conducted to verify whether the

Table I. Damages suffered by Colosseum through the centuries.

Year	Type of damage	Notes
138-161	Fire	Antonino Pio
217	Fire or lightning	Alessandro Severo/Macrino
250	Fire	
443	Earthquake	Engraving still visible inside Colosseum
508	Earthquake	Damage to podium and arena; three engravings on reutilized marble stones, still visible inside (fig. 2)
615-618	Earthquake	Adeodato (uncertain account)
795-816	Earthquake	Leone III (uncertain account)
801	Earthquake	Reported by various sources
847	Earthquake	Pillars supporting the wooden ceiling of the upper arcade collapsed
1032-1048	Earthquake	Benedetto IX (uncertain account)
1073-1085	Earthquake	Gregorio VII (uncertain account)
1091?	Earthquake	Engraving in church of S. Maria in Trastevere
1231-1255	Earthquake	(uncertain account)
1332	Restoration	Bull hunt in honor of Frederick of Bavaria; at this time the monument is intact suggesting that previous damage had been mild or already repaired
1349	Earthquake	After several hystorical sources, arcades of southern external ring collapsed («cecidit aedificiarum veterum neglecta civibus, stupenda peregrinis moles»; Petrarca)
The amphitheater begins being demolished; according to various available documents, the peak of this activity dates to the XVII century. The structure of the Colosseum is weakened, such that in		
1703	Earthquake	Restorations begin in 1807 by Pope Pio VII. Before end of restorations three external arcades (second ring) collapsed
1812	Earthquake	Another arcade in the second ring collapsed
The restoration is completed in 1845. The Colosseum assumes its present shape and is given the ability to resist better more recent earthquakes. The restorations of the arcades that had fallen or had been removed are extremely obvious even for the non-specialist. At any rate, all the damage occurs at locations corresponding with the trend of the Fosso Labicano and as far as its external edge (fig. 3).		

heterogeneity of the damage observed in the different parts of the monument could also be associated with the variability of the geological conditions of the area where it was built.

2. Investigations of the subsurface geology

Following a procedure that can now be adopted for all of Rome's historical center, the detailed structure of the subsurface in the Colosseum area was reconstructed using a large number of data from wells drilled within and around the monument and matching the inferred stratigraphies with up-to-date knowledge on the local geology (Marra *et al.*, 1994; Marra and Rosa, 1995; see fig. 4).

2.1. *Main stratigraphic traits*

The historical center of Rome is characterized by the existence of a Pliocene bedrock at shallow depth. This bedrock consists of marly-

Fig. 2. An inscription engraved in a stone located near the main entrance of the Colosseum. The stone commemorates the restoration decreed by the prefect Decio Mario Venanzio Basilio to repair the damage caused by an *abominandi terrae motus* (abominable earthquake).

clay marine sediments (Monte Vaticano Unit) and is found at elevations around the present sea level. Overall the bedrock trend is regular and exhibits a gentle southeastward slope, its continuity being interrupted only by paleodrainages which incised deeply during the largest peaks of sea retreat. In the Colosseum area, however, the Pliocene substratum has been lowered by about 10 m with respect to the surroundings. Five main Pleistocene sedimentary cycles following an equal number of erosional episodes related to glacio-eustatic fluctuations and tectonics can be recognized overlying the Pliocene bedrock in the sorrounding area. After the end of the second of these deposition cycles the normal sedimentation pattern starts being complicated by the emplacement of significant amounts of volcanic rocks related to the activity of the Sabatini and Albani volcanic districts, located to the northwest and to the southeast of Rome, respectively. These rocks consist of both air fall deposits and pyroclastic flows emplaced during numerous successive cycles related to the paroxysmal phases of volcanic activity.

The oldest of the identified erosional phases is that responsible for the planation of the Pliocene bedrock. The deposits associated with the subsequent rise of sea level consist of a sequence of gravels and gray fluvial-lacustrine clays with frequent intercalations of peat levels (Paleotiber 2a Unit). A second depositional cycle follows a phase of erosion which carved into recently deposited sediments and in some

Fig. 3. An aerial view of the Colosseum showing the perfect coincidence between the trend of the Fosso Labicano Valley and the southern portion of the monument, where nearly all the damage is concentrated. Dashed lines indicate the limits of alluvial deposits. Dots indicate the location of drillings that provided data for the investigation of the local stratigraphy. A-A′: location of the restored portion of the inner ring.

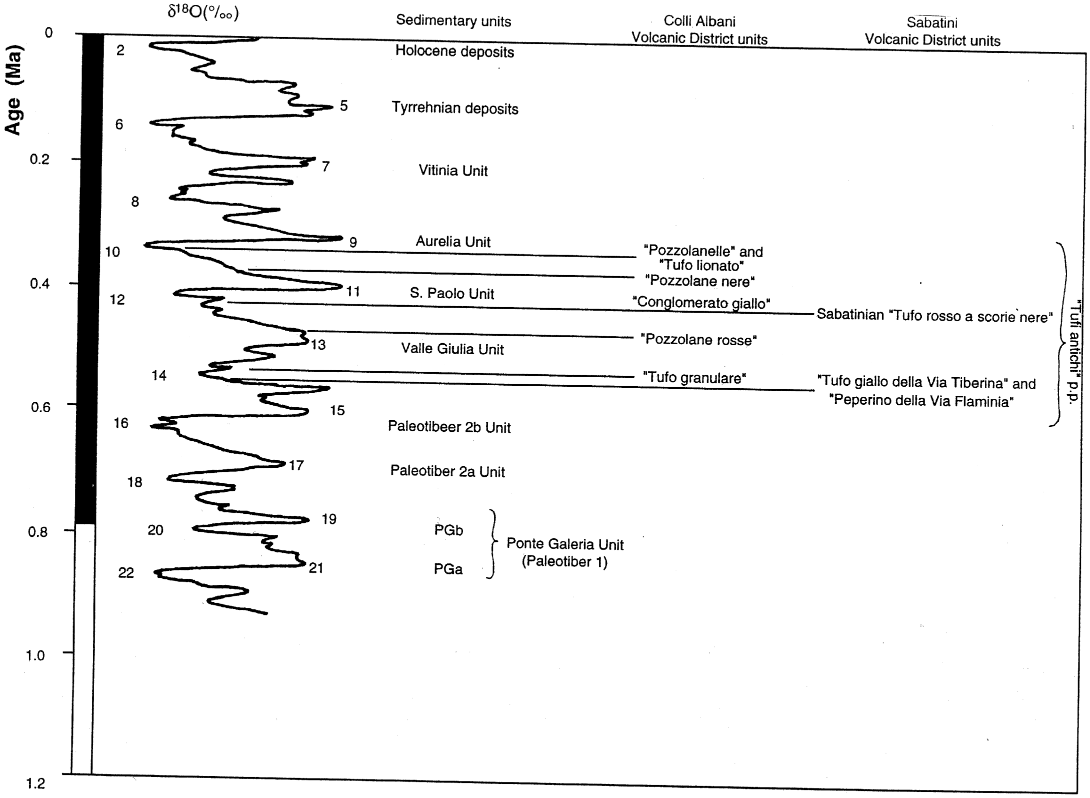


Fig. 4. A correlation between the Middle-Upper Pleistocene stratigraphic units (sedimentary and volcanics) and the oxygen isotope time-scale matching the glacio-eustatic fluctuations, after Marra *et al.*, 1994.

instances affected the Pliocene bedrock. The incisions that resulted from this erosional phase were subsequently filled up by a sequence made up of sandy silts and yellow sands rich in calcareous concretions which is indicative of a marshy-lacustrine depositional environment (Paleotiber 2b Unit). The apex of this depositional phase is marked by the beginning of the activity of the Sabatini and Albani volcanic districts (about 0.6 Ma: Cioni *et al.*, 1993; Barberi *et al.*, 1994). The thickest volcanic unit, which is widespread in Rome's historical center, is composed of an alternation of air-fall deposits (which can be attributed mainly to the Sabatini volcanic district) and reworked epivolcanites («Tufi antichi» p.p. *Auct.*), which are interbedded by several pyroclastic flow units. Around the apex of the subsequent erosional phase the first pyroclastic flow units from the Sabatini («Peperino della Via Flaminia» and «Tufo giallo della Via Tiberina» *Auct.*) and the Colli Albani («Tufo granulare» *Auct.*) volcanic districts were «channeled» along the Tiber River valley, but only a limited number of outcrops representing this event are visible at present (such as near Porta Cavalleggeri, the Colli Capitolini and the Colle Palatino) due to subsequent river erosion. The only remaining outcrops of rocks that can be related to the subsequent deposition cycle (Valle Giulia Unit) are found along the flanks of the river valley. These rocks, which are made out of phytoclastic travertines containing layers of reworked volcanites, are found abutting the scarps marking the flanks of the valley and almost always conform to the underlying «Tufo granulare» (first pyroclastic flow unit from the Colli Albani). The deposits of the second pyroclastic flow unit from the Colli Albani («Pozzolane rosse» *Auct.*), which were emplaced during the subsequent erosional phase, do not seem to have reached the area under investigation.

The following sedimentary cycle is represented in this area essentially by a clay deposit (San Paolo Unit). This unit may attain a significant thickness and is seen to fill up small lacustrine basins probably created following the erosion and reworking of recently emplaced volcanites. This is also suggested by the fact that to the southeast the unit can be correlated with the «Conglomerato giallo» *Auct.*, an epivolcanite that was derived from reworking and re-deposition of the second pyroclastic flow unit from the Colli Albani in a fluvial environment.

During the erosional phase following the deposition of the San Paolo Unit here is the emplacement of the third («Pozzolane nere» *Auct.*, not outcropping in the studied area), fourth and fifth pyroclastic flow units from the Colli Albani («Tufo lionato» and «Pozzolanelle» *Auct.*). In particular the deposits of the fourth pyroclastic flow («Tufo lionato» *Auct.*) are widespread along the left side of the Tiber valley and clearly rest on a paleomorphological surface as they directly overlie various pyroclastic units associated with older cycles. The large thickness and lithic consistency of this pyroclastic unit played a fundamental role in shaping up the Roman landscape as they allowed the generation of rocky landscapes such as those seen at Colle Capitolino and Colle Palatino simply by selective erosion. The «Tufo lionato» was partially eroded shortly after its deposition because this took place at the apex of an erosional phase that is responsible for the layout of a drainage network that is essentially the same we see today.

In the areas adjoining the main outcrops of the fourth pyroclastic flow, the basal portion of the deposits associated with the subsequent rise in sea level (Aurelia Unit) exhibits abundant volcanic minerals derived from the reworking of the nearby pyroclastic unit. Toward the top these deposits turn into lacustrine and marshy clays completely filling up the existing incisions and even reaching the top of the main Roman hills during the peak of sea level rise.

In the area of Latium the Aurelio depositional cycle is followed by two additional sedimentary cycles (represented by the «Vitinia Formation» and by deposits associated with the Tyrrhenian stage: Conato *et al.*, 1980). The deposits associated with these cycles, however, are found only near the modern coast of the Tyrrhenian Sea, while they do not appear to be represented nor are the related erosional cycles documented in our study area.

The most recent Quaternary erosional phase is that associated with the Würmian regression (about 0.018 Ma), which is responsible for a significant lowering of the base level. During this phase the urban section of Tiber River deepened to the point that it carved into the Pliocene bedrock to a depth of – 60 m below the present sea level. As a consequence, all of the tributaries also deepened significantly. The valleys created during this phase were subsequently filled up by Holocene alluvial sediments following the rise in sea level to its present elevation. The recent alluvial deposits are formed by a basal layer of gravels varying in thickness between about ten meters at the Tiber River valley and a few meters along subordinate valleys. The bulk of the alluvial sequence is instead represented by poorly- to non-consolidated clay and sandy-clay sediments. These deposits are water-saturated owing to the fact that they are effectively always below the local level of the water-table, and are characterized by poor geotechnical properties due to their weak cohesiveness and large compressibility.

2.2. *Geomorphological features*

The original morphology of the Roman countryside has been significantly modified following thousands of years of anthropic activity such as excavating, filling up for reclamation purposes, heaping of debris and garbage, wrecking and reconstructing buildings, filling and canalizing watercourses, all of which have greatly modified the physical features of the area. We must therefore consider what is commonly referred to as *«riporto antropico»* (artificial landfill) as the most recent layer of the local stratigraphy. This layer ranges in thickness from 0 to over 20 m and has extremely variable lithologic features depending on its components and on the purpose for which it was used. One of the most significant anthropic alterations in the area is the excavation of the southern slopes of the Colle Quirinale, that was commissioned by Emperor Trajan with the purpose of establishing the market and forum which still bear his name, and that of the Collina Velia, which was removed to give way to the creation of *Via dei Fori Imperiali* at the end of the 1920's. The Collina Velia formed a saddle connecting the southwestern slopes of the Colle Oppio to the Colle Palatino and was carved in fluvial-lacustrine sediments of the Aurelia Unit that were more erodible than the tufaceous rocks forming the top of the two hills. Finally, in the area where the Anfiteatro Flavio was subsequently erected, emperor Nero requested the creation of an artificial lake by damming downstream the watercourse that flowed through the present Via Labicana.

2.3. *Hydrogeological features*

As we mentioned earlier, from a geological point of view the Labicana Valley (also known as Valley of the Colosseum or of the Anfiteatro) is characterized by a sequence of deposits (both volcanic and sedimentary) which are hardly or not at all permeable. These deposits overlie a layer of gravel which in turn rests over clay Pliocene sediments representing the lower impermeable boundary for all groundwater circulation within the whole area of Rome. As a result of this setting, only the gravel bears significant aquifers. In the area, the top of the gravel sequence is found at an elevation that is a few meters below the modern sea level. The important Würmian erosional phase, which shaped up the Tiber River and its tributaries, carved deeply into the volcanic and sedimentary sequence in the area that now corresponds to the Labicana Valley. The incision also affected the basal clays and proceeded down to 10-15 m below the present sea level, thus involving the water-bearing gravels. This implies that numerous small springs must have existed along the once exposed contact between the gravels and the underlying Pliocene clays prior to the subsequent filling by Holocene alluvial deposition. The steep valley that connected the area to the Tiber River (from about – 10/ – 15 m below present sea level to – 50 m of the Tiber River floor around the Circo Massimo) was continuously fed by these springs, which are thought to have located a few hundred meters upstream from the area presently occupied by the Anfiteatro Flavio. The gravel layer cropped out at both sides of the valley.

Following a phase of backfilling associated with a rise in sea level, the valley floor was leveled up to an elevation of 14 m above the present sea level, about 7-8 m below the present land level which stands at an elevation of 22 m. The alluvial «mattress», which is formed mostly by fine-grained deposits (silts and sandy silts) partially covered the springs reducing their natural discharge. At the same time, however, the alluvial cover is known to act as an impermeable level for groundwater resulting both from natural rainfall or from leakage of aqueducts and sewers. The combination of these elements results in the generation of shallow suspended aquifers confined within 7-8 m depth and therefore mostly within the ancient artificial landfill. Unfortunately the available data do not allow the hydrogeology of the area to be reconstructed in detail since no data concerning the level of the water table are reported in the logs of the numerous wells perforated in the area. Nevertheless one can refer to the elevation of Rome's sewage system on the assumption that it was built just above the level of the water-table. The elevation of a water source located in the underground part of San Clemente church can also be used as a reference level. Correlations can also be attempted with the piezometric elevations measured in wells located on the Palatino Hill and with the elevation of the Giuturna spring, located in the Foro Romano, which certainly gushes from the gravels. The data from the Palatino Hill, however, are indicative of a rather low elevation of about 9 m above present sea level. This is a result of the fact that the hill, which can be schematized as a rectangular box, is in hydrogeological contact with the gravels only in its eastern section, whereas on the remaining three sides it has been deeply eroded by deep incisions which certainly affected also the gravels thus draining the aquifer and depressing the water-table.

Around the beginning of this century the water gushing in San Clemente was intercepted and channeled in a tunnel with the purpose of draining underground excavations beneath the church. The tunnel runs for about 800 m to the north of the Colosseum until it reaches the nineteenth-century-sewer of Via di San Grego-

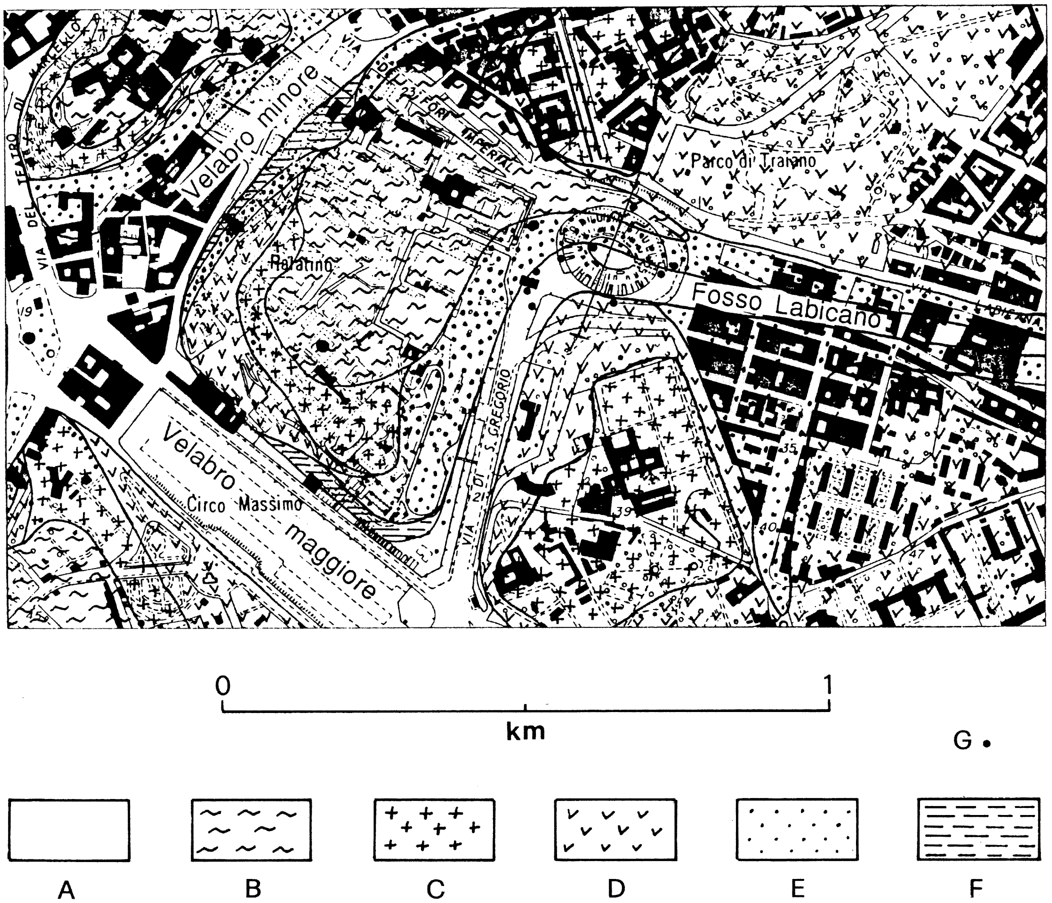
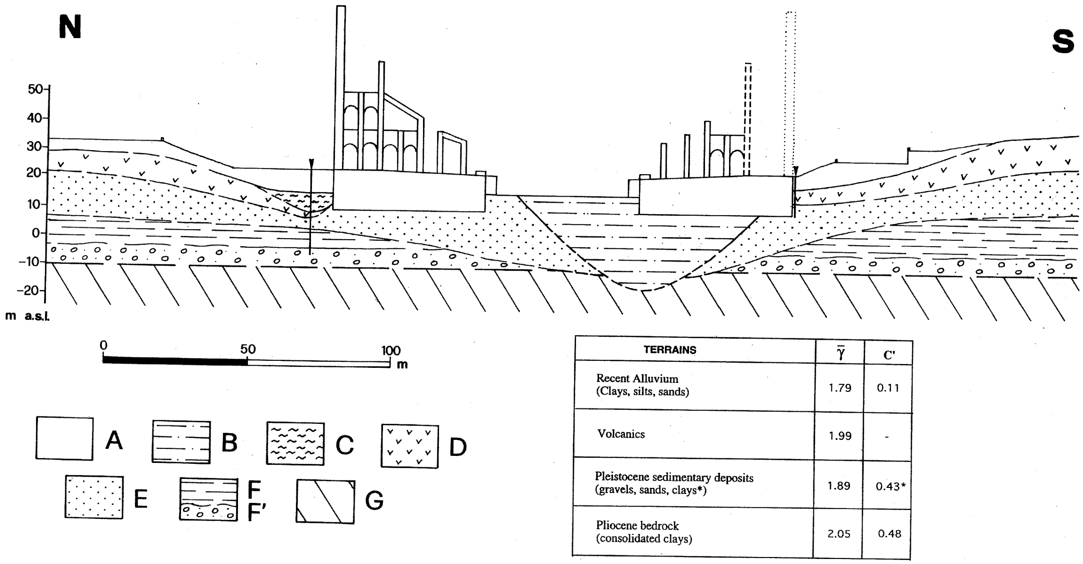


Fig. 5. Geologic sketch of the Colosseum area. Legend: A = Holocene sediments filling up the valley of Velabro Minore (on the northwest side), of the Fosso Labicano (Via di San Gregorio), and of Velabro Maggiore (Circo Massimo), all of which merge into the Tiber River valley (Via del Teatro di Marcello); B = «Aurelia Unit» (Middle Pleistocene); C = «Tufo lionato» *Auct.*; D = «Tufi antichi» p.p. and «Tufo granulare» *Auct.*; E = Paleotiber 2b Unit (Middle Pleistocene); F = Paleotiber 2b Unit (Middle Pleistocene); G = location of drillings that provided data for the investigation of the local stratigraphy.



TERRAINS	$\bar{\gamma}$	C'
Recent Alluvium (Clays, silts, sands)	1.79	0.11
Volcanics	1.99	-
Pleistocene sedimentary deposits (gravels, sands, clays*)	1.89	0.43*
Pliocene bedrock (consolidated clays)	2.05	0.48

Fig. 6. North-south section across the Colosseum area, showing the mean values of the most significant geotechnical parameters for the main groups of deposits. Legend: A = man-made landfills of Roman to modern age; B = recent alluvial deposits (Holocene-Present); C = Aurelia Unit (Middle Pleistocene); D = «Tufi antichi» p.p. and «Tufo granulare» *Auct.* (Middle Pleistocene); E = Paleotiber 2b Unit (Middle Pleistocene); F-F′ = Paleotiber 2a Unit (Middle Pleistocene); G = Pliocene bedrock.

rio. Due to its elevation (about 12 m above present sea level), its general geochemical characteristics and its conductivity (650 μsiemens/cm), the San Clemente church source must be the result of water circulation within the gravels. The source itself could represent an artificial catchment of one of the previously mentioned springs made with the purpose of providing water to the Tempio di Mitra, an ancient temple buried under the church. The elevation of the source and the elevation of the sewers can be combined to obtain an estimate of the piezometric level within the aquifer formed by the gravel layer. In the study area this level should be around 10-12 m above present sea level, that is, about 10 m below the present land level. In contrast, the shallow water flow observed in the hypogeum of the Colosseum and in part of the network of tunnels found in the Colosseum Valley can be related to circulation within the alluvial sequence and has virtually no hydrogeological significance.

3. Discussion and conclusions

The Colosseum was built over a small fluvial valley carved in Pleistocene volcanic and continental sedimentary deposits of the Fosso Labicano, a third-order tributary of the Tiber River that was created by the same phases of erosion and backfilling that generated the *Forma Urbis* during the past 150000 years. Figure 5 summarizes the structure of the subsurface beneath the Colosseum, showing that the southern section of the amphitheater lies directly above an elbow formed by the Labicana Valley, a modest incision that was filled up during the Holocene.

Figure 6 shows a north-south section of the Colosseum area, whereas fig. 7 is a stereogram that schematizes the 3-D geometry of its subsurface. These figures give an overview of the present morphology of the area and of the existence of various depositional cycles filling up valleys carved in recently deposited sediments.

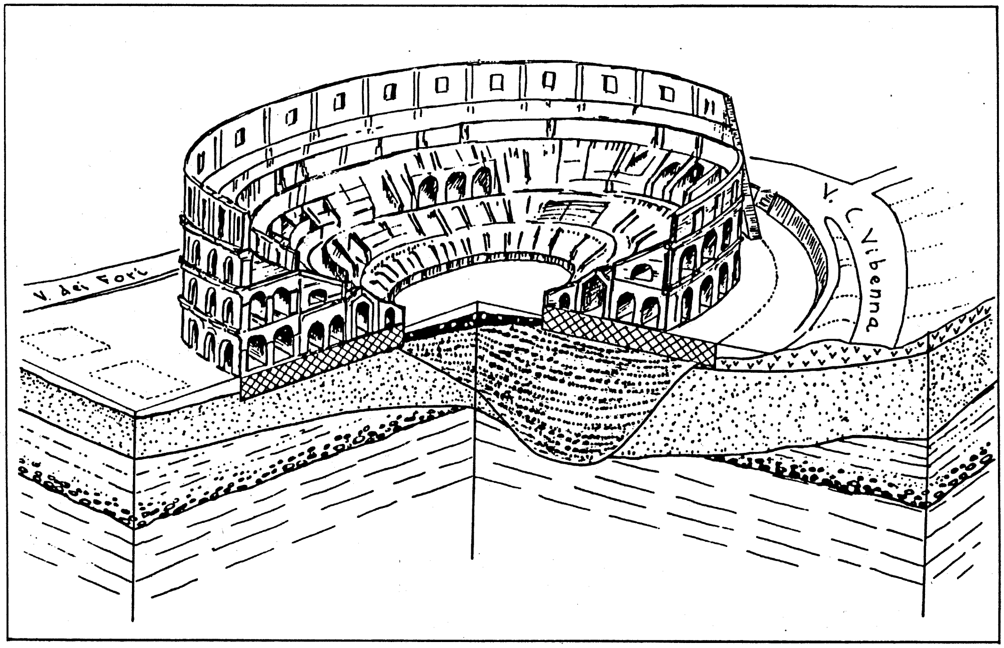


Fig. 7. Stereogram showing the main traits of the subsurface morphology in the Colosseum area.

In particular figs. 6 and 7 show the profile of the ancient Valle Labicana, subsequently filled by Holocene alluvial. The maximum depth of this ancient incision was deduced on the basis of indirect data since none of the wells drilled along its axis reached its substratum.

The reconstruction of the local trend of the drainage network (shown in fig. 6) and particularly of the subsurface geometry of the Velabro Minore and Velabro Maggiore valleys, for which both the maximum depth and gradient are known, has yielded a very reliable estimate of the corresponding values for the Valle Labicana. It is clear that the section of the Fosso Labicano that lies beneath the southern portion of the Colosseum has incised as deep as the depth of the underlying Upper Pliocene marly clays. As a consequence, rocks with largely different rigidity, density and cohesiveness (see the table in fig. 6) are in contact in this area at around 30 m depth. These are exactly the geological features after which a local amplification of the seismic response is expected producing large differential motions (see Moczo *et al.*, 1995 this volume). The concentration of damage related to earthquakes in the southern portion of the Colosseum seems indeed strictly related to the local geological heterogeneity.

At any rate the area of our investigation has very complex traits which differ, sometimes in a very peculiar fashion, from those characterizing other neighboring areas of Rome's historical center. The lower elevation of the Pliocene bedrock and of the bottom of the volcanites, the presence of a gravel layer that has been deeply altered by the circulation of acid fluids probably washed away from hydrothermal minerals (which were found within the deposits of Unit *a* of Paleotevere 2), and historical accounts concerning the proximity of sulfurous springs all suggest that the stratigraphic and structural setting of the area is more complex than that envisioned on the basis of the available data, and that it certainly deserves further thorough investigations.

Acknowledgements

Authors are grateful to the «Soprintendenza Archeologica di Roma» for their co-operation.

REFERENCES

AMBROSINI, S., S. CASTENETTO, F. CEVOLAN, E. DI LORETO, R. FUNICIELLO, L. LIPERI, and D. MOLIN (1986): Risposta sismica dell'area urbana di Roma in occasione del terremoto del Fucino del 13-1-1915, *Mem. Soc. Geol. It.*, **35**, 445-452.

BARBERI, F., G. BUONASORTE, R. CIONI, A. FIORDELISI, L. FORESI, S. IACCARINO, M.A. LAURENZI, A. SBRANA, L. VERNIA and I.M. VILLA (1994): Plio-Pleistocene geological evolution of the geothermal area of Tuscany and Latium, *Mem. Descr. della Carta Geol. d'Italia*, **49**, 77-133.

BOSCHI, E., A. CASERTA, C. CONTI, M. DI BONA, R. FUNICIELLO, L. MALAGNINI, F. MARRA, G. MARTINES, A. ROVELLI and S. SALVI (1995): Resonance of subsurface sediments: an unforeseen complication for designers of Roman columns, *Bull. Seismol. Soc. Am.*, **85** (1), 320-324.

CIONI, R., M.A. LAURENZI, A. SBRANA and I.M. VILLA (1993): $^{40}Ar/^{39}Ar$ chronostratigraphy of the initial activity in the Sabatini Volcanic Complex (Italy), *Boll. Soc. Geol. Ital.*, **112**, 251-263.

CONATO, V., D. ESU, A. MALATESTA and F. ZARLENGA (1980): New data on the Pleistocene of Rome, *Quaternaria*, **22**, 131-176.

CRANSWICK, E., K. KING, D. CARVER, D. WORLEY, R. WILLIAMS, P. SPUDICH and R. BANFILL (1990): Site response across downtown Santa Cruz, California, *Geophys. Res. Lett.*, **17**, 1793-1796.

MARRA, F., C. ROSA, D. DE RITA and R. FUNICIELLO (1994): Stratigraphic and tectonic features of the Middle Pleistocene sedimentary and volcanic deposits in the area of Rome (Italy), *Quaternary Int.* (in print).

MARRA, F. and C. ROSA (1995): Stratigrafia e assetto geologico dell'area romana, in *«La Geologia di Roma – Il Centro Storico»*, special volume *Memorie del Servizio Geologico*, **50**, 49-118.

MOCZO, P., A. ROVELLI, P. LABÁK, and L. MALAGNINI (1995): Seismic response of the geologic structure underlying the Roman Colosseum and a 2-D resonance of a sediment valley, *Annali di Geofisica*, **38**, 939-956 (this volume).

SALVI, S., E. BOSCHI, M. DI BONA, R. FUNICIELLO, L. MALAGNINI, F. MARRA, and A. ROVELLI (1991): Subsurface geology and variations of seismic response in the city of Rome, in *Proceedings Fourth International Conference on Seismic Zonation*, Stanford, California, 115-122.

SINGH, S.K., E. MENA and R. CASTRO (1988): Some aspects of source characteristics of the 19 September 1985 Michoacan earthquake and ground motion amplification in and near Mexico City from strong motion data, *Bull. Seismol. Soc. Am.*, **78**, 451-477.