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As you wander through the maze that is Rome on the floodplain, watch for the many escapes to higher ground via streets that follow the now well-hidden tributaries of the Tiber. These tributaries were once intermittent streams, sometimes requiring a boatman to cross, and some were stagnant, poorly drained marshes.

CHAPTER 6

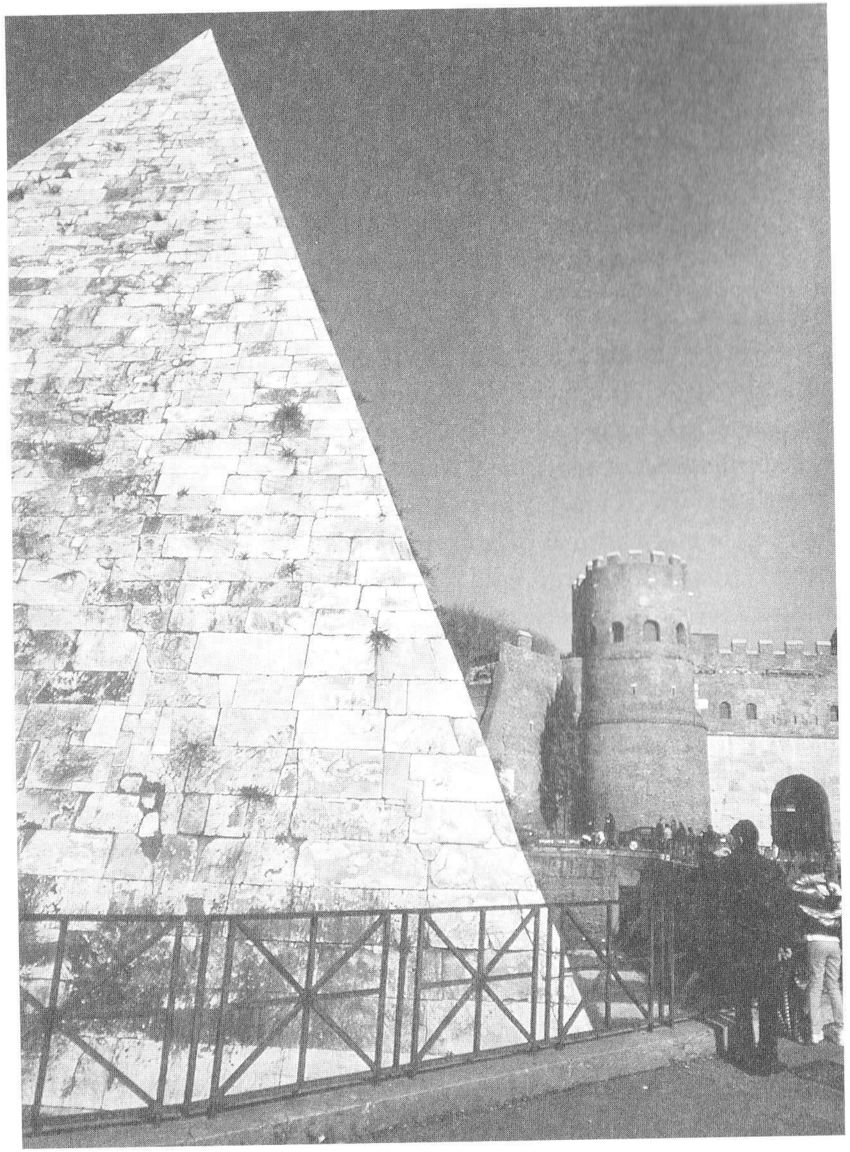
The Tiber's Tributaries in Rome

CLOGGED WITH HUMANKIND'S DEBRIS

THE MAJOR STREETS Via del Tritone, Via Barberini, Via Vittorio Veneto, Via Cavour, Via di San Gregorio, Via delle Terme Caracalla, and Via Labicana all rise into the seven hills of Rome along now-buried tributaries of the Tiber River. One of the tributaries, the Aquae Sallustianae, which was fed by the Sallustiane springs, flowed between the Pincian and Quirinal hills (a small drainage now followed by the Vie del Tritone, Barberini, and Vittorio Veneto) and into a swampy area used for grazing goats (called, not surprisingly, the "Goat Marsh"). Between the Viminal and the Esquiline hills was another stream whose waters passed between the Capitoline and Palatine hills, through the swamps of Lacus Curtius and Velabrum Minus, and finally into the Tiber. These tributaries that cut into the tuffs of the plateau now are partly filled with alluvium and man-made debris, which are important factors in the city's past, present, and future. As you traverse Rome, you're treading on layers upon layers of debris, most of which is tastefully overlain by buildings and pavement.

Going west down the Via Labicana toward the Colosseum, you are trekking along what was a swamp between the Esquiline and Celian hills. If you follow the Aurelian Wall west-southwest from San Giovanni in Laterano to the Baths of Caracalla, you are passing along the route of yet another stream that fed the swamp in the Valle delle Camene, which was eventually drained to become the Circus Maximus. At the end of the 3rd century B.C., Romans had to cross the substantial swamp by ferryboat. The Romans dug channels for the streams to eliminate the large, unhealthy swamps and, eventually, to create the water collection network called the Cloaca Maxima (the "Big Drain").

The Cloaca Maxima, still visible along the eastern bank of the Tiber near the Ponte Palatino, was ancient Rome's main storm sewer. It was



The Pyramid of Caius Cestius, a wealthy Roman magistrate buried here in 12 B.C., was incorporated into the Aurelian Wall nearly 300 years later. The land southwest of the pyramid became the Protestant Cemetery, which includes the graves of such dignitaries as the poet John Keats, Julius Augustus, the illegitimate son of Goethe, and Antonio Gramsci, the first leader of the Italian Communist Party. As you pass through the busy intersection of the Piazzale Ostiense, the pyramid and adjacent ruins

originally built to drain the central part of the city, especially during heavy rains that produced flash floods. Reputedly begun by the Etruscan king Tarquin the Proud to drain the tuff plateau through the Velabrum and Argiletum valleys, the drain was an open canal until the 3rd or 4th century B.C., when Roman engineers began to cover it with stone arches. Like many such structures in the city, the Cloaca Maxima was built of durable tuff (*Tufo pisolitico, Tufo Giallo della Via Tiberina*, and the *peperino* of Gabii, all discussed in chapter 3). These semicircular arches are nearly 5 meters in diameter and are still intact after more than 2,000 years.

The Tiber's tributaries, which once so clearly delineated the seven hills of Rome, obviously are not so easily seen in the 21st century—in part because of the closely spaced buildings throughout the city, but chiefly because the streambeds have been so well masked by man-made debris.

Debris: Engineer's Curse and Archeologist's Treasure

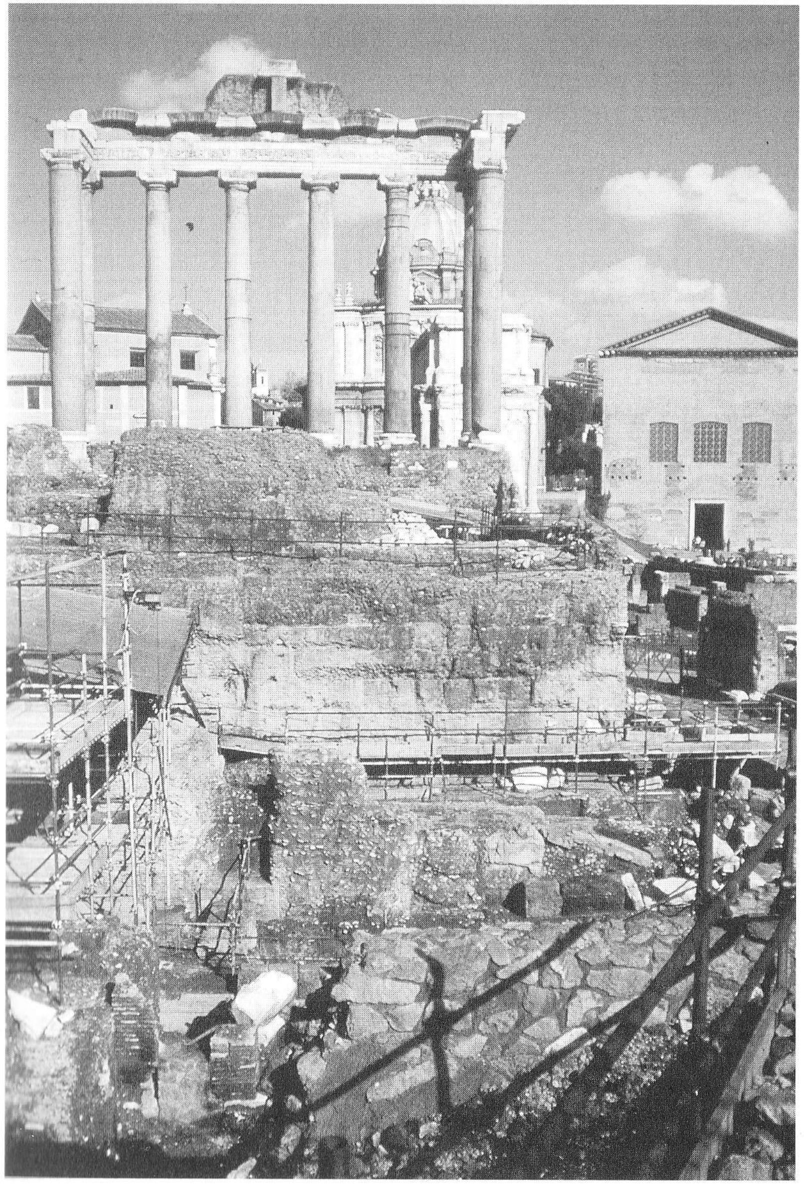
Humans generate and accumulate a lot of waste. We sack it, stack it, hide it, burn it, recycle it, or pay someone to take it elsewhere—anywhere we can't see it or smell it. In today's world, with greater material consumption, we generate increasingly enormous masses of debris that must be disposed of or recycled. Over the last 3,000 years, surely the debris accumulating in Rome was equally undesirable, but it is now eagerly excavated by archeologists in their search for clues to the past. Wherever the written word hasn't survived, we depend on accumulated waste for information about a community's lifestyles and infrastructure. You can visit the Roman fora and watch archeologists avidly digging through both the layers of debris left by everyday life and the major "marker beds" that are the recognized products of invasion, fire,

appear to be in a hole; actually, they have not sunk but were slowly surrounded by rising debris left by Rome's residents and catastrophes like the fire of A.D. 64. Layers of debris in the area of Piazzale Ostiense are 5 to 10 meters thick, and the base of the pyramid is 3 to 4 meters below today's streets.

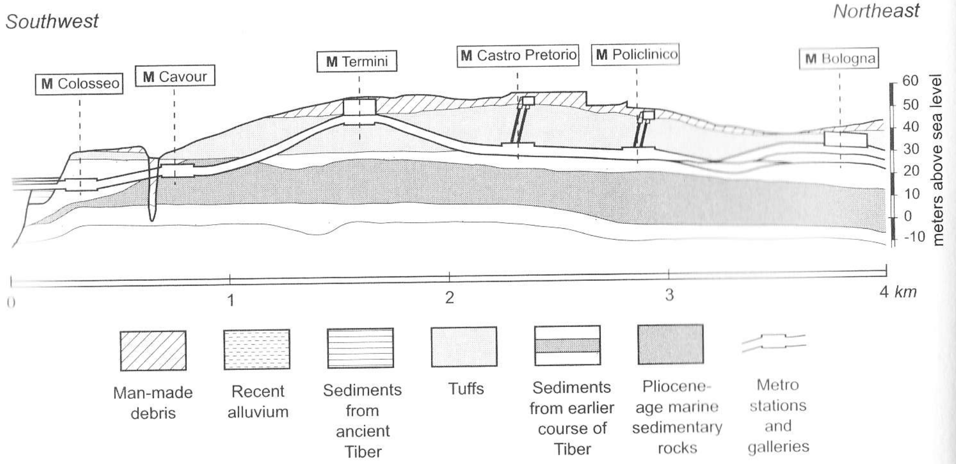
demolition, and reconstruction. If you look carefully, you'll observe the complexity and heterogeneity of the layers and appreciate the years of education and experience that lie behind archeological observations.

We know this region has been occupied for at least 14,000 years, although it is difficult to identify Paleolithic and Neolithic sites below the younger debris of the city. Stone tools, pottery, and (eventually) copper weapons found in and around Rome are evidence of the first 10,000 years of human occupation. The copper most probably came from mines in Tuscany, near Monte Amiata. Obsidian tools likely had sources in Sardinia or the volcanic islands of Lipari and Palmerola. During the Bronze Age (approximately 2300 to 1000 B.C.), residents occupied multiple sites along the Tiber (as revealed in excavations at Sant'Omobono, Cisterna, and Veii). Throughout the time of Republican and Imperial Rome, with its population then reaching a million, continuous construction of new buildings, greater demand for imported consumer goods (including building stone and oil containers), and the generation and burial of waste substantially increased the rate at which the city rose above its original geologic foundation. This process has changed in the last few decades because debris is being hauled into the adjacent countryside, a practice that will undoubtedly confuse future generations of archeologists.

Geologists are interested in the debris left by previous Roman residents because it has modified the terrain. There have been so many human-caused changes that one of Rome's seven hills—the Viminal—is all but invisible to the casual observer. Throughout the historical center of Rome, nearly everything is covered by at least 2 to 5 meters (6.6 to 16 feet) of debris. On the alluvial plain in the neighborhoods of Trastevere and Pigna, the debris is 5 to 10 meters (16 to 33 feet) thick; along what were tributary streams flowing into the Tiber, the debris layers are 10 to 15 meters (33 to 49 feet) thick. Within the limits of the Aurelian Walls, there are 93 million cubic meters (121 million cubic yards) of man-made debris. This is a lot of material! However, the citizens of Rome have had 3,000 years during which they slowly collected the waste, buried or mounded it, and modified the natural terrain. The accumulation has not been a steady process; it has fluctuated from ordinary daily trash accumulation to massive layers produced by earth-



In archeological excavations in the Roman Forum, it is clear that the city has evolved atop its own debris; in this case, we see rubble from Republican Rome through to modern constructions such as the Curia, visible behind the Temple of Saturn on the right. The Curia was the chamber of the Roman Senate.

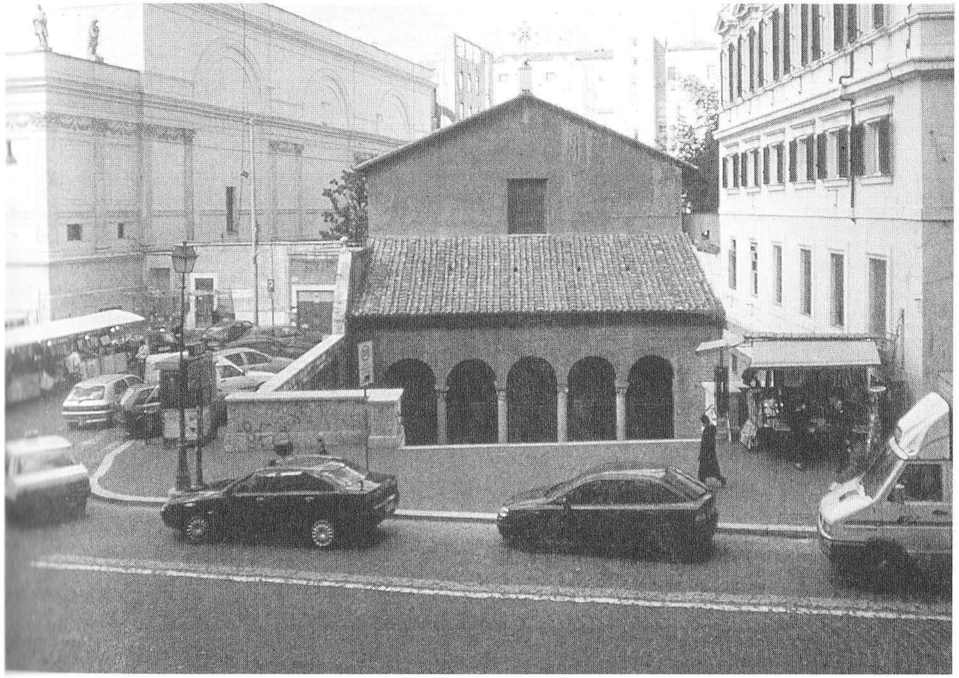


You get an idea of the remarkably thick layer of man-made debris that covers the city by studying this geologic cross section along the Metropolitana B (subway) between stations at Piazza Bologna and the Colosseum. For example, the ravine near Cavour station is filled with 20 meters (66 feet) of debris. The illustration is exaggerated vertically to show the relations between geologic units (measured in meters above sea level).

quakes, fires, invasions, or large-scale renovations of the city by leaders like Mussolini.

On a first visit to Rome you might be forgiven for thinking that nearly all the major structures were built in holes. The Church of San Vitale, next to the Palazzo di Esposizioni on the Via Nazionale, is 3 to 4 meters (10 to 13 feet) below street level. The base of the Pyramid of Caius Cestius, or the Piramide, along the Via Ostiense at Porta San Paolo, is also 3 to 4 meters below the numerous buses and cars that roll past this unique monument. Even the base of Trajan's Column and most of the buildings in the Roman fora rise out of depressions. Be reassured—these monuments and churches, ranging in age from the 1st century B.C. to the 16th century A.D., are not sinking; they have been slowly engulfed by the accumulated debris of an evolving city.

Deposits more than 15 meters (49 feet) thick are located where builders piled the debris from construction, industry dumped its refuse, or locals simply wanted to fill in an annoying ravine. Familiar features of Rome that overlie thick debris layers include the Piazza Barberini, Ter-



The small Church of San Vitale, near the Palazzo di Esposizioni on the Via Nazionale, sits well below street level, surrounded by the debris that has accumulated since medieval times.

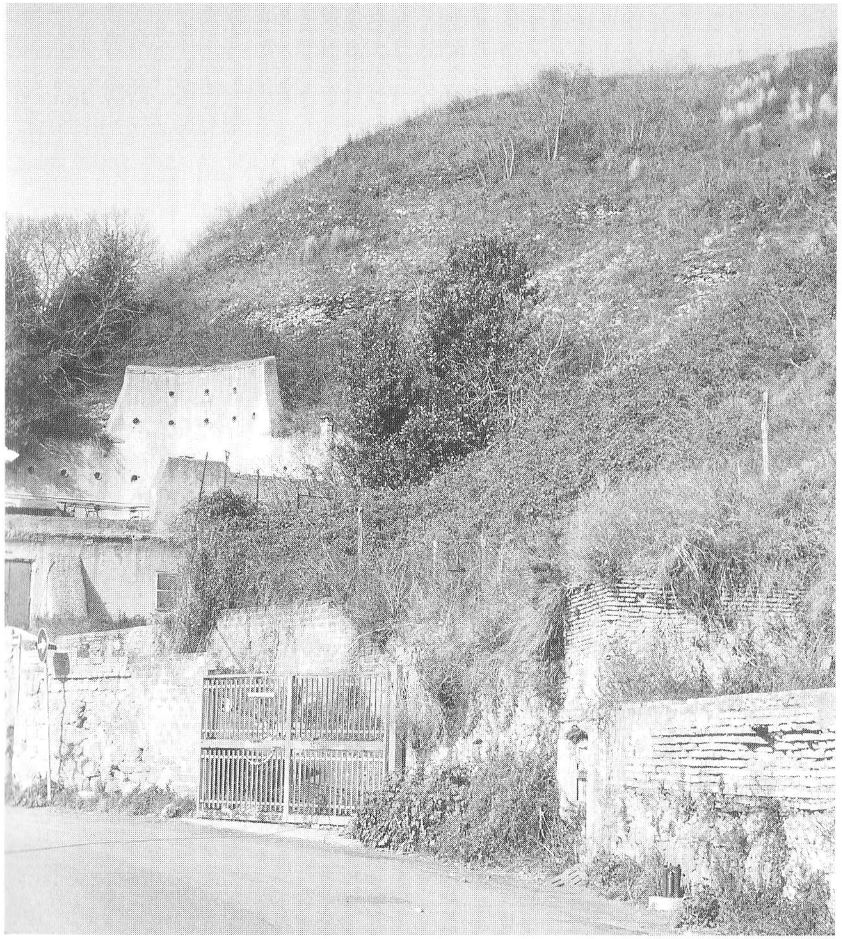
mini Station, the southwest embankment of the Circus Maximus, Via Cavour, Porta Melonia, and Piazza Tuscolo.

The winner for thickest debris deposit in Rome is the Monte Testaccio, a 250-by-180-meter (820-by-590-feet), 36-meter-high (111-foot) hill in the Testaccio neighborhood. The volume of this man-made hill is 1.6 million cubic meters (2.2 million cubic yards)! The hill was a dumping ground for warehouses and workshops in the "emporium zone" along the Tiber River south of the Aventine Hill. The Emporium consisted of a river port and warehouses constructed with tuff blocks that covered an area 467 meters (1,530 feet) long and 60 meters (197 feet) wide. Much of what arrived at the river port first went to warehouses and workshops in what is now the Testaccio neighborhood.

Monte Testaccio is composed of mostly broken amphorae (terracotta jugs) used to import oil from around the Mediterranean. Rodri-

This aerial photograph shows the area of the Monte Testaccio, a 36-meter-high (111-foot) hill of debris, mostly broken amphorae accumulated between about A.D. 145 and 255. Imperial Rome's major river port was nearby, and the neighborhood around Monte Testaccio was an industrial district.

guez-Almeida, in his analysis of Roman trade based on the components of the hill, estimated that the number of broken amphorae totaled 53,359,800, which would have contained 37 million cubic meters (nearly 10 billion gallons) of imported olive oil! Even averaging this volume of oil over the 110-year lifetime of the landfill, the per capita



The Monte Testaccio is a man-made hill now surrounded by residences and restaurants.

annual consumption would have been 34 liters (9 gallons), assuming a population of 1 million. This estimate seems rather high, but we must remember that oil was used for lighting and cosmetic purposes, as well as for cooking. Other debris components include chunks of pozzolan concrete, plaster, broken roof tiles, bits of stone pavement, and fragments of glass and ceramic oil lamps—much like modern landfills. After the fall of Imperial Rome, the Testaccio Hill went virtually unnoticed until the 18th and 19th centuries, when it became a tourist attraction. Today, the ancient industrial zone is becoming a popular site for restaurants and nightclubs.

The Palazzo Valentini, which houses the offices of the Provincia di Roma, is located immediately north of Trajan's Column, east of the Piazza Venezia, and is a potential victim of history and gravity. Follow along as we begin a virtual ascent through the complex and numerous layers beneath the Palazzo Valentini. The debris sequence begins with the Temple of the Deified Trajan, built by Hadrian around A.D. 117 on a substantial stone foundation. Nearby were Trajan's Forum (the largest of the Imperial fora), and Trajan's Column. The temple fell into disuse after the fall of the Roman Empire, and the site became a rubble pile. From the 5th to 12th centuries A.D., the temple was smothered by one of Rome's medieval quarters. Between 1583 and 1585, this neighborhood was demolished to build the Palazzo Borrelli, which was never completed. Later construction (A.D. 1650 to 1689) extended the palazzo toward Trajan's Column, and in about 1740, the building became the Church of Santissimo Nome di Maria. It came under new ownership in 1750 when the Imperial cardinals carried out work to restore the library. Between 1796 and 1830, the new owner, Vincenzo Valentini (thus, its current name), added a new section that had a view of Trajan's Column. The Provincia di Roma took over the palazzo in A.D. 1874, remodeling it and adding another level. In the mid–20th century, part of the building was turned into a bomb shelter.

To sum up, the man-made debris under the palazzo, representing the ebb and flow of Roman history, is between 6 and 16 meters (20 and 52 feet) thick. The heterogeneity of the debris deposits results in irregular compaction and subsidence under the weight of the palazzo's foundation. The difference between the compaction of unconsolidated medieval and Renaissance debris layers and the rock foundation of the Temple of the Deified Trajan has led to cracking and even tilting of sections of the overlying palazzo. The palazzo is not the only important building that is threatened in this manner.

In August 1969, in the Palace of Justice (Palazzo di Giustizia di Roma, or Il Palazzaccio), a granite corbel collapsed, fell through the ceiling, and landed in a ground-floor hall. Located near Castel Sant'Angelo between the Tiber and the Piazza Cavour, the palace was built in 1893

directly over a spring on the right bank of the river. The corbel fell because differential subsidence of the palazzo's foundation was tearing the building apart. When it was examined in 1970, the palazzo had more than 450 cracks on each of its three levels. Precise leveling surveys made after the cracks were mapped revealed that the building was subsiding at about 5 millimeters (one-fifth of an inch) per year. That alone wouldn't be catastrophic, but the subsidence is not uniform below this enormous building. The facade nearest the Piazza Cavour had sunk 50 centimeters (20 inches) between 1893 and 1970, but in more recent times, most of the subsidence has occurred on the opposing façade, nearer the Tiber.

We know that cracking and tilting of parts of the palace are caused by differential compaction again, but in this case, by unconsolidated river deposits (sand, gravel, and clay) and man-made debris (including the remnants of Imperial Roman ruins) underlying the palazzo; the deposits are not compressed equally under the weight of the stone palazzo, and some deposits sink more than others. Building over a spring without considering the effects of water-saturated sediment also added to the problem. Furthermore, engineers investigating the stability of the palazzo found that the foundation itself lacked rigidity; thus, it could not "float" as a single block on the underlying sedimentary and debris deposits.

In general, early Roman engineers constructed the city's buildings on stable foundations. There were exceptions, however, such as the Colosseum, which was constructed over a contact between alluvium and the rock of the Oppian Hill. Even just after medieval times, builders were already facing the difficulties of laying foundations on heterogeneous debris layers accumulated throughout earlier Roman history. Today, most of the younger buildings suffer only from annoying cracks, but the effect of differential subsidence can lead to the more serious problem of tilting, which requires repair and retrofitting.

Difficulties associated with the lateral and vertical heterogeneity of both man-made debris deposits and unconsolidated alluvium have provided a key to understanding another problem: the way Rome's buildings and monuments respond to earthquakes, which are so common in Italy.

Geologists Evaluate the Risk of Earthquakes

To evaluate the earthquake risk to man-made structures, we need to look beneath, at the rock or sediment type as well as the thickness and shape of each deposit. We need a geologic evaluation and, if we are lucky enough to have access to sophisticated computer databases, some numerical modeling of the site in order to estimate any strong ground motion that would accompany a future earthquake. Structures built on rock have the greatest chance for survival. Those built on deposits of poorly consolidated alluvium, especially in narrow valleys, are subject to amplified ground motion and thus have an increased risk of serious damage. We can also extract earthquake histories by digging trenches across faults to look at indicators for ground movement and by collecting material for radiometrically dating sediment layers left by past earthquakes.

We must not only determine the rock types (usually from local outcrops) but also understand something about their geometry and distribution. Given that old cities like Rome have covered most of the outcrops with man-made debris, it is difficult to evaluate what underlies the city unless you have a large drilling budget that allows you to poke holes through the debris. Geologists can use information about damage to historical structures caused by past earthquakes to predict zones where buildings are vulnerable to strong ground acceleration. Compilations of the time and degree of damage from earthquakes will also help us develop the data sets we need to estimate future risks.

Earthquakes in Rome?

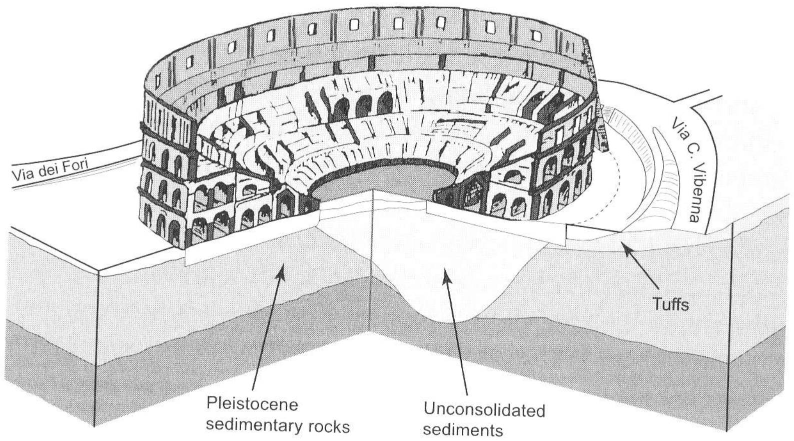
A tablet located in the entrance of the building that has become a symbol of Rome and the Roman Empire—the Colosseum—describes the generosity of Decius Marius Venantius Basilius in subsidizing repairs after earthquakes that occurred between A.D. 443 and 484. Rome is

subject to both small and large earthquakes, and the chronicle of these events is one of the best in the world because of Rome's long historical record. The monuments of Rome are proud survivors of seismic activity, but geophysicists and conservators alike are concerned about the potential damage from future earthquakes.

The Flavian Amphitheater—better known as the Colosseum—is easily recognized by people everywhere because of its asymmetry: the northern half has four levels of arches and looks complete, whereas the southern half has two and one-half to three levels remaining and is obviously damaged. This damage appears to have been caused mostly by earthquakes over the last 1,900 years and rather less by citizens and builders "mining" the structure for construction material.

One of the authors of this book (Funiciello) and the geophysicist Antonio Rovelli of the Italian Institute of Geophysics have studied earthquake effects on major Roman monuments, including the Colosseum. They discovered that damage to the amphitheater by the many earthquakes that have hit Rome during the last two millennia was related in large part to the underlying geologic deposits. Roman engineers were superb, but they did not consider the basic issue of geologic underpinnings before building this arena. This failing is not unique; construction today in most of the world's cities suffers from the same problem: a lack of understanding of the geologic foundation below (or, in cities with hills, the geology above).

Using data from earlier geologic mapping and a series of exploration drill holes, Funiciello and Rovelli found that the Colosseum had been constructed across the boundary (in geologic terms, the *contact*) between Pleistocene age sedimentary rocks and tuffs (volcanic deposits from the Alban Hills) and the unconsolidated alluvium of a creek that ran between the Palatine, Esquiline, and Celian hills and then into the Tiber through what is now the valley containing the Circus Maximus. Adding further instability, a small valley once dammed to form an artificial lake was, in turn, covered with a layer of burned debris left by the great fire of A.D. 64 (carbonized wood from the fire was discovered during geo-engineering drilling). Vespasian, the first emperor of the Flavian family, who succeeded Nero, decided that the small valley was the perfect site for a great arena, which he had constructed in little more than five years (his son Titus dedicated the arena in A.D. 80).



As you can see from this diagram of the Colosseum (Flavian Amphitheater), the north side of the Colosseum (to the left), which is underlain by marine sedimentary rocks and tuff, suffered only light damage during the earthquakes of the centuries. The southern side, overlying an ancient creek filled with poorly consolidated sediment, was severely damaged by excessive ground acceleration within the alluvium during large earthquakes.

Despite its massive, 13-meter-thick (43-foot) concrete foundation, the variation in rock types under the stadium becomes evident when one looks at structural damage caused by a few large earthquakes. After A.D. 484, the Colosseum was gradually abandoned as a site for sporting activities; it was used by criminals as a refuge and by others as a corral for cattle. During the 13th century, it became a fortress for a wealthy family. The debris left after earthquakes served for a while as an ersatz "quarry" before Pope Benedict IV saved this landmark by consecrating it.

Using the results of geologic drilling to visualize the three-dimensional framework of the site, Funiciello and Rovelli simulated the ground acceleration that would have occurred below the stadium during an earthquake. In the unconsolidated stream sediments of the tributary underlying the southern half of the Colosseum, the ground acceleration was strongly amplified, enhanced by the shape of the valley. Large earthquakes heavily damaged the portion of the Colosseum underlain by a sediment-filled creek bottom, but adjacent portions located on rock suffered only light damage.

Basic data for an earthquake history should include the degree of damage to buildings, bridges, and monuments; however, not every historical record indicates if an earthquake was responsible for property damage. In ancient Rome, buildings often collapsed, even without earthquakes. During Imperial times, Emperor Augustus limited the height of private buildings to 21 meters (70 feet), and anyone who wished to build above that height needed the emperor's permission. In the following century, Trajan further limited construction to about 18 meters (60 feet). These regulations were prompted when a period of enormous demand for low-cost housing resulted in less-than-excellent projects. Tall tenements frequently collapsed because of poor construction, but their destruction was assured during earthquakes. As is often the case in the modern world, cheap housing provided great profits but put the residents at risk. The writer Juvenal, who died around A.D. 130, lamented the unstable, badly constructed buildings of Rome: "We live in a city that is supported, more or less, by props." Some Italians agree, saying that not much has changed, especially with the apartment houses put up quickly after World War II in response to a postwar housing crisis.

In early documents, earthquakes were lumped into the same category of disaster as war, revolt, and invasion. Dates for earthquakes that occurred before A.D. 1000 are not precise, especially for events between A.D. 500 and 1000. The first recorded description of a Roman earthquake was by Livy, writing in the final decades of the 1st century B.C., who mentions the tremors of 461 B.C.: "The ground was shaken by a violent earthquake." Livy, in this terse account, described the event in the context of miracles that occurred that year. Not much was said about actual damage to the city except for the falling of large objects. An earthquake in 83 B.C. damaged public buildings and houses, and Appian (2nd century A.D.) interpreted the event as a portent for civil war (this is certainly plausible—the same happened in Managua, Nicaragua, in 1972). Other significant earthquakes noted by Roman writers occurred in 179 B.C., about 71 B.C., and A.D. 15, 51, 443, 484 or 508, 801, and 1091.

One of the most damaging earthquakes affecting Rome occurred on September 9, 1349. Near the epicenter in the central Apennines, the intensity was Mercalli grade X; in Rome it was grade VIII. The poet

TABLE 6.1
Large Earthquakes That Caused Damage in Rome from the 13th Century A.D. to the Present

Zone of Epicenter	*Year*	*Intensity, Epicenter*	*Intensity in Rome*	*Comment*
Umbria-Marche Apennines	1279	IX	V	—
Central Italy	1349	X	VII–VIII	Serious damage to the basilicas and medieval towers
Aquilano	1461	X	V	No description
Umbria Apennines	1703	XI	VII	Serious damage to many buildings
Aquilano	1703	X–XI	VII	Serious damage
Abruzzo Apennines	1706	X–XI	V	
Alban Hills	1806	VIII	V	Minor damage to some buildings
Roman area	1811	VI	V–VI	
Roman area	1812	VI–VII	VI	Partial collapse of many buildings
Alban Hills	1892	VII–VIII	V	Minor damage
Roman area	1895	VII	V–VI	Some serious damage
Alban Hills	1899	VII	VI	Some serious damage
Roman area	1909	VI	IV–V	Minor damage in Monte Mario
Alban Hills	1911	VI	IV–V	Some minor damage
Marsica	1915	XI	VII	Much damage and some partial collapse
Roman area	1919	V–VI	V	Some minor damage
Alban Hills	1927	VIII	V	Some minor damage
Val Nerina	1979	VIII	V	Some minor damage
Roman area	1995	VI	IV–V	Some minor damage
Umbria-Marche Apennines	1997	VIII–IX	V	Some minor damage

Source: Donati, Funiciello, and Rovelli 1998.

Petrarch, who was in the city for the Jubilee of 1350, found the city "prostrate," citing severe damage to the structures most frequently visited and admired by pilgrims, including bell towers and basilicas. Worried about the expected influx of pilgrims, Pope Clement VI concentrated on repairing damage to the most important basilicas: San Paolo,

TABLE 6.2
The Mercalli Earthquake Intensity Scale

Scale	*Intensity*	*Description of Effect*	*Corresponding Richter Scale*
I	Instrumental	Detected only by seismographs.	—
II	Feeble	Some people feel it.	—
III	Slight	Felt by people at rest, like a large truck passing.	Less than 4.2
IV	Moderate	Felt by people walking. Loose objects on shelves rattle.	—
V	Slightly strong	Awakens sleepers. Church bells ring.	Less than 4.8
VI	Strong	Trees sway. Suspended objects swing. Objects on shelves fall off.	Less than 5.4
VII	Very strong	Mild alarm among people. Walls crack. Plaster falls.	Less than 6.1
VIII	Destructive	Moving cars cannot be controlled. Chimneys fall, and masonry is fractured. Poorly constructed buildings are damaged.	—
IX	Ruinous	Some houses collapse. The ground cracks, and pipes break.	Less than 6.9
X	Disastrous	There are many ground cracks. Many buildings are destroyed. Some liquefaction of ground and many landslides.	Less than 7.3
XI	Very disastrous	Most buildings and bridges collapse. Roads, railways, pipes, and cables are destroyed.	Less than 8.1
XII	Catastrophic	Total destruction of man-made structures. Trees are torn out of the ground. The ground rises and falls in waves.	Greater than 8.1

Saint Peter, and San Giovanni in Laterano. This may have been the same earthquake that caused major damage to the Colosseum, leaving it half in ruins, as we see it today.

Seismic historians have had better documentation since medieval times for evaluating the earthquake intensity and subsequent damage of historic tremors.

The Earthquake of January–February 1703

> A series of earthquakes, causing violent shaking and notable damage, terrorized the residents of the city. This violent earthquake originated in the Apennines of Umbria and Abruzzo and was possibly the most important earthquake in the history of central Italy. Ground motion, occasionally with intensities of MCS grades IX and X, destroyed numerous towns, left thousands of victims, and produced ample evidence of effects on the landscape and groundwater.
>
> The people of Rome living in areas where the most severe ground motion occurred [about MCS grade VII—on the Tiber's floodplain and tributaries], were found in a grave state of terror and exhaustion, continually rebuilding and adding supports to structures and putting up notices of death and destruction. All spent nights in the open during the bad winter weather and not in the buildings.
>
> On the first day of March, 1703, an indication of the climate that reigned in the city was the band of criminals who posted a notice predicting the imminent fall of the city, to encourage the inhabitants to abandon their homes and then to rob them. The general fear led to the numerous religious functions celebrated in Rome during the following year. (Molin and Guidoboni 1989)

The ground motion in Rome during this event caused serious damage, mostly on January 14, and was also disastrous near Norcia; on February 2, the quake caused catastrophic damage in the city of L'Aquila and further damaged Roman buildings weakened during the first earthquake. Damage recorded in Rome included the collapse of a house near Santa Prassede and destruction of a loggia parapet near the "Quattro Fontane," which killed two brothers. Despite their solid appearance, town walls partially collapsed. Roof gables fell in Trastevere, and deep fissures opened in the walls of many public buildings. Many Roman monuments were damaged; particularly hard hit was the Colosseum, where three arches of the second enclosure on the south side were ruined (facing the Church of San Gregorio). The effects on groundwater, as described by Molin and Guidoboni, were notable in many of the city's wells ("For a while, the water was turbid and had a

bad odor. Pressures in water systems dropped") the result of disrupted springs and broken pipes.

The most serious Roman earthquake of the 20th century occurred on January 13, 1915. The epicenter was located 80 to 100 kilometers (50 to 60 miles) north of Rome, in the Lazio-Abruzzo Apennines, where the intensity was Mercalli grade XI. This quake was felt throughout Italy and in parts of Yugoslavia. All wards and quarters of Rome were affected, although the extent varied. Most of the damage occurred in structures located on the alluvium of the floodplain and tributaries, and it was severe in all older floodplain neighborhoods, including Testaccio and Prati. The earthquake crumbled parts of the Aurelian Wall near the Porta del Popolo and Porta Maggiore, and near Porta Furba a part of the Claudian aqueduct was destroyed. Serious damage occurred in the churches of Sant'Agata de Goti and Santa Maria della Scala, the campanile of Sant'Andrea delle Fratte, and the cupola of San Carlo ai Catinari.

Sources of Earthquakes That Affect Rome

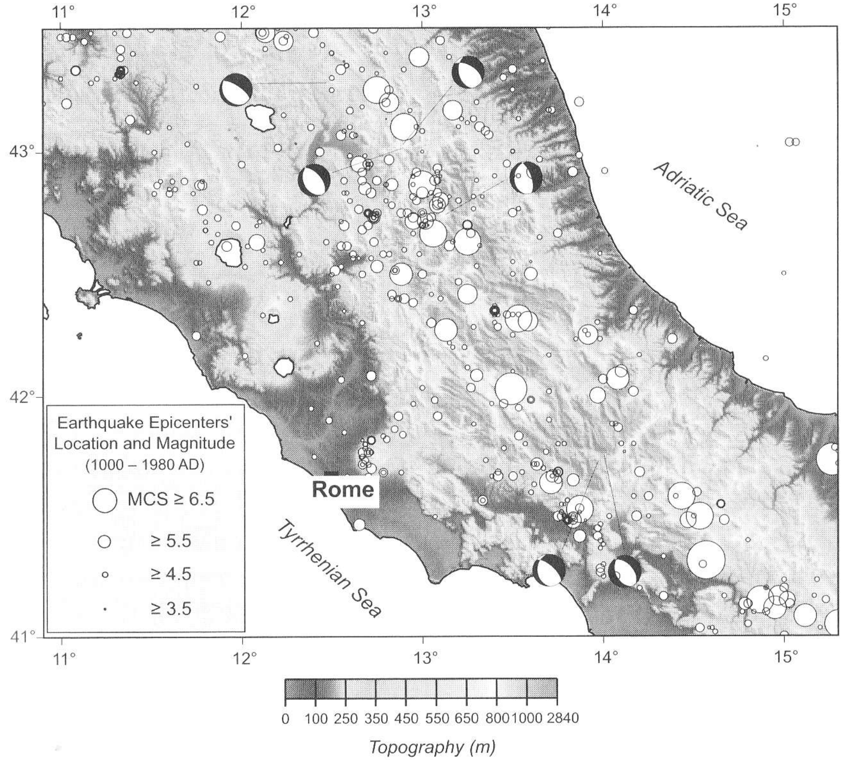
The earthquakes felt in Rome historically originate in three areas:

- Within a 15-kilometer (9-mile) radius of the city center—These earthquakes have magnitudes of less than Mercalli IV and shallow epicentral depths; they are rarely felt and are detected only by sensitive seismometers.
- Within "the Roman area"—Frequent earthquakes in the Alban Hills volcanic field have magnitudes of about Mercalli V; their cause is often attributed to either an influx or cooling (and shrinking) of molten rock located at great depths below the volcanic field. Along the Tyrrhenian coastline, infrequent earthquakes, with magnitudes of about Mercalli V to VI, are rarely felt within the city.
- Within 60 to 130 kilometers (37 to 81 miles) of Rome—Seismically active areas of the central Apennines have been the sources for all major earthquakes in central Italy. The larger quakes produce maximum intensities of Mercalli VII to VIII in Rome. Earth-

TABLE 6.3
Earthquakes and the Great Basilicas of Rome

Basilica	*San Giovanni in Laterano*	*San Paolo fuori le Mura*	*Saint Peter's (Vatican)*	*Santa Maria Maggiore*
Geologic Foundation	Tuff plateau	Across a boundary between tuff and alluvium	Complex overlap of Plio-Pleistocene marine sedimentary rocks, tuffs, and alluvium	Tuff plateau
Degree of Damage and Year	Roof collapse (9 September 1349) Varied damage to annexes (March 22, 1812) Plaster fell (July 7, 1899) The statue of Saint Paul fell from the facade (January 13, 1915)	Serious damage that required radical reconstruction of the roof, floors, and outside doors (April 29, 801) Campanile collapsed (sited on alluvium) and serious roof damage (September 9, 1349) Damage to clock walls (March 22, 1812) A capital fell from a column (November 11, 1895) Damage to the facade and apse. The marble cross over the entrance fell. Damage to the mosaics (January 15, 1915)	Unspecified damage (September 9, 1349) Light damage to the cupola and falling plaster (February 2, 1703) Some damage to the vault (March 3, 1812) Accentuated previous damage to the cupola lantern (January 11, 1895) Light damage and re-opening of older cracks and falling plaster (January 13, 1915)	Light damage to the vault (March 22, 1812) Unspecified damage to the apse (August 31, 1909)

Source: Data from Molin et al. 1995.



Looking at the epicenters of large earthquakes in the Italian Peninsula between A.D. 1000 and 1980, we can see that those of most of the large earthquakes that have damaged Rome are in the nearby Apennine Mountains, whereas few really damaging earthquakes originated along the coastal plain or in the volcanic fields that flank Rome. "MCS" refers to the Mercalli Cancani Sieberg earthquake intensity scale. (Historical and instrumental data are from Camassi and Stucchi 1997)

quakes with intensities of greater than VII occur about every 500 years; those with intensities of VI to VII occur, on average, every 200 years.

Geologists have both observed and inferred faults below Rome that pose little risk to the city. The greatest hazard stems from the large earthquakes that originate in the nearby Apennines, especially when ground motion is amplified within alluvial deposits such as those found below the Tiber's floodplain. Rome's archeological monuments offer some insight into the degree of damage to a building during a single earthquake, which is related to the monument locations—on rock or alluvium.

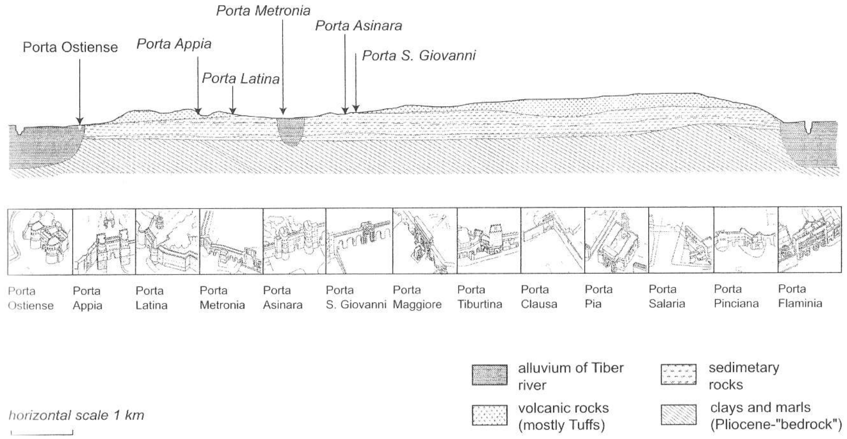
The Aurelian Wall

The Aurelian Wall, Rome's defensive perimeter over the centuries, crosses nearly all the geologic units and terrain of Rome. One of the authors of this book (Funiciello) and his colleague I. Leschiutta used the Aurelian Wall to interpret the importance of geologic setting when calculating risk to man-made structures. They assembled a geologic cross section along the wall and used historical records to evaluate damage to both the wall and its gates. Most earthquake damage over the centuries has been to the Porta Metronia and Porta Ostiense (today's Porta San Paolo), where foundations were built on the poorly consolidated alluvium deposited in deep channels cut by the Tiber and its tributaries.

The Vatican

Located on a low extension of the Janiculum Hill that extends northeastward into the floodplain of the Tiber, the site of the Vatican has been occupied since Etruscan times. This low ridge is about 60 meters (197 feet) high and consists of Pliocene age claystones and sandstones, which are overlain by Pleistocene age stream deposits and tuffs from the Alban Hills volcanic field. Thick alluvial deposits wrap around the toe of the hill.

The Circus of Gaius and Nero, the first large structure to occupy the site, was tucked into the hillside and extended out over the alluvial plain. In A.D. 64, when the city of Rome burned, Peter and Paul were reputedly carrying out their apostleships. At the beginning of the 1st century A.D., Peter's tomb, adjacent to what was Nero's circus, was at the center of a growing necropolis. Around A.D. 320, Emperor Con-



Geologic cross section below the Aurelian Wall. Gates most heavily damaged by earthquakes are those located on alluvium rather than rock.

stantine ordered the first basilica dedicated to Saint Peter to be constructed along the east-west base of Nero's Circus. Constantine's basilica survived for more than 1,000 years but by 1452 was in desperate need of repairs. Rather than rebuilding the old basilica, Nicholas V wanted a new church, but the old basilica was not torn down for another 50 years. Julius II hired Bramante to destroy the old church and to design the new one, for which construction took 120 years.

During construction of the present Saint Peter's Basilica, designers proposed that two campaniles (bell towers) flank the entrance. Work on the first bell tower began in 1612 and continued until 1641, but a sinking foundation required a scaled-down version of the original design, and the plan was in trouble. Bernini and others made an effort to save the campanile, but Pope Innocent X ordered its demolition. The problem, probably exacerbated by earthquakes, was that the towers were located on the alluvial plain and not on rock. Saint Peter's Basilica itself is located on rock and doesn't suffer the consequences of an unstable foundation. The contact of rock with alluvium runs across the front of the basilica, more or less at the head of the piazza (plaza). The piazza, flanked by 284 travertine columns, is an ideal construction on alluvium; it's a monumental space—exactly what was needed to set off the basilica's facade and to host the large crowds that attend ceremonies there.

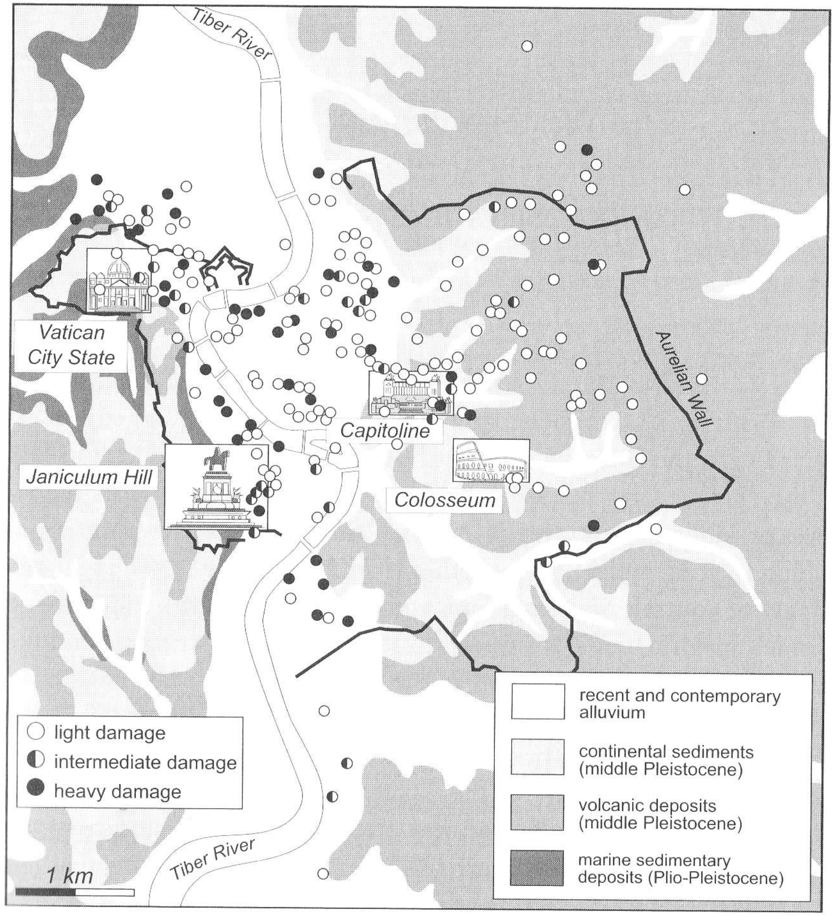
More Clues from Conservation and Restoration of Historic Buildings and Monuments

From the beginnings to A.D. 2000, monuments and important buildings were often restored following earthquakes, floods, and significant political events such as Alaric's sack of Rome in A.D. 410, as well as during preparations for Jubilee years. The amount of money spent on restoration is useful as an indicator of actual earthquake damage following documented events. Engineers can use such seemingly unrelated historical detail, information from drilling, and models of earthquake effects to evaluate the risk to new structures planned for Rome. Geologists and engineers from the National Seismic Service and the Ministry of Public Works have evaluated seismic risk for every building in the historical center of Rome, as well as for the city's infrastructure, including gas and water distribution systems.

For the Jubilee year 2000, Rome undertook the mammoth task of not only cleaning most of its major monuments (and you are fortunate to see the glorious results today) but also retrofitting them to withstand future earthquakes. The magnitude of the effort required the combined financial support of resources available to architectural historians and archeologists and those from the Ministry for Civil Protection.

Most of the work to evaluate Rome's earthquake vulnerability has focused on the historical center. The effort now must be extended into the suburbs, where scant attention has been given to the geologic foundations beneath new apartment complexes and industrial and business centers. The most growth, which has occurred since the great earthquake of 1915, has taken place in areas that were open countryside at that time, and therefore we have limited data to help us predict the potential risks of earthquake damage in these newly built-up locations.

In Rome, geoscientists and government groups are working together to find ways to help citizens avoid earthquake-related disasters. Urban administrators in other parts of the world could learn from the Roman example: look at possible earthquake sources (the geologic foundations



This map showing the basic geology of the historical center of Rome indicates those monuments that have required repair and restoration after earthquakes. The most heavily damaged areas are those on the Tiber River floodplain, where the sites are underlain by thick deposits of river sands and gravels.

upon which their cities have been constructed) and examine records of what has occurred in the past. No one has yet predicted an earthquake, but it is possible to predict structural damage by an earthquake before it happens and find ways to mitigate the dangers.