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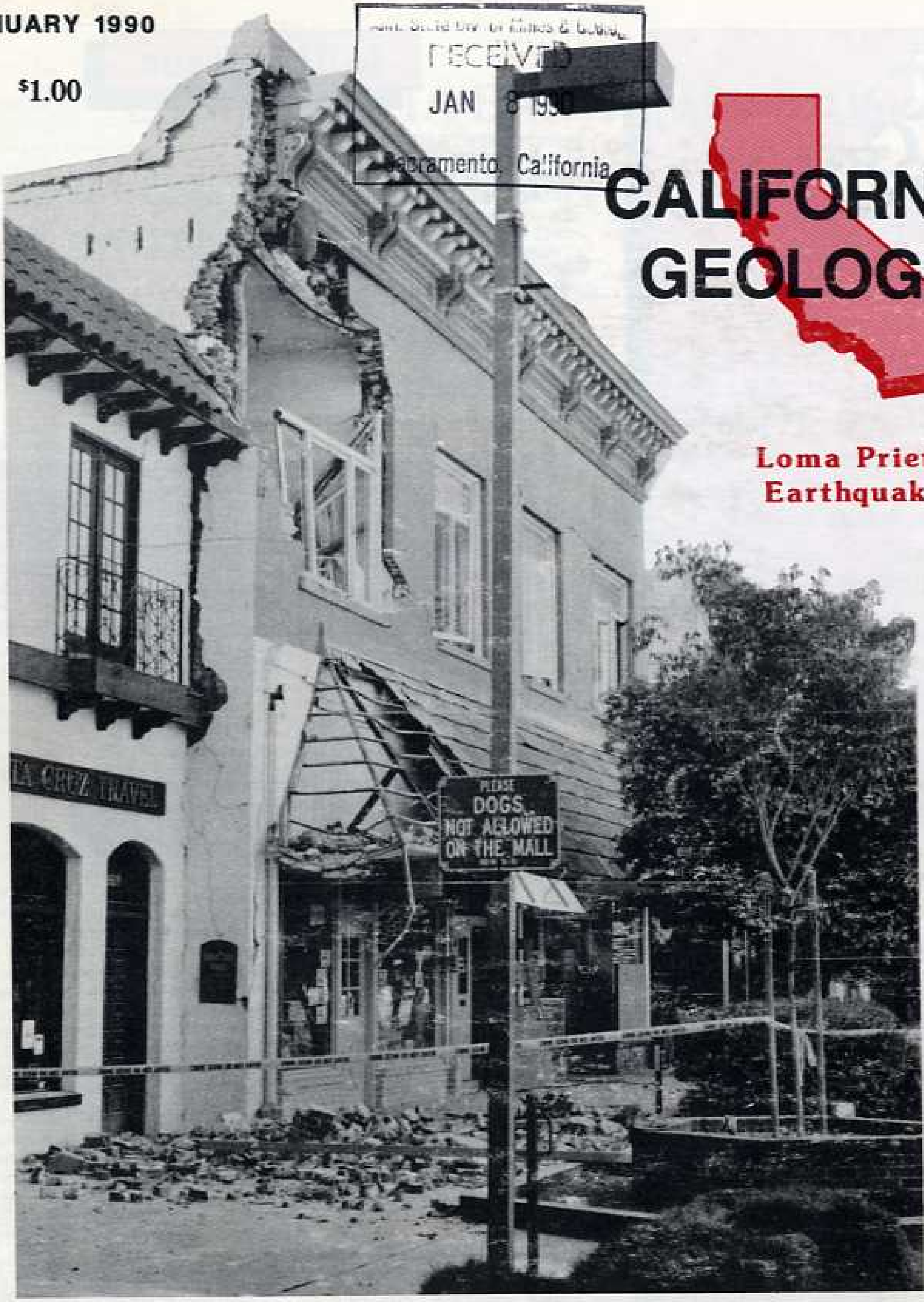
CALIFORNIA GEOLOGY

Loma Prieta Earthquake



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Effects of the Loma Prieta Earthquake
October 17, 1989

San Francisco Bay Area

By

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Photo 1. Partially collapsed house, Los Gatos, California.

INTRODUCTION

Anyone who was watching the world series on Tuesday, October 17, 1989 knows what happened in the San Francisco Bay area at 5:04 p.m. on that day. For several days immediately after the earthquake I surveyed damage and geologic effects caused by the temblor to document effects of the earthquake that were not well covered in the media. This photo essay offers some observations on the damage that occurred throughout the San Francisco Bay area (Photos 1-14).

The San Francisco Bay area is located in one of the most seismically active regions of the world, where the North American and Pacific plates collide (Atwater, 1970). Repeated offset along the San Andreas fault system plate boundary has resulted in more than several hundred miles of displacement over the last 30± million years (Atwater, 1970; Fox and others, 1985; Stanley, 1987; Graham and others, 1989). Most of the stress across this tectonic suture is accommodated by right-lateral motion, although a compressional component is reflected in the continuing uplift of the California Coast Ranges.

TABLE 1. SAN FRANCISCO BAY AREA EARTHQUAKES RESULTING IN SIGNIFICANT DAMAGE[1]

Year	Epicenter	Fault	Magnitude*	Intensity**
1836	Hayward	Hayward	7 ±	IX-X
1838	San Francisco	San Andreas	7 ±	X
1852	SF Peninsula	San Andreas	?	VIII
1858	San Jose	Hayward	?	VIII
1861	Livermore	Calaveras	7 ±	VIII
1865	Santa Cruz Mts.	San Andreas	7 ±	VIII-IX
1868	Hayward	Hayward	6.7	IX-X
1906	San Francisco	San Andreas	8.3	XI
1911	San Jose	Hayward	6.6	VII-VIII
1954	Watsonville	San Andreas	5.2	VIII
1969	Santa Rosa	Healdsburg	5.7	VII-VIII
1989	Santa Cruz Mts.	San Andreas	7.1	IX-X[2]

[1] Historic earthquakes with a Modified Mercalli Intensity of VIII or greater compiled from Coffman and von Hake (1973), Youd and Hoose (1978) and Jennings (1985).
[2] Estimated by author
* Richter scale magnitude is based on the energy released by the earthquake. It is a logarithmic scale based on pi where an increase in magnitude of 1.0 reflects a 33 fold increase in the energy released by the earthquake.
** Modified Mercalli Intensity Scale (Wood and Neumann, 1931) is based on the damage resulting from the earthquake and thus reflects both geologic and engineering factors. An intensity of VIII is defined by considerable damage, including partial collapse, to ordinary buildings and fallen chimneys. An intensity of XII describes total destruction.

Over time, the collision of the Pacific and North American plates has caused recurrent earthquakes separated by periods of relative seismic quiescence. The Loma Prieta earthquake is the latest in a series of destructive earthquakes that have rocked the San Francisco Bay area during historic times (Table 1). The epicenter was located on the San Andreas fault roughly 56 miles south of San Francisco in the Santa Cruz Mountains. Hundreds of aftershocks were recorded during the weeks after the earthquake.

Photo 2. Collapsed chimney and fireplace showing total destruction of masonry but little structural damage to the wood-frame house.

Photo 3. Car crushed by falling bricks from a masonry building.

OVERVIEW OF DAMAGE

Immediately after the shaking subsided, clouds of dust rising from crumbled structures in west Oakland were visible in Berkeley. Later that night the only light visible in the city of San Francisco was from the fire raging in the Marina district. Sixty-seven people were killed by the direct effects of the earthquake and hundreds of others were injured. The estimated cost of earthquake-related damage ranges from five billion dollars to more than ten billion dollars. Most of the damage, however, was concentrated in relatively few areas and much of the Bay area was relatively unscathed. Damage was generally limited to locations near the epicenter, where ground shaking was severe, and to areas underlain by poorly consolidated deposits or artificial fill, particularly where ground settling and liquefaction occurred.

Structural Damage

Hundreds of buildings were damaged in the city of San Francisco. The affected buildings were located in several districts. The worst impacted area of the City was the Marina district. Thirty-five buildings in this area were destroyed and about 150 others were structurally damaged. The area is underlain by sand fill emplaced after the Panama Pacific Exhibition in 1915. Many buildings on landfill in the area south of Market Street were heavily damaged and some will be demolished. Liquefaction of fill in the Mission district also damaged some buildings beyond repair. Scattered damage occurred in the Richmond, Sunset, Haight, and other districts, but generally damage was less severe than in areas underlain by man-made fill or unconsolidated deposits.

Closer to the epicenter severe ground shaking caused extensive damage. In Santa Cruz, virtually the entire downtown mall and several hundred houses were either severely damaged or destroyed. Many homes were flattened in the nearby Santa Cruz mountains. In Watsonville and Los Gatos major damage occurred in both downtown and residential areas. Stanford University sustained structural damage to a number of buildings (including Geology Corner of the Quad). Collapsed and structurally compromised buildings were also reported from Gilroy, Hollister, San Jose, and Oakland. Damage to chimneys, sidewalks, roadways, and parking lots was widespread throughout the Bay area and in some places damage was severe. The most lethal (and best publicized) catastrophe was the collapse of the Cypress structure on Interstate 880 in Oakland. In addition, a portion of Highway 101 also collapsed and severe damage to structural supports occurred on several other elevated highways.

Causes of Damage

Usually, earthquake-related damage can be attributed to fault rupture, severe ground shaking, landsliding, or liquefaction. Only the latter three occurred at several locations in the Bay area during the Loma Prieta earthquake. The distribution and severity of the resulting damage reflects the interaction of the earthquake, man-made structures, and local geologic conditions. Given the location and size of the earthquake, the distribution and severity of damage were to be expected.

GROUND SHAKING

The intensity of ground shaking at a specific location is a function of the distance from the earthquake epicenter and the way in which seismic waves propagate through different kinds of subsurface materials. At a given distance from the epicenter, ground motion will be strongest in poorly consolidated deposits or artificial fill, somewhat less strong in

Photo 4. Collapsed apartment building in the Marina district, San Francisco.

Photo 5. Severely damaged building in downtown Los Gatos. Few of the surrounding buildings showed external signs of severe structural distress, although many windows were shattered throughout the downtown area.

alluvium, and of minimal strength in bedrock. Local topography can also increase the severity of ground shaking by focusing seismic waves onto narrow ridgetops. The severity of damage will depend on both the magnitude and frequency of ground acceleration and on the design of structures. Neither the location nor the magnitude of earthquakes can be controlled. Therefore, potential damage from future ground shaking can only be mitigated by tailoring structural designs and land use to the local geologic setting.

During the Loma Prieta earthquake severe ground shaking caused a variety of damage to structures. The worst ground shaking appeared to occur in the Santa Cruz Mountains where many buildings were damaged or destroyed by ground cracking and shaking, as well as landsliding. Farther from the epicenter, the damage due to groundshaking was much more selective due to both local geology and type of buildings. For example, many houses not bolted to their foundations partially collapsed and some older houses suffered severe damage from partial failure of their foundations (Photo 1).

Photo 6. Partially collapsed building in the downtown Santa Cruz mall. Notice how the masonry had been covered by a layer of plaster.

Photo 7. Collapsed double-deck portion of Interstate 880 in west Oakland. Few of the people who were on the lower deck survived when the support columns sheared and the upper deck collapsed.

Photo 8. Collapsed portion of Highway 101 over Struve Slough near Watsonville. Note the support columns that punctured the roadway.

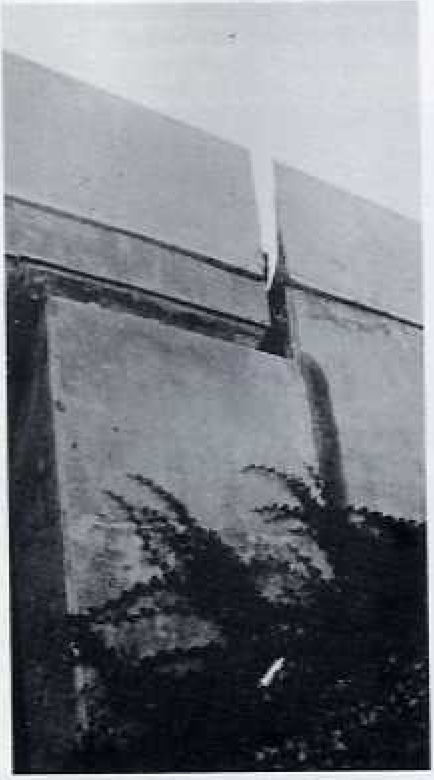

Photo 9. Expansion joint on the Highway 92/101 cloverleaf. The two sections of concrete are separated by styrofoam to allow them to readjust during severe ground shaking. Separation at this particular joint appeared to be on the order of several inches.

Some brick structures fared quite poorly during the earthquake. Unreinforced masonry has little shear resistance or tensile strength; it can carry the compressive load of its own weight but is vulnerable to displacement and failure when sheared or stretched.

Thousands of chimneys were damaged throughout the Bay Area (Photo 2) and damage to masonry buildings ranged from complete collapse to the partial loss of brick facades (Photo 3). In San Francisco, buildings in the downtown area and south of Market Street sustained severe structural damage. Five fatalities resulted when part of the top story of a brick office building collapsed onto cars. Many buildings in the Marina district lost all or pieces of their brick facades and many of the facades that did not fail catastrophically were extensively fractured. Large apartment buildings collapsed into first floor parking garages (Photo 4); some four story units were compacted to two stories tall during the earthquake. Loss of water pressure due to damaged water mains inhibited efforts to fight a conflagration fed by ruptured gas lines. The areas of San Francisco where ground shaking was especially destructive are mostly underlain by fill and unconsolidated deposits.

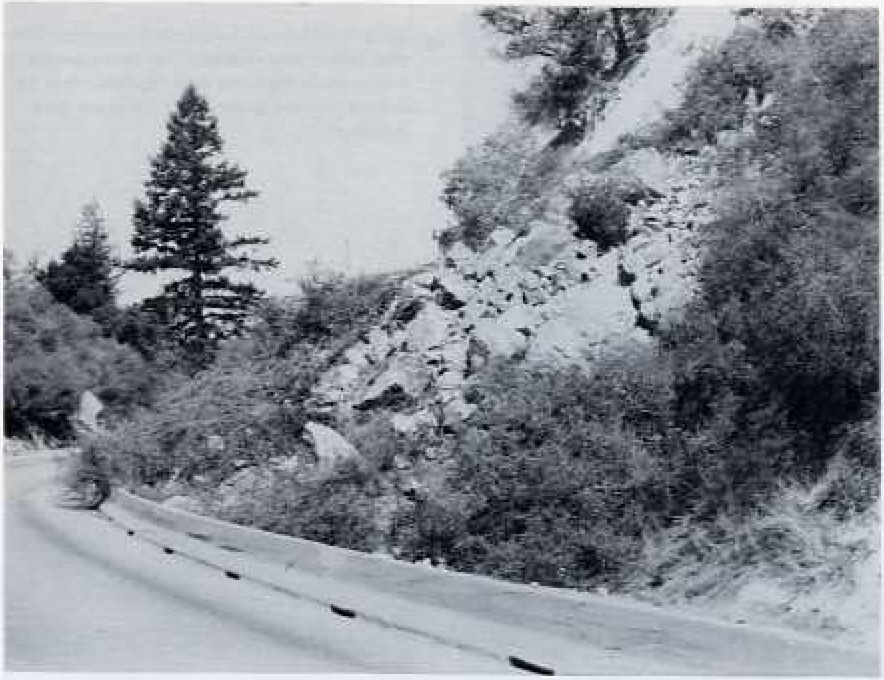

Photo 10. Rock avalanche from a cut slope on Highway 17 west of Summit Road in the Santa Cruz Mountains. The landslide stopped against the center divider and buried the eastbound lanes. Debris was still falling from the scarp two days after the earthquake.

Many old brick buildings in downtown Oakland were severely damaged. Masonry buildings in downtown Los Gatos and Santa Cruz were also completely or partially collapsed (Photos 5 and 6). Some newer concrete buildings were damaged, although the vast majority of structural damage that was observed involved either residences that had detached from their foundations or unreinforced masonry buildings.

Damage was quite variable to the freeways throughout the region. The most spectacular example was the collapse of Interstate 880 (Photo 7). The specific causes of this failure are being investigated. Highway 101 also collapsed near Watsonville (Photo 8) and many other freeways sustained structural damage. In Oakland, Highway 980 and the MacArthur Maze developed cracks in the support columns. Across the bay in San Francisco, the Embarcadero Freeway and a portion of Highway 280 were also severely damaged. An illustration of the behavior of one newer design is shown by the performance of the Highway 92/101 interchange in San Mateo. Expansion joints in this structure separated up to several inches during the earthquake (Photo 9), but did not disengage.

Photo 11. Ground cracks near Summit Road in the Santa Cruz Mountains. Initially interpreted as fault offset, many similar features throughout the area were due to large-scale landsliding initiated by the earthquake.

Photo 12. Damage at the Port of Oakland due to liquefaction and slumping of fine-grained, well-sorted sand fill.

Photo 13. Crater resulting from liquefaction of dune sand underlying a parking lot next to the Watsonville Slough at Pajaro Dunes. Ripples still preserved on the surface of the collapsed blacktop indicate that water and sand were flowing out of cracks in the pavement prior to its collapse. After the shaking began to subside, the water pressure supporting the pavement fell and the surface collapsed into the hole left by the evacuated sand.

In addition to the obvious damage to many structures, hidden structural damage may have weakened other buildings. The extent and severity of hidden structural damage will be very hard to assess and may never be completely known.

LANDSLIDES

Landsliding has also long been recognized as a potential consequence of earthquakes (Keefer, 1984). Seismic events can both initiate landsliding and reactivate older massive landslides (Lawson and others, 1908; Harp and others, 1981). Consequently, the best mitigation is to avoid building in areas of slope instability. However, it is sometimes difficult to predict where new or reactivated landsliding may occur during earthquakes.

Most of the landsliding clearly attributable to the Loma Prieta earthquake was located in the Santa Cruz Mountains. Many roadcut failures occurred along Highway 17 between San Jose and Santa Cruz and one rock avalanche entirely blocked the eastbound lanes (Photo 10). The ground surface ruptures originally portrayed in media reports as fault offsets were actually due to large-scale landsliding caused, or reactivated, by the earthquake (Photo 11). In the Santa Cruz Mountains many homes have been either destroyed or are threatened by ground movement which may be aggravated by winter rains.

Landsliding also occurred on coastal bluffs and sea cliffs along the San Mateo County coastline. Apparently one person was killed by sea cliff collapse during the earthquake.

LIQUEFACTION

Liquefaction can occur when saturated, cohesionless soil experiences a cyclic shear stress. Fine-grained, well-sorted sands are most susceptible to liquefaction because they tend to contract upon shearing. Seismic shaking settles the saturated, loosely packed sand, reducing the pore space, increasing pore pressures, and reducing the effective stress. In essence, the grains are supported only by the fluid. The ground may then deform either moderately (ground cracking) or catastrophically (ground flow) before the sand regains stability. Structures built on areas that liquefy may collapse as a result of ground failure and movement. The best mitigation is to avoid building in areas likely to liquefy during seismic shaking. Many existing buildings throughout the San Francisco Bay area are located on poorly consolidated deposits or man-made fill potentially subject to liquefaction during earthquakes. These areas may experience ground failure even when distant from the earthquake epicenter.

Evidence for liquefaction is easily destroyed. Much of the evidence that was observed had already been obscured to some degree by rain and/or cleaning crews. However, sand boils in the Port of Oakland, the Marina district, and at the Santa Cruz Boardwalk were observed. Sand that appeared to have risen through cracks in the pavement in parts of the area south of Market Street in San Francisco suggest that some liquefaction may have occurred there as well. These areas have a high water table and are underlain by fine-grained sand. Apparently, extensive ground failure also occurred in the area near the toll plaza of the Bay Bridge. In most of these areas the damage due to liquefaction was limited to cracked or cratered pavement (Photos 12, 13, and 14). Perhaps the most dramatic example of this type of deformation was the structural damage to buildings in the Marina district.

CONCLUSIONS

Most of the damage from the Loma Prieta earthquake can be attributed to strong ground shaking, landsliding, or liquefaction. Each of these processes impacted man-made structures differently, reflecting the properties of both the structure and the underlying geologic materials. The most severe damage caused by ground shaking occurred in areas near the epicenter or located on poorly consolidated deposits or man-made fill. Ground shaking primarily affected unreinforced masonry structures, toppling chimneys throughout the region and partially to completely collapsing some brick buildings. Liquefaction affected areas underlain by fine-grained, well-sorted sand, resulting in damage to parking lots and contributing to major structural damage in the Marina district, and possibly south of the Market district. Landsliding primarily occurred in steep terrain near the epicenter where ground shaking was most severe.

The types and distribution of damage are very similar to those observed in previous earthquakes in this region confirming once again that areas of poorly consolidated deposits or fill and unreinforced masonry buildings pose serious hazards to public safety during major seismic events. The major lesson that can be learned from the Loma Prieta earthquake is not new. To minimize the damage from the catastrophic earthquake that is eventually coming, it is important both to identify areas and structures that are susceptible to severe damage during earthquakes and to adapt engineering designs to local geologic conditions.

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Photo 14. Pressure ridge developed on a parking lot at the Santa Cruz Boardwalk. Sand boils were also observed on the nearby pavement.

Earthquake Energy

Question:

How much larger was the San Francisco earthquake of April 18, 1906 than the Loma Prieta earthquake of October 17, 1989?

Answer:

The amount of energy released during the San Francisco earthquake of April 18, 1906 was over 63 times the amount of energy released during the Loma Prieta earthquake of October 17, 1989. This value is based on the Richter Scale magnitudes of 8.3 and 7.1 respectively and is derived using the following formula:

$$\sqrt{1000}^{(8.3-7.1)} \approx 63.1$$

For a half-unit increase in the Richter Scale (for example M=5.0 to M=5.5) there is a factor of the square root of 1,000 (approx. = 31.62) raised to the 0.5 power or 5.62 times the amount of energy released. For a unit increase in the Richter Scale (for example M=5 to M=6) there is a factor of the square root of 1,000 raised to the first power or 31.62 times in the amount of energy released. For a 1.5-unit increase in the Richter Scale (for example M=5.0 to M=6.5) there is a factor of the square root of a 1,000 raised to the 1.5 power or 177.83 times the energy release. For a two-unit increase in the Richter Scale (for example M=5 to M=7) there is a factor of the square root of 1,000 raised to the second power (or squared) or 1,000 times in the amount of energy released.