crust also produced a setting for the beginnings of volcanism, an activity that continued intermittently from about 600,000 to 3,500 years ago in volcanic fields that flank Rome to the north and south.

The pulling apart of the Tyrrhenian coastal plain over the last 20 million years had formed elongate basins up to 10 kilometers (6 miles) wide and 2,500 meters (8,200 feet) deep, bounded by "normal" faults (in which one side moves down relative to the other) that are more or less parallel to the coast. The subsiding basins were rapidly filled with debris washed down from the Apennines or from the volcanoes that were erupting during the same period. Because they were close to the coast, sediments were deposited both above and below sea level, thus getting a sequence of interbedded marine and "continental" sedimentary rocks in the area of Rome. Regardless of the type of motion (pushing or pulling), the structural trends of features such as the Apennine mountain chain or coastal basins have stayed more or less the same over the last several hundred million years.

The depth of the Tiber River valley has changed a great deal over the last 13,000 years. The river quickly eroded its valley and tributaries to develop equilibrium relative to the sea, which was once nearly 70 meters (230 feet) below its present level. As sea level rose, the Tiber stopped eroding and began depositing sediment, which is now quite thick below the Tiber as it passes through Rome.

Each of the major events that occurred during this timeline of 300 million years took tens of millions to millions of years—with two exceptions: the arrival of humans 600,000 years ago (just 0.2 percent of the timescale) and the founding of Rome 2,800 years ago (a mere 0.0006 percent of the timescale). Despite the ways we have changed the face of the planet, *Homo sapiens* hasn't been around for long.

CHAPTER **2**

Center of the Western World

THE CAPITOLINE (CAMPIDOGLIO) HILL

THE CAPITOLINE HILL is one of the most-photographed hills in the world, although most camera-bearing tourists don't realize the significance of this promontory behind the Roman Forum. Many of the large brown blocks of tuff (consolidated volcanic ash) used to construct the Forum were excavated from the flanks of this hill, but the summit itself was and remains one of importance. This small plateau (about 0.1 square kilometers or 24 acres) was the center of power and religion for what was Western civilization 2,000 years ago. Among the seven hills of Rome, the Capitoline is one of three nearest the Tiber (Capitoline, Aventine, and Palatine) that were important for both defense and access to the river so crucial to Roman commerce.

There is much to see on these 24 acres. Go south from the Piazza Venezia along the Via del Teatro di Marcello and look up through tree-lined slopes to the relatively modern palazzos (now mostly museums) on the summit, where decisions were once made that affected the entire Western world. There are many optional routes here.

If you choose to go northwest, you can approach the plateau topped with the Piazza del Campidoglio via the ramp designed by Michelangelo (the Cordonata) in 1559–66 (go ahead—feel important!).

If, instead, you continue along the Via del Teatro di Marcello, around the hill at the Via Jugaro to the Via di Monte Caprino and up the steps toward the Via del Tempio di Giove, you will be circumnavigating the Tarpeian Rock, a cliff along the southern edge of the plateau that was used as a platform for throwing traitors to their death.

Today the plateau summit includes the Piazza del Campidoglio, designed by Michelangelo, and buildings on three sides: the Palazzo Senatorio (Rome's Town Hall), the Palazzo dei Conservatori, and the Palazzo Nuovo (the last two are now museums worth visiting).

On the northern slope of the Capitoline, above the busy Piazza Venezia, is the Vittorio Emanuele Monument, an easily identified limestone landmark that was built between 1885 and 1911 to honor the first king of a unified Italy.

The Capitoline Hill is one of the smallest of Rome's seven hills and consists of three geologic units produced by activity over the last 600,000 years: sands and lake deposits from the floodplain of the ancient Tiber, interbeds of travertine left by mineral springs, and pyroclastic flow deposits (tuffs) erupted from volcanoes in the Alban Hills as well as a carapace of river and lake sediments. As is the case with the other six hills, this promontory is held up mainly by the tuffs left by eruptions in the Alban Hills volcanic field, southeast of Rome.

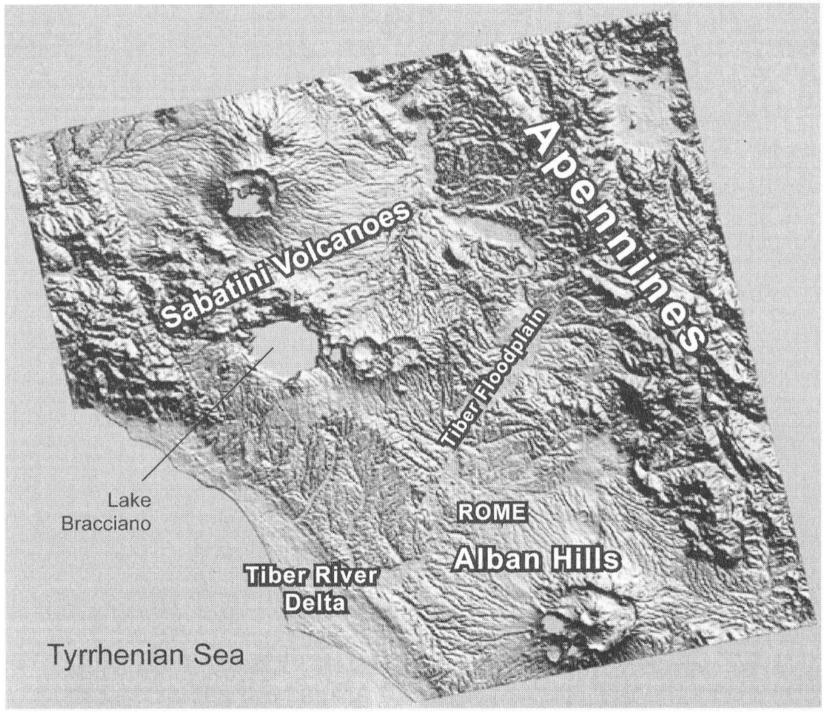
You may ask, "Volcanoes in Rome?"

Volcanoes—In Rome?

The "grand tour" of Europe during the 18th and 19th centuries invariably included a visit to Vesuvius. Great artists and writers, including Joseph Wright of Derby, Johann Wolfgang von Goethe, and Mark Twain, were enthralled by then-active Vesuvius's eruptions and quiet contemplation of the historic last days of Pompeii. The volcanoes of the Phlegrean Fields, Etna, and Stromboli—all farther south—were often cited by both pagan and Christian theologians as possible entrances to the underworld. In fact, the science of volcanology began in Italy with observations of Vesuvius and Mount Etna.

Today's tourists commonly include visits to at least one of Italy's well-known volcanoes on their itineraries . . . but volcanoes near Rome *itself*? Most tourists and even many Romans are unaware that the city is flanked by two very large volcanic fields: the Alban Hills to the southeast and the Sabatini volcanic field to the northwest. The seven hills of Rome owe their very existence to the volcanoes of the Alban Hills. The threat of volcanic eruptions is not imminent, but these volcanic fields are "geologically young" (less than a million years old).

Looking southeast from the Capitoline summit in the park near the Temple of Jupiter, you can see the volcanic Alban Hills (Colli Albani), site of the "Castelli Romani" and the pope's summer palace at Castel

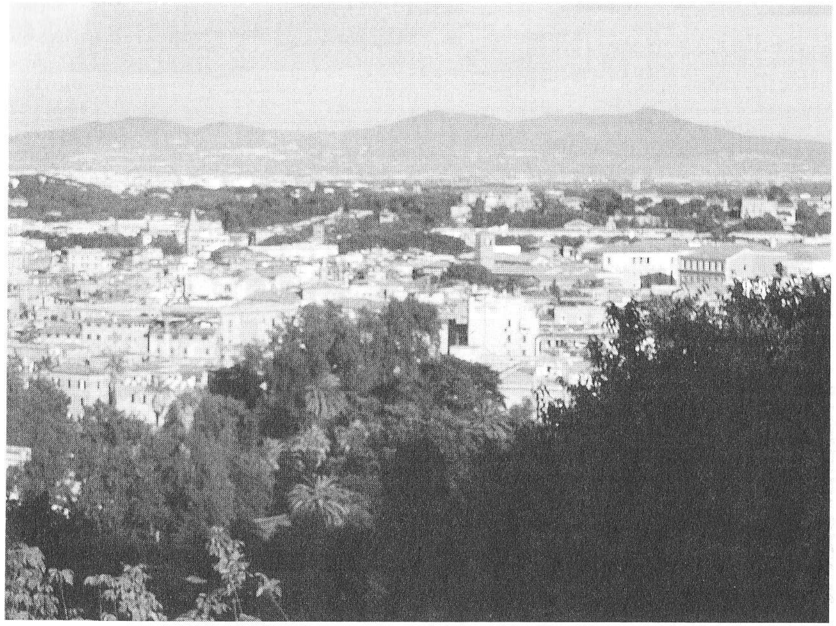


This digital elevation map provides an excellent view of the basic structures and the relationships between the Latium volcanoes (the Alban Hills and the Sabatini volcanic fields), the Apennines, and the Tiber River delta.

Gandolfo. The massif visible from the Capitoline is an accumulation of overlapping deposits from large and small eruptions from more than seventy-two craters that were active intermittently over the last 600,000 years. The tuffs and lava flows of the Alban Hills cover an area of about 1,600 square kilometers (633 square miles); on a clear day, you can see their inverted shieldlike outline from the Capitoline or the Janiculum Hill or by looking southeast along the Circus Maximus.

A Brief History of the Alban Hills

Approximately 50 kilometers (31 miles) in diameter, the Alban Hills span the coastal plain between the Apennines and the sea. The hills rise to an elevation of nearly 1,000 meters (3,300 feet) above sea level, where

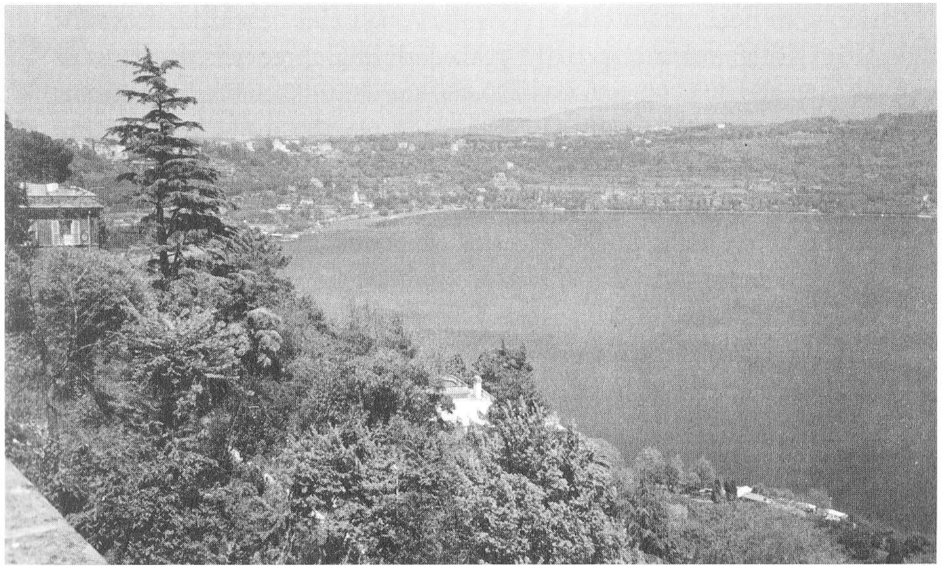


The Alban Hills volcanic field, as seen from Monteverde above the Trastevere neighborhood in eastern Rome. The summit of the Alban Hills consists of a wide collapse crater (caldera) and irregular high ground, reflecting smaller volcanoes erupted after the caldera collapse (see the previous figure for a map view).

the broad summit is dominated by a caldera (collapse crater) that is now mostly buried by material from younger volcanoes. The crater lakes of Albano and Nemi (Lacus Albanus and Lacus Nemorensis) provide the most obvious evidence of past volcanic eruptions and can be visited during a day trip from Rome.

In ancient times, the Alban Hills were more heavily vegetated and exhibited a greater diversity of plants than we see today. The forested slopes were once covered with oak, hazel, and maple trees, but only rare patches of the mixed forest now remain in the Chigi and Arriccia parks. The chestnut tree (a symbol of the Campagna Romana) has replaced most of the mixed forest, having been introduced to the area in the 17th century.

Much of the volcanic field is now covered with small towns, villas, monasteries, and vineyards. Archeological evidence from the Alban



Lago di Albano (Lake Albano) is one of the youngest volcanoes on the slopes of the Alban Hills volcanic field. The papal summer palace is located on the rim of this deep crater, which was formed during multiple eruptions of overlapping volcanoes. The youngest (Late Bronze Age) volcanic deposits were erupted from Lake Albano and reach the edge of modern Rome.

Hills, particularly around the edges of the Nemi and Albano lakes, indicates that humans have occupied the area since the Bronze Age. Such early sites, including some of the many scattered villages across the Campagna Romana, provided a framework for the development of Roman civilization. Historic and prehistoric sites within the Alban Hills are testimony to the presence of countless generations who were attracted to this gentle volcanic terrain, with its excellent water sources and fertile soils.

The plateau that slopes from the summit of the Alban Hills into Rome allowed the city to gradually expand upward and outward into the countryside to the southeast. There is historical evidence that the ancient Latin settlement of Alba Longa, along the margin of Lake Albano, has always had strong connections with Rome. In contrast, Rome was slow to develop to the north and west because of the natural barriers of the Tiber and the steep slopes of Monte Mario, which restricted communication and transport toward Lake Bracciano.

Can we forecast an eruption in the Alban Hills? Probably not. The Alban Hills' volcanic activity peaked during three phases, between 600,000 and 300,000, between 300,000 and 200,000, and again between 200,000 and 20,000 years ago. To most people, this seems long ago, but to geologists it was "just yesterday." Enough time passed between the periods of volcanic activity for six soils to have been formed on ancient slopes before being buried by later eruptions; these ancient soils are now visible as "marker beds" that separate the volcanic ash deposits and lavas of each eruption phase. One of this book's authors (De Rita) has observed that the periods of volcanic activity occurred during times of lower sea level (during the ice ages) and that volcanic activity may have been stimulated by lowered pressure in magma (molten rock) chambers underlying the volcanoes. Volumes of erupted ash and lava decreased steadily with time, from 283 cubic kilometers (68 cubic miles) during the first eruption phase to 6 cubic kilometers (1.4 cubic miles) during the second, and to 1 cubic kilometer (0.25 cubic mile) during the third. This may indicate waning activity, but we don't really know if these volcanoes are extinct. To determine the risk related to volcanic eruptions is difficult, and the significance of these numbers certainly has not decreased real estate values!

Deposits from the Alban Hills' earliest eruptions are now buried under younger volcanoes, so we don't have a complete record of the earliest volcanic activity. As far as we know, 98 percent of the tuffs and lavas that exist today in the Alban Hills were erupted between 600,000 and 300,000 years ago. Most of the volcanic field's deposits were produced by pyroclastic flows (mixtures of hot volcanic ash and gases) that moved in all directions for tens of kilometers and into what is now Rome. The largest eruptions—nearly all of which occurred when rising magma mixed with groundwater in deep aquifers (below the coastal plain)—produced pyroclastic flows that rushed 30 to 50 kilometers (19 to 31 miles) from their craters at hurricane velocities, covering collectively about 1,000 square kilometers (386 square miles). Consolidated volcanic ash deposits left by the pyroclastic flows progressively modified the drainage network that flowed into the ancient Tiber by clogging valleys around the volcanoes. The pyroclastic flows that reached what is now Rome buried the ancient Tiber River, forcing it to the west. After these catastrophic eruptions, a 10- to 12-kilometer-diameter caldera

dominated the summit of the volcanic field. The Tuscolano-Artemisio caldera may have gradually subsided in a piecemeal manner before being filled with ash and lava. Lava flows that erupted during this period are 30 meters (98 feet) thick at the caldera's rim.

Eruptions at vents within the summit caldera continued intermittently over the period between 300,000 and 200,000 years ago. The products of these eruptions include the Faete cone and, more notably, the Capo di Bove lava, which flowed down a northwest-trending valley toward the ancient Tiber, creating a sloping plateau later followed by the ancient Appian Way. Much of the stone used to surface the durable highways near Rome came from this lava flow.

The most recent crater-forming eruptions of the Alban Hills occurred between 200,000 and 20,000 years ago at the craters of Pantano Secco, Prata Porci, Valle Marciana, Castiglione, Nemi, Arricia, Giuturna, and Albano. The largest of these, Lake Albano, consists of five overlapping craters and is flooded. The 3.5-by-2.4-kilometer (2.2-by-1.5-mile) crater is 442 meters (1,450 feet) deep, with a water depth of 175 meters (574 feet).

Geologic and archeological studies in 2001 and 2002 have changed our views of the volcanic risks posed by the Alban Hills. Civil works excavations on the Ciampino plain (immediately southeast of Rome, just outside the ring road) revealed two previously unknown explosive volcanic deposits and several volcanic mudflow deposits. Eruption activity from the Lake Albano crater is much younger than was previously believed, extending well into the Holocene (the last 10,000 years). Catastrophic overflows from the lowest rim of the lake left significant mudflows—as recently as the 4th century B.C.—that formed the smooth surface of the Ciampino plain. The overflows may have been triggered by sudden injections in the lake bottom of carbon dioxide—rich fluids that are present underneath the volcano even today. High carbon dioxide releases continue to be a hazard in the Alban Hills, especially in residential areas and vineyards near Ciampino Airport and Bagni di Tivoli.

Strong to moderate discharges of both carbon dioxide and hydrogen sulfide, commonly associated with volcanic fields, increase when there are earthquakes; this phenomenon has been noted here at least fifteen times during the last 200 years. It's possible that the greatest threat posed by the Alban Hills at this time is the emission of carbon dioxide, which, because it is heavier than air, can pool in depressions such as craters and basements. When there is no wind, the gas can be a severe hazard, suffocating any form of animal life unlucky enough to enter one of these depressions.

Lake Albano's water level can rise when carbon dioxide accumulates in the bottom of the lake, but the depth can also vary as a result of rainfall or fluctuation in withdrawal by water utilities. Early Roman engineers kept the water level constant at 293 meters above sea level by means of an underground drain that may have been excavated as early as the 4th century B.C. For unexplained reasons, the lake level has been dropping recently, exposing old beaches and Roman ruins.

Lake Nemi also has a drain that dates to the 4th century B.C. The lake was drained entirely between 1927 and 1932 to salvage two Roman ships that were built for Caligula and used for holiday celebrations and religious ceremonies; the ships were destroyed by a fire in 1944. Unlike Lake Albano, Lake Nemi is now heavily polluted.

The best vineyards in the Alban Hills are located in the broad floors of the craters of Valle Marciana, Pantano Secco, and Prata Porci in the western part of the volcanic field. Here the local grapes (varieties of Malvasia), grown on American rootstock, produce a dry white wine. The craters are excellent sites because the deposits are very permeable and the soils are rich in potassium. Vineyards located on the tuff plateaus or in crater bottoms allow easy harvesting, but in the past the vineyards were also located on crater sides, where they were harvested by hand. The best exposures face south, southwest, and northwest. The combination of volcanic soils and microclimate produce excellent straw-yellow, dry wines; these "golden wines" from the Alban Hills have been popular since before Imperial Roman times to the present.

Is Rome Threatened by Volcanic Eruptions?

As you stand at your viewpoint on the Capitoline Hill, do you need to worry about being wiped out by an eruption? We don't know. Nothing catastrophic has happened here for thousands of years, but the processes that shape our planet work on a timescale that is very different

from that of human history. The famous eruption of Vesuvius in A.D. 79 followed a long period of inactivity—long enough that neither the Greeks nor the Romans knew that Vesuvius was a volcano. There have been recent swarms of small earthquakes below the Alban Hills, with focus depths of 4 to 6 kilometers (2.5 to 3.7 miles), which have been interpreted as energy releases from a cooling magma chamber (note an emphasis on "interpreted"). One of these earthquake swarms occurred from 1989 to 1990, with up to forty small earthquakes each day. As you read earlier in this chapter, there is also a possible risk from massive eruptions of carbon dioxide from Lake Albano.

Ancient Romans were very concerned about portents, and extreme attention was paid to any unusual natural event. Livy, Pliny the Elder, Orosius, and Julius Obsequens described interesting groups of portents, including "rains of stones together with babies," which, considering the duration of the event and the atmospheric and acoustic phenomena, were interpreted as volcanic. There may be a link between "rains of stones" and the locations of recent gas emissions, especially an explosive release of carbon dioxide. Another interpretation of such reported events is that they could have been gas emissions that accompanied the collapse of a sinkhole. A similar historic event occurred in the Sabatini volcanic field near Monte Soratte, where gas was released and blew rocks out of a hole in the small Lago Puzzo crater.

Some events described by ancient Roman writers could have been phreatic eruptions (steam blasts that take place when pressure within a geothermal system exceeds that of the overlying rock). Phreatic eruptions occur in many parts of the world in association with volcanic eruptions, sometimes far from any volcanoes with recent activity, and even when drillers lose control of a steam well, causing a "blowout." Phreatic eruptions occurred in the Roccamonfina area about 290 B.C., and there is evidence of historic phreatic blasts throughout the Phlegrean Fields near Naples.

Both Julius Obsequens and Pliny the Elder reported that the Alban Hills burned at night in 129 B.C. However, there is no verification of any volcanic activity in the Alban Hills at that time—this event was more likely a forest fire or brushfire.

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You can descend from the Capitoline Hill from the park near the Temple of Jupiter or from the Piazza del Campidoglio by way of the Via del Tarpeo to the Via della Consolazione. Below the eastern edge, along the Via della Consolazione, you actually see outcrops of the tuffs that make up this famous hill—a sight guaranteed to make a geologist's pulse race in this city that is mostly buried by man-made debris and buildings! When you finish your visit to the Forum, climb to the verdant plateau of the Palatine Hill, which has been occupied since the Iron Age and by tradition is where Romulus founded the City of Rome in 753 B.C.

CHAPTER 3

Palaces and Gardens

THE PALATINE (PALATINO) HILL

. . . but were I Brutus,
And Brutus Antony, there were an Antony
Would ruffle up your spirits and put a tongue
In every wound of Caesar that should move
The stones of Rome to rise and mutiny.
—WILLIAM SHAKESPEARE, *Julius Caesar*

THE PALATINE HILL is evident from all sides, its prominent, tablelike form covered with ruins and trees. One of Rome's top attractions, the Palatine is believed to be the first of Rome's seven hills to be inhabited—and perhaps the original nucleus from which the great city evolved. It was strategically located close to the Tiber, yet high enough for defense and a good breeze on hot summer days. To see the overall form of this small plateau, start at the northwest end of the Circus Maximus and walk southeast. This allows a view of the end of this rectangular plateau and its ruins. When you reach the end of the circus, turn left up the Via di San Gregorio and walk along the eastern margin of the hill toward the Colosseum. This will take you to the entrance to the Roman Forum and your access to the Palatine Hill. One ticket pays for your entry to both sites. Follow signs to various access points (the steps at Atrium Vestae, Santa Maria Antiqua, or the Clivus Palatinus road).

The Palatine is composed of rocks very similar to the sequence that underlies the Capitoline: a series of pyroclastic flow deposits (tuffs) from the Alban Hills that overlie river and marsh deposits. Overlying the tuffs is a veneer of sediment from younger rivers and adjacent marshes. The more or less tabular stack of deposits was later incised by streams flowing from the plateau into the Tiber, leaving the present tuff plateau as an erosional remnant.

The Palatine is a quiet place, with pleasant breezes and surrounded by cliffs or steep slopes. You can imagine why this 44-acre plateau was a desirable location, perhaps from the earliest settlements in what is now Rome into the 16th century, when it was home of the Farnese Gardens built by Cardinal Alessandro Farnese. Although most of the later Imperial palaces of Augustus, Tiberius, Caligula, and Domitian are constructed of brick, the earliest stone buildings, including the Temple of Cybele, were constructed of tuff from the plateau itself.

What Are Tuffs?

The term *tuff* is derived from *tufo*, a word originally used by Italian quarrymen for a rock that can be cut with a knife. *Tuff* is used by geologists to designate consolidated deposits of ash, pumice, and rock fragments left behind by explosive volcanic eruptions, similar to the material underling much of the Capitoline and Palatine hills. A variety of tuffs have been used throughout the history of Rome. In guidebooks and art books describing the architecture and archeology of Rome, you'll see a bewildering number of names applied to these rocks—a nomenclature that has evolved over the past 2,000 years. The most confusing of these terms is *tufa*, sometimes used in place of *tuff*. Within the world of geologists, these terms refer to two very different rocks. The first, *tufa*, is actually a carbonate spring deposit, whereas *tuff* refers to a consolidated volcanic ash deposit. Even more confusingly, *tuff* in Italian is *tufo*. So, to test your understanding, which are the correct words for the consolidated volcanic ash deposits left by explosive volcanic eruptions—*tuff*, *tufa*, or *tufo*?

The ideal tuffs for quarrying are those from volcanoes that quickly erupted large volumes of volcanic ash particles and gas; the ash and gas sped across the countryside as density currents (pyroclastic flows), burying the land with thick ash deposits within minutes or hours. The consolidated deposits left by pyroclastic flows are called *ignimbrites*. The large volcanoes located north and south of Rome are somewhat unique because of the type of explosive eruptions that shaped their craters and produced the deposits on their flanks. The usual energy of explosive volcanic fragmentation was augmented when rising magmas

encountered groundwater in limestone aquifers that underlie the coastal plain near Rome (these limestones correlate with those exposed in the Apennines). Such an eruption phenomenon, referred to as *hydrovolcanic*, occurs when very hot (magma) and cold (water) fluids mix. The resulting explosions are similar to the phenomenon so feared within foundries, where even a small amount of water in the bottom of a mold can lead to catastrophic explosions as the mold is filled with molten metal. Pyroclastic flow deposits left by hydrovolcanic eruptions consist of extremely fine-grained, glassy ash particles that are chemically unstable when deposited and are subsequently altered by water and steam. The minerals formed during the glass-water interaction bind the ash particles, thus creating the durable stone that was—and still is—quarried in and around Rome.

Another, very dense, type of tuff consists of ash and pumice particles that are actually welded by the residual heat of the deposit within weeks or months after deposition—this rock is called a *welded tuff*. In these tuffs, *fiamme* (black, flame-shaped pumice fragments flattened and welded by the weight of the overlying hot deposit) are disseminated through the rock. Welded tuffs are not common around *either* of the Roman volcanic fields, but can be found farther north, near Cimino and Viterbo, where they are quarried for use throughout central Italy as architectural trim and sculpture.

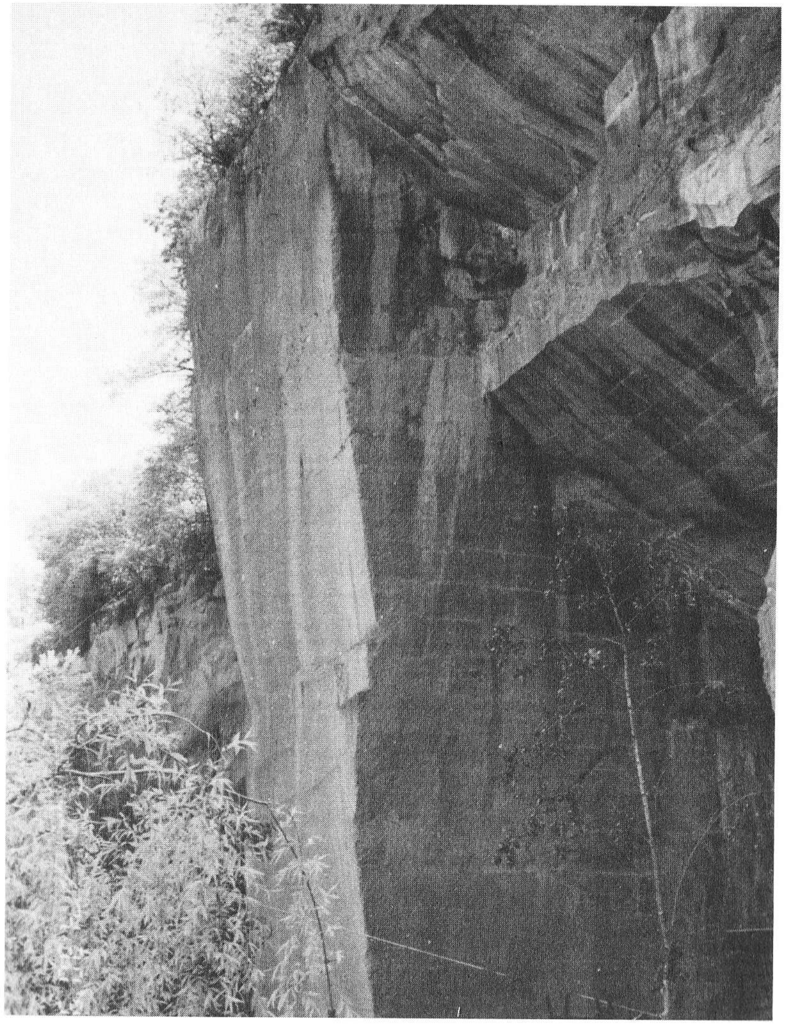
Tuffs and Rome

Rome occupies a striking, unique place within the rugged, mountainous Italian Peninsula, sitting as it does on a fertile plain crossed by the Tiber and Aniene rivers. When the very young volcanoes of Latium erupted large volumes of volcanic ash and pumice as pyroclastic flows that coursed down ravines and valleys, they filled valleys and actually changed the courses of the Tiber and Aniene rivers. The tuffs were easily eroded, yielding a landscape that is subdued, well-watered, and fertile. The rich volcanic soils provided grasses necessary for large herds and flocks of grazing animals, and the eroded tuff deposits became a countryside that was easily traversed.

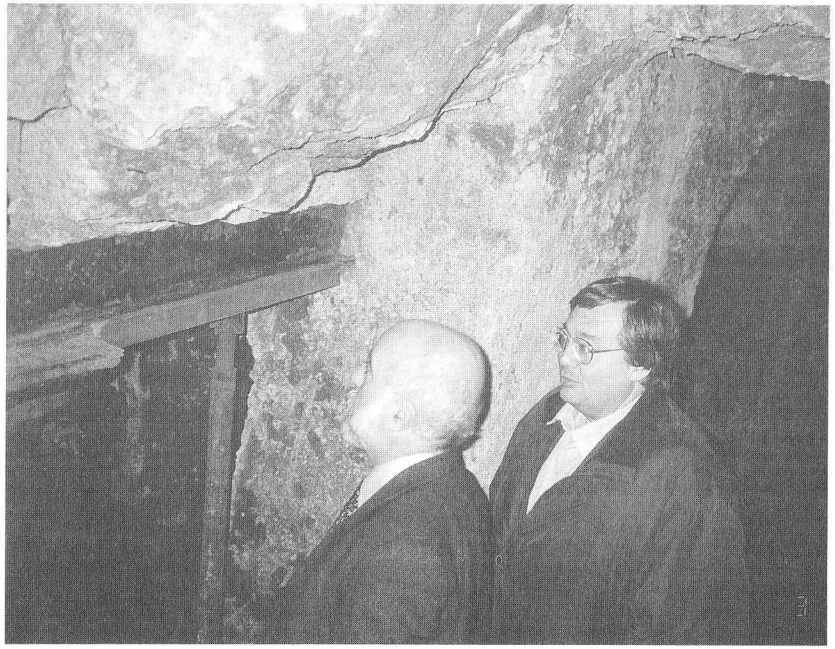
The benefits of this terrain led to prosperity but also to trouble: wealthy settlements evoked the envy and cupidity of neighbors living in the hardscrabble limestone mountains near Rome, where defense was easy but making a living from the land was difficult. Soon, more secure sites were essential for the populations along the Tiber and on the tuff plateaus. The hills created by erosion now provided defensive locations as well as easily quarried building materials. What we term the "seven hills of Rome" are the remnants of the tuff plateau.

This geologic setting strongly influenced Roman architecture through the use of the local tuff deposits for construction stone. The volcanoes around Rome produced large volumes of ash and pumice (collectively, several hundred cubic kilometers; compare this to Mount St. Helens' output of one-half of a cubic kilometer in 1980), leaving deposits that are massive, mostly without fractures, and strong—yet soft enough to be easily cut, excavated, and shaped. It is not surprising that these rocks became a foundation of Roman construction practices. Roman tuff quarries have been found in many places, especially under the seven hills and along the Aniene River. Surface tuff quarries are especially well preserved in the Alban Hills town of Marino, where the tool marks are still evident from the 1-meter-thick (about 1-yard) blocks that were cut by ancient Roman quarrymen. Tuffs of several kinds were available to the Romans and were used in proportion to their accessibility and the ease of transport into the city.

Wherever tuff deposits exist throughout the world, from Italy to Mexico, ancient humans quickly learned to excavate spaces for living quarters, storage, and even burial of the dead. It has always been easier to excavate than to build. The Etruscans and then the Romans were no exception; they used natural cavities for shelter and excavated larger homes into the soft tuffs of Latium. Centuries of experience with tuff shelters and underground quarries may have taught the Romans that the most stable shape for such a cavity is that of a vault or arch—natural openings have this shape, and artificial ones acquire it through a process of collapse. Perhaps these observations led to the vault and arch as stable construction elements, freeing Roman architects from the severe limitations of the traditional column and lintel technique and ultimately leading to the architectural explosion that became a hallmark of Roman civilization.



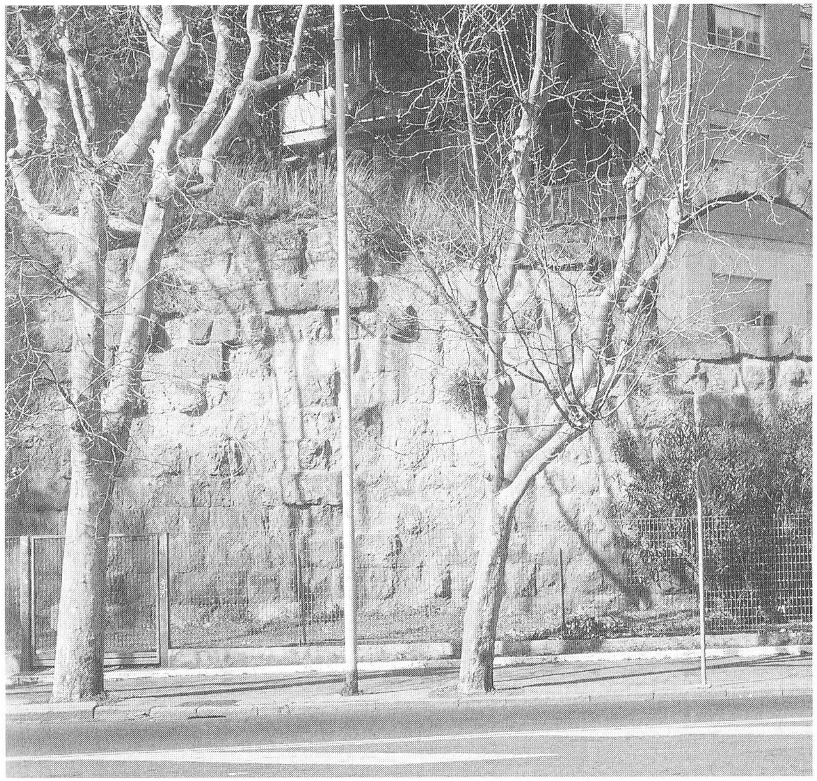
In this surface quarry in tuff deposits in the town of Marino, in the Alban Hills, early quarrymen's tool marks are still visible along the wall. These quarries follow an ancient valley filled with tuff deposits. The Roman quarrymen cut blocks that were about 1 meter (a yard) thick to be transported to Rome.



Underground Roman stone quarries and catacombs were excavated, mostly in tuff deposits, in and around Rome. In the Tomb of the Scipios, located along the ancient Appian Way, the quality of Roman stonemasonry can be seen in the close fit between the tuff block and the underlying tuff deposit. University of Roma Tre engineers Prof. Carassiti and Dr. Brancalone examined the tomb to evaluate its stability and state of preservation.

Tuffs Used in Rome

Tufo pisolitico, the most common building stone used by people in Rome from the 6th to the 5th centuries B.C., was quarried in deposits left by eruptions of the Tuscolano-Artemisio volcano of the Alban Hills between 600,000 and 300,000 years ago. The deposits of fine-grained volcanic ash contain accretionary lapilli (spheres made up of concentric layers of fine ash so that they look like small onions or hailstones when cut open; also called *pisolites*), as well as trunks or the casts of trees knocked down by the rapidly moving pyroclastic flows. When exposed, these deposits have a dirty-brown appearance, which was caused by



Blocks of *Tufo pisolitico* were used to construct the Servian Walls, the first defensive walls around Rome, which were built in the 6th century B.C. You can see this wall remnant near the Piazza Albania, at the foot of the Aventine Hill.

water and steam that quickly altered small glass shards to clay and other finely crystalline minerals.

Pyroclastic flows emanating from the Tuscolano-Artemisio volcano reached the valleys of the Tiber and Aniene rivers, leaving sequences of 5- to 10-meter-thick deposits in what is now Rome. The *Tufo pisolitico* has been exposed in quarries throughout Rome, including on the slopes of the Palatine Hill. Early settlers excavated both shelters and tombs in these tuff deposits and quarried the tuff for building stone.

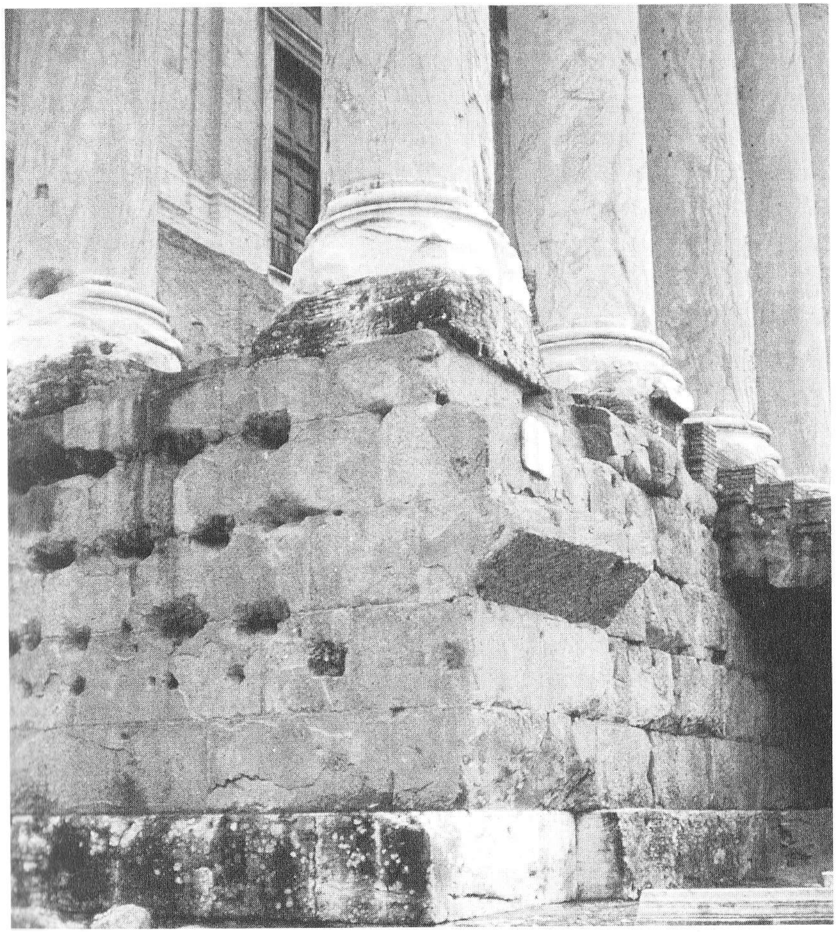
When improved transportation was available to the early Romans, their tried-and-true *Tufo pisolitico* was abandoned. After victories in the war with the Gauls and the conquest of Veii in 396 B.C., Rome acquired new territory north of the city, where the *Tufo Giallo della Via Tiburtina* is exposed. The Romans found that its strength made the *Tufo Giallo* a more effective building stone, and it was already being used for that purpose by the Etruscans. Quarries near the Tiber River made it possible to transport the tuff by barge into the city.

The *Tufo Giallo* was deposited by a large eruption of the Sacrofano volcano in the Sabatini volcanic field located about 30 kilometers north of Rome. This eruption occurred about 500,000 years ago and, like many other Latium events, was particularly energetic because it was hydrovolcanic. The tuffs were deposited by at least seven pyroclastic flows, which collectively covered an area of about 400 square kilometers and had a total volume of 8 cubic kilometers (2 cubic miles).

The *Tufo Giallo* was used throughout the Roman period; one good example is the altar of the Temple of the Deified Julius Caesar in the Roman Forum. The earliest known use of the stone was to restore the Servian Walls in 396 B.C. after they were damaged by the Gallic invasion. Where now visible, the restored walls are constructed of blocks 59 centimeters (23 inches) high, placed with the long dimensions alternately horizontal and vertical; some sections of the wall are as large as 10 meters (33 feet) high and 4 meters (13 feet) thick. Later restoration of the Servian walls occurred in many places, as we can see from imperfect junctions between *Tufo Giallo* blocks. The total length of the new (and restored) wall was about 11 kilometers (6.8 miles), enveloping an area of 426 hectares (about 1,050 acres); this enclosure made Rome the largest city on the Italian Peninsula.

Architectural guidebooks often refer to *peperino* tuff, which was quarried from two similar fine-grained deposits, the *lapis Gabinus* and *lapis Albanus*. The *lapis Gabinus* was erupted from the Gabii or Castiglione craters, and the *lapis Albanus* from the Albano crater in the Alban Hills volcanic field (where quarries are still active today). These tuffs are easy to cut yet provide relatively strong blocks. Both the *lapis Gabinus* and *lapis Albanus* peperino tuffs were commonly used throughout Imperial Roman times after a good transportation system had been established along the Via Prenestina and Via Appia.

Romans could now choose building stones for their strength and appearance, no matter how far the quarries were from the city. Today we can see numerous examples of these various tuffs from many periods



Tuff blocks in the foundation of the Temple of Antoninus and Faustina, in the Roman Forum, are partly *lapis Albanus*, one of several types of tuff favored by Imperial Roman builders.

of Roman history. The *lapis Gabinus* and *lapis Albanus* are well displayed in the Imperial fora. In the most ancient of these tuff constructions, the Temple of Antoninus and Faustina was constructed partly with *lapis Albanus*. In a later time, the Forum of Augustus was constructed largely with *lapis Gabinus* and *Lionato* tuff from the Alban Hills. *Lapis Gabinus* was also used for the foundation and walls of the Tabularium, which forms the base of Michelangelo's Palazzo Senatorio. The *Lionato* tuff was used for the back wall of the Forum of Augustus and for the substructure of the Temple of Mars Ultor, which abuts it. Contemporaneous use of both *lapis Gabinus* and *Lionato* tuff in the same period suggests that the two rock types were obtained from quarries that were not far apart. In fact, the *lapis Gabinus* quarries were located along the border of Castiglione crater close to the *Lionato* tuff quarries that were sited along the Via Tiburtina.

Monuments in the central area of Rome that include *peperino dei Colli Albani*

- Tullian Prison (3rd century B.C.)—lower rooms (possibly *Tufo lionato*?)
- Temple of Magna Mater (Temple of Cybele) (3rd century B.C.)
- Paving of the Forum (100–80 B.C.), close to Lacus Curtius and the Comitium
- Sanctuary of Sant'Omobono (100–80 B.C.)—foundations and external blocks
- Forum Holitorium (90 B.C.)—Ionic temple, both tuff and travertine; wall of the cella
- Tabularium (78 B.C.)—fluted half columns
- Forum Holitorium (80–50 B.C.)—Doric temple and foundation
- Temple of Saturn (42 B.C.)—podium, faced with travertine
- Forum of Augustus (ca. 25–2 B.C.)—back wall
- Temple of Mars Ultor (2 B.C.)—substructure
- Temple of Castor (131 B.C.)—Augustan restoration
- So-called Temple of Portunus (late 4th–1st centuries B.C.)—with other tuffs and travertine
- Temple of Antoninus and Faustina (A.D. 141)—external walls

(*From Bianchetti et al., 1994*)

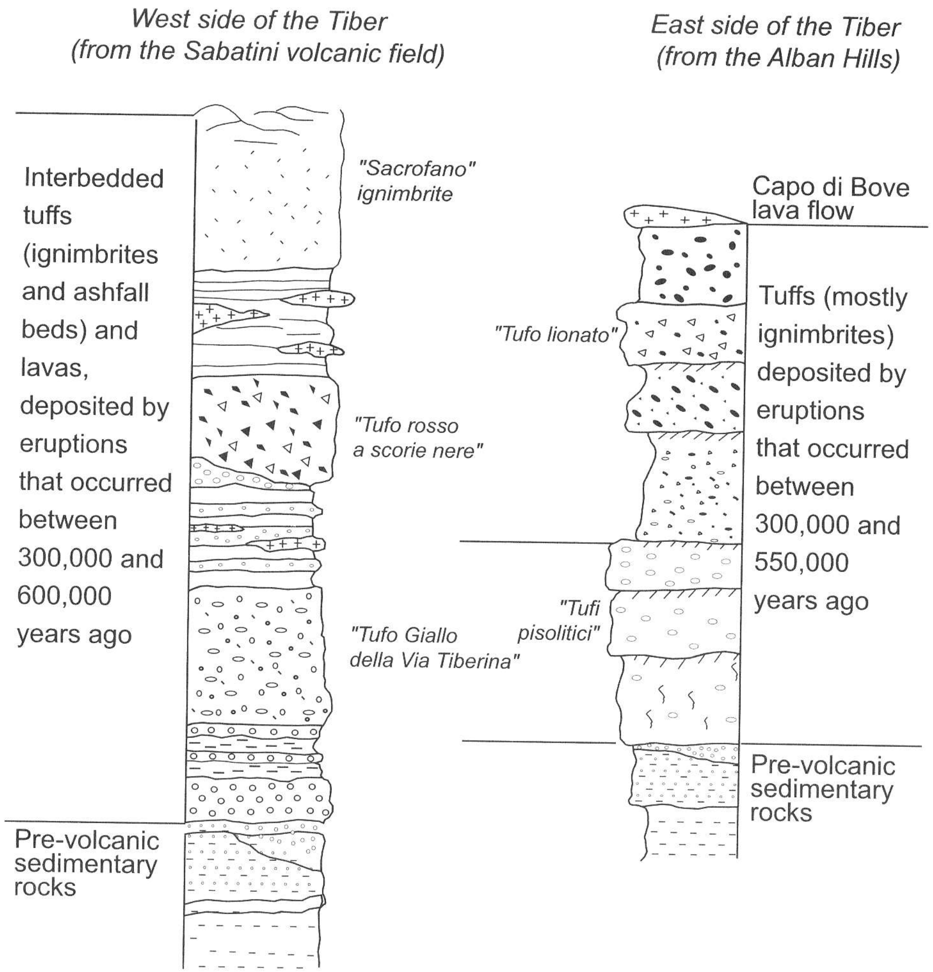
The *Lionato* stone used during Roman times probably came from near Settecamini and Salone, where the local name is *Tufo dell'Aniene* (named for an area near the intersection of the modern Via Tiburtina and the Gran Raccordo beltway). Other quarries in the same deposit were closer to the city, at the foot of the Monteverde Hill, where the stone was called—yes, you guessed it—*Tufo di Monteverde*. The Monteverde quarries were used only for a limited time, however, because of the poor stone quality there and the constant danger of collapsing pit walls.

Sperone, a deposit of welded scoria (known as volcanic cinders in the United States), was formed during lava fountaining along linear vents that crossed the central Alban Hills; this deposit underlies the northern border of the Tuscolano-Artemisio volcano. The semimolten scoria fragments were welded when they accumulated around the crater. The massive reddish gray rock is easily cut and transported. This rock was used relatively little, however, probably because of limited access to and transportation from the quarries; nevertheless, we find it as the structural base of the Colosseum, the most important modern symbol of Imperial Rome. Although no Roman-age *sperone* quarries have been found, it is likely that they were located near the Alban Hills towns of Grottaferrata and Frascati, where they would have been close to roads leading into Rome. There are outcrops of *sperone* near the site of ancient Tusculum, where there is a well-preserved Roman village with a small theater, all built with *sperone*.

Preservation of the Tuff in Roman Monuments

In 1990, archeologists and experts on monument conservation came together in a rather distant location—Easter Island, Chile—to consider how tuffs were used for construction by ancient civilizations and how to preserve the products. Italian experts on stone preservation shared their experiences with those facing similar problems at sites from Mexico to Indonesia. Appropriately, the meeting was sponsored by the International Centre for the Study of the Preservation and Restoration of Cultural Property, which is located in Rome on the right bank of the Tiber. At the time Roman engineers quarried and transported these tuff blocks, wouldn't they have been astounded to know that their work would be the subject of an intellectual exercise in a new Western world they didn't know existed?

Although certainly adequate for their purpose and actually having stood the test of time, the tuffs used by Romans for construction are beginning to show signs of wear and tear. After their excavation, tuff blocks within the Roman city are deteriorating, partly because of their



Volcanic rocks (mostly ignimbrites) for construction were brought to Rome from the Alban Hills and Sabatini volcanic fields, whose tuff deposits meet at the Tiber and overlap in places. The types of tuff highlighted in this sketch were (and still are) quarried for both building stones and feedstock for pozzolan concrete.

ability to absorb water and the heterogeneity of many of the blocks. Many examples are visible in the Forum below the Palatine Hill. One of the most interesting is the foundation of the Temple of Antonius and Faustina, where you can see the original bedding left by the pyroclastic flow that formed the tuff—great stuff for a volcanologist trying to un-

You can see tuff outcrops along the Via della Consolazione, along the southern base of the Capitoline Hill. The hill is composed of several tuffs (pyroclastic flow deposits) from the Alban Hills volcanic field.

ravel past volcanic activity, but of serious concern to a construction engineer or preservationist. The coarser grained layers in these tuff blocks have been eroded by wind and water, leaving the finer grained layers to stand out as ridges close to the original quarried surface. As long as these blocks are kept moist, they appear to retain their shape (one reason many were used to line cisterns and sewers, which are so well preserved that they could be used today if needed). Conservationists' studies at Italian universities and elsewhere are examining possible ways to preserve the crumbling tuff blocks. The work to date, using chemical approaches, has taken place in the laboratory; field tests have been limited. The problem facing these researchers is how the chemical treatments would stand the test of time. Would these blocks of tuff last another 2,000 years if treated, or would they best be left alone?

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On the Palatine Hill, the great palaces of Septimus Severus, the stadium, and the Domus Augustana were all built of brick on older stone buildings that were constructed of tuff blocks. Although tuffs form much of the foundation of Rome, bricks and concrete are some of the most visible construction materials used throughout its history.

By this time, you may be looking for some peace and tranquillity. Cross the Circus Maximus and walk to the public rose gardens located on the northeastern slope of the Aventine Hill. This is your entrance to the Aventine, one of the seven hills that is now characterized by quiet neighborhoods, churches, and parks.

CHAPTER **4**

The Aventine (Aventino) Hill

We descended a good depth in the bowells of the Earth, a strange and fearefull passage for divers miles.
—JOHN EVELYN (1620–1706), *Diary*

THE AVENTINE HILL is larger (0.4 square kilometers, or 96 acres) and somewhat more geologically complex than the Palatine. In a few respects, however, the Aventine mirrors the Palatine's form and is separated from it only by the small valley that is the Circus Maximus. The southernmost of the seven hills and closest to the Tiber, in Roman times the Aventine was dissimilar to the Palatine in that it was a residential area for middle-class citizens. Today it is one of Rome's most elegant neighborhoods.

Like the Palatine Hill, the Aventine is easily recognizable as a plateau from all sides. The most interesting and accessible approach is from the Circus Maximus to the Piazzale Ugo de Malfa, where streets radiate to the west across the Aventine. The Aventine is an excellent point from which to view the Circus Maximus, the Palatine Hill, and segments of the historical center of Rome. On clear days, you'll see the volcanic field of the Alban Hills, the source of most of the pyroclastic flows that make up the seven hills of Rome.

One of the largest of the seven hills, the Aventine is a little different than the rest. Much of the northern slope, adjacent to the Circus Maximus, consists of a sandy claystone in the form of a low hill that was later buried by pyroclastic flows (tuffs) from the Alban Hills volcanoes. The main part of the Aventine plateau is underlain by the tuffs, which filled and leveled the older terrain. Romans often quarried tuff underground for building stone, and the Palatine Hill is permeated with ancient Roman quarries. You could justifiably ask, "When it was readily available above ground, why did the Romans use underground quarries?" Economics. Because surface land was so valuable and because open quarries were heavily taxed. To see tuffs used for a defensive wall, examine remnants of the Servian Wall along the southern edge of the Aventine Hill at the Piazza Albania.

Ancient City Walls

Cities need protection during troubled times, and eventually defensive walls were constructed to encircle Rome. King Servius Tullius reputedly erected the first Roman walls during the 6th century B.C., and remnants are still visible at the base of the Aventine Hill near the Piazza Albania. The Servian Walls were constructed of *Tufo pisolitico* blocks quarried within the city. Some of the quarries for these blocks are still visible in archeological excavations below the Termini Station and at the eastern edge of the Aventine Hill. Defensive walls followed the Pomerium, a sacred line that marked the perimeter of a Roman settlement. The Pomerium was marked by boundary stones and blessed with sacred ceremonies; there could be no construction, cultivation, or burial along this line. However, cities grow, and the lines evolved. Originally, this line encompassed only parts of the seven hills, but it obviously expanded with the growth of Rome.

Little is left now of the Servian Wall built with the relatively soft *Tufo pisolitico*, but its construction marked the beginning of 2,300 years during which Rome constructed, destroyed, and reconstructed its defensive walls. In some walls, more compact, stronger stones from a variety of tuff deposits were stacked in horizontal rows (*opera quadrata*). After being arranged in rows, the blocks were bound with "double-T" metal clamps. Quarrymen marked the blocks with Greek letters to keep track of their work when it came time to collect payment for their services. You can see examples at Termini Station and on the Aventine Hill near the Piazza Albania.

Underground Rome is vitally interesting to diverse groups: officials of the City and Province of Rome, who worry about the risk of streets or buildings collapsing into an ancient tunnel; archeologists, who are always excited by a newly discovered necropolis or catacomb; business opportunists, who view the underground as a space for commercial storage or growing mushrooms (an important ingredient in Roman

cooking); and a new breed of urban speleologists, who simply enjoy the challenge of underground exploration.

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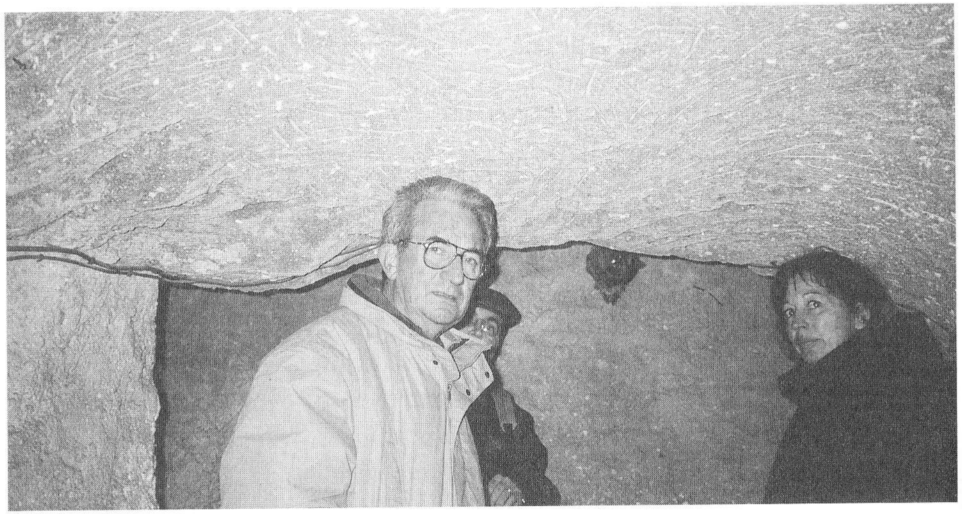
The pleasant Via San Giosafat, on the Aventine Hill, is underlain by ancient quarries. These Aventine quarries are widespread and extend under the Piazza Albania. Italian geologists Walter Santoro and Vittorio Federici have been investigating an ancient quarry complex under the southeastern part of the Aventine by drilling exploration boreholes and examining the samples they collect to determine rock types and the properties that define rock strength. First, the geologists lowered cameras through small boreholes to view the tunnels. After a preliminary evaluation, a few wider bores (of about 1-meter diameter) were drilled, and the geologists themselves were lowered into the tunnels to survey and evaluate the stability of the tuff quarries. This approach involves careful geologic mapping, precise engineering, and a bit of "Indiana Jones" (without the snakes).

The quiet, beautiful Aventine Hill neighborhood provides no indications of a serious hazard—possible collapses into ancient underground quarries, which are a problem throughout Rome. As old as many of the streets and buildings of modern Rome may be, they are still the youngest of many historical layers that make up this city, and they mask the labyrinth of tunnels that lies underneath. Despite valiant efforts by geologists, engineers, archeologists, and utility workers, occasionally buildings and streets collapse into underlying tunnels.

No one knows precisely the magnitude of Rome's underground real estate. In some respects, trying to determine its size is similar to guessing the extent of an ant colony on the basis of the surface hole and mound. Why is Rome underlain by a labyrinth? Over the last 2,800 years, tunnels have been excavated for both economic and funerary purposes—chiefly for construction materials and places to inter generations of the dead. In addition, there were underground springhouses, cisterns, drains, theaters, houses, villas, churches, and, recently, utility tunnels. All the tunnels are man-made; none are natural. Many underground cavities are mentioned in historical records, but just as many were buried and forgotten after the destruction that accompanied earthquakes, fires, and invasions.



Rome is underlain by a labyrinth of tunnels that were cut for the purpose of quarrying the stone or for catacombs, shrines, and chapels. Today, these spaces are attracting interest from widely diverse groups: archeologists, safety experts, business opportunists, tourists, and speleologists. In the Tomb of the Scipios, spaces were carved in tuff deposits along the Appian Way. Tool marks are still visible on the ceiling of this tomb, which was active from the 3rd century B.C. to the 1st century A.D. The tomb was discovered 300 years ago by an Appian Way cantina owner who was digging a new basement.

One of the most famous underground structures in Rome is now open for tours. When Nero's "Golden House" (Domus Aurea) was built after the great fire of A.D. 64, the buildings covered 200 acres of the Esquiline Hill. No expense was spared in creating this sumptuous Imperial home. After Nero's suicide in A.D. 68, the Domus Aurea was forgotten (*damnatio memoriae*) to erase the memory of the unpopular emperor. The palace was progressively covered by portions of the Colosseum and by the Baths of Titus and Trajan. Only some subterranean rooms of the Imperial apartments have survived, along with well-preserved frescoes, and are accessible along the Via Labicana below the Oppian Hill.

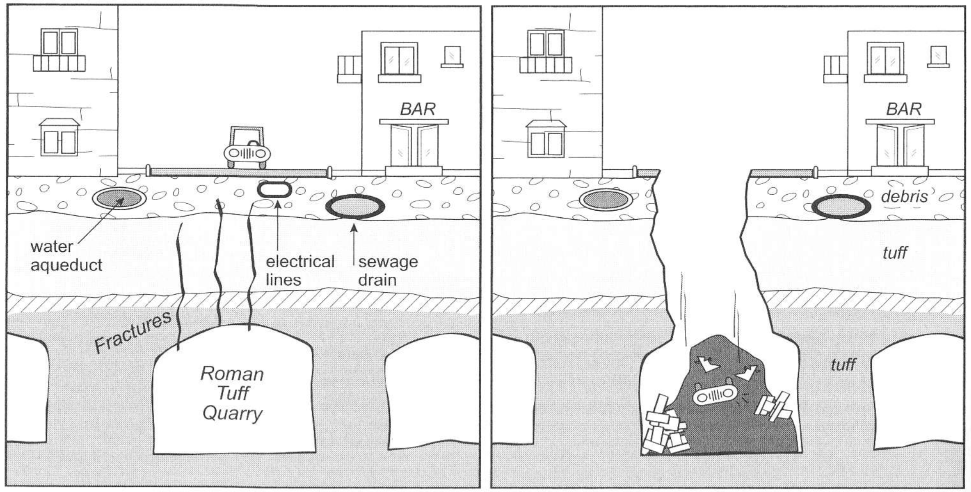
Contrary to the ideas put forth in popular movies, tunneling in ancient times had little to do with intrigue or religious freedom; it occurred simply because much of Republican and Imperial Rome was underlain by thick tuff deposits. The relatively soft tuffs were easy to

excavate and, as discussed earlier in this book, provided reasonably good (and cheap) building stone. Underground quarries may have several levels and are usually within the first 4 to 15 meters (13 to 50 feet) below the ground surface. To safely cut and remove rock, Roman quarrymen used a "room and pillar" technique—something like an exaggerated version of an underground parking garage, except that the quarries' stone pillars are much thicker than the concrete pillars of a parking garage. Rooms are between 2 to 3 meters (7 to 10 feet) wide and 2 to 5 meters (7 to 16 feet) high, and the pillars are 5 to 25 meters (16 to 80 feet) on an edge. With the huge demand for construction stone in Rome, the tunnel networks eventually grew to underlie all the tuff plateaus, including the seven hills. Although the quarries were relatively safe when excavated, some of the stone pillars are beginning to degrade and fail, especially after centuries of constant vibration and irregular weight distribution of the evolving city overhead.

The Catacombs, multilevel tunnel networks excavated to inter the dead, expanded rapidly when Christian and Jewish communities of Rome began to choose burial rather than cremation, which generated a land shortage for above-ground tombs and cemeteries. Another factor might have been a shortage of fuel wood that increased the expense of cremation. Catacomb internment was an efficient use of space, and it allowed families to place the deceased faithful near a sacred place or the remains of a saint. Eventually, the Catacombs became tourist attractions. For example, in the Jubilee Year of 1450, the catacombs of San Sebastiano attracted tens of thousands of pilgrims.

You can see how the geologic setting made it easy to excavate catacombs if you follow the Appian Way to the catacombs of San Sebastiano and San Callisto (Callixtus), the oldest official Christian cemetery in Rome. Walking from the city, you pass under the city wall at Porta San Sebastiano and up a gently rising plateau, formed when pyroclastic flows erupted from the volcanoes of the Alban Hills. Within this tuff, the catacombs of San Callisto were established by the Deacon Callixtus in A.D. 199 and then expanded when he was pope (A.D. 217–22). These catacombs once held the remains of the nine popes who reigned between A.D. 230 and 283; all remains were later moved to the Vatican.

The catacombs of San Callisto are on four levels, the deepest of which is 20 meters (65 feet) below the surface, and are composed of 20 kilometers (12 miles) of narrow galleries along which the dead were in-



Rome's underground cavities are historically important, but they present a potential hazard for the modern city, as shown in this diagram.

terred in *loculi* (niches) above the gallery floor. After an internment, the loculus was sealed with stone and plaster. The stability of the narrow galleries is evident; there are few signs of collapse during the last several thousand years. Some of the catacombs were discovered by accident (the catacombs of San Callisto were encountered in 1578 by a workman digging in a vineyard), and it's possible more will be found in the future (one hopes *not* as the result of the collapse of overlying apartment buildings). Tunnel complexes also underlie the Via delle Sette Chiese and the Via dell'Arco Travertino, streets that pass through modern suburbs along the city's southeastern edge. Complex tunnel networks beneath the many densely packed apartment buildings raise questions about the safety of the area.

When engineers Federico Pagliacci and Maurizio Conti were contracted to evaluate an ancient tunnel system underlying the Santa Beatrice School on the Aventine, they employed some modern techniques. You can imagine the scene. Watching workers drill into a cavity at perhaps a few meters an hour, more or less, you get into a somnambulant rhythm—the penetration rate and pitch of the spinning pipe create a comfortable feeling about extracting a good core. It is a time for

It's easy to recognize the potential dangers posed by unstable tunnel networks in this photo of a Roman street that has collapsed into an underground cavity.

daydreaming. Suddenly, the drill string drops abruptly after entering a cavity, disturbing this reverie, shaking the drill rig sharply, and surprising the driller, judging by the expletives he emits. The process is repeated again and again in a series of small-diameter boreholes that will identify the basic outline of the underground tunnels. Now, workmen insert a small, high-resolution television camera and a rod with meter marks (for scale) into adjacent boreholes. By scanning 360 degrees with the camera, they produce a group of images they can use to map the tunnels without actually entering them. With a general idea of the shape and size of the tunnels, the engineers develop a plan for stabilizing the cavities. Workers insert stiff but expandable plastic tubing into the holes and pump concrete through the tubing to form supporting columns that will, engineers hope, reinforce these ancient tunnels.

Archeologists in Rome view the underground more as a part of the cultural heritage than as a geotechnical hazard. One of the goals of the City of Rome is to identify and preserve tunnel systems, especially if they involve underground cemeteries or temples. Other important features of Roman heritage are the tunnels carved for ancient aqueducts and water distribution systems or for drainage systems.

In addition to the professionals evaluating underground Rome, a determined group of volunteers make up the first group of urban speleologists (known in North America as "spelunkers"). This group is adding to the wealth of information about Roman history by creating Web pages and handbooks on subterranean Rome, which sun-weary tourists can use as guides or for a virtual tour to Rome's more famous subsurface attractions.

The subsurface of Rome needs systematic mapping to identify and evaluate all ancient quarries, catacombs, and tunnels used for aqueducts. Depending on your interest—engineering geology or entrepreneurial possibilities, for example—the ancient underground quarries can be a fascinating historical resource or a menace. Rome's underground should be evaluated for the potential collapse hazard and as possible space for commercial development. Despite 3,000 years of history, there is still challenge in the exploration of Rome.

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While on the Aventine Hill, visit the early Christian Basilica of Santa Sabina, which overlooks the Tiber River. The park next to the basilica provides excellent views across the Tiber's floodplain into Trastevere and the Vatican. From this vantage point, it is easy to see why the Tiber has been so important to Rome—both as the chief means of transport and as the source of catastrophic floods.

CHAPTER 5

The Tiber Floodplain, Commerce, and Tragedy

The City of Rome is nearly all inundated by water. Along the riverbanks, since 1846, there have been no similar cases where water has risen over a meter above the average level of the river. The Via della Tipografia, where our newspaper is printed, is also under water. The water reached a meter. Piazza Colonna, toward 11 A.M., was under water. At present, flooded are: La Lungara, Piazza della Rotonda, Piazza Pia, Piazza Navona, Piazza Giudia, Piazza Montanara, Il Ghetto, namely, Via Fiumara, Piazza S. Andrea della Valle, Piazza S. Eustachio, Piazza and Via del'Orso, Piazza Campo de' Fiori, and the street of Via Tor di Nona, the Ponte S. Angelo at the Montebianco end, along the Piazza dell' Orso, S. Lorenzo in Città.
Il Tribuno, December 28, 1870

WITHOUT AN excellent map and a good sense of direction, you can become thoroughly disoriented as you explore the area of Rome that is on the Tiber's floodplain. One solution is to stay on the busy streets that follow the riverbank (the Lungotevere, "along the Tiber"). The scenery is superb, and you can spend days studying the bridges, but you must eventually enter the districts, such as Trastevere or the Campo de' Fiori, that sprang up along the margins of one of the world's best-known rivers. In search of famous sites in this area, nearly every visitor to the Eternal City ends up at the Pantheon. We begin our visit to the floodplain neighborhoods at Santa Maria Sopra Minerva, which is close to the Pantheon.

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One of the few examples of Gothic architecture in Rome, the Church of Santa Maria Sopra Minerva is in the heart of the historic district.

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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

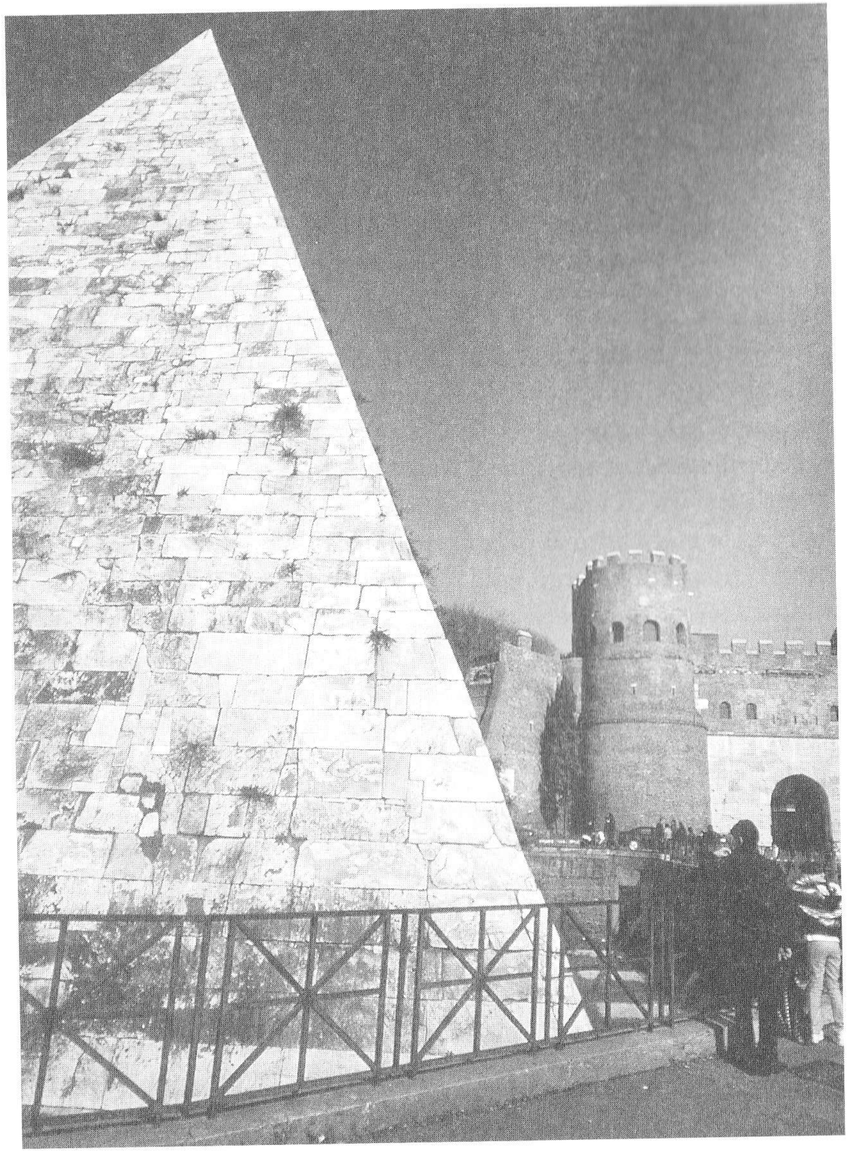
The Tiber's Tributaries in Rome

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

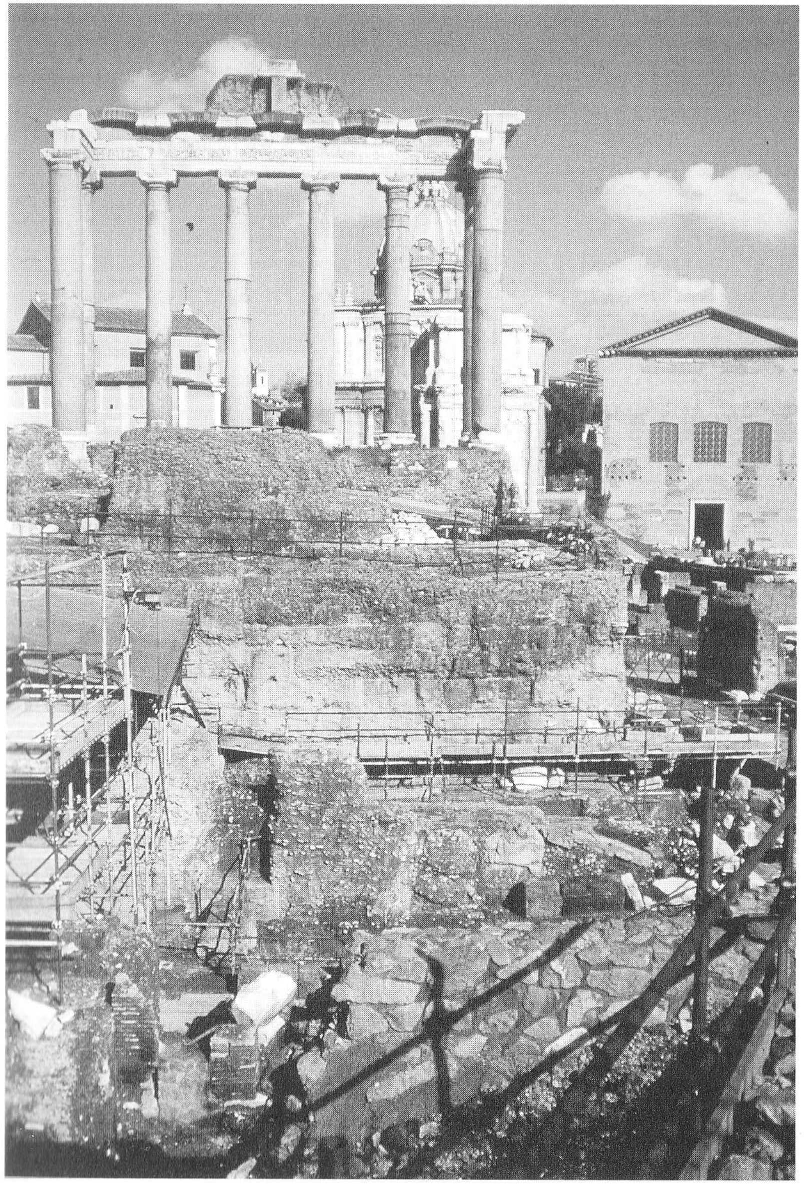
Humans generate and accumulate a lot of waste. We sack it, stack it, hide it, burn it, recycle it, or pay someone to take it elsewhere—anywhere we can't see it or smell it. In today's world, with greater material consumption, we generate increasingly enormous masses of debris that must be disposed of 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.

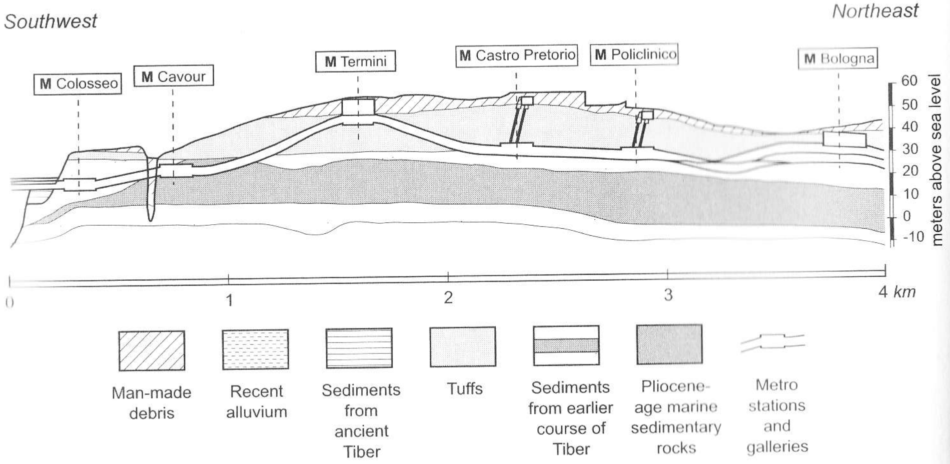
demolition, and reconstruction. If you look carefully, you'll observe the complexity and heterogeneity of the layers and appreciate the years of education and experience that lie behind archeological observations.

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.

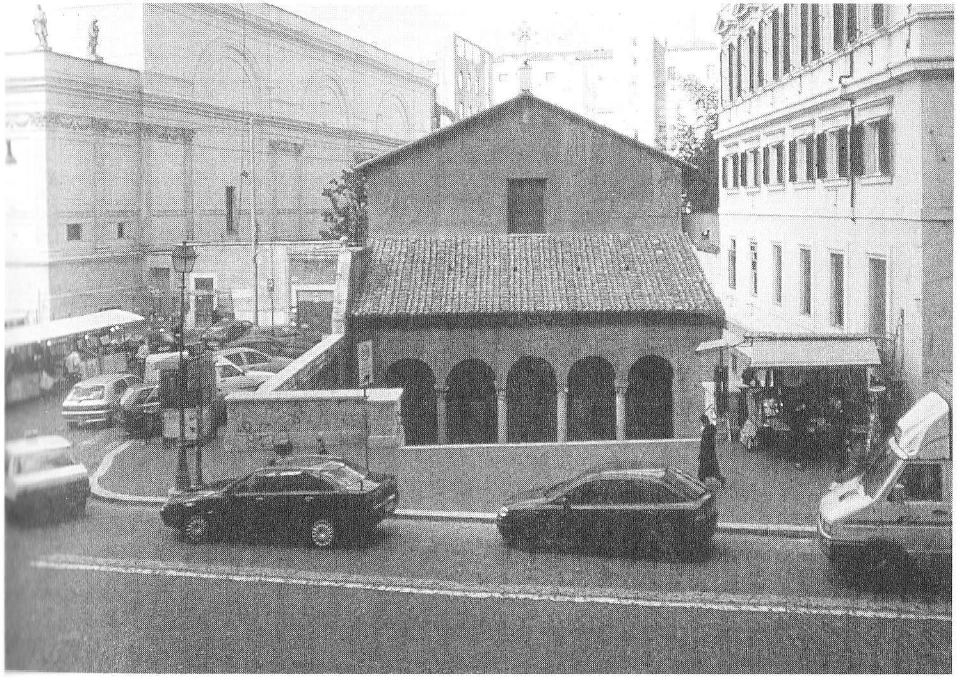


You get an idea of the remarkably thick layer of man-made debris that covers the city by studying this geologic cross section along the Metropolitana B (subway) between stations at Piazza Bologna and the Colosseum. For example, the ravine near Cavour station is filled with 20 meters (66 feet) of debris. 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.

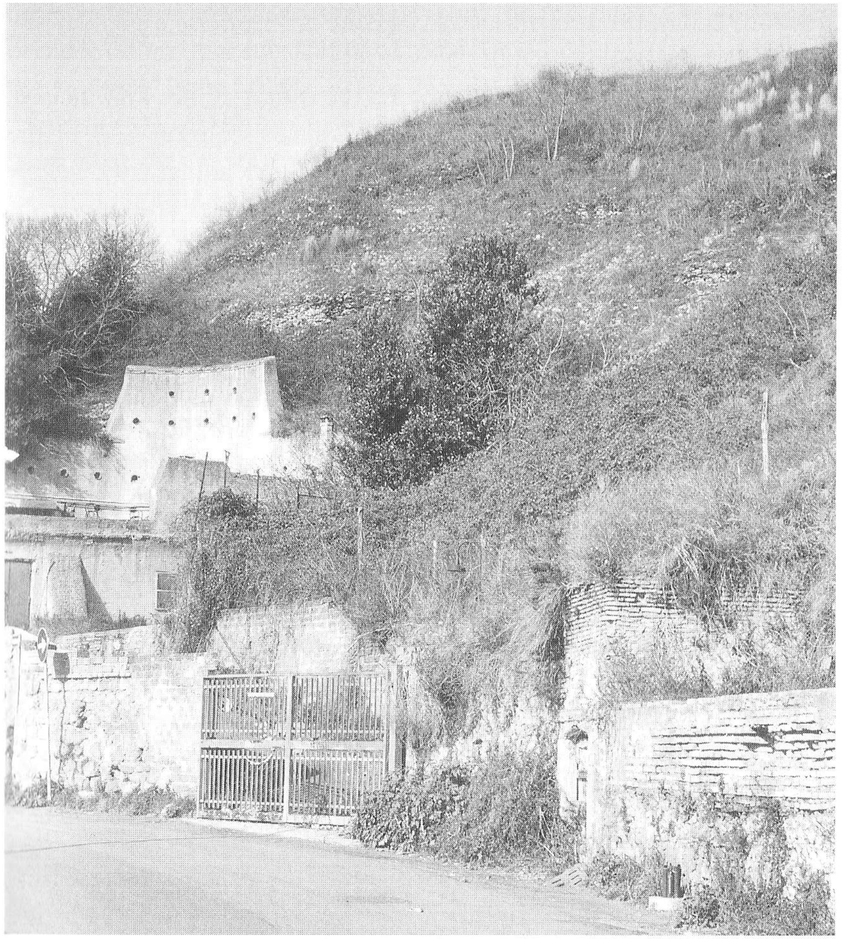
mini Station, the southwest embankment of the Circus Maximus, Via Cavour, Porta Melonia, and Piazza Tuscolo.

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?

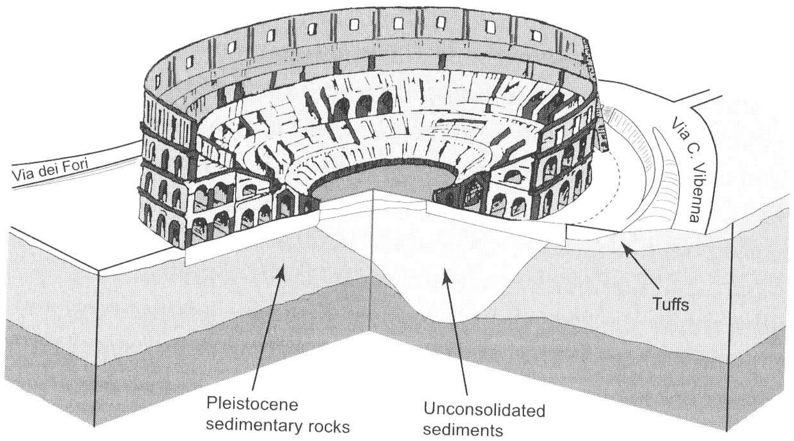
A tablet located in the entrance of the building that has become a symbol of Rome and the Roman Empire—the Colosseum—describes the generosity of Decius Marius Venantius Basilius in subsidizing repairs after earthquakes that occurred between A.D. 443 and 484. Rome is

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

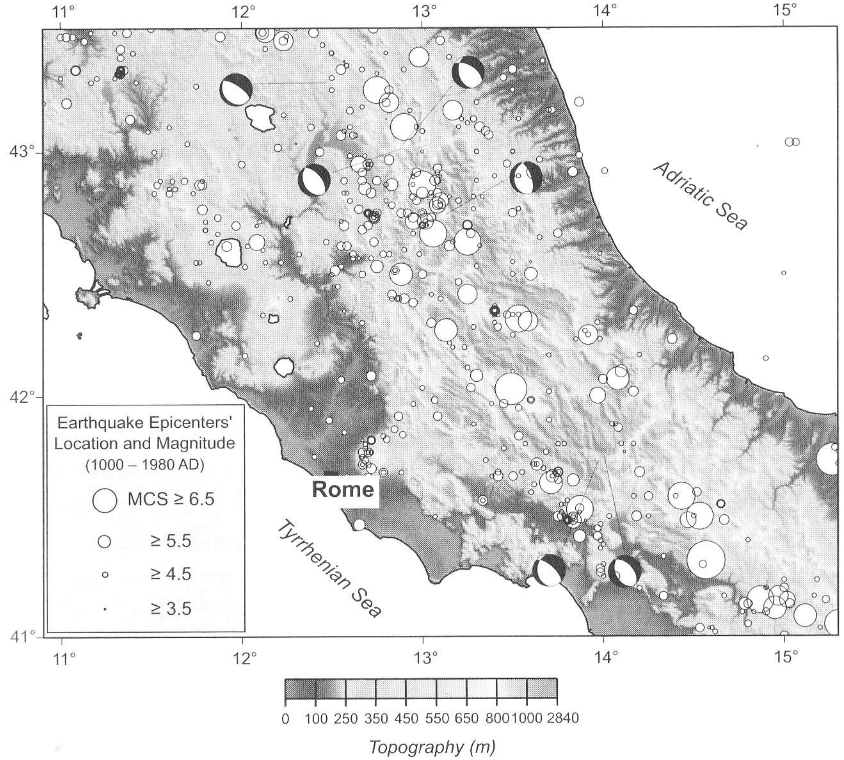
The earthquakes felt in Rome historically originate in three areas:

- 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.

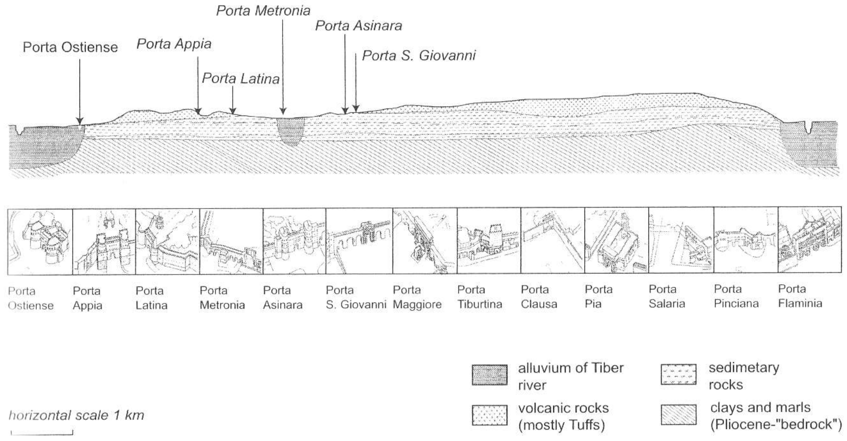
The Aurelian Wall

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.

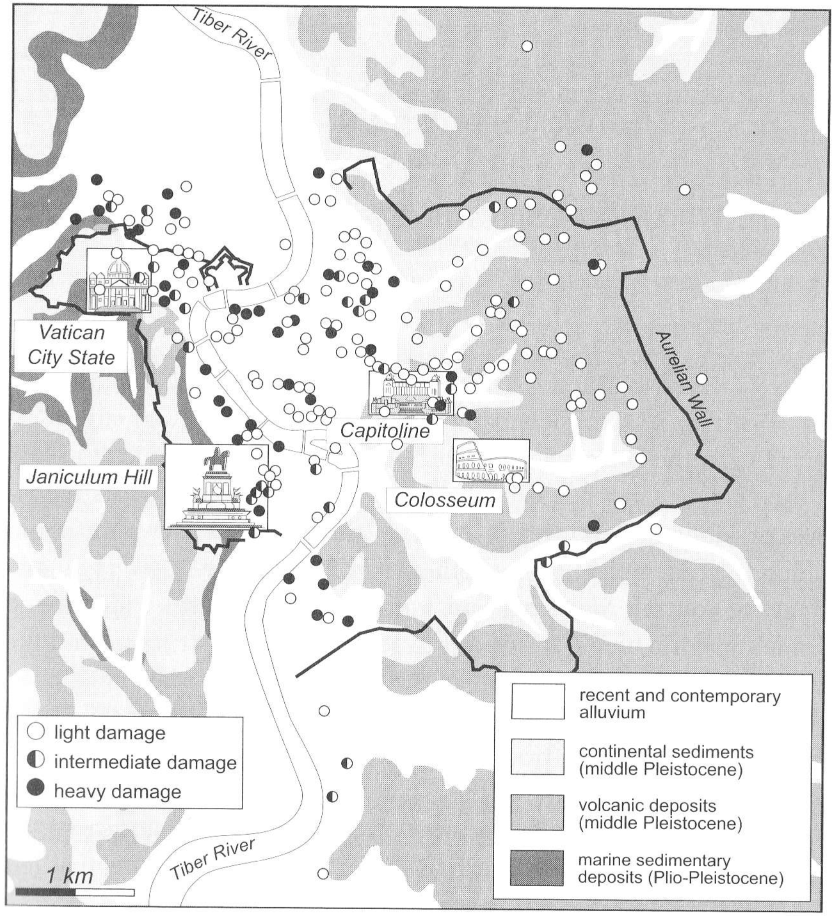
More Clues from Conservation and Restoration of Historic Buildings and Monuments

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.